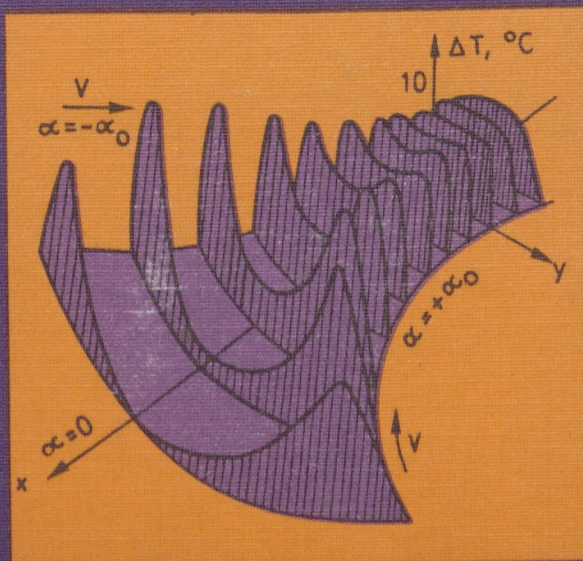


László Halász

Control methods in polymer processing



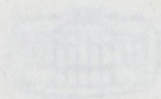
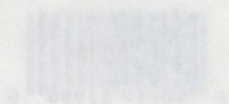


**Control methods
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László Halász D. Sc.

Military Technical Institute of
the Hungarian Army
Budapest, Hungary

NTFI



1993, 1994, 1995, Budapest 1993

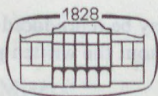
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Akadémiai Kiadó, Budapest 1993

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Introduction

For a considerable time the equipment used in the polymer processing and rubber industries was at a minimum level and no essential improvements occurred until the mid-sixties when the automatic open loop and closed loop control systems appeared, primarily as a consequence of analysis of the processes. These enabled the application of automatic process control, and development processes accelerated quite significantly as a result. Soon after, the computer entered the scene of process control, and subsequently, a computer-aided process control system evolved. From this point on, processing machines were provided with a control system capable of controlling the process variables to a certain degree. Thus increased efficiency of the machines became one of the basic considerations for application of further automation and some control and/or guidance mechanisms were built into existing equipment.

Apart from controlling individual machines, controls to suit the entirety of the technological processes could now be developed, aided by computers.

In this book, the controls of polymer processing methods are discussed from the various aspects of the processes, and as a result the course of the process and the factors influencing the quality of the product have come increasingly under consideration. The control methods employed for each of the individual processes will be presented in detail.

In Chapter 1, the fundamentals of the control, the general common features of polymer processing methods employed, the control variables and the measuring methods of the individual processes are analysed.

In the following chapter the mixing processes, the control methods of the mixing equipment, working either intermittently or continuously, are discussed.

Chapter 3 examines the parameters describing the calendering process of sheet and coating systems with specific emphasis on the control methods of calendering.

In Chapter 4 the working processes and the controls of the screw plasticating units are analysed. The text deals with the plasticating capabilities of a single screw unit, working either continuously or intermittently, as well as that of the twin screw units operated continuously. The factors influencing the quality of the melt are investigated together with the control of the operation of the plasticating units.

The process analysis of tube and sheet production lines and the control methods employed in the case of extruders are discussed in Chapters 5 and 6.

Chapter 7 deals with the actual process and control of film blowing.

Chapter 8 describes the blow moulding processes, including the analysis of the effects of the variables that influence quality aspects of the finished product(s), and this provides an opportunity to present an overview of the control methods employed.

The analysis and the control methods of injection moulding processes are considered in Chapter 9.

The structure of the individual chapters remains the same throughout the book. Each chapter is intended to provide a brief description of the parameters of the technological equipment employed. The steady state models of the processes concerned and the interrelationship of the parameters that influence quality are considered. The dynamics of the processes are described, and finally, a summary of the control methods is presented, applicable at various levels of operation and quality.

This book is hoped to fill a gap in plastic manufacturing control processes.

1 Fundamentals of Control Engineering

1.1 The Definitions and Classifications of Controls

The control application is an operation which puts a particular process in motion, changes that process, or stops it. During the application of a control, some kind of technical process is corrected in order to sustain its preplanned progress. The controlled technical process is that in which the process is under control, while the chosen parameter of the process, which is to be maintained at a specified value, is the controlled variable. The parameter which is capable of influencing the value of the controlled parameter is called the corrected variable, the modification brought about is termed the correction [1–11].

During the application of control the defined parameters of the process, called the controlled parameters, must be altered in a predetermined mode. Such parameters may be certain physical characteristics of the output material and the energy flow, such as the melt temperature, the heating body temperature or any internal parameter characteristic of the state of the process. The values of the controlled parameters are affected by the properties of the input material, by the energy flow and by the external environment; the latter is called the disturbing factor. The values of the controlled parameters would deviate from the set parameters due to the effects of the disturbances, unless the control equipment corrects these. The correction applied affects that parameter of the controlled process, which is specifically suited to bring about the appropriate influence on the controlled variable, which then becomes the corrected variable. The partial operations of the control process are as follows:

- (a) sensing: obtaining information about the process to be controlled;
- (b) evaluation: making a decision based on the sensed information, indicating that interference with the process is necessary;
- (c) actuating: a command is given to make corrections; and
- (d) correction: interference occurs to influence the processes by means of actuating corrections.

In general, the information is obtained by means of sensors. The evaluation of the information may be based, for instance, on comparisons of variables, to evaluate whether or not these values are the same or not the same. Based on the results obtained by this evaluation, actuating follows. The effects of actuating run through the transfer elements in the form of signals and then, modified on various members or units of the control chain, the signals enter the regulating control unit, which is brought into operation to achieve the desired effect. The signals are characterized by their information contents. The signal is a specific single value or a change in value of a physical state parameter, which is suitable for transmitting the information

unambiguously assigned to it. The control system itself consists of the equipment to be controlled and the instrument(s) capable of application of controls to such equipment. During the application of controls changes are brought about in the system. To bring about a desired change in a physical system a certain time-lag is required, this is a characteristic feature of any dynamic system. A dynamic system may be defined as a system, in which the momentary value of the output signals depends on the momentary and previous value(s) of the input and output signals and also on the rate of their change. The control chain may be considered to be a series of structural units which transport the effects of the control units. The most convenient way to analyse the functioning of a control system is to represent the system symbolically by a block diagram or a flow chart. The structural parts are represented by blocks, while the flow of the signals is represented by arrows. Thus the block diagram is a representation of the control chain to show the applied principles.

The structural parts of the control system are: the active unit, its elements and the signal wires. The active unit is an autonomous element of the control system which can solve a control task. The parts of the flow chart are the block, the controlled section, the direction of the signals and the signals themselves. The block is essentially a concept, representing the signal-forming features of a part of the control system chosen. The controlled section is a block containing the signal transfer capabilities of the equipment to be controlled. The direction of the signals represents the direction in which these signals pass through the blocks. The input signal is an independent external signal, which brings the block into operation, while the output signal is a signal produced during the operation of the block.

The control operations may be classified into two main operational systems, namely, the open loop and the closed loop systems. The signals are generated in the open loop control system by the actuating signal of sensor, x_a , the signals pass through the control chain, and the corrected variable of the final control element x_m becomes one of the input signals of the controlled equipment. After the required effect of the control action is accomplished the control action is terminated. In a closed loop control system the signals are initiated by the actuating signal x_a which represents the difference of the preset reference input, x_s , and the primary feedback x_c depending on the momentary value of the controlled variable, x_c , and these signals pass through the units in the control system, thus the output signal of the controller is the operating signal, x_{op} , the output signal of the operating unit is the corrected value x_m , which is one of the input signals of the controlled section. The corrected variable gradually diminishes the deviation between the controlled variable, x_c , and the predetermined value in the controlled equipment.

1.1.1 Open Loop Controls

In the case of the open loop system the system is governed by the input of the final control element in the form of actuating signals, according to a predefined order. The control chain is open in the sense that the control variable does not affect the original actuating signal. The actuating signal may be one or more well-defined characteristics of

the controlled process, but it may also be an external signal independent of the process. It may only be possible to eliminate the effects of the disturbances to a limited degree.

The different types of open loop control modes differ from each other basically in the design modes of controls. The control chain of the open loop system consists of two parts, the control(s) and the controlled section. In the case where a scheduled control is required with a time-lag, the main unit of the control equipment is the schedule storage, while in the case of programmed control application the main unit is the condition storage. These two types of the open loop control methods are collectively called programme or time schedule control. In follow-up control the most significant unit is the command unit.

The actuating signal of the schedule control is time. A schedule may be stored in the appropriate schedule storage. The final control element operates according to the preset schedule to achieve the desired effect in the process. The field of application of the schedule control is, however, limited, since it is seldom possible to make an accurate schedule in advance, and the effects of the unforeseen disturbances cannot be eliminated. The schedule control is mostly utilized for temperature control according to a preset programme or for the automatic starting and stopping of one of the units of the equipment at a given time.

In programmed control, the appearance of one or usually more actuating signals, that is, the establishment of certain conditions produces the input signal of the final control element. The actuating signals bring about the desired effect determined in the control programme. The process of programmed control may be divided into cycles, where final control elements are differently positioned. The individual cycles follow each other in a definite sequence, which is defined by a schedule plan. This schedule contains the conditions of terminating the previous part of the process and the beginning of the next one. These conditions may be determined from the specific cycles of the process. In programmed control, condition storage is required instead of the schedule storage for the development of the control mode. The condition storage ensures that the final control elements can start the necessary process schedule when certain conditions of the process are fulfilled.

The actuating signal of the follow-up control is given by the command signal, which may be a physical quantity chosen arbitrarily but appropriately. Change in the command signal is usually monitored by a separate sensor, and its output now becomes the actuating signal. This signal is transmitted to the command unit, which, in turn, operates the final control element by means of the operating signal. The signal of the final control element corrects the process of the controlled section as desired. Consequently, the control chain of the follow-up control consists of a sensing device measuring the command signal, a control unit, the final control element and the controlled section.

An open loop control may be assembled using connecting control units and basic elements or semi-conductor logical circuits. The parts of the control systems may be as follows:

- A controlled equipment on which process control is applied, where, from the control's point of view, the knowledge of the laws governing the operation of the process is important.

- The final control elements brought into operation on the effect of the output of the control equipment realizing the desired control effect.
- The control equipment produces the signals needed to control the process. It makes the final control elements operate and, hence, controls the process in accordance with a predefined programme, or predefined control input.

The block diagram of an open loop control is shown in Figure 1.1.a). Here, following the direction of the signal, the following units can be identified:

- information-sensing and actuating units (sensing elements),
- information processing, transmitting and logical decision making units (the control equipment),
- the final control elements influencing the controlled equipment.

The control equipment consists of various building blocks, elements, modules and devices. The building blocks are, generally, complex devices, such as part units and instruments, which are, however, able to perform independent operations and to carry out certain tasks. The larger units are assembled from elements. The building blocks are usually larger units, containing a number of elements. The functional unit is an assembly of the building blocks and elements designed to carry out complex but well-defined tasks.

The material and energy flows that take place in the controlled equipment prompt the detecting elements to supply the signals needed by the open loop control to accomplish and check its designated tasks. In the open loop systems the actuating units are connected with the units performing logical decisions and processing infor-

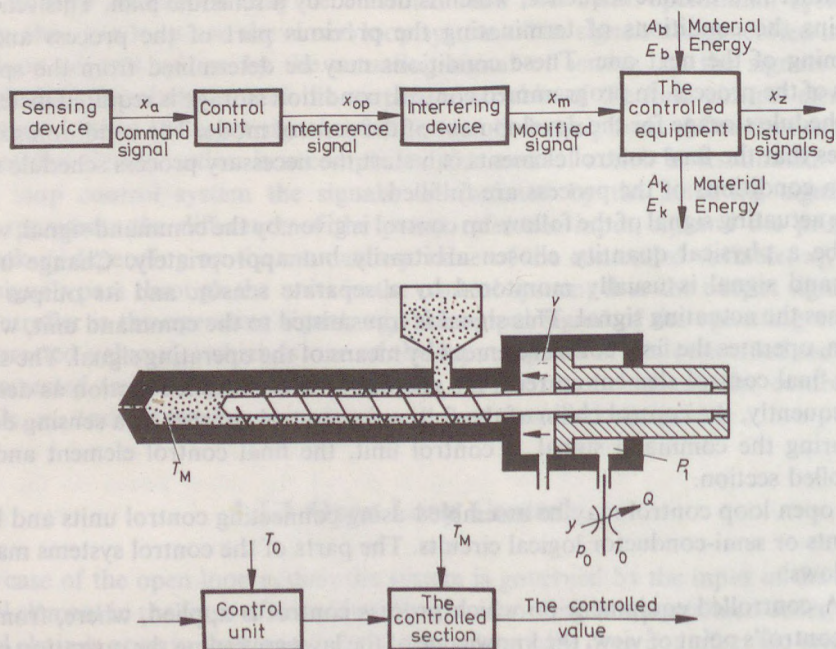
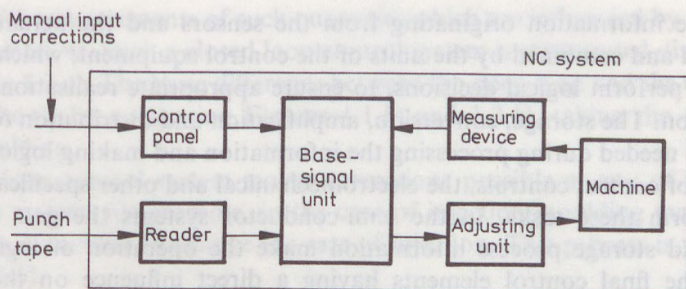
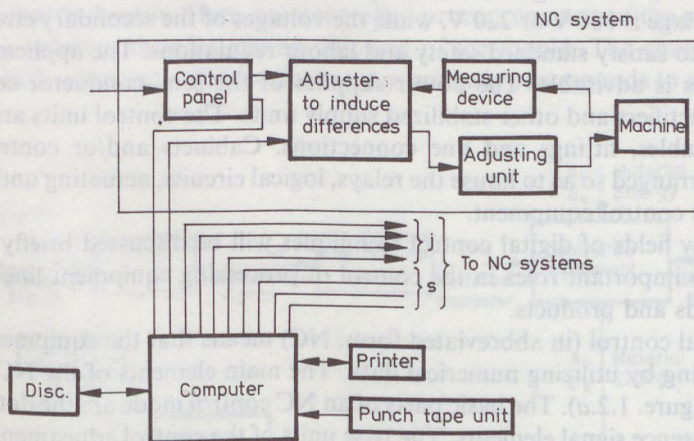


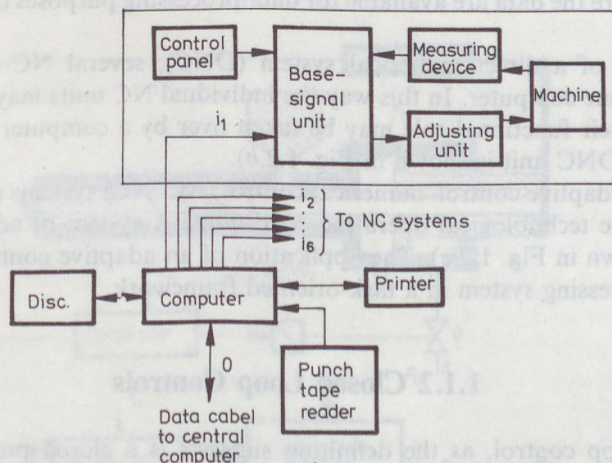
Fig. 1.1. Impact sketch of regulators, to regulate the speed of injection moulding



a)



b)



c)

Fig. 1.2. Numerical controls, direct numerical controls, and adaptive controls [1]

mation. The information originating from the sensors and the actuating units is transformed and combined by the units of the control equipment, which process the signals and perform logical decisions, to ensure appropriate realisation of the final control action. The storage, conversion, amplification and distribution of the signals received are needed during processing the information and making logical decisions. In the case of contact controls, the electromechanical and other specifically designed relays perform these tasks. In the semi-conductor systems the gate circuits, the inverters and storage process information make the operation of logical decision possible. The final control elements having a direct influence on the controlled equipment may be either electric, hydraulic or pneumatic.

The circuits performing the control operations are connected to transformers. The primary voltage is 380 V or 220 V, while the voltages of the secondary circuits should be selected to satisfy standard safety and labour regulations. The application of very low voltages is advisable. The power supplies of the semi-conductor control units consist of rectifiers and other stabilized supply units. The control units are connected by wires, cables, fittings and line connections. Cabinets and/or control consoles should be arranged so as to house the relays, logical circuits, actuating units and other parts of the control equipment.

Some new fields of digital control techniques will be discussed briefly which play increasingly important roles in the control of processing equipment lines producing plastic goods and products.

Numerical control (in abbreviated form: NC) means that the equipment performs the processing by utilizing numerical data. The main elements of the NC system are shown in Figure. 1.2.a). The basic parts of an NC control mode are the data input unit and the reference signal elements. The base units of the control adjustment system are the measuring and adjusting units. The data input unit comprises a reading unit and a memory where the data are available for data-processing purposes during manufacturing.

In the case of a direct numerical system (DNC), several NC equipments are connected to one computer. In this way the individual NC units may be made much simpler and their functional role may be taken over by a computer. The schematic diagram of a DNC unit is shown in Fig. 1.2.b).

The use of adaptive control-numerical control (AC-NC) systems make it possible to optimize the technological operating conditions. A system of adaptive machine control is shown in Fig. 1.2.c). The application of an adaptive control system optimizes the processing system in a task-oriented framework.

1.1.2 Closed Loop Controls

The closed loop control, as the definition suggests is a closed process. Here, the sensing element of the control measures the controlled variable and modifies the corrected variable accordingly, in the controlled process the controlled variable is determined by the corrected variable, thus, the changes provide feedback information to the control, in the form of measured results. Hence, closed loop control processes

commence with measurements of such quantities which are influenced by the control processes themselves. Such a closed loop control system is represented diagrammatically in Figure 1.3.a). The basic difference between the open loop and the closed loop controls is shown by comparing Figures 1.1.b) and 1.3.b), taking the example of injection moulding.

The open loop control system makes corrections possible at any of the specific points of the system; for example, in the case of injection moulding machines, the system makes it possible to change the rate of injection. This process is represented by Figure 1.1.b).

The correction is made by variable y (an adjustment is made by a wheel). The control module in this case consists of an oil tank, which maintains an oil pressure p_0 at the adjustable throttle. Here, the controlled process consists of the processes of the hydraulic cylinder, the plasticating unit and of the mould. The control module performs its task when each wheel adjustment y precisely corresponds to an injection

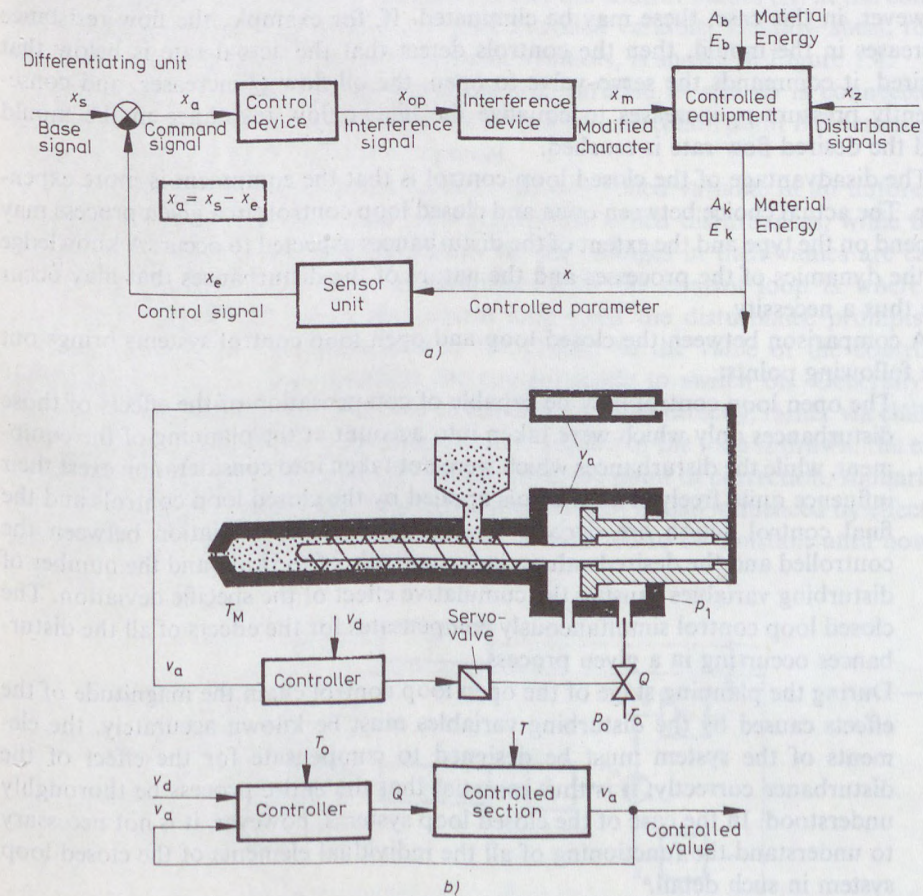


Fig. 1.3. Impact sketch of controls for controlling the velocity of injection moulding

rate v . This is possible only when all the other variables are kept constant in the mould tool, i.e. the pressure and the temperature of the oil, the melt temperature, the viscosity of the hydraulics oil, the melt viscosity and the flow resistance. In the case of the control equipment shown in the diagram all these merely mean that the rate of injection drops upon the application of stronger throttling of the oil flow, Q . The value of the ensuing rate, however, depends on the given mould and other variables.

This clearly shows the deficiency of the open loop control: unknown disturbances also participate in the determination of the output values. Thus, the open loop system is a suitable control method of a specific process only when the disturbances that may possibly occur influence the control variables only to a minor degree.

The schematic diagram of the closed loop system controlling the rate of injection is given in Fig. 1.3.b). In contrast to the open loop system, here the rate of injection (v_d) is set and the actual rate (v_a) is continuously monitored by the sensors. The control mode makes a comparison between the desired and the actual values and it continuously adjusts the servo-valve, so that the two values coincide.

The same disturbances act on the closed loop processes as on the open loop system; however, in this case, these may be eliminated. If, for example, the flow resistance increases in the mould, then the controls detect that the actual rate is below that desired, it commands the servo-valve to open, the oil flow Q increases, and consequently pressure p_1 increases to equalize the higher flow resistance in the mould and the desired flow rate is reached.

The disadvantage of the closed loop control is that the equipment is more expensive. The actual choice between open and closed loop controls in a given process may depend on the type and the extent of the disturbances expected to occur. A knowledge of the dynamics of the processes and the nature of the disturbances that may occur are thus a necessity.

A comparison between the closed loop and open loop control systems brings out the following points:

- The open loop control may be capable of compensation of the effects of those disturbances only which were taken into account at the planning of the equipment, while the disturbances which were not taken into consideration exert their influence quite freely. The controls applied by the closed loop controls and the final control action are derived on the basis of the deviation between the controlled and the desired values, independently of the kind and the number of disturbing variables causing the cumulative effect of the specific deviation. The closed loop control simultaneously compensates for the effects of all the disturbances occurring in a given process.
- During the planning stage of the open loop control chain the magnitude of the effects caused by the disturbing variables must be known accurately, the elements of the system must be designed to compensate for the effect of the disturbance correctly; it is thus essential that the entire process be thoroughly understood. In the case of the closed loop systems, however, it is not necessary to understand the functioning of all the individual elements of the closed loop system in such detail.
- One of the characteristic features of the open loop system is that a well-dimen-

sioned open loop system is capable of maintaining the controlled variable at the desired value, since it detects the disturbing variable directly and makes the correction before the controlled variable shifts from the desired value. The principle of the operation of the closed loop control system is based on detectable differences, which initiate the operation of the controller.

- An advantage of the open loop system is that in the absence of feedback, problems associated with stability do not arise.

1.2 Features of the Closed Loop System

The closed loop consists of two parts: the controlled process (manufacturing plant) and the control devices. The control devices are in contact with each other at those points at which corrections are made and measurements are taken. The common characteristics of the controlled process (S) and the control modes (R) at the contact point are the controlling variable and the controlled variable. The flow sheet, representing the closed loop controls in terms of symbols, is shown in Figure 1.4.

The control R (which yields the correction variable at site B) is connected at measuring point M . The measuring point M and the correction point B determine the controlled process part S of the equipment.

The effects which influence the value of the controlled variable in an unforeseen way, independently of the closed loop system, are called disturbances, while those variables which give rise to disturbances via the changes in their values are called disturbing variables. The point of disturbance in the control loop is where the disturbing variable enters. In the control loop itself the disturbance prompts the control into operational mode, due to the change in the value of the controlled variable and this, in turn, prompts the control mode to switch on. Generally the disturbing variables do not affect the controlled variables directly, rather via changes in the process. Thus, when a simplified representation of the loop is drawn, the entry of the disturbing variables is usually indicated at the point of correction, similarly to that of the correction variable. The closed loop system is also influenced by effects to change the value of the controlled variable, considered to be constant until now, in

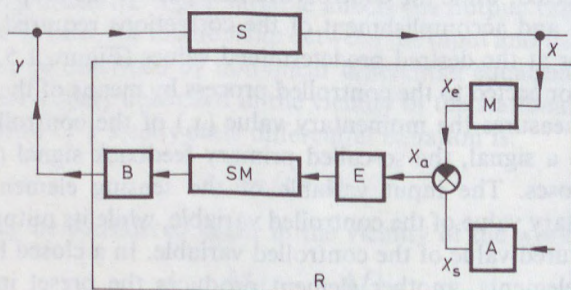


Fig. 1.4. An operational control loop

accordance with the process. Such a correction, which is intended to change the value of the controlled variable (and to be maintained by the control) is called guidance, while the variable causing the change is called the control input (x_1). The equipment intended to induce a change in a setting is to be connected to the control mode. Thus, in the simplified representation the entry of the guidance may be placed (and this is the usual case), at the same position in the loop where the controlled variable appears, that is, to the point at which measurements are taken.

The closed loop control may also be classified on the basis of the change of the controlled variable. The setpoint of the controlled variable is that value, which is set by the control and intended to be maintained by the control.

When the setpoint is set manually and is left unaltered, it is termed a fixed point control. This fixed value remains valid until it is changed again manually. If the setpoint changes automatically according to a predetermined time function, then it becomes a time schedule control. If this control is a function of the value of another variable, it is called a follow-up control.

Controls may be classified according to the type of correction variables. Those controls where the correction variable may acquire any value within a certain range of correction, are called continuous controls. The range of the correction is that region of values, where these controls are capable of setting the values of the correction variables.

Where non-continuous controls are employed the correction variable may only acquire certain defined values, while those which may acquire two different values are called dual position controls. The latter is also a non-continuous control.

To move the final control elements (or regulating units) and hence to change the value of the correction variable, certain quantities of energy are required. Where the sensor itself is capable of providing the power needs, this power may be obtained from the sensor that is, from the process. Such controls do not need an auxiliary power source. If the final control element is operated by an auxiliary power source, this is then termed control operation by auxiliary power.

The closed loop itself may be divided into two well-defined, distinct parts, namely, the controlled section (S) and the control unit (R). The controlled section is that part of the closed loop system, which is independent of the controls, but it is still an indispensable component of the process. Thus, the given process section is some kind of technical equipment. It becomes an integral part of the controlled process when the controls are connected, while the controls are that part of the loop which is used for the determination and accomplishment of the corrections required to maintain the corrected variables at the desired predetermined values (Figure 1.5.).

The control is connected to the controlled process by means of the sensing element (M). The latter measures the momentary value (x_s) of the controlled variable and transforms it into a signal, the so-called primary feedback signal (x_e), suitable for comparison purposes. The input variable of the sensing element is always the measured momentary value of the controlled variable, while its output variable is the signal of the measured value of the controlled variable. In a closed loop, in addition to the detecting elements, another element produces the preset input (x_p), representing the desired value of the controlled variable. This is the preset signal-producing

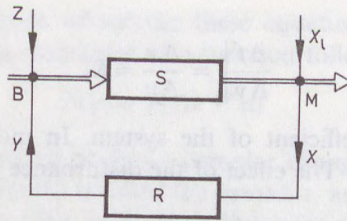


Fig. 1.5. Constituent parts of a control loop

element (A). Naturally, the preset signal must be produced in terms of the same physical quantity than the control signal to allow direct comparison. Where a constant value control is employed, the preset input is a long-term constant, called the reference signal (x_p).

The operation of the closed loop control is based on the differences between the control and the reference input. Therefore, the above two variables need to be continuously compared against each other, and for this purpose it is often necessary to employ an additional differentiating element (D) to produce the so-called actuating signal (x_a) to initiate the corrections. The differentiating element has two input signals, such as the control input and the primary feedback signals and its output signal is the actuating signal. The power output of the actuating signal is generally less than the power output needed to correct the controlled process. In this case it is necessary to include in the system an amplifier (E), which increases the power output of the actuating signal, utilizing an external energy source.

The final control element usually consists of two parts, one element is the actual final control element (B), while the other is the auxiliary motor (SM), etc., driving the final control element. In addition to the above, other elements may also be included in a closed loop system, for example, the so-called compensating element to improve the functional quality of the closed loop system.

1.2.1 The Steady State of the Closed Loop

The effect of the elements in the closed loop on the control process depends only on the laws according which the input variable affects the output variable in the given element. In a general case, the relationship between the input and the output variables of the process can be described by non-linear differential equations. For simplicity, these equations are usually linearized in the vicinity of the stationary working point. The general solution of a steady state differential equation is:

$$x = f(y, z) \quad (1.1)$$

This equation may be considered linear in the vicinity of the working point 0:

$$\Delta x = \left. \frac{\Delta f}{\Delta y} \right|_0 \Delta y + \left. \frac{\Delta f}{\Delta z} \right|_0 \Delta z \quad (1.2)$$

If $\Delta z = 0$, the formula

$$\left. \frac{\Delta f}{\Delta y} \right|_0 = \frac{\Delta x}{\Delta y} = K_s \quad (1.3)$$

represents the transfer coefficient of the system. In most cases this can only be determined experimentally. The effect of the disturbance is obtained by substituting $\Delta y = 0$

$$\left. \frac{\Delta f}{\Delta z} \right|_0 = \frac{\Delta x}{\Delta z} = K_z \quad (1.4)$$

The transfer properties of the closed loop system are expressed in a steady state by the equations (1.3) and (1.4). The transfer coefficients K_s and K_z give the degree of influence exerted on the controlled variable by the control and disturbing variables. The simplest controls consist of a proportional member, which amplifies or reduces the actuating signal x_a by a factor K_p , depending on whether $K_p > 1$ or $K_p < 1$. Hence, the operating signal y is given by the following equation

$$y = K_p x_a + y_0 = K_p (x_s - x) + y_0 \quad (1.5)$$

Here, if $x_a = 0$, the value of y may even be zero.

Combining equations (1.3), (1.4) and (1.5), the closed loop system gives the relationship

$$x = K_s y + K_z z \quad (1.6)$$

$$y = K_p \cdot x_a \quad (1.7)$$

By eliminating the operating signal y , the behaviour of the closed loop in a steady state becomes

$$x = \frac{K_s K_p}{1 + K_s K_p} x_s + \frac{K_z}{1 + K_s K_p} z \quad (1.8)$$

The fraction $1/(1 + K_s K_p)$ gives the extent to which the closed loop system attenuates the effect of a given disturbance, as compared with the open loop control. The smaller the value of the above fraction, the weaker is the influence of the disturbance on the controlled variable. This means that attempts should be made to make K_p as large as possible.

1.2.2 Time Functions and Linear System Analysis

It has so far been ignored that in every system, in practice, a certain time lapse exists until the output variable x_{out} attains a new steady state induced by a change of the input variable, x_i .

The relationship between the input and the output variables of the transmitting system may be expressed by non-linear differential equations in a general case. Such a system of equations may be investigated by transforming the expression into linear differential equations with constant coefficients:

$$a_n x_a^n + a_{n-1} x_a^{n-1} + \dots + a_1 x_a + a_0 x_a = b_m x_e^m + b_{m-1} x_e^{m-1} + b_1 x_e + b_0 x_0 \quad (1.9)$$

One of the general methods of solving these equations is to use the Laplace transformation. The Laplace transform of a function follows the correlation

$$F(p) = \int_0^\infty f(t) e^{-pt} dt \quad (1.10)$$

The Laplace transformation thus assigns a complex change function $F(p)$ to a time function $f(t)$. Such an assignment is called the operator, and such methods based on Laplace transformation are called, collectively, operator methods.

Now, consider a system, which can be represented by a differential equation of the second order, where the input signal is designed by y , while the output signal is designed by x . The expression is:

$$a_2 \ddot{x} + a_1 \dot{x} + a_0 x = b_1 \dot{y} + b_0 y \quad (1.11)$$

By assuming initial zero conditions, the Laplace transformation gives:

$$a_2 p^2 x + a_1 p x + a_0 x = b_1 p y + b_0 y \quad (1.12)$$

From this the transfer function is derived as:

$$F(p) = \frac{x(p)}{y(p)} = \frac{b_1 p + b_0}{a_2 p^2 + a_1 p + a_0} = K \frac{T_3 p + 1}{T_2^2 p^2 + T_1 p + 1} \quad (1.13)$$

$$\text{where } K = \frac{b_0}{a_0}; T_1 = \frac{a_1}{a_0}; T_2^2 = \frac{a_2}{a_0}; T_3 = \frac{b_1}{b_0}$$

The quantities T have the dimensions of time, therefore these are time constants. K is the transfer coefficient which expresses the relationship between the steady values of x and y , provided that the steady value of y is constant.

In order to make comparisons possible between the various systems it seems feasible to derive the solution of equation (1.9) for entirely determined input functions, the so-called examining functions.

Step Functions

At time $t=0$, let the input function $x_i(t)$ change abruptly to value x_{i0} . Then,

$$x_i(t) = x_{i0} S(t) \quad (1.14)$$

where $S(t)$ is the unit step function, with the boundary conditions:

$$S(t < 0) = 0$$

$$\text{and} \quad S(t > 0) = 1 \quad (1.15)$$

Its Laplace transformation is:

$$\mathcal{L}[S(t)] = \frac{1}{p} \quad (1.16)$$

Multiplying the transfer function by $\frac{y}{p}$ and taking the inverse transformation of the formula obtained, a solution of the differential equation of the system under con-

sideration is obtained, belonging to the step function input signal. Figure 1.6. shows the input and output functions of a system with proportional operation characteristics. The curve represents one of the possible solutions of the above differential function. A further effect is represented in this figure, which sometimes occurs in an actual system. This is that the output variable $x_{out}(t)$, does not change at all during the so-called "dead time" (T_d) after connection is made with the input variable. After the lapse of this dead time T_d , the output variable $x_{out}(t)$ corresponds exactly to the solution of equation (1.9). The quotient, $x_{out}(t)/x_{i0}$ is the transfer equation of the system. In practice, it is rather difficult to define the constants a_n , b_m from the transfer function derived graphically. The dead time T_d , the starting time T_i and the lag time T_l have proved fairly useful in practice for the approximate characterization of the system. The starting time T_i , and the lag time T_l may be determined in the following way. Draw a tangent to the inflexion point of the curve $x_{out}(t)$, the point of intersection with the abscissa yields time $T_d + T_i$, while the point of intersection of the tangent and the value corresponding to the new constant state gives the sum of $T_d + T_i + T_l$. The transfer factor K_s of the transfer element is obtained from the quotient $K_s = \frac{x_{i0}}{x_{out0}}$.

Impulse Function

By choosing a Dirac function $\delta(t)$ as the generating function, the input impulse function and the response function are shown in Figure 1.7. The special form of the Dirac delta function is:

$$\lim_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} \int_0^{\varepsilon} \delta(t) dt = 1 \quad (1.17)$$

The Laplace transform of this formula equals unity, so the inverse transform of the transfer function gives just the solution of the differential equation of the system

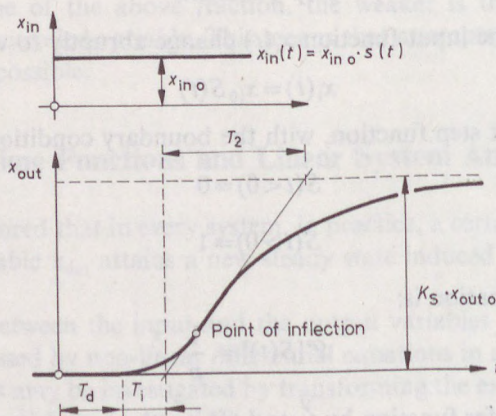


Fig. 1.6. Step function and its response

T_d , dead time; T_i , start time; T_l , lead time; K_s , gain factor

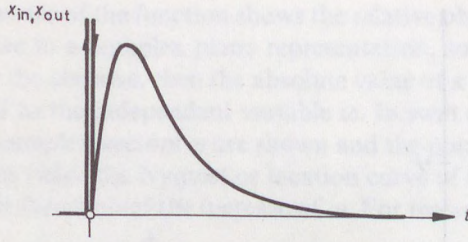


Fig. 1.7. Impulse function and its response

analysed belonging to the Dirac impulse case. This is often called the weight function of the system. This function is shown in Fig. 1.7, where the weight function is $g(t) = x_{out}/x_{i0}T$. If this is known, the output variable $x_{out}(t)$ may be calculated for any $x_i(t)$, by using the following equation:

$$x_{out}(t) = \int_0^t x_i(\tau)g(t-\tau) d\tau \quad (1.18)$$

Sine Function

The system may be generated by a periodically changing signal, for example, by a sine function with amplitude y and cycle frequency ω . Once the self-excitation processes are over, the output signal of a linear system also changes according to a harmonic function, with a frequency equal to that of the input signal but with a different amplitude and phase. The relationship between the generating function and the response function of the system is given by the frequency function. Let us now consider a system that can be characterized by a second-order differential equation. The generating function is

$$y(t) = y_0 \sin \omega t \quad (1.19)$$

then

$$x(t) = x_0 \sin(\omega t + \varphi) \quad (1.20)$$

Substituting into the differential equation and transforming the trigonometric functions by the Euler function, gives:

$$\begin{aligned} x_0 e^{i\varphi} (ia_2 \omega^2 + a_1 \omega - ia_0) e^{i\omega t} + x_0 e^{-i\varphi} (-ia_2 \omega^2 + a_1 \omega + ia_0) e^{-i\omega t} = \\ = y_0 (b_1 \omega - ib_0) e^{i\omega t} + y_0 (b_1 \omega + ib_0) e^{-i\omega t} \end{aligned} \quad (1.21)$$

The frequency function is:

$$F(\omega) = \frac{x_0}{y_0} e^{i\varphi} = \frac{ib_1 \omega + b_0}{-a_2 \omega^2 + ia_1 \omega + a_0} = K \frac{i\omega T_3 + 1}{-\omega^2 T_2^2 + i\omega T_1 + 1} \quad (1.22)$$

The transfer coefficient and the time constants are the same as given by equation (1.13) above. Thus, it can be seen that the frequency function could have been derived by substituting $i\omega$ for p in the transfer function. This approach is generally valid.

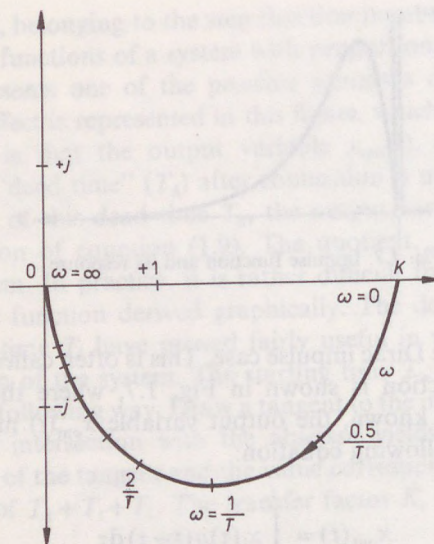


Fig. 1.8. Proportional, constant time section, Nyquist's curve

From equation (1.22) it is obvious that the frequency function is a function with complex variables. Here, instead of time, the frequency function ω is employed. The absolute value of the frequency function yields the relationship between the am-

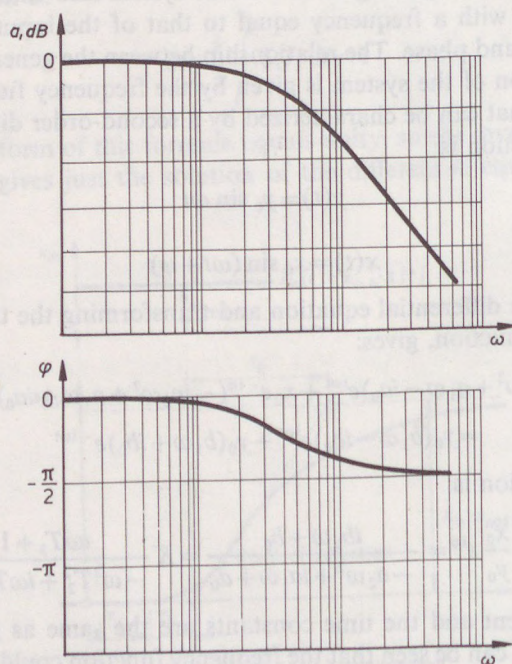


Fig. 1.9. Proportional, constant time section, Bode diagram

plitudes of x and y , the arc of the function shows the relative phase deviation between x and y . Plotting these in a complex plane representation, so that the actual component is depicted on the abscissa, then the absolute value of a given function and an arc value are assigned to the independent variable ω . In such a representation, only the end points of the complex vectors ω are shown and the points are connected with a continuous line. This yields the Nyquist or location curve of the system. The arrow on the curve shows the direction of the increase of ω . For instance, the location curve of the frequency curve $F(\omega) = \frac{K}{i\omega T + 1}$ is shown in Figure 1.8. It may be pointed out

here that the scales of the angular frequency are not uniform, thus representation over several orders of magnitude is difficult. For this reason, a more common practice is to represent the absolute values and the arc of the frequency function in separate coordinate systems. The logarithm of the angular frequency is depicted on the abscissa, the arc of the function on one of the ordinates, while the absolute values of the function, expressed in decibels, are depicted on another ordinate. (The measured decibel values are equal to the twentyfold multiple of its base 10 logarithm.) This is the Bode diagram of the given system, see Figure 1.9. The Nyquist and Bode diagrams play important roles in the analysis of the stability of systems.

Some of the differential equations, symbols, and the frequency functions of some of the simpler transfer blocks are summarized in Table 1.1. The control chains and loops are produced by a combination of the transfer blocks. Figure 1.10. shows the basic combinations of the transfer blocks. In Figure 1.10.a) the blocks, connected in series having transfer functions F_1 and F_2 are presented, expressed by the equation:

$$x_{out} = F_1 F_2 x_i \tag{1.23}$$

showing the relationship between the input and the output variables.

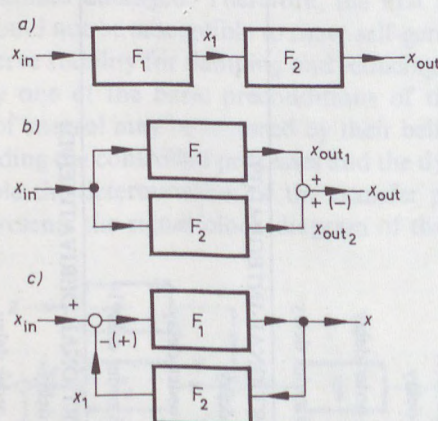


Fig. 1.10. Base combination on transfer members
a) Connection in series, b) Parallel connection, c) Feedback connection

Table 1.1.1. Classification of simple transfer members

Type	Equation	Frequency function
PROPORTIONAL(P)		
without delay	$T_0 V = U$	$F(i\omega) = \frac{1}{T_0}$
with 1st order delay	$T_1 V' + T_0 V = U$	$F(i\omega) = \frac{1}{T_1 i\omega + T_0}$
with 2nd order delay	$T_2 V'' + T_1 V' + T_0 V = U$	$F(i\omega) = \frac{1}{T_2 (i\omega)^2 + T_1 i\omega + T_0}$
INTEGRAL(I)		
without delay	$V = R_{-1} \int U dt$	$F(i\omega) = R_{-1} (i\omega)^{-1}$
with 1st order delay	$T_1 V' + V = R_{-1} \int U dt$	$F(i\omega) = \frac{R_{-1} (i\omega)^{-1}}{T_1 i\omega + 1}$
with 2nd order delay	$T_2 V'' + T_1 V' + V = R_{-1} \int U dt$	$F(i\omega) = \frac{R_{-1} (i\omega)^{-1}}{T_2 (i\omega)^2 + T_1 i\omega + 1}$
PROPORTIONAL-INTEGRAL(PI)		
without delay	$V = R_0 U + R_{-1} \int U dt$	$F(i\omega) = R_{-1} (i\omega)^{-1} + R_0$
with 1st order delay	$T_1 V' + V = R_0 U + R_{-1} \int U dt$	$F(i\omega) = \frac{R_{-1} (i\omega)^{-1} + R_0}{T_1 i\omega + 1}$
with 2nd order delay	$T_2 V'' + T_1 V' + V = R_0 U + R_{-1} \int U dt$	$F(i\omega) = \frac{R_{-1} (i\omega)^{-1} + R_0}{T_2 (i\omega)^2 + T_1 i\omega + 1}$
PROPORTIONAL-DERIVATIVE(PD)		
without delay	$V = R_1 U' + R_0 U$	$F(i\omega) = R_1 i\omega + R_0$
with 1st order delay	$T_1 V' + V = R_1 U' + R_0 U$	$F(i\omega) = \frac{R_1 i\omega + R_0}{T_1 i\omega + 1}$
with 2nd order delay	$T_2 V'' + T_1 V' + V = R_1 U' + R_0 U$	$F(i\omega) = \frac{R_1 i\omega + R_0}{T_2 (i\omega)^2 + T_1 i\omega + 1}$
PROPORTIONAL-INTEGRAL DERIVATIVE(PID)		
without delay	$V = R_1 U' + R_0 U + R_{-1} \int U dt$	$F(i\omega) = R_1 i\omega + R_0 + R_{-1} (i\omega)^{-1}$
with first order delay	$T_1 V' + V = R_1 U' + R_0 U + R_{-1} \int U dt$	$F(i\omega) = \frac{R_1 i\omega + R_0 + R_{-1} (i\omega)^{-1}}{T_1 i\omega + 1}$
with 2nd order delay	$T_2 V'' + T_1 V' + V = R_1 U' + R_0 U + R_{-1} \int U dt$	$F(i\omega) = \frac{R_1 i\omega + R_0 + R_{-1} (i\omega)^{-1}}{T_2 (i\omega)^2 + T_1 i\omega + 1}$

The entire transfer function is the product of the individual transfer functions. In Fig. 1.10.b) a parallel connection is plotted, obeying the following equation:

$$x_{\text{out}} = x_{\text{out1}}(I)x_{\text{out2}} = (F_1 + F_2)x_i \quad (1.24)$$

Figure 1.10.c) shows the feedback circuit diagram. This feedback may be positive or negative depending on the sign at the point of comparison. The transfer function is:

$$x_{\text{out}} = \frac{F_1}{1(\pm)F_1F_2} x_i \quad (1.25)$$

The positive sign relates to a negative feedback, the negative sign corresponds to positive feedback. From the three basic circuits, optional variations can be built to fit specific applications.

1.2.3 Requirements for the Closed Loop Control System

The task of the closed loop control system is to keep the controlled variables at the given values. In practice, no closed loop control system exists capable of fulfilling this intended task adequately. Therefore, the requirements embodied in the closed loop control system must also be governed by economic considerations. These requirements generally concern

- (a) the range of stability,
- (b) the control deviation in stationary operation,
- (c) the quality of the control processes.

Automatic closed loop control, in general, is accomplished via elements with delay. As a result, in the closed loop system, action is followed by a delayed reaction, which makes the closed loop control susceptible to self-generating oscillations. If the controls are designed and set properly, the possible ensuing oscillations become damped and soon cease, otherwise the amplitude of oscillations will increase progressively, and the equipment becomes damaged. Therefore, the first requirement is that the closed loop control should not be susceptible to these self-generating oscillations and that it should have reserve stability for damping and reducing these generated oscillations. Stability is only one of the basic preconditions of the proper operation of controls. The quality of control may be assessed by their behaviour under operating conditions. Understanding the controlled processes and the dynamic behaviour of the controls makes possible the determination of the transfer properties of the closed loop. Figure 1.11. represents the signal block-diagram of the loop. The disturbance

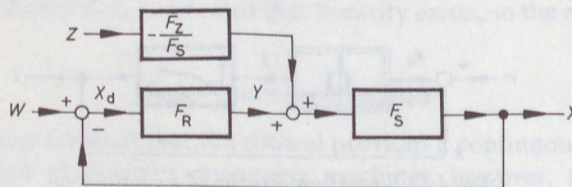


Fig. 1.11. Control loop, signal flow diagram

affects the controlled variable through F_z (it is assumed that there is only one disturbing variable). The entry point of the disturbance is frequently shown before the particular section of the process being controlled. Changing Figure 1.11. accordingly, the arrangement depicted in Figure 1.12. is obtained. If $F_s = F_z$, the effect of the change in the disturbing variable is the same as that of the change in the operating variable thus the following relationship may exist between the input and output variables:

$$x = \frac{F_R F_s}{1 + F_R F_s} x_i + \frac{F_z}{1 + F_R F_s} z \quad (1.26)$$

The first term of the right hand side of the equation is the resultant transfer function related to the preset signal, while the second term is the resultant transfer function, related to the disturbing signal. The denominator of the transfer function shows the stability of the system.

The merits of the closed loop control may be judged by the following considerations:

If the loop is influenced by the above characteristic effects, the value of the controlled variable is altered. This alteration comprises both temporary and long-term components.

If the control input (x_i) is changed abruptly by a value corresponding to the unit jump function in the closed loop, the process of control starts on the effect of the actuating signal appearing at the output of the comparison control unit. The momentary value of the controlled variable ($x = f(t)$) will not be identical with the preset value x_p . The difference between the momentary value and the control value is the control deviation. In the case where a deviation exists also in the steady state of control, this is referred to as a sustained deviation. This sustained deviation is a measure of the static accuracy of the control. After an abrupt disturbance in the loop, the controlled variable does not reach its new stabilized value (x_{st}) immediately. That part of the control deviation which changes with time is called transient control deviation. The overshoot or excess correction (Δx_{ov}) represents the maximum deviation originating from the new stabilized value. The permitted control deviation ($\pm \Delta x_{all}$) represents the maximum allowable deviation which must not be exceeded in the given technical process.

Thus,

$$\Delta x_{ov} \leq \Delta x_{all}$$

The control time (T_c) is that time period, after which the controlled variable is allowed to differ by not more than the limiting value of the dynamic accuracy requirements (x_l) from its stabilized value. Finally, the accuracy of the controls is

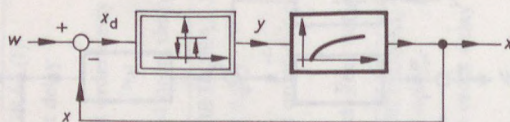


Fig. 1.12. Signal flow diagram of a control loop
The disturbing characteristics are converted to interference characteristics

also judged by the number of the oscillations of the controlled variable, occurring during the time period of application of controls. The quality of the process control is adequate when the sustained deviation is below the acceptable value and when the control time, the extent of over-correction and the oscillation numbers together do not exceed a certain predetermined value.

The process of control may be divided into two parts: transfer processes and steady state processes. The features of the transfer process are determined by the dynamic properties of the blocks constituting the closed loop system of controls, while the characteristics of steady state processes are determined by the static properties of the loop blocks.

In order to make the closed loop operate efficiently, the controls must be fitted to the loop in such a way that the behaviour of the closed system will become optimal. The determination of optimal behaviour depends on the purpose of the application and on the effects of the oscillations of the controlled variables.

1.2.4 Special Circuits of the Closed Loop System

Up to this point a single loop of the closed loop system had been analysed. In the following, some of the more complicated systems of considerable importance in practice are investigated.

Cascade Controls

In complex controlled processes it is often impossible to achieve satisfactory results with a single loop control. In such cases the controlled processes are subdivided into distinct parts. Thus one or more auxiliary controlled variables are also included in the total control system, in addition to the main controlled variable. Here, the main controller provides the preset signal to the auxiliary or follow-up controls.

Multivariable Controls

In a given piece of technological equipment there are usually numerous loops which may be set according to given rules, when the controlled variables are independent of each other. The basic characteristics of a multivariable control system will be described by taking a two-variable control system as an example. Here the canonical P method of representation is used for the block diagram illustration (Figure 1.13.). The fundamental concept of this method is that in each case a single input is made in order to learn about and define the transfer properties of the process, and the responses of both outputs are detected. It is assumed that linearity exists, so the effects may simply be summed.

Non-Continuous Controls

It has so far been assumed that the control provides a continuous, varying output signal. In the case of polymer processing machines, however, two-position and three-position controls are quite common.

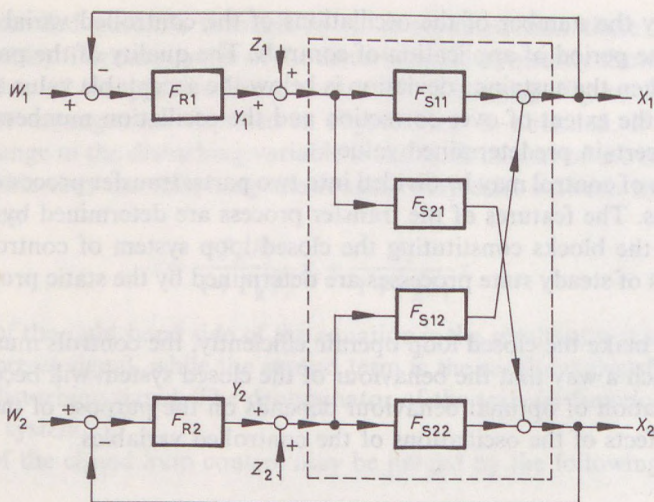


Fig. 1.13. A signal flow diagram with two parameters; a canonical P diagram

Two-Stage Controls

The two-stage controls consist of switches with only two possible positional modes, such as the ON position: $y = Y_h$ and OFF position: $y = 0$. In Figure 1.14. a loop with such two-stage controls is shown. The process under consideration is a first order delay system with a dead time of T_d , where

$$F_s = \frac{K_s e^{-T_d p}}{T_1 p + 1} \quad (1.27)$$

In Figure 1.15. the response and the step function of the closed loop and the change of the correction variable are shown. At time $t=0$ the preset signal is changed from $w=0$ to $w=w_0$. The actuating signal, x_d , now steps to the value of w_0 , the two-position control is switched to the ON position and releases a correction signal y_k . After dead time T_l the controlled variable begins to increase exponentially, while simultaneously the actuating signal decreases. However, the two-position block does not switch on precisely at the time when the value of x_a is reached, it switches on when the value of x_a exceeds the value $a + x_u$, or its value falls below $-x_u$. Owing to the existence of dead time in the process, the effect of the operating variable can

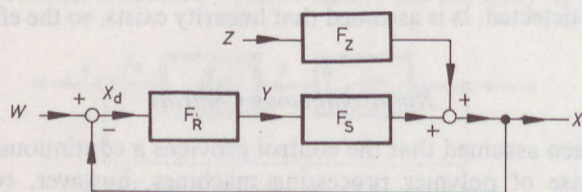


Fig. 1.14. Control loop with a two-position switch

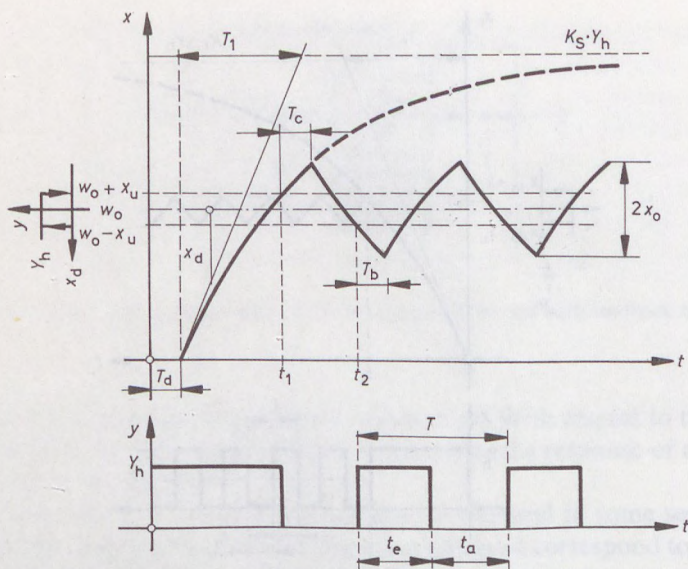


Fig. 1.15. Two-position controls, depicting the controlled features and the disturbing features as a function of time $2x_u$ hysteresis of a two-position member

be detected only after time T_1 , and when it reaches the value of $a + x_u$ the control is switched on again. From here on this procedure is repeated, thus, the controlled variable oscillates around the reference input value w_0 . Thus, the corresponding change in correction variable will be a periodic switch on and off function. The control described above suffers from a significant disadvantage, that the x_u value must be kept at a predetermined minimum value, otherwise the frequency of switching on and off will be very high. In order to ensure general application of two-stage controls, the two-stage block is provided with feedback information (Figure 1.16.). Figure 1.17. shows the response to the jump function of a two-stage block with feedback. Thus it is possible to make the controlled process operate on the mean value of the operating variable. By analysing the change of the operating variable shown here, it can be shown that the control resembles the behaviour of a continuous PD control. The

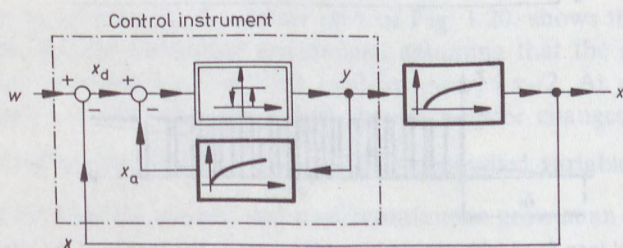
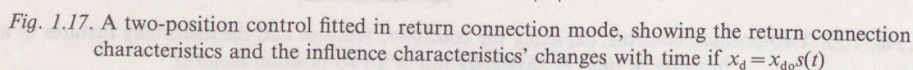
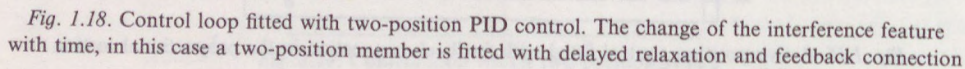


Fig. 1.16. A two-position control fitted with feedback connection in the proportional section



two-stage block with feedback may be regarded as equivalent to a continuous PD control, thus a sustained deviation persists. This disadvantage can be completely overcome if the two-stage block is provided with a damping feedback system (Figure 1.18.). This unit exerts its effect by producing longer impulses initially, followed by a shorter impulse, when the actuating signal changes in a step-like fashion. Once this feedback is terminated, the length of the transmitting impulses increases continuously.



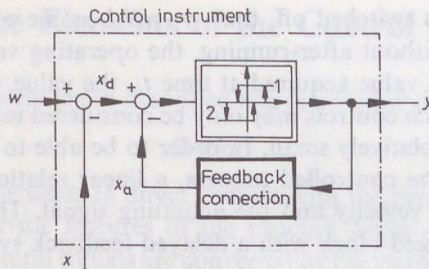


Fig. 1.19. A two-position member with two switching positions and with feedback connections

until the control will remain permanently switched on. With respect to the change in the mean value of the correcting variable, it resembles the response of a continuous PID control to a step function.

In cases where heating or cooling processes are required in some sections of the controlled process, the heating and cooling processes must correspond to the momentary state of the controlled process concerned. For this purpose two-stage controls are used, with two switching positions (Figure 1.19.). While heating is necessary, it operates in position 1, and while cooling is necessary, it operates in position 2. The operating methods in all instances resemble simple two-position controls. It is possible to supply varying feedback information to each of the switching positions, so that the controls may have different dynamics in the heating and in the cooling modes.

Three-Stage Stepping Controls

A three-stage block usually consists of a three-position amplifier switch, operated by means of servomotors, and its position, regarded as the correction variable y , is utilized to induce continuous changes in the material flow or in the energy flow of the process. Figure 1.20. shows a loop which consists of a three-stage block, a servodrive and a control loop. As long as the actuating signal $|x_a| < x_t/2$ the block does not come into operation, thus $y_1 = 0$. If, however, the signal exceeds this value, the output signal of the three-stage block is the largest operating signal, $y_1 = y_k$. The servomotor rotates with its highest attainable speed. If, now, the actuating signal does not cease in time (i.e. $x_a < \frac{x_T}{2} - 2x_u$) then the signal will cover the entire correction path Y_k in time T_y . The lower part of Fig. 1.20. shows this change as a function of time for the individual parameters, assuming that the reference input signal changes from value $w=0$ at time $t=0$ to $w=w_0 > x_T/2$. As a consequence, the value y_1 jumps to the value Y_{1k} , while the servomotor changes the operating signal y according to the formula $y = \frac{t}{T_y} y_k$. The controlled variable x will change only after the dead time has elapsed and it will continue to grow at an increasing rate. In time t_1 , the value of x will follow the relationship $x(t_1) = w_0 - \frac{x_T}{2} + 2x_k$, while

the three-stage block is switched off, thus, y_1 will become equal to zero. Where the servo-drive operates without after-running, the operating variable will not increase and it will maintain its value acquired at time t_1 , the value which is approached by the control variable; such controls may only be considered useful where the inertia of the process section is relatively small. In order to be able to connect the three-stage servomotor block to the controlled process, a linear relationship must be ensured between the operation velocity and the actuating signal. This may be achieved by providing the three-staged block with a delayed feedback system.

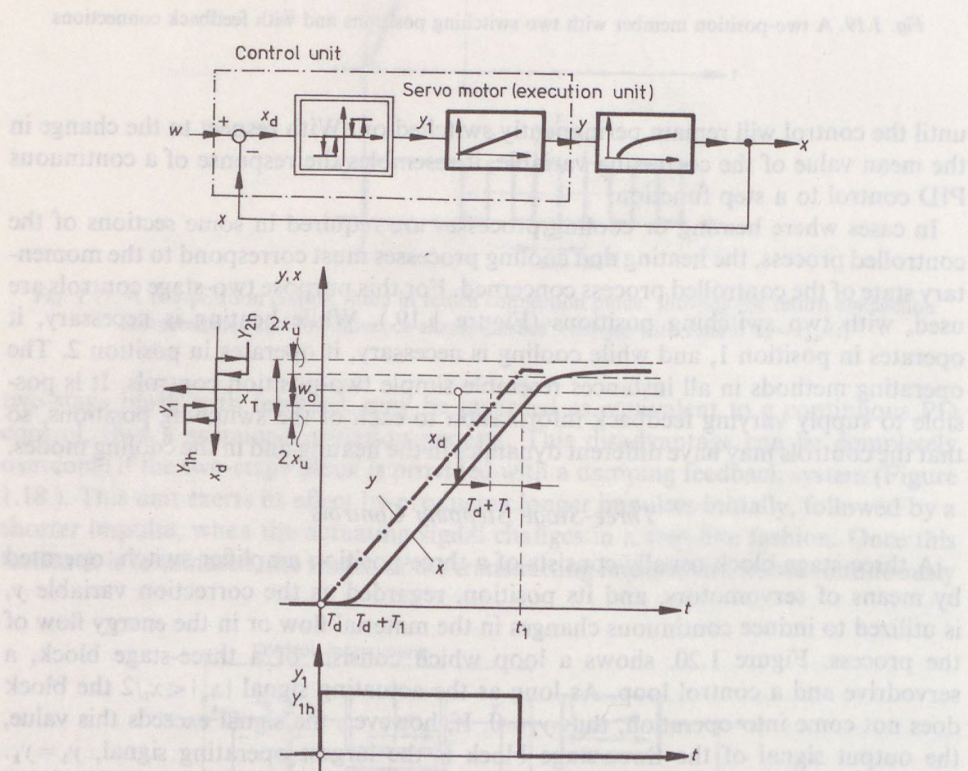


Fig. 1.20. Control loop, fitted with a three-position member in a servo motor (an execution unit) and proportional section

Lower diagram: changes of the controlled three-position member, x ; the output, y_1 ; and the interference, y ; with respect to characterization in all three cases. In instances of stable control processes $2x_u$ represents the hysteresis of the three-position member, while x_T represents the insusceptible region of the three-position member

1.3 The Elements of the Control Chain

The elements of the control chain described above are now discussed in more detail.

Sensors

These are detecting elements in direct contact with the process, with input signals as one of the characteristic features of the process, while their output signal is a natural signal. These natural signals are converted by the measuring transformers into uniform signals. In the polymer processing industry the most important data to be measured are temperature, pressure, viscosity, velocity, the number of revolutions per unit time, the thickness and the distance travelled. Certain problems associated with the measurement of these data will be discussed shortly in the following chapters.

Transducers and Capacitors

The natural signals given out by the detecting elements are converted into transmittable unit signals. The capacitors are devices into which the detectors and the unified output signal transformers are built to form a single unit.

Operational Elements

The operational elements perform mathematical calculations on the data available in the form of electric, pneumatic or hydraulic signals. The operations carried out may be, for example,

- linearization of the transfer function,
- calculation of other, related values from measured results,
- conversion of the measured data (for example, by integration),
- control based on predetermined functions.

The actual elements may perform addition, multiplication, integration, etc.

Converters

Converters are units for combining parts of the process control equipment into a unified, single entity. Where a computer process control equipment is used, the most important converters are the analogue-digital converters.

Information Processing Units

The information processing units are the display units, the data recording units, the value indicators and the controls. The display units may be dial instruments or screen display units. The data recording units, generally, consist of point and line printers with six to twelve channels. In the case of digital control equipment the most suitable method may be data recording with the aid of punched cards, or by magnetic tape. The limit value indicators give out logical signals at predetermined values of the continuous signals. They operate primarily safety indicator and locking equipment.

In the control equipment a sequence network of semiconductors connects the

two-position input and output signals according to a predesigned programme. This logical network receives the input signals from two-position sensors (including items such as end position switches, limit value indicators and so on). In addition to this, some of the input signals are provided by the keyboard of the operating equipment itself. Some of the output signals are used to switch on indicator lights, which provide information about the actual running of the control programme, while some of the output signals may cause relays to start motors, open and shut valves, and so on.

The controls compare the signals originating from the control points with the stored data and send output signals according to a preset algorithm. The output signal produced by the control may be either continuous or intermittent. In a continuous control mode the reference input comes either from the external reference input source or it is derived from an internal reference input element. This "differential element" produces the actuating signal derived from the difference of the control signal and the reference input signal. This is transmitted to the signal-forming element. The switches of the mode make it possible to transduce the signal automatically or manually. Follow-up control of the continuous controls is often used in continuous feeding systems or drive controls.

Where stage controls are utilized, the control outputs are intermittent. The stage controls are applied to switch on the servo-motors and to control processes with long time constants. In general, in the case of polymer processing equipment, stage controls are used for temperature control.

In the case of digital controls, differences are derived, thus, differentiation is made between the emitted coded digital signals. Control algorithms of a higher order may be made when digital controls are used as compared with the simple analogue controls. Such a digital control system is shown in Figure 1.21. It connects the signals of the analogue storage on the input multiplex element (1) one by one to the input of the analogue-digital converter (2). The control (3) operates according to the DDC algorithm, that is, for all channels it establishes the difference between the signals of the converter (2) and of the reference register (4), which are compared with the previous values stored in its memory. In the knowledge of the actual value of the

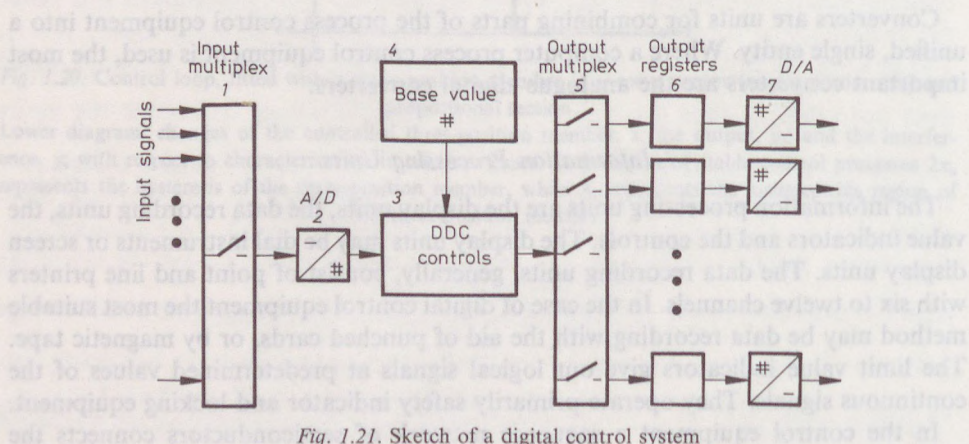


Fig. 1.21. Sketch of a digital control system

actuating signal and its change and utilizing constants of the given channel it calculates the actual value of the control output signal and it changes the content of the output register of the given channel (6) through the output multiplex element (5). The analogue-digital converter (7) produces an analogue current signal that corresponds to the value of the register. The computer process control system contains digital controls. The final control elements may be electrical, pneumatic or hydraulic equipment. The typical unit in the first category is the servomotor, while the latter two typically involve various types of valves.

1.4 Process Control by Computer

Figure 1.22. represents a system of process control by computer in two different aspects. Part *a* shows the relationship between the separate elements in the system. Part *b* shows the functions that are realizable in a process control performed by a computer.

Looking at the first section of the above Figure one can say that the process consists of a complex production line of equipment with an output of some kind of product from certain raw materials and energy to which sensing devices are connected, which produce information to be processed by the computer. Upon suitable conversion of the information given out by the computer, this information now acts on the equipment of the technological process. The computer is in bilateral contact with the operator of the system; it provides information about the general running of the process and about some possible unforeseeable events that may occur. At the same time the computer receives information about changes to be made of its own control

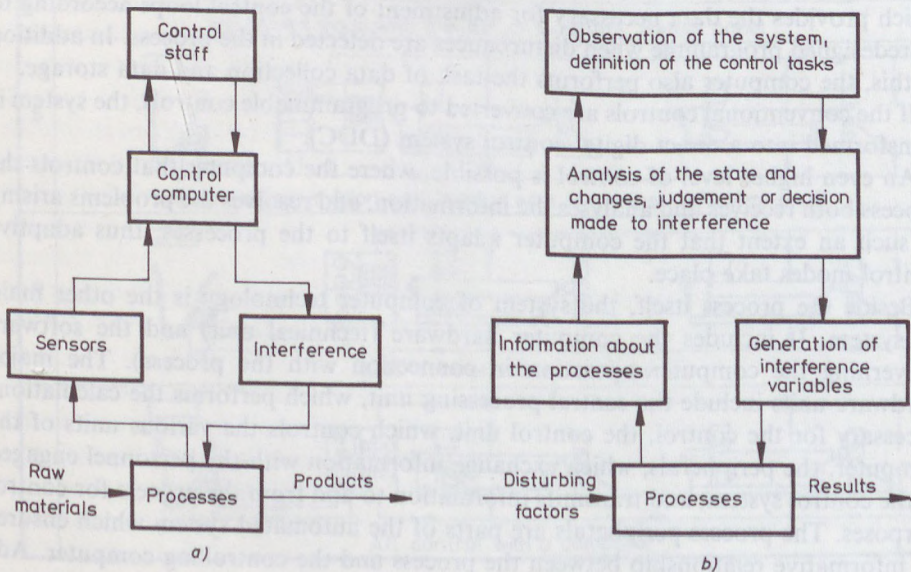


Fig. 1.22. Flow chart of a computer controlled process

activities. Figure 1.22.b) depicts the information flow chart. The process may be regarded as an information conversion unit, where different disturbances and correction variable signals produced by the control system are the input signals, while the output signals consist of information which is necessary for the operation of the control system, and of that indicating the efficiency of the ongoing process. The information gathered at a low control level about the operation is processed in order to determine the momentary condition of the process concerned, in order to find out what variables are included and, in view of these, what is the best way to influence the running of the process. The decision, based on the results of the information, is converted into relevant signals and transmitted to certain input points of the process. The above mentioned low level of decision is connected with a higher level of decision-making process, where the general operation of the system is evaluated and the control targets are established.

In Figure 1.23. the various levels of controls are surveyed, taking the sheet extrusion process as a particular example. The first level consists of on-location controls, or open loop controls, present in all equipment used. Here, a control system maintains the values set manually, thus, the system consists of value maintenance controls. At the next higher level the same functions are realized, however, these are not attached specifically to a given group of machinery, since the control centre supplies the data for the purposes of adjustment, while at the next level up, once again, data are made available for operator use from some sort of data base to be utilized at the start-up stage of the equipment, or when a product change is intended. In these instances it is still the operator who makes the necessary adjustments to the machine in order to eliminate possible occurrence of undesirable processes, and the precision of the adjustments made largely depends on the skills of the operator.

At the next control level up, a process computer takes over the tasks of the operator which provides the data necessary for adjustment of the control loops according to a predesigned programme when disturbances are detected in the process. In addition to this, the computer also performs the task of data collection and data storage.

If the conventional controls are converted to programmable controls, the system is transformed into a direct digital control system (DDC).

An even higher level of control is possible, where the computer that controls the process both receives and analyses the information, and resolves the problems arising to such an extent that the computer adapts itself to the processes, thus adaptive control modes take place.

Beside the process itself, the system of computer technology is the other main subsystem. It includes the computer hardware (technical unit) and the software (governing the computer operation in connection with the process). The major hardware units include the central processing unit, which performs the calculations necessary for the control, the control unit, which controls the various units of the computer, the peripherals, which exchange information with the personnel engaged in the control system, and transmits information to and from the process for control purposes. The process peripherals are parts of the automated system which ensures an informative relationship between the process and the controlling computer. Additional parts of the control system are the sensing and the correcting units.

The software of the computer may also be divided into two major parts, the basic software and the user software. The basic software is an integral part of the computer, it controls the computer's basic functions. The control program consists of the actual, or so-called user programme. The latter controls the computer operations to be

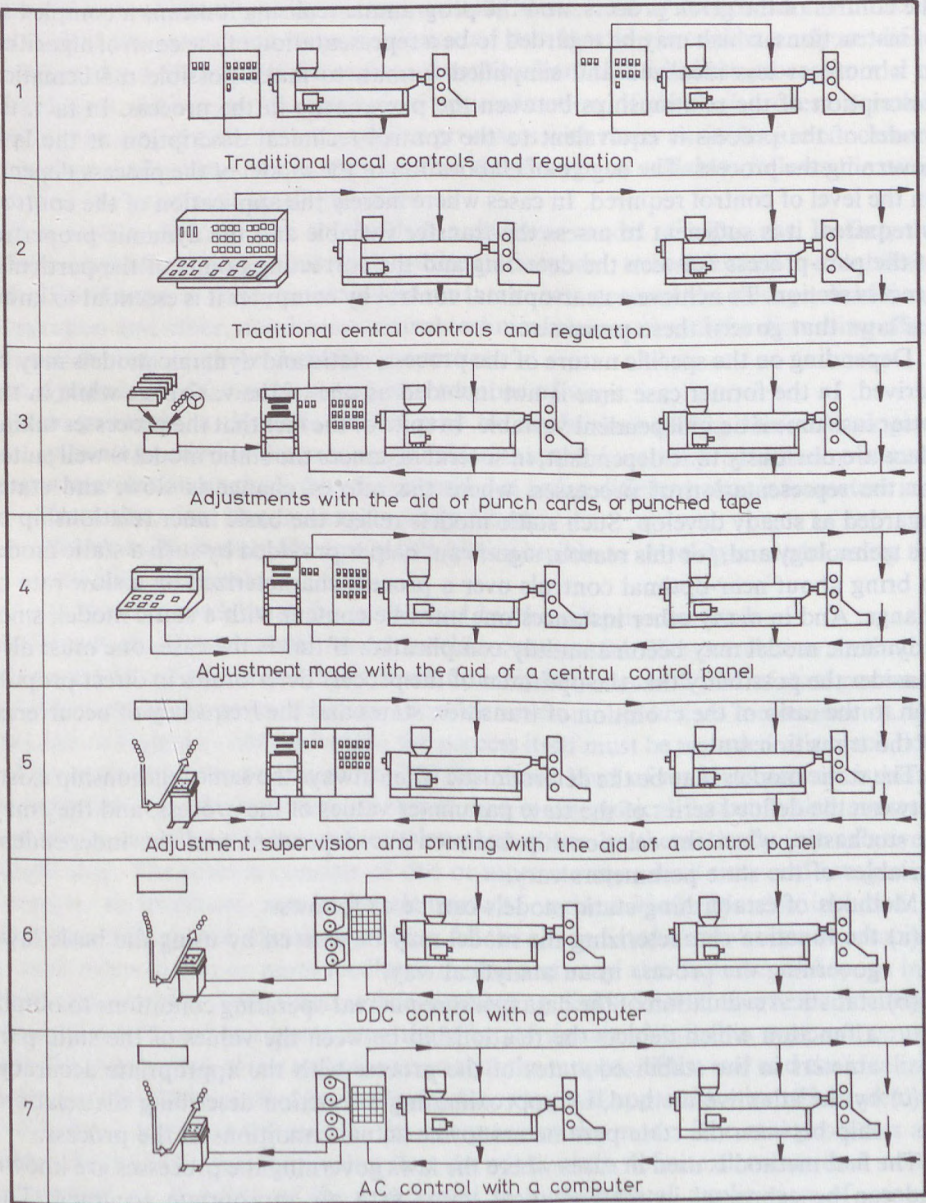


Fig. 1.23. Control processes applied in laminate and plain foil productions

performed, thus, it includes the actual checking and control tasks to be performed. The software contains an algorithm describing the steady state and the dynamic process characteristics, and determines the computer's reactions to external changes in the process in accordance with the overall control task. (Thus, the control programme may be regarded as the realisation of the control algorithm mentioned before.) The algorithm itself describes the logical and mathematical relationships in the control of the given process, and the programme realising it means a complex set of instructions, which may be regarded to be a representation of the control algorithm in a more or less idealized and simplified format, to make possible mathematical description of the relationships between the phenomena in the process. In fact, the model of the process is equivalent to the control technical description of the laws governing the process. The degree of elaboration of the model of the process depends on the level of control required. In cases where merely the application of the controls is required, it is sufficient to assess the transfer variable and the dynamic properties of the part-process between the detecting and the correcting points of the particular process section. To achieve a near-optimal control by computer it is essential to know the laws that govern these processes.

Depending on the specific nature of the process, static and dynamic models may be derived. In the former case time is not included as one of the variables, while in the latter case time is an independent variable. In spite of the fact that the processes taking place are obviously time dependent, in several instances the static model is well suited for the representation of processes, where the rate of change is slow, and states regarded as steady develop. Such static models reflect the basic inner relationship of the technology and, for this reason, significant help is provided by such a static model to bring about near-optimal controls over a process characterized by a slow rate of change. And in many other instances one must be content with a static model, since a dynamic model may become unduly complicated. If this is the case, one must also consider the possibility that the optimum of the process deteriorates in direct proportion to the ratio of the evolution of transition states and the frequency of occurrence of the transition states.

The static models may be the deterministic when always the same relationship exists between the defined series of the state parameter values of the process, and they may be stochastic, when the relationship between the dependent and the independent variables of the state parameters vary.

Methods of establishing static models can be as follows:

- (a) the function characterizing the model may be derived by using the basic laws governing the process in an analytical way,
- (b) statistical evaluation of the data measured in real operating conditions to obtain a function which depicts the relationship between the values of the state parameters in the stabilized states of the process with the appropriate accuracy,
- (c) by the adaptive method, by approximating a function describing the relationship between the state parameters to the actual conditions in the process.

The first method is used in cases where the laws governing the processes are known and can be expressed in mathematical terms with an appropriate accuracy. The second method may be applied more generally. Here, the state parameters of the

process are measured repeatedly at regular intervals and in sufficiently stabilized states of the process thus the average values of the parameters are determined with the required statistical accuracy from the series of values obtained from these repeated measurements. It is then possible to set up a regressive model with the aid of a computer and this can be used to establish the necessary control algorithm. The inadequacy of this method lies in the assumption of a stabilized steady state.

In the case of the adaptive method, initially some kind of functional relationship is assumed between the state parameters, and this function is continuously modified to reduce the deviations of the real state vectors from this fictitious process model to a minimum. Although this method of approximation of the real process is rather time-consuming in cases where complex processes with many variables are concerned, its immense advantage lies in the fact that the change of variables follows the attributes of the processes, in all instances.

It is a more difficult task to establish a dynamic model of a process. In fact, the dynamic model must also contain the entire static model, to be achieved in a stabilized state. Furthermore, the dynamic model must take into account the storage, dead time, integration and other, non-linear control technical elements, and the disturbing effect of environment on these dynamic properties.

A dynamic model can be set up in a number of ways:

- in principle, a dynamic model may be established during the technological planning period of the process, provided that the dynamic properties are known;
- a correlation analysis may be carried out using different state parameters and from this, time factors may be established;
- based on Kalman's filter principle, it is possible to develop a model using the statistics of signals;
- a dynamic model may be established by the adaptive method.

Derivation of a deterministic model is seldom successful. The correlation method is often used for calculation of the time relationship between each pair of state parameters. This method, however, requires a considerable number of data measurements. On the basis of Kalman's filter principle, the process itself must be regarded as a black box.

The analysis of the processes implies that some kind of an ideal process is being investigated. The ideal process, of course, is a mathematical fiction, which makes it possible to describe and survey complex phenomena mathematically in a relatively simple way. The process consists of one or more storage, dead time and integrating elements, furthermore, non-linear elements of various kinds are also included as separate entities in this idealized process. All the above listed elements can be attached to each other in one or more feedback modes and may also form several loops in a given process. The loops and other connecting links formed from the idealized elements mentioned can operate on the effect of signals identical in type and course with the signal input of the real process so that the outputs of the real and the idealized processes agree with each other within a close range of approximation. The extent to which this occurs is a measure of the adequacy of the mode. The real processes are primarily characterized by the fact they do not contain definite elements that would correspond to elements of the types used in a theoretical application of control technique, since these do not include pure storage and integrating elements.

The types of computerized process controls can be as follows:

- (a) Direct Digital Control (DDC). In this case the computer takes the place of the conventional analogue controls. In the control loops digital controls are used. In the process control the computer investigates the existence of a value in the algorithm of the open and/or closed loop controls after sampling the measured parameters and signal processing. Where such correlations exist, the computer performs the given control algorithm and produces the operating signal based on the sample values. In the simplest case the DDC produces the usual PID compensation so that the primary feedback is available in the form of a sample series with a cycle time ΔT and the output is calculated in a cyclical mode. Where DDC is employed, the control equation of PID may be expressed as

$$x_{out} = K_p x_{am} + \Delta T K_i \sum_{i=0}^m x_{ai} + \frac{K_d}{\Delta T} x_{am} \quad (1.28)$$

where x_{out} is the control output, x_a is the actuating signal, K_p is the proportional transfer coefficient, K_i is the integration transfer coefficient and K_d is the differential transfer coefficient. In the relationship $\Delta x_{am} = x_{am} - x_{am-1}$, x_{am} and x_{out} represent the actuating and the control output signals of the m^{th} cycle. ΔT represents the time period between sampling activities. The algorithm expressed for x_{out} gives the control output dependent on the momentary position of the control, stored by the peripherals of the computer. The calculation of the desired change in the control output is more frequent, since the summation representing integration is more cumbersome, due to the necessity of storage of many previous data.

The critical point of DDC application is the required reliability. A defect in the computer may result in substantial errors, so that auxiliary equipment (an auxiliary computer and auxiliary control unit) is employed in order to attain the required level of reliability.

- (b) If Set Point Control (SPC) is used, the control is carried out by the analogue control unit, but the preset signal is adjusted by the computer. In a simpler case the operator changes the reference input of all the loops from central controls with automatic recording of the time and value of change. In such instances, from the point of view of the computer, off-line control takes place. At optimum control the reference inputs that satisfy the conditions of optimum control, are determined by the computer and thus, on-line control mode occurs.
- (c) Sequential control by computer. In this case the computer takes over the control functions, or part of the control functions of the control units built from individual logical circuits.
- (d) Optimization of the processes by computer. Here, the computer defines the optimum conditions according to a given function and it corrects the processes accordingly.

1.5 Characteristics of the Polymer Processing Methods

The definitions of polymer processing methods, as operational modes, have already been outlined, and the general method of process analysis has been presented above. In this book the following processing methods will be discussed:

- mixing,
- calendering,
- screw plasticating,
- sheet extrusion,
- tube and profile extrusion,
- film blowing,
- blow moulding, and
- injection moulding.

If the processes to be examined are divided into operational parts, differentiation may be made between the following items:

- screw plasticating (melt forming) processes,
- plasticating processes that take place at the gaps between rotating rolls,
- shaping processes that take place in the gap between rotating rolls,
- continuous shaping processes that take place in dies,
- non-continuous shaping processes in the mould,
- non-continuous after-forming in the mould,
- continuous after-forming and cooling,
- non-continuous cooling in the mould, and
- continuous cooling.

In the case of screw plasticating a homogeneous melt is produced from a solid base material. The part processes in the screw plasticating units consist of the transport of the solid material, the melting and the melt homogenization processes. The continuous operating screw plasticating units include single and twin screw extruders, as well as screw mixers. The plasticating units of the injection moulding machines operate non-continuously. The inner mixers resemble in certain aspects the screw plasticating units and the roll mills. The rotors rotate in a closed space, either heated or cooled. The material flow between the rotors and the walls is similar to the flow in the screw channels, while the flow between the two rotors resembles the flow between the rolls. The plasticating process between the rotating rolls is typical of a roll mill and the calender processes. In calendering the shaping process takes place at the gap. The flow through the dies is characteristic of the tube, profile and sheet extrusions, film blowing and blow moulding, while non-continuous flow is a feature of injection moulding. In the case of blow moulding the finished product acquires its final shape in an intermittent after-forming process. Continuous after-forming and cooling occur during calibration in tube extrusion process and during blowing in the case of film blowing processes. Non-continuous cooling takes place during injection moulding and blowing. Continuous cooling processes occur during cooling of the product emerging from the calenders and in the case of tube, profile and sheet extrusions.

The main characteristics of the products made by the above processing methods are:

- the measured accuracy of the product,
- surface quality,
- homogeneity,
- strength (to specifications).

The above-listed characteristics are influenced by the technological parameters employed in the given process; these include the pressure, the temperature and the viscosity of the material and their distribution. Thus, the parameters to be controlled are the characteristics of the products and the technological parameters related to these. Another group of parameters is the characteristics of the technological equipment and machines used in the specific process which may be the wall temperature of the machinery in which these technological processes take place, the number of revolutions, the torque, the power requirements of the rotating unit, and so on. The ultimate task of the processing method is to maximize productivity with the desired product quality. Thus, all control processes include some parameters that determine some specific flows (for example mass flow).

There follows a survey of the measuring methods of some of the more relevant parameters of the control processes, which are the drive control occurring in most of the processing methods, together with the so-called "synchronous run" control.

1.5.1 Measuring Methods [12–15]

1.5.1.1 Temperature Measurements

In polymer processing the following temperature measuring tasks may be included:

- temperature measurement of the material (melt temperature measurements),
- wall temperature measurements, which include the roll temperatures, mould wall temperatures and the wall temperatures of the plasticating unit,
- temperature measurements of the heating or cooling medium,
- temperature measurements of both the intermediary products and the finished product.

Those temperature sensors, which are in contact with the material are called contact thermometers. The thermoelements and the resistance thermometers are included in this category. If it is not possible to make direct contact between the thermometer and the material, the temperature may be measured by thermometers based on radiation measurement, called optical pyrometers.

The thermometers that are in general use in the processing industry are tabulated below:

Site of temperature measurements	Thermometer type		
	Thermo- couples	Resistance thermometers	IR
Melt temperature in screw channel	+		
in space in front of screw	+		
in mould	+		
in air	+		+
Wall temperature plasticating units	+	+	
inner mixers	+	+	
Roll temperature	+	+	+
Mould temperature	+	+	
Parison temperature (at blowing)	+		+
Surface temperature	+		+
Cooling medium temperature	+	+	
Oil temperature	+	+	

The temperature sensing part of thermocouple thermometers is made from two different metal wires welded or soldered together. On heating the junction point, a direct voltage develops at the ends of these conductors, whose magnitude depends on the type of metal used and upon the temperature difference between the heated junction point and the cooler ends of the wires.

Resistance thermometers measure the change of resistance that result from the change in temperature of these conductors and semi-conductors. The substances may be certain metals, or some types of semi-conductors. The temperature dependence

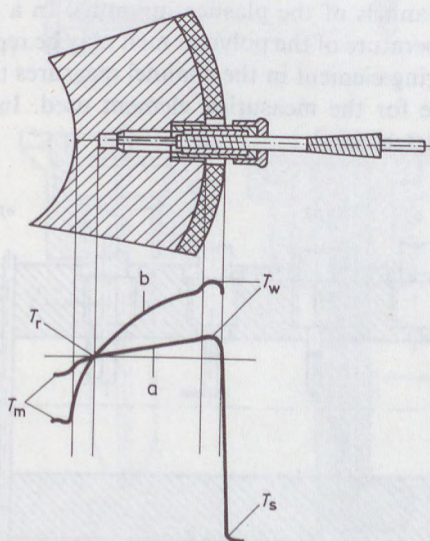


Fig. 1.24. Temperature drop occurring as a result of measuring the wall temperatures of the barrel
a. in case of low heat conduction, b. in case of good heat conduction.

T_w is the temperature of the heating body, T_s is the surrounding temperature, T_r is the controlled temperature, T_m is the temperature of the material

(the temperature factor) of the resistance is the principal feature of the substance used. The change in resistance of the measuring substances must be sufficiently reproducible. The most suitable substances are nickel and platinum. The resistance is measured, in most instances, by means of a bridge circuit.

Bodies radiate heat in proportion to their temperature. Certain pyrometers utilize the total radiation emitted by an object in a broad wavelength region to measure temperature. Partial radiation measuring pyrometers measure radiation in a narrow wavelength region. The infra-red thermometers belong in this latter group, they operate at $3.43 \mu\text{m}$ in the temperature range between 20 and 350°C .

The three most characteristic temperature measurement types are: the wall temperature measurements, the temperature measurement of a flowing medium and surface temperature measurements.

Figure 1.24. shows the temperature changes during wall temperature measurements. Here, the heating body is situated on the external surface of the wall. The temperature sensors, in such cases, must be placed close to the inner surface of the wall, since the temperature of the wall must approximate the temperature of the substance.

The requirements of the wall thermometers are:

- a narrow diameter to be built in the wall,
- a small mass to minimize time delays,
- a low specific heat of that part of the measuring device that separates the measuring cell from the body,
- rapid replacement during operation of the equipment.

The measurement of the temperature of the material in use is not a simple task, especially inside the channels of the plasticating units. In a given channel the local distribution of the temperature of the polymer melt may be represented by a parabolic curve, thus, the measuring element in the channel measures the average temperature in the section available for the measuring element used. In practice the following temperatures may be determined:

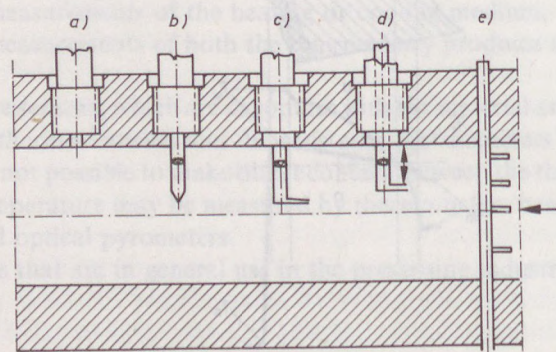


Fig. 1.25. Measuring devices employed to measure the temperature of the material
a. temperature measuring device, used to measure the temperature near the wall, b. immersion thermometer, c. thermometer with a hook, d. movable thermometer, e. thermometer employed to measure the temperature profile

— the average temperature,

$$\bar{T}_a = \frac{1}{R} \sum_i T_i \Delta r_i \rightarrow \frac{1}{R} \int_0^R T(r) dr \quad (1.29)$$

where R is the radius of the channel, and T_i is the local temperature measured within a radius interval of Δr_i ,

— the corrected average temperature, given by the relationship:

$$\bar{T}_{ac} = \frac{2\pi}{R^2 V} \sum_i T_i V_i \Delta r_i \rightarrow \frac{2\pi}{R^2 V} \int_0^R T(r) V(r) dr \quad (1.30)$$

Figure 1.25. shows thermometers utilized for measuring the temperature of the material; a) with temperature sensor positioned along a wall, b) immersed ther-

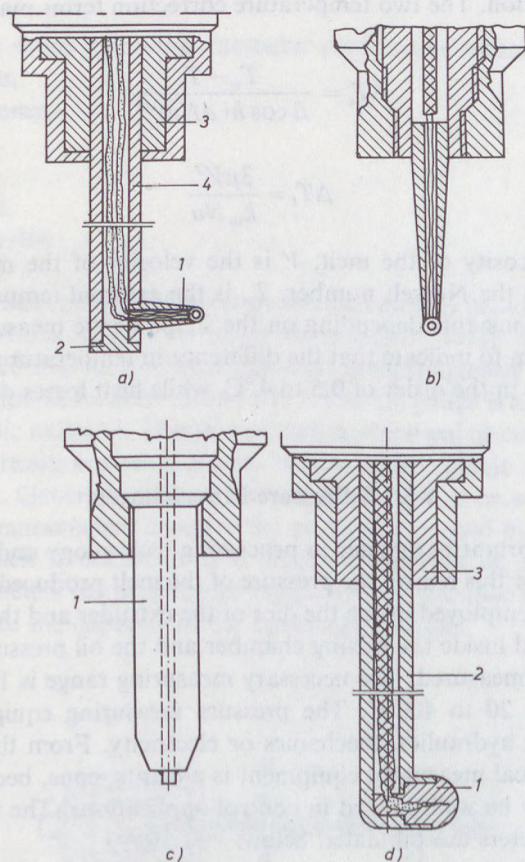


Fig. 1.26. Construction of the thermometers used to measure the temperatures of the material
a) 1 and 2 are made of stainless steel, 3. insulator, 4. stainless steel. b) temperature sensor c) 1. insulator, d) 1. insulating material, 2. stainless steel, 3. insulator

nometer, c) thermometer with a hook, d) movable thermometer, e) a temperature profile measuring device.

In Figure 1.26. a schematic view of the individual measuring elements is shown. Diagrams *a*), *b*), and *c*) are sensors measuring the temperatures at given points, while the sensor shown in diagram *d*) is a temperature measuring device with varying length suitable for measuring the temperature profile. The sensor denoted by *e*) measures the temperature of the melt in the channel at several points simultaneously.

The temperature measured by the sensor submerged in the molten flow deviates from the true melt temperature, partly owing to the heat of friction at the surface of the heat sensor, and partly owing to the drop of temperature due to the loss of heat during conduction across the heat sensors. The real temperature may be expressed as:

$$T = T_0 + \Delta T_c - \Delta T_f \quad (1.31)$$

where T_0 is the measured temperature, T is the true temperature, ΔT_c represents temperature deviation due to heat conduction, while ΔT_f is the temperature deviation caused by friction. The two temperature correction terms may be defined by the relationships:

$$\Delta T_c = \frac{T_w - T}{B \cos h(ANu)^{1/2}} \quad (1.32)$$

and

$$\Delta T_f = \frac{3\mu V^2}{k_m Nu} \quad (1.33)$$

where μ is the viscosity of the melt, V is the velocity of the melt, k_m is the heat conductivity, Nu is the Nusselt number, T_w is the external temperature of the wall, and A and B are constants depending on the shape of the measuring element.

Experiments seem to indicate that the difference in temperature due to loss of heat from conduction is in the order of 0.5 to 4 °C, while heat losses due to friction range from 1 to 10 °C.

1.5.1.2 Pressure Measurements

Pressure is an important parameter in processing technology and process control in many instances. For this reason the pressure of the melt produced by the plasticating units, the pressure employed inside the dies of the extruder and the injection moulds, the pressure applied inside the mixing chamber and the oil pressure of the hydraulic system are usually measured. The necessary measuring range is 100 to 1500 MPa at temperatures from 20 to 400 °C. The pressure measuring equipment operates on principles of either hydraulics, mechanics or electricity. From the point of view of automation, electrical measuring equipment is advantageous, because the measured electric signals may be well utilized in control applications. The field of application of various manometers are tabulated below:

Location of pressure measurements	Strain gauge	Mechanical	Piezo-resistance	Piezo-electric	Capacity	Inductive	Magneto-elastic
Melt pressure							
in screw channel	+				+	+	
in space in front of screw	+				+	+	
in mould	+				+	+	
Air pressure							
in film bubble		+					
in blowing parison	+			+			
Cooling medium		+					
Hydraulics	+	+	+	+	+	+	+

There are thus seven types of manometer used in this technology:

- strain gauge,
- piezo-resistance,
- inductive,
- capacity,
- piezoelectric,
- magneto-elastic,
- mechanical.

In the case of strain gauges the pressure measurement is based on the measurement of elongation caused by a force acting on the measuring body. The measured elongation is transformed into an electrical quantity, most frequently it is determined as a change in resistance. In its most usual form the strain gauge is a resistance wire glued on paper or plastic material. This device and its electrical circuit is shown in Figure 1.27. The piezo-resistance manometers measure the change in resistance due to pressure changes. Generally, silicon monocrystals with p or n doping are applied.

The inductive manometers measure the movement caused by pressure applied on a membrane, which is deformed as a result of pressure, in an inductive way. In capacitive manometers the pressure applied alters the distance between the plates of a condenser, hence the capacity of the condenser changes.

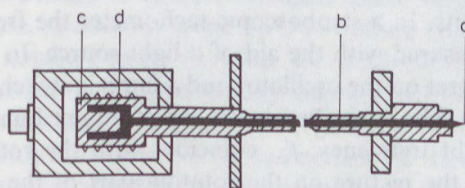


Fig. 1.27. Strain measuring device, stamp manometer
a. measuring membrane, b. mercury, c. measuring roll, d. strain gauge

Table 1.2. Characteristic features of various manometers employed to measure the pressure of molten fluids

Manufacturer	Type	Principles of measurement	Sensitivity mV/V	Error %	Reproducibility %
Dynisco	PT 420	strain gauge, mercury	3.33	± 0.5	± 0.1
Dickersbach	A AWM D	mechanical mechanical mechanical-pneumatic	—	± 3 ± 3 ± 3	± 0.1
Gentran	GT 72/73	strain gauge	3.0	—	± 0.1
Rosemount	1401	pneumatic	—	± 1.5	± 0.5
Sensotos	MPT	strain gauge	1.5 to 3.0	± 0.5	0.1

The piezoelectric manometers work on the principle that electric charges develop on the application of pressure, the charges are converted to a change in potential difference which is then measured. For this type of measurement quartz crystals are used.

Magnetoelastic pressure measuring devices work on the principles of permeability changes induced by a change in pressure.

The manometers equipped with membranes and tube springs belong to the category of mechanical pressure measuring devices. Table 1.2. summarizes the characteristics of some manometers.

1.5.1.3 Rotational Speed Measurements

For processing machinery one of the most relevant parameters is the rotational speed arising from the need to adjust the rate of rotation of the rotors, rolls and the turn of screws. Methods used to measure the rotational speed may involve:

- stroboscopes,
- tachogenerators and
- impulse methods.

Stroboscope tachometer

The stroboscopic tachometers are generally used in research and development purpose plasticating units. In a stroboscopic tachometer the frequency of the rotational movement is measured with the aid of a light source. In the stroboscope the frequency of rotation is set on the oscillator and a lamp is switched on and off at this frequency via a rectifier. The lamp illuminates a picture fixed on the rotating part of the machine. If the light frequency, f_m , coincides with the rotating frequency, f_R , the observer conceives the picture on the rotating part of the equipment as being stationary. Naturally, a still picture is formed only if the picture appears at the same position in the time of both flashes, that is, when the rotating frequency equals with

that of the flashlight frequency or it is its integer multiple. Expressed in mathematical terms:

$$f_R = k f_m \quad k = 1, 2, \dots, n \quad (1.34)$$

In practice, it is advisable to choose first a higher frequency, f_{B1} , where the picture appears to be stationary and then to reduce the frequency of the rotation until a still picture is again obtained (f_{B2}). In this case

$$\begin{aligned} f_R &= k f_{B1} \\ f_R &= (k+1) f_{B2} \end{aligned} \quad (1.35)$$

from which it follows that

$$f_R = \frac{f_{B1} f_{B2}}{f_{B1} + f_{B2}}$$

which gives the rotation frequency to be determined. This method, however, is not suitable for low revolution rates.

The method does not demand the use of a robust equipment, however, duplicate measurement values need to be obtained to determine the correct revolution number. The error of this method is about $\pm 5\%$. It is particularly suitable for taking rapid control measurements.

Tachogenerator

In essence, this is a small alternating current generator with a permanent magnet as the rotating part. The rotating part is connected to the rotating object either directly or indirectly. The rotating object induces an alternating voltage in the stationary part, where the induced voltage is nearly proportional to the speed of rotation. Tachogenerators are used in a range of 100 to 10 000 min^{-1} , with gears in the range from 2 to 1000 min^{-1} . The error of the measurement is less than $\pm 1\%$. The working temperature range is from -25 to $+100^\circ\text{C}$, with a temperature factor of $0.4\%/^\circ\text{C}$.

Impulse Tachometers

Impulse tachometers are applied in instances where the mechanical gear transmission cannot be used, or in cases, where the revolution number to be measured is excessively low. Impulse tachometers may work using principles of either induction or optics. The inductive tachometers consist of permanent magnets in a cross position, a coil and an iron core. A notch is made on the rotating object and the tachometer is placed near this notch. During rotation the distance of air gap between the tachometer and the rotating part periodically changes with the rotation. In the iron core a flux change occurs, and the voltage developed in the coil is proportional to the revolution number. Only a single notch has to be made on the rotating part, provided that this is made of a material which can be magnetized; if this is not the case, then a disc made from a magnetizable material must be placed on it to form an outside surface.

The operation of another group of impulse tachometers is based on the Hall effect. In this case the magnetic flux change induces a Hall voltage, proportional to the revolution number. Expressed mathematically:

$$U_H = \frac{R_H}{d} IB \quad (1.36)$$

where U_H is the Hall voltage or current, B is the magnetic flux, R_H is the Hall constant and d is the plate thickness. Another type of induced impulse tachometer exists, where an oscillator feedback system is used through the air gap between the rotating body and the tachometer. In the air gap the feedback abates because of the vortex current, so that the deviation of the oscillator may be measured as a voltage through a resistance.

Yet another group of impulse tachometers operates in practice, based on optical principles.

The frequency measured by impulse tachometers is expressed as:

$$f = N \frac{P}{60} \quad (1.37)$$

where N is the revolution number, while P represents the number of cogs, magnetic poles or notches. In the case of electromagnetic distant transmitters the voltage is characterized by the following factors:

- the voltage is directly proportional to the revolution number, disregarding the effects of the temperature and temperature losses. The deviation is lower than $\pm 1\%$,
- at very low revolution numbers the amplitude of the induced voltage is practically zero, thus this method is not suited for measuring low revolution numbers,
- the resultant voltage decreases with increasing distance between the cogs or the poles,
- increased cog sizes or increased pole surfaces increase the voltage.

Electromagnetic transmitters may be used in the range from -10 to $+60^\circ\text{C}$; some special transmitters may be operated at temperature ranges of -50 to $+200^\circ\text{C}$. The impulse tachometers that utilize the Hall effect and those which operate on optical principles may also be used in low revolution number measurements.

1.5.1.4 Torque-Meters

In the processing industry torque measurements are regarded as important and are often used parameters, because the torque is closely related to the energy uptake of the given process. A change in torque may be a measure representing a complex change occurring in the parameters of the material being processed.

When measuring the torque of a rotating body, the torsion, proportional to the torque, is measured in almost all cases. The relationship between the torque (M) and the angle of twist (φ) on a material with length l , diameter D and modulus G , is given by:

$$\varphi = \frac{32l}{\pi D^4 G} M \quad (1.38)$$

The quantity to be measured here is the angle of twist (ϕ), by means of a strain gauge, or in an inductive mode, by means of either capacity or photoelectric methods.

Using a strain gauge, an elongation is developed on the surface axially, due to torsion, and this is sensed by the strain gauges. The gauges are inserted on the surface around the symmetry axis at angles of 45° and 135° and connected a Wheatstone bridge via four sliding rings and brushes.

The inductive equipment measures the angle of twist in terms of change of induction.

In the case of capacity torquemeters, the surface of one of the condenser sheets fixed to the axis changes in direct proportion to the angle of twist.

1.5.1.5 Viscosity Measurements

Viscosity is a suitable and unambiguous parameter to characterize the quality of the melt. Thus, the quality of a product may be well affected by measuring and controlling the viscosity of the molten material continuously. Viscosity measurements specially play an important role in the control of the screw plasticating processes. Two different methods are normally utilized in continuous determination of viscosity, these are the ultrasonic and the rotation methods.

An ultrasonic measuring device [17] consists of a source of radiation emitting oscillations at a frequency of about 850 kHz, with one or more sensor heads, which measure the time taken for the sound to pass through the melt. This is proportional to the magnitude of the spacing between the molecules of the molten matter, affected by the pressure and temperature. The integrated dynamic viscosity, related to the cross-section area is measured which depends on the nature, the temperature, the pressure and the shear rate of the material.

In the rotation method [18 and 19] a measuring head is fitted to the screw end (Figure 1.28.), which is allowed to rotate with the screw to give a torque measurement. From the torque measured and the pressure gradient along the measuring tip, viscosity can be precisely determined [19].

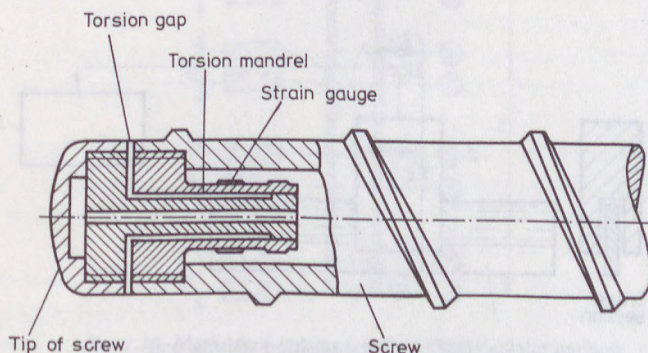


Fig. 1.28. Extruder screw cross section with a built-in strain gauge

1.5.1.6 Time Measurements

This parameter is relevant in cases of intermittent and cyclic processes; that is, in injection moulding and film blowing. The main requirements for chronometers are:

- high accuracy,
- the reproducibility of the adjusted values,
- long term durability.

Into polymer processing machines either electromechanical or electronic time relays or time switches are built in. The time relays are driven by synchronized motors, these belong to the first category and operate in the range of 1 to 300 seconds with a reproducibility of $\pm 3\%$. In the time switches the impulses given out by the oscillator are transmitted to a counter. The last decade, called the time base is determined by the time intervals between the impulses passing through a gate. The same method may also be used to measure the tripping and dropping times of the relays. In such instances the first impulse is given by the voltage as the relays are switched on or off, while the second impulse is given by the closing and the opening of the contacts.

1.5.1.7 Position Sensors

In the case of cyclically operated machines, it is necessary to sense the position of some of the moving parts. Figure 1.29. shows a digital position sensor. Here, the measuring bar (1) is made of glass and is given a special code. The reading head (2) moves along the coded measuring bar, and it scans the codes photoelectrically. The device emits a light beam through the coded measuring bar. The intensity of the radiation changes as a function of the opaqueness of the code signals. This radiation of varying intensity is sensed by the photo transistors and transformed into electric signals. Thus, the reading head fitted to the moving object transmits information regarding the distance covered by the object to the electronic position sensor (3). The usual resolving power of a digital position sensor is 0.5 mm.

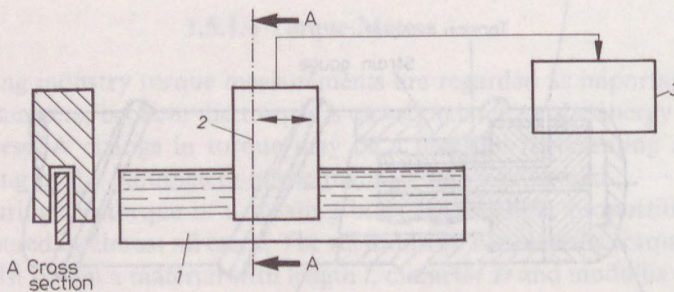


Fig. 1.29. A digital position sensing unit

1. coded, or calibrated measuring rod, 2. position sensing reading head, 3. position sensor

1.5.1.8 Velocity Measurements

In the polymer processing industry, in many cases, it is necessary to measure the velocity of the product flow. In these processes the following different velocities may need to be measured:

- the pull-off velocity in calendering,
- the pull-off velocity in tube, sheet and profile extrusion processes,
- the roll-up velocity of the film tube,
- the velocity of the parison in blow moulding.

The method of velocity measurement, in most cases, is related to the measurement of revolution number. Another method that is used in film blowing, to measure the velocity of bubbles. The bubbles are traced by measuring the distances and times with the aid of photocells (Figure 1.30.). The cutting equipment gives the first time value, which is transformed by the signal of the photocell LS1 into the first time interval. The other initial time values are given by the photocells LS2, LS4 and LS6, while the end points of the time intervals are given by the photocells LS3, LS5 and LS7. The velocity of the bubbles is expressed by the equation $v = \frac{\Delta l}{\Delta E}$.

1.5.1.9 Determination of Sizes

Size determination may be divided into two major groups:

- width and length measurements and
- thickness measurements.

Measuring methods may be classified into the following groups:

- optical,
- mechanical,

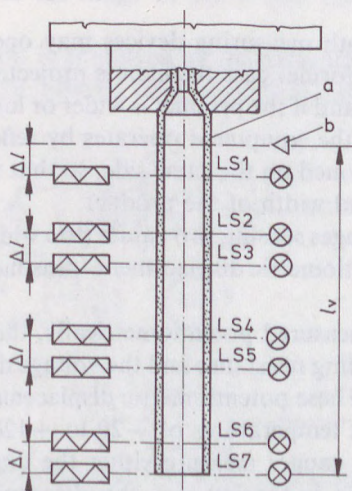


Fig. 1.30. Method of measuring the velocity of the parison

a. parison b. the positioning of the photocells to measure the velocity of the parison.

- ultrasonic,
- radioactive,
- infra-red measuring, and
- inductive methods.

The particular use of each of the above measuring methods is summarized in tabular form below:

Processing method	Optical	Mechanical	Ultrasonic	Radio-isotope	IR	Inductive
Profile extrusion						
length	+	+				+
cross-section	+	+	+	+		+
Tube extrusion						
length	+	+				
wall thickness			+	+		+
Sheet extrusion						
length	+	+				+
width	+	+				+
thickness			+	+	+	
Calendering width	+	+				+
thickness			+	+	+	
Film blowing width	+	+				
thickness					+	

The optical width and length measuring devices may operate on traversing or on reflection principles. In the former case the light is projected onto a photocell placed opposite of the light source and if the product is wider or longer than specified it stops this light radiation. Where the equipment operates by reflection, the source of light and the photocell are positioned on the same side, so that the signal of the photocell will depend on the measured width of the product.

The mechanical width gauges sensing two values (too wide or too thin), contain two contact switches, or a potentiometric displacement transducer that makes continuous sensing possible.

Where displacement is measured potentiometrically, the displacement is detected by the sliding part of the sliding resistance and the voltage directly proportional to the displacement is measured. These potentiometric displacement devices are used in the range 1 to 1000 mm and at temperatures of -20 to $+120^{\circ}\text{C}$.

The ultrasonic thickness gauges measure either the ultrasonic resonance, or the ultrasonic impulse reflections. In the first case, the ultrasonic sound reflected and that emitted from the underside of the film or sheet being measured can resonate and produce standing waves. The standing waves develop only if the required thickness

is an integer multiple of the wavelength of the waves. The thickness of the layer is given by:

$$d = \frac{kv}{2f_k} \quad (1.39)$$

where k is the order of harmonics, v is the velocity of ultrasonic sound in the material under consideration, and f_k is the resonance frequency.

In the ultrasonic impulse method the time of reflection of the ultrasonic sound from the top and the underside of the sheet is measured, since this time is dependent on the thickness ($d = vt/2$) of the material, thus, its thickness can be determined accurately by two time sequences of ultrasonic impulses.

The radio-isotope thickness gauges operate on the principle that the radiation passing through the material weakens in direct proportion to the thickness of the material. The two fundamental methods of the measurement are the measurement of the penetration and the measurement of back-scatter. The former method is used for the thickness of the finished products, such as films and coated products, while the latter method is utilized in measuring the thickness of coating on products.

Figure 1.31. shows a schematic diagram of an isotopic thickness gauge. The radiation from the isotope (1) penetrates through the material being measured (2) and passes to the ionization chamber (3). The radiation from the source (7) penetrates through the sheet and enters the compensation ionization chamber. The difference between the ionization currents in the ionization chambers depends on the thickness of the material to be measured and produces a drop in voltage across the resistance (4), which is converted by instrument (12) into alternating current. The reference sheet (6) is moved by equipment (9) controlled from the amplifier (11) until the currents of the two ionization chambers are equalized. The obtained value of sheet thickness is shown on the measuring device (8) or printed out by the printer (10). Radiometric thickness gauges are used in the range 10 μm to 800 μm , up to a maximum temperature of about 80 $^{\circ}\text{C}$.

Where infrared absorption is employed as the measuring technique, the method involves the absorption of an infrared light beam that either penetrates through the

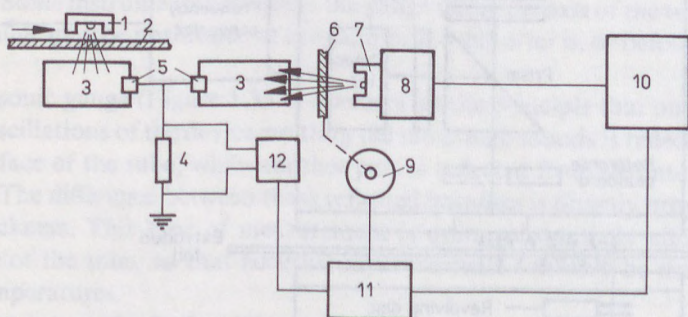


Fig. 1.31. Isotopic measuring device used in calenders

1. radiation source, 2. foil, 3. ionization chamber, 4. resistance, 5. counter, 6. reference plate, 7. compensating radiation source, 8. synchronizer, 9. deflection device, 10. printer, 11. amplifier, 12. measuring transformer

polymer film, or is reflected from the sheet surfaces (Figure 1.32.). The degree of absorption depends on the path length of the light beam and hence, on the thickness of the film. Two different wavelengths are usually employed, one is the absorption, the other is the reference wavelength. The thickness gauge moves over the film or sheet at a predetermined speed, so that the gauge determines the average thickness. The infrared absorption method may be applied in the range of thickness $6\text{ }\mu\text{m}$ to $1300\text{ }\mu\text{m}$.

The inductive thickness gauges work on the principle that a vortex flow is generated in a metal conductor placed in a region of high frequency. A magnetic field is produced by a high frequency oscillator in the head of the thickness gauge. This magnetic field induces a vortex current in the conductor opposite the measuring head. The direction of the magnetic field of the vortex flow is opposite to the direction of the magnetic field developed in the measuring head. This magnetic field is weakened in direct proportion to the distance between the high frequency measuring head and the metal conductor. By placing an insulator between the measuring head and the metal conductor, the extent of the attenuation will depend on the thickness of this insulating material.

In Figure 1.33. inductive, radiometric and ultrasonic tube-wall thickness gauges are shown. The inductive instrument measures the wall thickness of the material at four different points in each measuring cycle. The instrument is suitable for measuring the thickness of tubes of 40 to 150 mm diameter and wall thickness of 20 mm maximum. The radiometer measuring instrument (Fig. 1.33.b) senses the differences between the radiation intensities reflected from the inner and the external walls of the tube. In practice an isotope radiation source with alpha radiation Am^{241} and an ionization chamber detector are used. The minimum measurable tube diameter is 20 mm, while the maximum is 200 mm. In the case of polyethylene the maximum measurable wall thickness is 50 mm; it is 20 mm in the case of polyvinyl chloride. Greater wall thicknesses may also be determined using more penetrating radiation. The applied

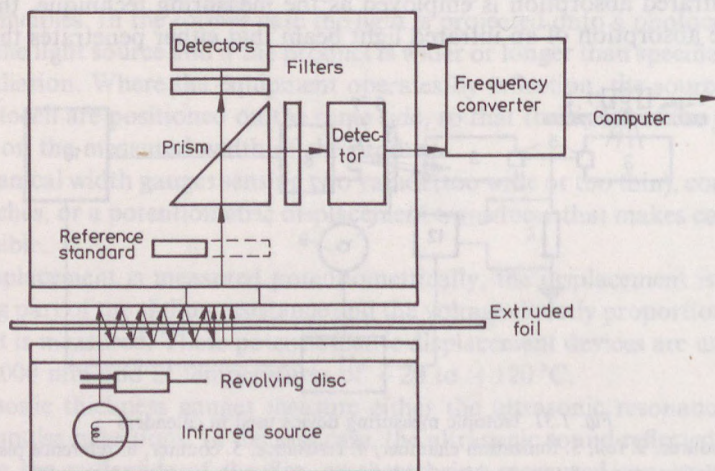


Fig. 1.32. Sketch of an infrared absorption thickness-measuring device

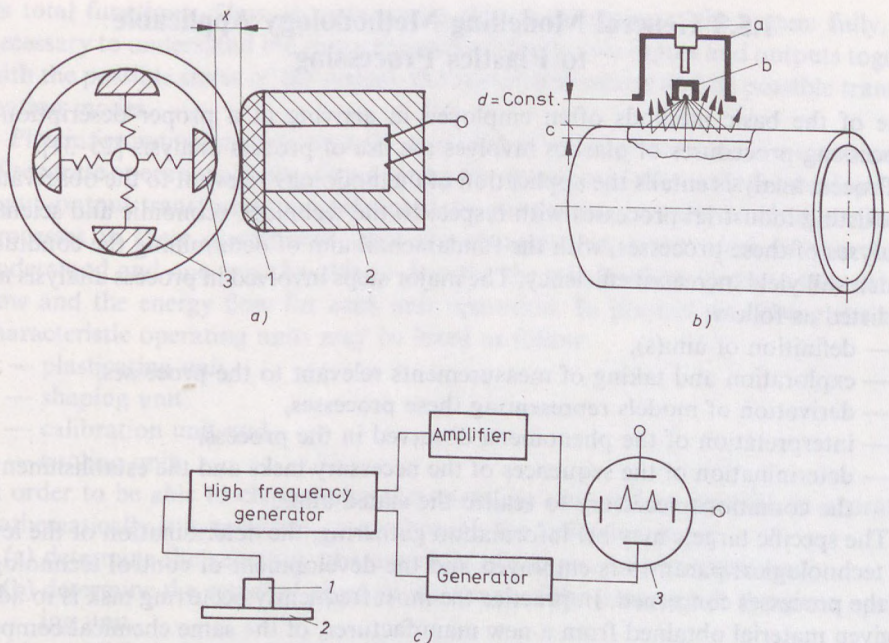


Fig. 1.33. Tube wall thickness measuring devices

- a) Wall thickness measuring instrument, working on induction principles, 1. core, 2. secondary coils, 3. primary coils;
- b) Wall thickness measuring device working on the principle of radiometry, a. detector, b. radiation source;
- c) Wall thickness measuring device operating on the principle of ultra-sound, 1. detecting head, 2. the object measured, 3. sensing device

gauges measure the wall thickness along the circumference of the tube in such a way that the measuring head of the instrument rotates around the outside circumference of the tube. Some instruments also move the gauge along the axis of the tube. The wall thickness gauge may be positioned at the calibre, at a site after it, or before the pull-off equipment.

The ultrasonic gauge (Figure 1.33.c) operates on the principle that one part of the ultrasonic oscillations of the device emitting the ultrasonic sounds is reflected from the external surface of the tube, while another part is reflected from the internal surface of the tube. The difference between these reflected impulses is directly proportional to the wall thickness. This type of measurement is quite substantially affected by the temperature of the tube, so that accurate measurements can only be made at near-constant temperatures.

The measuring methods for other parameters of the finished product are not discussed here, since they are rarely utilized in the application of control techniques. For interested readers, there is an abundance of literature available on the subject [12–15].

1.5.2 General Modelling Methodology Applicable to Plastics Processing

One of the basic methods often employed in arriving at a proper description of processing procedures of plastics involves the use of process analysis [25–31].

Process analysis entails the application of methodology relevant to the observation of existing industrial processes with respect to the technical, economic and scientific analyses of these processes, with the fundamental aim of determining the conditions which will yield increased efficiency. The major steps involved in process analysis may be listed as follow:

- definition of aim(s),
- exploration and taking of measurements relevant to the processes,
- derivation of models representing these processes,
- interpretation of the phenomena observed in the process,
- determination of the sequences of the necessary tasks and the establishment of the conditions necessary to realize the stated aims.

The specific targets may be: information gathering, the determination of the levels of technological parameters employed and the development of control technologies of the processes concerned. In practice the most frequently occurring task is to adapt a given material obtained from a new manufacturer, of the same chemical composition, as a substitute for the currently employed material in the given technological process. In such instances the technologist must know what kind of information needs to be obtained on the properties of this substitute material, and he must be able to assess how such information relates to the technological parameters employed in the processes. Another frequently occurring task is to solve the problems of control or to raise the existing application of control to a higher level. In order to accomplish these tasks, a practical approach is often to break down the processes taking place in plastics processing equipment into discrete units.

One of the characteristic features of the plastics processing operation is that the processing involves certain physical, or more exactly, certain rheological and thermal changes of the material. The operational units in processing of plastics may be simple or complex units. The entirety of the system is broken down into unit elements as a first approximation. These may be detached from their environment, and interfere with the environment. The system transforms the effects of the environment, and thus affects the environment at the same time. The influence of the environment upon the system is called input, while the effects of the system affecting the environment is termed the output. The reaction of the system to the influence of the environment is determined by the current state of the system. The response of the system involves a certain time delay, thus, to induce a change in the system upon the effect of a certain input to lead to some sort of output, a certain time lapse is necessary. The functioning of the system in terms of the environment is thus determined by this input–output transformation. Where this transformation is the result of a known process, this transformation is called the system's algorithm. If the internal structure of the system is not known, than the system is treated as a "black box". The structure of the system may be determined by examining the system's subfunctions in a logical breakdown of

its total functions. Thus, in order to be able to characterize the system fully, it is necessary to understand the characteristics of the various inputs and outputs together with the possible states of the system, the system's structure and its possible transformation modes.

Plastic formation processes may be regarded as whole systems, or as a combination of separate operational units. Considering the operational units as individual systems, input-output transformations take place in these units. In order to characterize the processes in these operational units the changes that occur must be thoroughly understood and one must be able to describe the relationships between the material flow and the energy flow for each unit operation. In plastics processing the most characteristic operating units may be listed as follow:

- plasticating unit,
- shaping unit,
- calibration unit and
- cooling unit.

In order to be able to characterize the operating unit and to describe its operation mathematically it is necessary to go through the following steps:

- (a) determine the geometry characteristic of the given operational unit,
- (b) determine the essential physical feature(s) of the processes in the given operating unit,
- (c) establish the kinetic and thermodynamic changes that occur in the given operating unit (such as velocity, stress and temperature fields).
- (d) determine the relevant balance equations characteristic of the operating unit, describing changes of the field and time variables,
- (e) provide the state equations and other characteristic features relevant to the material used within the operating unit,
- (f) verify mathematical solution(s) related to the given operating unit. Steps necessary for deriving the mathematical solutions are as follow:
 - choose a frame of reference, relevant to the boundary conditions,
 - select the coordinate system,
 - rewrite the equation into a dimensionless form, and
 - determine solutions by approximations.

The processes occurring in each of the operating units cannot, in general, be fully described due to their complexity. It is thus advisable to apply the appropriate simplifications to arrive at a simplified equation with possible solutions. Mathematical simplifications may take the form of one or more procedures of the following types:

- the choice of a simplified, and, if at all possible, symmetrical geometrical model,
- the restriction of the problem to a localized, limited space, by subdivision of the processes into constituent parts, a method which makes it possible to simplify the boundary and the initial conditions together with simplification of the kinematic and thermodynamic fields,
- the simplification of equations with dimensionless criteria parameters,
- the simplification of state equations with the aid of suitable criteria parameters,
- finally, the provision of numerical solutions to the mathematical equations.

1.5.2.1 The Characteristic Equations that Occur in Processing of Plastics

For all of the interrelationships, characteristic extensive quantities and characteristic intensive quantities are involved. The energy changes that are induced as a result of the interactions are proportional to the relevant changes of the extensive quantities. The inhomogeneous nature of the intensive quantities bring about a flow of the extensive quantities. These flows are expressed by the derived balance equations. A general differential balance equation may be, for example:

$$\frac{\partial \Gamma_i}{\partial t} + \text{div} \left(\Gamma_i v + \sum_{k=1}^{n-1} L_{ik} \text{grad } y_{ik} \right) + \beta_i \frac{A}{V} \Delta \Gamma_i = q_i \quad (1.40)$$

where Γ_i is a general expression of density, v is the velocity, and L_{ik} is the conductivity, related to the differences of the intensive factor y_{ik} of the i th extensive quantity. Equation (1.40) is, thus, a derivation of the general transport equation and the Onsager relationship.

The first term of equation (1.40) on the left hand side of the equation represents the change in density with time, the second term of the equation consists of two subterms in brackets depicting the stream intensities; the first of these represents the convective (transport), and the second deals with the conductive part of the relationship. This stream is termed convective if the flow is associated with macroscopic movement, thus the convective stream intensities represent the multiplication of the given density and velocity values. The conductive member of the equation represents the stream without macroscopic movement originating from the inhomogeneous extensive field quantities. These convective and conductive streams are valid only for surfaces within the phase limitations. The third term on the left hand side of equation (1.40) represents the streams between these phases, where the stream transfer is directly proportional to the differences in intensities and the available surface areas between these phases. Here β_i is the transfer factor, A represents the surface area of the system, while V represents the volume of the system. The right hand side of the equation is the source intensity of the system.

From this general relationship it is possible to derive specific equations to characterize each individual operation, including the intensive and extensive quantities together with the transfer processes and source intensities. In the description of plastic manufacturing processes, it is the mass, the momentum and the energy balance that are normally employed.

Simplification of these equations can be achieved and derived from the general relationship, without defining the units of the members of such an equation. We now rewrite equation (1.40) representing the source density system q'_i with density Γ'_i , velocity v'_i , and transfer factor β'_i . In the derivation the following symbols are introduced:

$$C_r = \frac{\Gamma'}{\Gamma} \quad \text{the transformation multiple of the density of the extensive quantity,}$$

$$C_t = \frac{t'}{t} \quad \text{the time transformation multiple,}$$

$C_{v_i} = \frac{v'_i}{v_i}$	the transformation multiple of the i^{th} member of the flow velocity,
$C_k = \frac{K'_j}{K_j}$	the transformation multiple of the conductivity of the j^{th} intensive quantity,
$C_{y_j} = \frac{Y'_j}{Y_j}$	the transformation multiple of the j^{th} intensive quantity,
$C_\beta = \frac{\beta'}{\beta}$	the transformation multiple of the transfer factor,
$C_{\Delta\Gamma} = \frac{\Delta\Gamma'}{\Delta\Gamma}$	the transformation multiple of the differences of the intensive quantities,
$C_{x_i} = \frac{X'_i}{X_i}$	the transformation multiple of the i^{th} coordinate,
$C_q = \frac{q'_i}{q_i}$	the transformation multiple of the i^{th} source density.

The general equation (1.40) is now transformed into:

$$\begin{aligned} \frac{C_\Gamma}{C_t} \frac{\partial \Gamma}{\partial t} + \sum_{j=1}^3 \left(\frac{C_\Gamma C_{v_i}}{C_{x_i}} \frac{\partial \Gamma v_i}{\partial x_i} + \sum_{j=1}^n \frac{C_k C_y}{C_x} \left[k_j \frac{\partial^2 y_j}{\partial x_i^2} + \frac{\partial k_j}{\partial x_i} \frac{\partial y_j}{\partial x_j} \right] \right) + \\ + \frac{C_\beta C_\Gamma}{C_{x_i}} \frac{A}{V} \Delta \Gamma = C_q q \end{aligned} \quad (1.41)$$

Grouping each of the dimensionless quantities together:

$$\begin{aligned} \pi_\Gamma = \frac{C_\Gamma}{C_t} \quad \pi_{k_i} = \frac{C_\Gamma C_{v_i}}{C_{x_i}} \quad \pi_{eij} = \frac{C_{k_j} C_{y_j}}{C_{x_i^2}} \\ \pi_q = C_q \quad \pi_{\Delta\Gamma} = \frac{C_\beta C_\Gamma}{C_{x_i}} \end{aligned} \quad (1.42)$$

expressions in terms of quotients or coefficients, the criteria of each of the parameters may be written as follows, to give

$$\frac{\pi_\Gamma}{\pi_{k_i}} = \frac{x_i}{v_i t} \quad \text{homochronical or isochronic number,}$$

$$\frac{\pi_{k_1}}{\pi_{k_2}} = \frac{v_2 x_1}{v_1 x_2} \quad \text{divergency criterium,}$$

$$\frac{\pi_{eij}}{\pi_{k_i}} = \frac{k_j y_j x_1}{v_i x_i^2 \Gamma} \quad \text{invariant, Reynolds type relationship, representing the component in the } x \text{ direction of the } i^{\text{th}} \text{ conductive stream intensity, and the convective stream intensity is induced by the } j^{\text{th}} \text{ intensive quantity (3n exists as such),}$$

Table 1.3: Types of similarity invariants that may be derived from transport equations

Denominator/ Nominator	1 π_Γ	2 π_{ki}	3 π_{eji}	4 π_{eki}	5 $\pi_{\Delta\Gamma}$	6 π_q
1 π_Γ	1	$\frac{v_i t}{x_i}$	$\frac{k_j y_j t}{\Gamma x_i^2}$	$\frac{k_b y_b t}{\Gamma x_i^2}$	$\frac{\beta_i t}{x_i}$	$\frac{qt}{\Gamma}$
2 π_{ki}	$\frac{x_i}{v_i t}$	$\frac{v_i x_i}{v_i x_i}$	$\frac{k_j y_j x_i}{v_i x_i^2}$	$\frac{k_k y_k x_k}{\Gamma v_i x_i^2}$	$\frac{\beta_i}{v_k}$	$\frac{qx_i}{\Gamma v_i}$
3 π_{ejk}	$\frac{\Gamma x_i^2}{k_j y_j t}$	$\frac{\Gamma v_i x_i^2}{k_j y_j x_j}$	$\frac{x_i^2}{x_i^2}$	$\frac{k_k y_k x_i^2}{k_j y_j x_i^2}$	$\frac{\beta_i \Gamma x_i}{k_j y_j}$	$\frac{qx_i^2}{k_j y_j}$
4 π_{ekl}	$\frac{\Gamma x_i^2}{k_k y_k t}$	$\frac{\Gamma v_i x_i^2}{k_k y_k x_i}$	$\frac{k_j y_j x_i^2}{k_k y_k x_i^2}$	$\frac{x_i^2}{x_i^2}$	$\frac{\beta_i \Gamma x_i}{k_k y_k}$	$\frac{qx_i^2}{k_k y_k}$
5 $\pi_{\Delta\Gamma}$	$\frac{\beta_i}{x_i t}$	$\frac{\beta_i}{v_i}$	$\frac{\beta_i \Gamma x_i}{k_j y_j}$	$\frac{\beta_i \Gamma x_i}{k_k y_k}$	1	$\frac{qx_i}{\beta_i \Gamma}$
6 π_q	$\frac{\Gamma}{qt}$	$\frac{v_k}{qx_i}$	$\frac{k_j y_j}{qx_i^2}$	$\frac{k_k y_k}{qx_i^2}$	$\frac{b_i \Gamma}{qx_i}$	1

$\frac{\pi_{\Delta\Gamma}}{\pi_{k_i}} = \frac{\beta_i}{v_i}$ the ratio of the i^{th} transfer stream and the x directional convective stream,

and the Froude type invariant,

$\frac{\pi_q}{\pi_{k_i}} = \frac{qx_i}{\Gamma v_i}$ expressing the ratio of the source and the stream intensities.

Here, the general invariants of the equation are viewed as criteria parameters. These invariant factors may be derived using other divisions, or denominators. The terms

Table 1.4. Criteria parameters derived from balance equations

	Convection conduction	Transfer conduction	Source conduction	Local Change conduction	Local Change convection	Source convection
Mass Balance	$Pe = \frac{Vx}{D}$	$Nu_d = \frac{\beta_x}{D}$	—	$\frac{1}{F_i} = \frac{x^2}{Dt}$	$Ho = \frac{x}{vt}$	—
Momentum Balance	$Re = \frac{vxQ}{\eta}$	—	—	—	$Ho = \frac{x}{vt}$	$Fr = \frac{v^2}{gx}$
Energy Balance	$Pe = \frac{vx}{a}$ $Gz = \frac{vx^2}{aL}$	$Nu = \frac{\alpha x}{k}$ $Bi = \frac{\alpha x}{k}$	$Gr = \frac{b\bar{\tau}\bar{\gamma}x^2}{kL}$ $Br = \frac{\bar{\tau}\bar{\gamma}x^2}{k(T_j - T_0)}$	$\frac{l}{F_0} = \frac{x^2}{at}$	$Ho = \frac{x}{vt}$	—

used for dividing the equation are a matter of choice. The invariants obtained by such mathematical manipulation are listed in Table 1.3.

The collated criteria parameters derived from the mass, the momentum and the energy balances are presented in Table 1.4.

1.5.2.2 State and Material Parameter Equations Relevant to Polymer Processing

The processes that take place in each of the operating units related to the processing of plastics, play important roles in the constitutive equations and in the physical state equations.

The constitutive equations provide information on the time dependence of the relationship between strain and stress. Several comprehensive works are available which summarize the constitutive equations [28–31]. In order to describe these processes it is necessary to choose such a constitutive equation, which adequately describes the behaviour of a given material in the space where deformation occurs.

In order to arrive at a choice of a particular constitutive equation, three different criteria may be used. These are the Deborah number, the Weissenberg number and the parametric linearity number. The Deborah number is concerned with the behaviour of a material, it compares the relaxation time λ_1 to the deformation time. In fact it defines the state of the deformation space close to the constant deformation history.

The Deborah number is an approximate localized relationship expressed as

$$N_{De} = \lambda_1 \omega \quad (1.43)$$

where ω represents the characteristic frequency of flow. In case of simple flow:

$\omega = \frac{L_{||}}{v}$, where $L_{||}$ is a geometric size parallel to the direction of the deformation,

while v is the rate of deformation. Where the Deborah number is small, the relaxation processes of the material examined are fast, compared with the characteristic deformation time, thus, the behaviour of the material approaches the behaviour of a viscous material. In the case of large Deborah numbers, the relaxation times are long compared with the deformation times and the behaviour of the material resembles the behaviour of an elastic, solid material. The Deborah numbers close to zero thus refer to viscous materials, Deborah numbers greater than ten are characteristic of elastic materials, while numbers between these two extremes indicate a viscous-elastic behaviour of the material.

The ratio of the tangential versus normal stresses and with these, the roles of the localized normal stress relationship are expressed by the Weissenberg number, given by the equation:

$$N_{we} = \frac{\lambda_2 v}{L_{\perp}} = \frac{\tau_{11} - \tau_{22}}{\tau_{12}} \quad (1.44)$$

where v represents the velocity of deformation, $L_{\perp}$ is the relevant length perpendicular to the deformation space. The Weissenberg number represents the relative

velocity of flow. If the Weissenberg number is small, the normal stresses are negligible compared with the tangential stresses present.

The linear relationship of shearing forces may be characterized by the parametric linearity number, expressed as:

$$N_p = \frac{\lambda_2 v}{L_{\perp}} \quad (1.45)$$

where λ_2 represents the relaxation time. When the parametric linearity number is small, the behaviour of the material in simple shearing flow is also linear, thus the Newton equation is applicable.

The three dimensionless parameters can be utilized to derive a rheological classification system [28–29]. The relaxation characteristics can be determined experimentally, together with the functions of stresses related to viscosity and to normal stresses. Based on the above it is now possible to estimate the characteristic relaxation times (λ_1, λ_2). A code system has been devised constituting of three numbers which represent the three criteria. The first number characterizes the Deborah number. Very small Deborah numbers are represented by 0, small values are represented by 1, medium magnitude by 2, and a large Deborah number may be 3. Based on the above classification a viscous liquid is represented by zero, an elastic, solid material by 3; the equations describing speed of flow of a viscous–elastic behaviour may be represented by the number 1, while the group of integration equations are represented by the number 2. The second code number is provided by the Weissenberg number, which can take the value of 0 or 1, depending on whether the Weissenberg number does or does not approach zero. The third code number (either 0 or 1) provides the parametric linearity number.

For calculation of the dimensionless rheological parameters, it is necessary to have two characteristic relaxation times, one of which is connected with the tensorial, non-linear part of the rheological state equation, while the other is related to the parametric non-linearity of the same constitutive equation. The stress tensor may be written, in a fixed coordinate system, as follows:

$$\tau = f_1 \mu \Delta + f_2 \mu \lambda_1 \Delta \quad (1.46)$$

the stress tensor may be expressed by a series derived from the above two members of the strain rate tensor. The time parameter λ_1 represents the relaxation time characteristic of tensorial non-linearity. The functions f_1 and f_2 are dimensionless. Expressed in general terms:

$$f_j = f_j[(\lambda_2^2 II_{\Delta}); (\lambda_2^3 III_{\Delta}); C_j] \quad (1.47)$$

where II_{Δ} and III_{Δ} are the invariants of the rate of strain tensor which together with the time parameter λ_1 give a dimensionless quantity. The relaxation time λ_2 gives the parametric linearity; since when $\lambda_2 = 0$, the material is characterized by a permanent viscosity function, when λ_1 is equal to 0, the equation is tensorially linear; this is characteristic of inelastic liquids. λ_1 may be defined as:

$$\lambda_1 = \lim_{\omega \rightarrow 0} \frac{G'}{\eta' \omega^2} = \lim_{\dot{\gamma} \rightarrow 0} \frac{N_1(\dot{\gamma})}{\eta(\dot{\gamma})} \quad (1.48)$$

which relates to the dynamic viscosity, and it relates to the first normal stress function derived above.

λ_2 relates, on the other hand, to the viscosity function:

$$\lambda_2 = \left\{ - \left[\frac{\partial(\eta/\eta_0)}{\partial \dot{\gamma}} \right]_{\dot{\gamma}=0} \right\}^{1/2} \quad (1.49)$$

For the determination of the time parameter λ_1 , based on equation (1.48), the data of normal stress and viscosity measurements were utilized together with the measurements made following the termination of stress after the stopping of the stationary shearing flow. In this instance the maximum relaxation time is obtained from the initial slope of the curve given by the relationship:

$$\frac{\lg \tau(t)}{\dot{\gamma}_0} = \lg \eta_0 - \frac{t}{2.3 \lambda_1} \quad (1.50)$$

By application of this method, entire relaxation spectra may be written, which, in turn may be used for purposes of calculation of other rheological features. The relaxation characteristic of tensorial non-linearity can be calculated provided that the viscosity and the molecular weights are known, utilizing Rouse's theory

$$\lambda_1 = \frac{6}{\pi^2} \frac{\eta_0 M_w}{\rho RT} \quad (1.51)$$

where ρ designates the density of the polymer,

M_w represents the molecular weight of the material,

R is the general gas constant, and T is the absolute temperature.

The physical state equation shows the relationship that exists between items designating the physical state of the system, such as volume, pressure and temperature. The equations related to physical state may be derived with the aid of the van der Waal's equation, or from the potential barrier theory, or from relationships derived empirically. The total differential of density is:

$$d\rho = \left(\frac{\partial \rho}{\partial T} \right)_P dT + \left(\frac{\partial \rho}{\partial P} \right)_T dP \quad (1.52)$$

Introducing the heat expansion factor $\kappa = - \frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_P$ and the compressibility factor

$\beta = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial P} \right)_T$, the equation becomes:

$$d\rho = -\kappa \rho dT + \beta \rho dP \quad (1.53)$$

which may be regarded as a state equation, limited to small temperature or pressure changes. By taking into consideration for purposes of calculation the state equation, two dimensionless parameters may be defined; the first of these is expansion number from the relationship:

$$Ex = \frac{T}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_P = \kappa T \quad (1.54)$$

where T is a carefully chosen reference temperature. The expansion number gives an indication of the role of heat expansion. In the case where Ex is small, the role of heat expansion may be ignored.

The other is the compressibility number, given by the relationship:

$$Ko = \frac{P}{\varrho} \left(\frac{\partial \varrho}{\partial P} \right)_T = \beta P \quad (1.55)$$

where P is a carefully chosen reference pressure value. The compressibility number expresses the role of compression.

Some attributes of materials that play important parts in description of processes relevant in the plastics manufacturing industry are:

- thermal conductivity,
- specific heat,
- melting point,
- frictional constant of the solid polymer material,
- anisotropy coefficient of the solid polymer material,
- compacted and uncompact bulk densities of the solid polymer.

The thermal conductivity of both the solid polymer and the melt is a function of the temperature, although the temperature factor is rather small. A more important factor, particularly in the instances of granulated solid polymer material, is the uncompact volume, a factor that may be described by the relationship:

$$k_g = 2k\varrho_s / (3\varrho - \varrho_s) \quad (1.56)$$

where ϱ_s is the bulk density of the granules.

The specific heat of the mass of the polymer particles is a function of the weight/volume ratio and of temperature. The specific heat of the material, for all practical purposes, changes to any substantial degree only at or near the melting point temperature of the material. The relationship of the temperature and the uncompact volume [15] may be expressed by the following equation:

$$C_V = C_{V_0} (1 - \varrho_s / \varrho) + a_1 T + a_3 T^3 \quad (1.57)$$

The specific heat measured in constant volume is connected with the specific heat measured under constant pressure by the following relationship:

$$C_V = C_P - T v \frac{\alpha}{\beta} \quad (1.58)$$

where V is the specific volume of the material.

Melting heat may be regarded as constant for a given material in plastics manufacturing. The dimensionless parameter containing the fusion heat is the Stefan number:

$$St = \frac{\varrho_\delta C_\delta T}{\varrho_s [\lambda + C(T_\delta + T_0)]} \quad (1.59)$$

which compares the amount of heat required for heating the polymer melt and that consumed during transforming the solid polymer into a melt.

The frictional coefficient of the solid polymer is a dimensionless quantity, it expresses the ratio of the tangential and the normal stress components, thus

$$f = \frac{\tau_i}{\sigma_i} \quad (1.60)$$

The frictional coefficient, in the case of solid polymer materials, is a function of the temperature, the pressure and the sliding velocity of the material. In general, its value increases with increasing temperature, and decreases with increasing pressure.

The pressure distribution in a mass of polymer particles is not isotropic, unlike liquids. This non-isotropic behaviour is characterized by the anisotropy factor, the ratio of normal stresses:

$$p_k = \frac{\sigma_{ii}}{\sigma_{jj}} \quad (1.61)$$

The anisotropy factor is a function of temperature and pressure. This dependency is significant near the melting point of the material.

1.5.2.3 Initial and Boundary Conditions of the Processing System

The initial conditions of the entire system at time $t=0$ are the characteristics of the material entering through the orifice of the machine: temperature and pressure. For each of the characteristic units the distribution of temperature and pressure can be established as localized initial conditions at a given time.

The limiting values in solving the impulse equations are the actual values of stresses appearing at the boundaries of the specific space examined, or the velocity of material flow along the boundaries. For the movement of solid material, the stresses are usually given, while for melts the velocities are established. During the movement of a melt, the two characteristic limiting conditions are: the particular material adheres to the surface or it slides along it. In general, the sliding velocity is a function of the wall temperature and of the shearing forces acting on the wall surfaces.

Two dimensionless parameter criteria characterize these limiting conditions. One is the Bikermann criterion, which compares the adhesive forces with the frictional forces effective on the surfaces, expressed as:

$$Bk = \frac{\sigma_A}{fP} \quad (1.62)$$

where σ_A is the adhesive tension. The other parameter is the so-called Bebrisz number, the ratio of the external and the internal friction. This number is suitable, for polymers in the solid state, for characterizing the type of material flow (such as the movement of granules, or a plug type motion); in the case of a melt it is suitable for making distinction between the mechanisms of wall slip.

The boundary conditions necessary to solve the energy equation are: *first order*; where the temperature distribution at the boundary surfaces are known at a given time, the following expression holds:

$$T_w = f(t, x_i, w) \quad (1.63)$$

Table 1.5. Dimensionless parameters
summary table

Designation	Group	Definition
	<i>Equation</i>	
Reynold's number	Momentum equation	$Re = \frac{\text{Inertia}}{\text{Internal friction}} = \frac{\rho V x}{\mu}$
Euler number	Momentum equation	$Eu = \frac{\text{Pressure}}{\text{Inertia}} = \frac{\Delta P}{\rho v^2}$
Pressure parameter	Momentum equation	$\pi_p = \frac{\text{Pressure}}{\text{Internal friction}} = \frac{\Delta P x}{\Delta \tau}$
Froude number	Momentum equation	$Fr = \frac{\text{Inertia}}{\text{Gravity}} = \frac{v^2}{xg}$
Peclet number	Energy equation	$Pe = \frac{\text{Heat transport}}{\text{Heat conduction}} = \frac{\rho c v x}{k}$
Graetz number	Energy equation	$Gz = \frac{\text{Heat transport}}{\text{Heat conduction}} = XPe$
Brinkman number	Energy equation	$Br = \frac{\text{Dissipation}}{\text{Heat conduction}} = \frac{\bar{\tau} \bar{\gamma} x^2}{k(T_w - T_0)}$
Griffith number	Energy equation	$Gr = \frac{\text{Dissipation}}{\text{Heat conduction}} = \frac{b \bar{\tau} \bar{\gamma} x^2}{k}$
Nahme number	Energy equation	$Na = \frac{\text{Dissipation}}{\text{Heat conduction}} = \frac{b \bar{\tau} \bar{\gamma} x^2}{k}$
Deborah number	<i>Rheological state equation</i>	$N_{De} = \frac{\lambda_1 v}{L_{ }}$
Weissenberg number	<i>Rheological state equation</i>	$N_{we} = \frac{\lambda_1 v}{L_{\perp}}$
Parametric linearity number	<i>Rheological state equation</i>	$N_{pl} = \frac{\lambda_2 v}{L_{\perp}}$
	<i>Physical state equation</i>	
Expansion number		$E_x = \kappa T^*$
Compressibility number		$K_0 = \beta P^*$
	<i>Others</i>	
Stefan number	$\frac{\text{Heat absorbed by the molten material}}{\text{Heat absorbed by the solid material}}$	$St = \frac{\rho_n c_m \Delta T}{\rho_s [A + c_s (T_m - T_0)]}$
Bikerman number		$Bk = \frac{\text{adhesive force}}{\text{frictional force}} = \frac{\sigma_A}{fP}$
Bebris number		$Be = \frac{\text{external friction}}{\text{internal friction}} = \frac{f_{ou}}{f_{in}}$
Nusselt number (Biot number)		$Nu = \frac{\text{heat transfer}}{\text{heat conduction}} = \frac{\alpha x}{k}$
Fourier number		$Fo = \frac{\text{heat conduction}}{\text{localized heat flow}} = \frac{at}{x^2}$
Biró number		$Ba_1 = \frac{\text{force applied}}{\text{deformation force}} = \frac{\sigma A}{EA}$
		$Ba_2 = \frac{\text{deformation force}}{\text{cohesive stability (or rigidity)}} = \frac{EA}{\sigma_A A}$

$$X = \frac{x}{L}$$

The simplest possible case of the above is when the boundary temperatures are constant.

Second order; where the heat flow density is constant as a function of time at all points of the boundary surfaces, it may be expressed as:

$$k_{jw} \left(\frac{\partial T}{\partial n} \right) = q_{j, w}(t, x_i, r) \quad (1.64)$$

where $j=1, 2, \dots, l$, represent the boundary surface areas of the body. In a simpler case, the heat flow is constant.

Third order; where the amount of heat transfer across the surfaces is known, mathematically:

$$q_{j, w} = \alpha_j (T_{j, w} - T) \quad (1.65)$$

In the investigation of thermal limiting conditions, either the Nusselt or the Biot criteria are used:

$$Nu = \frac{\alpha}{k} x = Bi \quad (1.66)$$

Here, the parameter expresses the ratio of the intensity of energy transport from the environment to the surface and from the surface to the environment.

When $Bi \gg 1$, the conductivity factor of the energy flow into the environment is much greater than the energy flow received from the system, thus the temperature of the surface and of the environment will be identical. If, however, $Bi \ll 1$, the heat conductivity to the environment will be much smaller than the heat received from the system, thus, in the latter instance, the surface, with respect to heat transfer, will behave as an insulator.

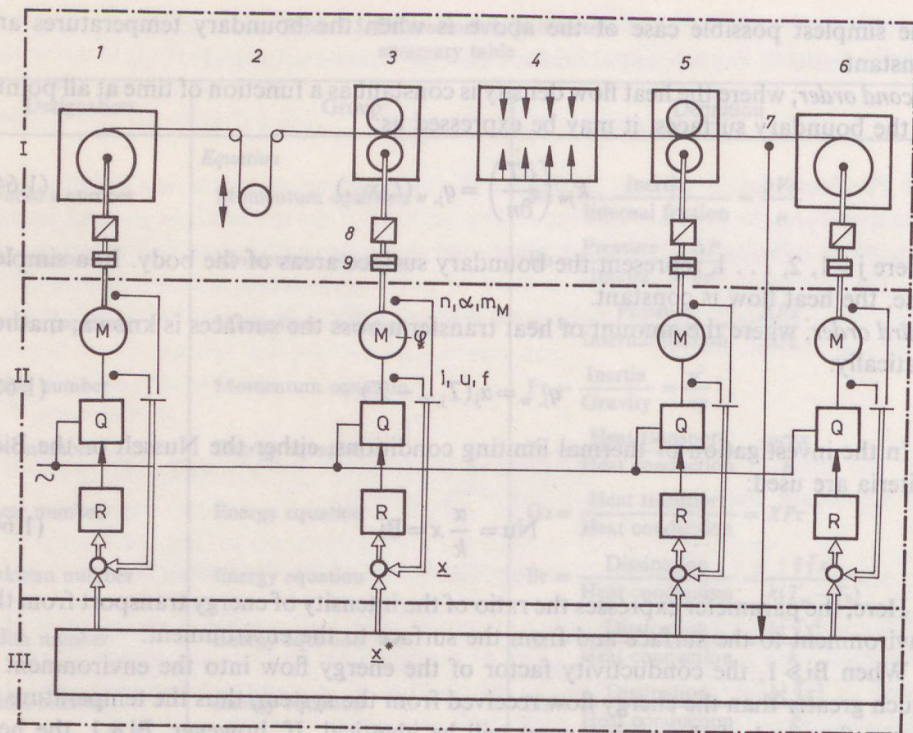
The dimensionless criteria parameters are summarized in Table 1.5. [31].

1.6 Driving and Take-off Equipment Employed in Polymer Processing Machinery

The driving units of the polymer processing machines are electric motors. Up till now, the control of the electrical drives of continuous production plants have been mainly implemented by analogue techniques [20—21]. The need for constancy of absolute values and speed relationship can be better achieved by the integrated circuits previously mentioned. In the following we shall deal with continuous moving webs.

In continuous production, installations are equipped with continuously moving webs. Three main sections are distinguished: the processing equipment, the drive system and the process control system (Figure 1.34.).

The processing machine (*I*) comprises mechanical parts for the entire plant. Beginning with unfinished stock (*I*), the web generally passes through a large number of driven or non-driven units (e.g. 2, 3 or 5), where forces are transferred to the web. The web is guided, transported and often simultaneously processed through these nips.



- 1 unfinished stock
 2 nip (dancing roller or actuating roller)
 1-2-3 section with variable length of web
 3, 5 nip
 3-5 section with constant length of web
 4 processing unit
 6 finished stock
 7 measuring element
 I process
 II drives
 III process control system

- M motor
 Q power supply
 R controller
 i current
 m_M torque of the motor
 n speed
 u voltage
 x^* reference value
 x actual value
 α angle
 ϕ flux
 $\sim$ power line

Fig. 1.34. A synchronously running system

Between the nips the web is essentially free of forces ("free web") and may have a fixed length e.g. between 3 and 5, or a variable length (in sections 1, 2 and 3). Number (4) is a processing zone through which the free web is run. At the end of the process the web is deposited in the form of finished stock, from which it may be removed for purposes of further processing.

The drive system consists of the drive motors M , acting as the electromechanical energy converter with the associated supply source Q . Important drive variables, such as the current (i), the voltage (u), the frequency (f), the field (ϕ), the torque (m_M),

the velocity (v) and the angle of rotation (α) may be controlled with assigned controls, represented in this example by R .

The predominantly-favoured drive motor these days is the DC shunt-wound motor with a resistor-fed armature and field, which may operate as a single, or a multi-quadrant drive. The armature voltage (μ_A) and the excitation voltage μ_E , by means of which the flux (φ) may be altered, are all available as control variables influencing the speed. The standard version of the speed-controlled module consists of a current-control loop with a superimposed speed-control loop.

Using a variable motor voltage, with variable frequency, a three-phase cage asynchronous motor may be controlled in the same way as a DC machine, with the aid of a static frequency change. The speed may be controlled by using a decoupling network with the same static and dynamic qualities as the DC machine.

The three-phase synchronous machine with DC supply to the excitation winding and a static frequency change of supply in the stator has a synchronous speed behaviour with an angle of rotation which is sinusoidally dependent on the torque. Therefore, a synchronous machine may be operated without speed regulation in numerous modes of application.

The so-called converter-fed motor operates as a DC shunt-wound machine with an electronic commutation and, thus, it has an asynchronous behaviour. It may be therefore equipped with an automatic speed control.

Using the process control system (Fig. 1.34. *III*) the reference values for all controlled quantities of the process, especially for the controlled drive variables are provided and, furthermore, the overriding control monitoring and signalling functions are carried out. One is dealing with a steady-state behaviour of a system with a continuous moving web. The mass flow is in a steady state, that is to say, a certain mass is transported through an arbitrarily chosen control volume enveloping the web per unit time, and this is a constant. The web velocity v and the web strain ε at each point of the web are linked by the relationship:

$$\frac{v}{1 + \varepsilon} = \text{const.} \quad (1.67)$$

In the case of constant temperature and moisture content along the web (Figure 1.35.), the following relationship holds:

$$\frac{v_{u1}}{1 + \varepsilon_{01}} = \frac{v_{u2}}{1 + \varepsilon_{12}} = \dots = \frac{v_{uk}}{1 + \varepsilon_{k-1, k}} = \frac{v_{u, k+1}}{1 + \varepsilon_{k, k+1}} \quad (1.68)$$

The steady values of the quantities of the processing machine are adjusted via the drive and the torque speeds. The angular velocity ω_k of the roll k is linked with the (angular) velocity of the circumference v_{uk} expressed by the relationship:

$$v_{uk} = R_k \omega_k \quad (1.69)$$

where R_k is the radius of the roll k . In the steady state, which is the case here, the following is applicable for the angle of rotation, α_k , within the time period $t_2 - t_1$:

$$\alpha_k(t) = \omega_k(t_2 - t_1) \quad (1.70)$$

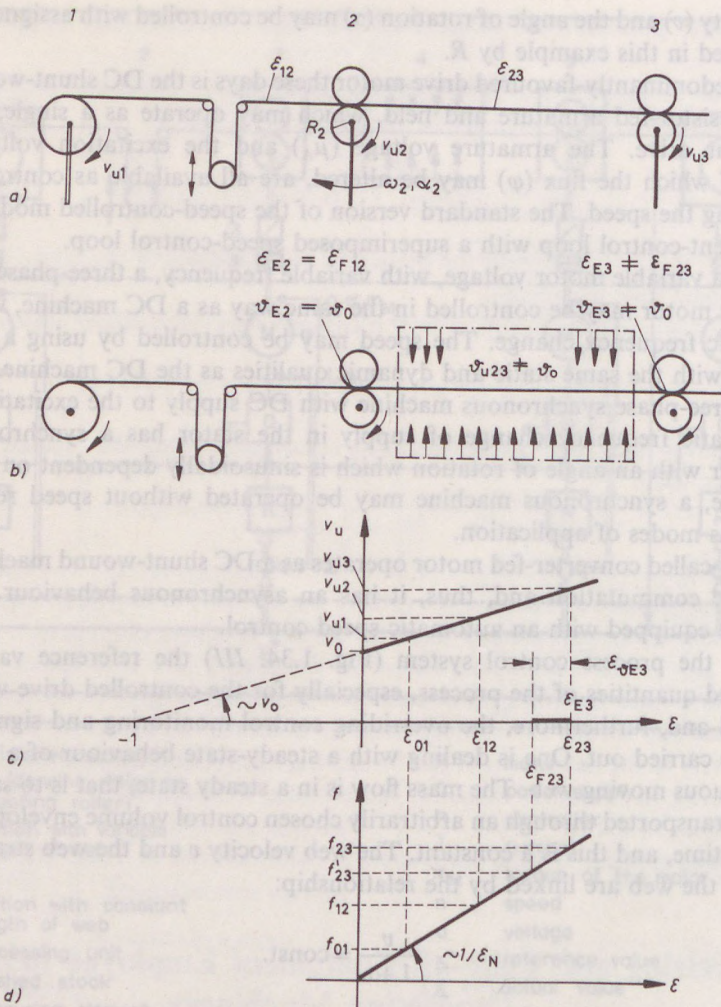


Fig. 1.35. Stationary state of a synchronously running system

- a) System at constant temperature $\vartheta = \vartheta_0$
b) System at variable temperature $\vartheta_{u23} \neq \vartheta_0$ in sections 2 and 3
c) Characteristic of strain and peripheral velocity
d) Characteristic of strain and tensile force

Symbols:

f tensile force (per unit)

R radius

v_0 velocity of the web at reference conditions ($\varepsilon = 0$)

v_{uk} peripheral velocity of the driven roller k

α_k angle of the driven roller k

ω_k angular velocity of the driven roller k

$\varepsilon_{k-1,k}$ strain at the input of nip k

$\varepsilon_{Fk-1,k}$ force-dependent strain in section $k-1, k$

$\varepsilon_{\vartheta Ek}$ temperature-dependent strain at the input of nip k

ε_N nominal value of strain

From equation (1.41) it follows that

$$\frac{v_{uk+1}}{v_{uk}} = \frac{R_{k+1}\omega_{k+1}}{R_k\omega_k} = \frac{R_{k+1}\alpha_{k+1}(t)}{R_k\alpha_k(t)} = \frac{1+\varepsilon_{k,k+1}}{1+\varepsilon_{k-1,k}} \quad (1.71)$$

Many of the processing machines require constant tensile forces of differing magnitude in the various sections. These quantities may be derived from the following equation:

$$\varepsilon_{F\ k-1,k} = \varepsilon_N f_{k-1,k} \quad (1.72)$$

Assuming constant velocity ratios $v_u \pm 1/v_{uk} = \text{const} \neq 1$, the "speed synchronism" may be expressed as follows:

$$\frac{\omega_{k+1}}{\omega_k} \neq 1 \quad (1.73)$$

and

$$\frac{\alpha_{k+1}(t)}{\alpha_k(t)} \neq 1 \quad (1.74)$$

Some processing machines, such as rotary printing presses, require a so-called angular synchronisation:

$$\frac{\alpha_{k+1}(t)}{\alpha_k(t)} = 1 \quad (1.75)$$

$$\frac{\omega_{k+1}}{\omega_k} = 1 \quad (1.76)$$

In this case, as expressed by equation (1.71), differing values of strain may only be handled by means of differing radii.

Assuming constant temperature and moisture content one obtains

$$\frac{v_{uk}}{v_0} = 1 + \varepsilon_N f_{k-1,k} \quad (1.77)$$

The difference between the tensile forces of the web is effective as the load force of the shaft of the drive of roll k . Using this as a variable, the relationship becomes

$$\frac{v_{uk}}{v_0} = \varepsilon_N (f_{k-1,k} - f_{k,k+1}) + \frac{v_{uk+1}}{v_0} \quad (1.78)$$

derived from equation (1.77) expressing the steady state characteristics of the machine.

It is necessary to control the speed and angle. The systems with speed and angle controls are listed below:

- speed controller, P ,
- speed controller, PT ,
- angle controller with P or PT speed controls,
- angle controller P_1 with P or PI_1 speed controls.

Where a P speed control is employed, a sufficiently high circuit gain must be planned in order to keep the control error low. In order to reduce the control error to near zero, either PI speed control must be used, or an angle control system with

angle control P may be superimposed. In polymer processing, correctable, adjustable and programmable controls may be used. In a digital system, the information may be processed as follows: the operator(s) make use of decimal numbers, while the system operates with corresponding binary numbers. The variables, which are mostly presented in analogue form, are converted to numbers by means of analogue/digital converters. In contrast to the analogue procedures, digital processes exhibit no drift. The accuracy of the digital control system is subject only to the number of digits provided. The adjustment of the desired value specified as a decimal number, for example, setting with decode switches or counting with key switches in conjunction with a set-point display, is rendered very simple. The set-point setting is precisely reproducible. Thus, due to the absence of drift and the high accuracy of quartz-stabilized frequency generators used in digital systems, the controlled variables have an extraordinarily high constancy. In the case of conventional digital speed control (hard-wired programmed digital control) a digitally operating system is superimposed on the basic analogue speed control loop.

The programmable control system for drive coordination is represented by the block diagram of Figure 1.36. The CPU is the brain of the system. It accepts the

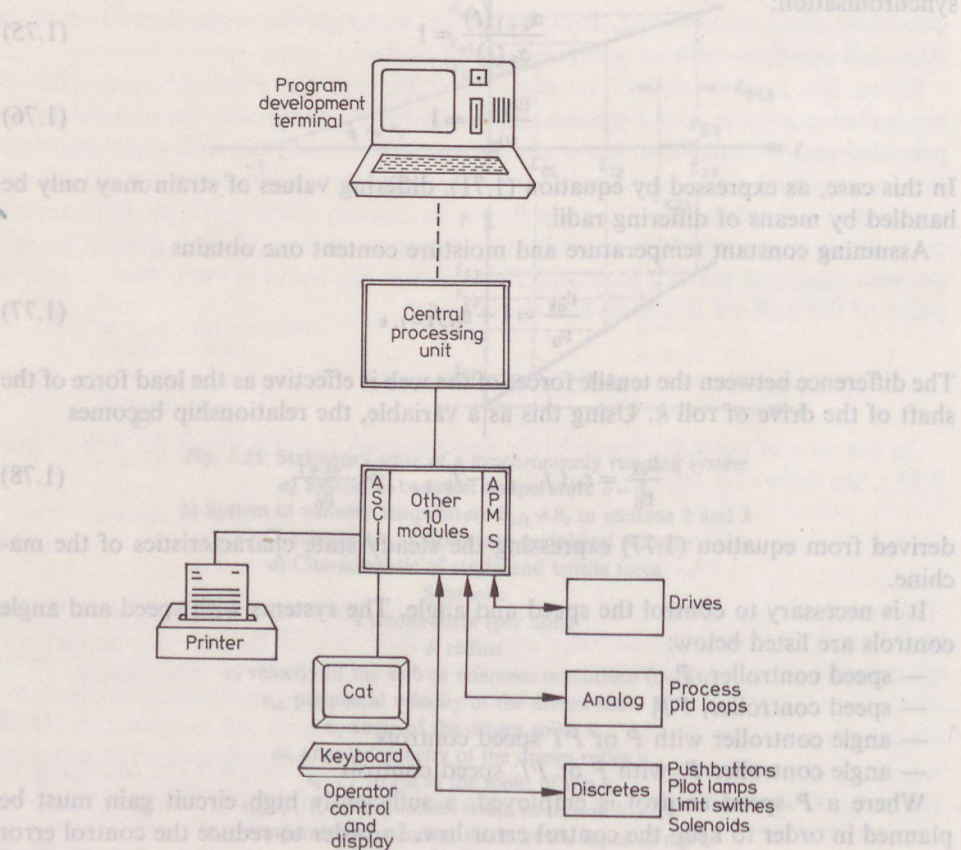


Fig. 1.36. Control programmed drive units

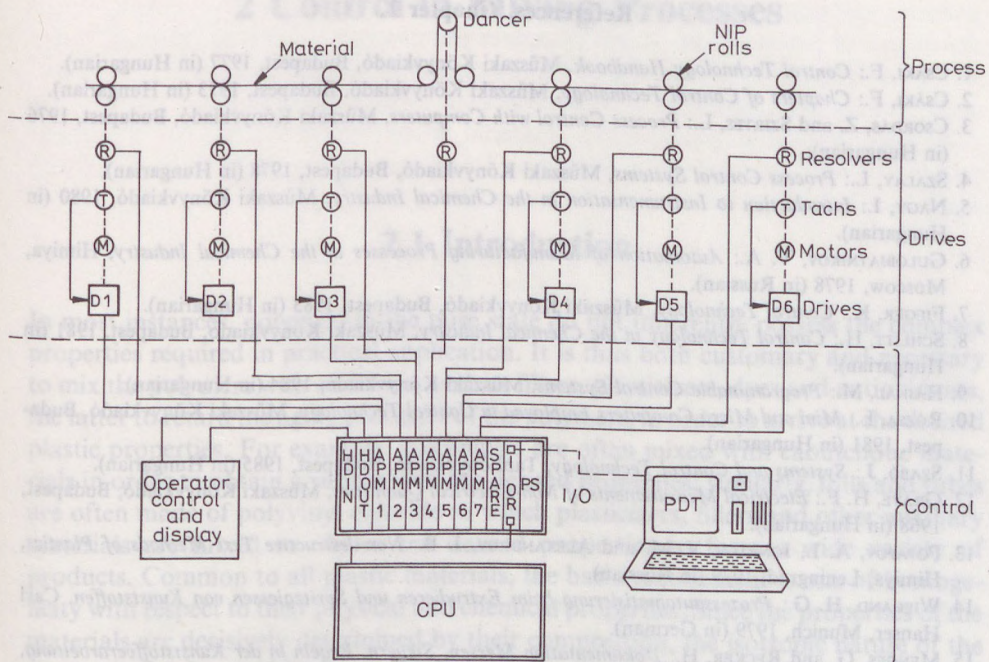


Fig. 1.37. Computer derived control system

functions programmed by the user to control the process, including alarm logging. It also controls production storage, process information and facilities retrieval of archived process settings. The CPU receives inputs from sensors such as limit switches, pushbuttons and position sensor commands, actuators, such as hydraulic cylinders and motors. It can make decisions based on the state of input and output, it counts and handles mathematical formulae or complex process control algorithms, similar to the PID control system. An engineer or a designer may use the Programme Development Terminal (PDT) to monitor and improve programming the operation of machines, based on commands received from the operator and from the display terminals. The input/output modules condition electrical signals received from the sensors and convert them to logical and numerical data, which are transferred to the CPU. Output modules convert logical and numerical values generated by the CPU to operate actuators and to display information on the machine state. In a coordinated drive application the ASCII/Basic I/O module performs the operator interface function. Another intelligent I/O module is called the axis-positioning module APM. The purpose of this is to control the position or velocity of the load precisely, driven by a closed loop servo mechanism. Figure 1.37. is a block diagram of a typical coordinated drive system. It consists of two groups of three roll stands with an intermediate dancer loop. Each of the roll stands is controlled by a drive and each drive is connected to a separate APM as shown in the Figure.

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2 Control in Mixing Processes

2.1 Introduction

In most instances, polymers in the pure state do not inherently possess the complex properties required in practical application. It is thus both customary and necessary to mix the polymers with additives, such as fillers, plasticizers, dyes and antioxidants, the latter to retard the aging processes of the polymers, in order to arrive at the desired plastic properties. For example, vulcanizers are often mixed with caoutchouc materials in order to obtain a rubber with the desired properties; similarly, foils and tubes are often made of polyvinyl chloride to which plasticizers, fillers and other auxiliary materials are mixed to obtain the desired properties to form a wide variety of products. Common to all plastic materials, the basic requirement is one of homogeneity with respect to their physical and chemical properties. Since the properties of the materials are decisively determined by their composition, the isotropic nature of the properties of the resulting material depends to a large extent on the homogeneity of the distribution of the materials added. The aim of mixing is to obtain a system with entirely disordered distribution from the initial system containing the additives in an ordered distribution.

The two basic methods used in mixing are batch processing and continuous mixing. The feature of the former method is that the components enter the mixing vessel either simultaneously or in a predetermined sequence and mixing is continued until the desired homogeneity is reached. A homogeneous mix is achieved by using mixers such as blade mixers, roll mills, internal mixers, etc. In continuous mixing modes, homogeneity of the mix is attained after a single mix: the polymer and the additives enter the equipment simultaneously at the same site and the removal of the ready mix is also continuous. Screw mixers operate in this manner.

In the following discussion the efficiencies of the mixing processes will be outlined, and the more important mixers with continuous or intermittent operation will be surveyed. In conjunction with these, the factors influencing homogeneity of the mix will be examined, the control of these factors, and finally, some automated mixing processes will be discussed.

2.2 Characteristics of the Mixes and the Mixing Processes

A polymer mix is a multi-component system obtained from different amounts of liquid and solid material in a mixing process. The final mixture is a multicomponent dispersed medium, characterized by the size, shape and structure of the dispersed

particles and their spatial distribution. The fundamental characteristic of the mix is the degree of homogeneity, which compares the momentary concentration distribution with either an ideal state or with the distribution of the concentration in the initial state. Taking the example of a two-component system and assuming that the main component is a liquid or a liquid-like material, while the additive consists of particles uniform in size, the probability of finding k particles in the sample from a mix with ideal distribution may be derived by using the equation:

$$W(K, n, p) = \frac{n!}{K!(n-K)!} p^K (1-p)^{n-K} \quad (2.1)$$

where p is the ratio of the additives in the mix. The standard deviation of the above binomial distribution is:

$$\sigma^2 = \frac{p(1-p)}{n} \quad (2.2)$$

In this way, the homogeneity of the mix can be established by comparing the data obtained in the analysis of several samples to the binomial distribution.

For a finite number of samples, the standard deviation of the average of the samples is derived by the relationship:

$$S^2 = \frac{1}{N-1} \sum_{i=1}^N (X_i - \bar{X})^2 = \frac{1}{N-1} \sum_{i=1}^N X_i^2 - \frac{1}{N(N-1)} \left[\sum_{i=1}^N X_i \right]^2 \quad (2.3)$$

The different characteristics of the degree of homogeneity are determined from the binomial distribution of the ideal state and from the standard deviation obtained from the samples. The most frequently utilized characteristics are summarized in Table 2.1 [1-6], where $\sigma_0 = p(1-p)$ describes the standard deviation of the unmixed state. The advantage of the quantity H_2 is that its value, ranges from 0 to 1, where 0 represents the initial state of the mix (i.e. prior to mixing), while 1 represents the ideal mixed state. I is the inhomogeneity of the system, thus, I is regarded as the reciprocal value of the characteristics of homogeneity.

In addition to the degree of homogeneity, the mix is also characterized by the localized structure of the agglomeration, the dimensions and concentrations of the aggregates of the additive which determine the regional structures. These may be expressed in terms of the scale and the intensity of segregation. The scale of segregation means the average distance between the identical components, while the intensity of segregation is the difference between the average and the local concentrations of the given component.

The above features are characteristic only of the mix, however, they provide no information on the influences exerted on the resultant mix by the parameters of the mixing processes themselves. The mixing process may be regarded as a combination of dispersion and distribution. During dispersion the size of the particles is reduced. In the distribution process the randomness of the spatial distribution in the system is increased with no change in the dimensions of the particles. The dispersion processes play an important role particularly in cases of mixing different additives. The two basic categories of mixing the additive materials are:

Table 2.1. Mix characteristics

Symbols	Definitions
H_1	$\frac{s^2}{\sigma^2}$
H_2	$\frac{\sigma_0^2 - s^2}{\sigma_0^2 - \sigma^2}$
H_3	$1 - \frac{\ln \sigma_0^2 - \ln s}{\ln \sigma_0^2 - \ln \sigma}$
H_4	$\log \frac{1}{1 - \sqrt{\frac{\sigma_0^2}{s^2}}}$
I	$\frac{100}{x} \sqrt{\frac{1}{N-1} \sum_1^N (x_i - \bar{x})^2}$

- mixing of a powdered additive, so that the need to alter the particle size(s) of the additive material does not arise, thus, uniform distribution is only to be achieved,
- mixing of the additive with the polymer includes both the reduction of particle size of the additive and its uniform distribution.

In the former case only distribution takes place, while in the latter case both dispersion and distribution occur.

Dispersive mixing is characterized by a reduction of the particle size of the additives. The success of these processes depends on the shearing forces employed. This was demonstrated experimentally, when a two-particle agglomerate was placed in a viscous liquid and their separation was observed [3].

Let us now consider a two-particle agglomerate in Figure 2.1., and imagine that one of these two particles is positioned in the origin of a moving coordinate system. During mixing, the position of the second particle varies continuously related to the position of the first particle. Both particles are of spherical shape of the same size, with radius R . Assume further that other particles do not exert any influence on this two-particle agglomerate, thus the mix may be regarded as infinitely dilute. Let the critical radii of the two particles be r^* , above which their mutual attractive forces are negligible. In the medium, surrounding this agglomerate, a one-directional shearing force is applied.

If a relative movement takes place between the liquid and one of the two particles, where the flow rate of the liquid exceeds that of the particle, the liquid will increase the speed of the particle. The frictional force may be derived from Stokes Law thus the two components of the interaction force between the liquid and the surface of the particle may be expressed as:

$$F_d = 6\pi R\mu \left[\dot{\gamma}y - \left(\frac{dx}{dt} \right) \right] \quad (2.4)$$

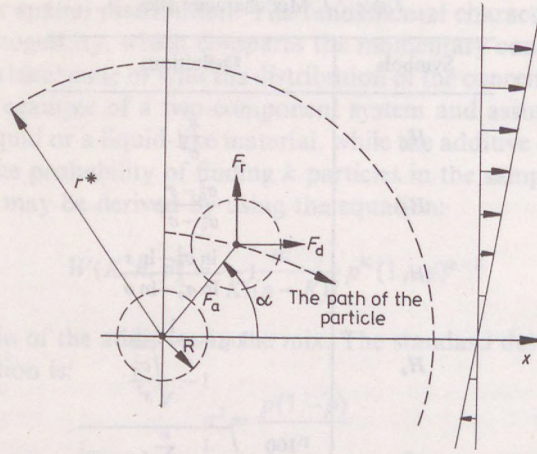


Fig. 2.1. The path described by particles during dispersion

and:

$$F_r = -6\pi R\mu \left(\frac{dy}{dt} \right) \quad (2.5)$$

where $\mu = \dot{\gamma}y$ is the speed of the liquid, dx/dt is the speed of the particles in the x direction, and dy/dt is the speed of the particles in the y direction. The central force holding the two particles together acts along the straight line connecting the mass centres of the two particles, and we can examine the resultant of the forces originating from friction along this straight line, being the two projections of two forces (vectors) in this direction, thus:

$$F_d = F_a \cos \alpha \quad (2.6)$$

and

$$F_r = F_a \sin \alpha \quad (2.7)$$

Substituting into equations (2.4) and (2.5), after the necessary rearrangements one obtains:

$$\left(\frac{dx}{dy} \right) - \left(\frac{x}{y} \right) = -Kr^* \quad (2.8)$$

where

$$K = \frac{6\pi R\mu\dot{\gamma}}{F_a} = \frac{6\pi R\tau}{F_a} \quad (2.9)$$

while τ is the shearing stress acting on the liquid. Let $r = x + y$ and let the boundary condition for the solution of equation (2.8) be $[x_0, y_0]$ as the initial coordinate point, then:

$$\left(\frac{x+y}{x_0+y} \right) \frac{y_0}{y} = \exp \left[Ky_0 \left(1 - \frac{y}{y_0} \right) \right] \quad (2.10)$$

is obtained. It can be seen that the dispersion depends on parameter K , the critical

radius, r^* , and the initial position of the agglomerate. Dispersion is determined by the shearing stresses in the system.

In the mixing processes, polymers may be regarded as liquids of high viscosity. When liquids of high viscosity are mixed, the role of diffusion is negligible, turbulence does not occur, and the mixing process is laminar. The process of laminar mixing is characterized by the scale and intensity of segregation. In a deformation process related to mixing the scale of segregation is given by the average distance between layers of a given component by the so-called striation thickness. This may be calculated as follows [7]:

Let A_0 be the surface element determined by vectors $\mathbf{a}$ and $\mathbf{b}$ (Figure 2.2.). Vector $\mathbf{c}$ is defined as the product of vectors $\mathbf{a}$ and $\mathbf{b}$, it is perpendicular to the ab plane, and its magnitude is twice of the area A_0 of the triangle thus

$$|\mathbf{a} \otimes \mathbf{b}| = |\mathbf{c}| = 2A_0 \quad (2.11)$$

Assuming that the material fraction containing the surface element is subjected to a homogeneous deformation in the x , y and z directions, and the principal elongation ratios are λ_x , λ_y , λ_z , the change of the area may be determined by the change of vectors determining the surface element.

The new vectors are:

$$|\mathbf{a}' \otimes \mathbf{b}'| = |\mathbf{c}'| = 2A. \quad (2.12)$$

Expressing the deformed surface in terms of vector components:

$$A = \frac{1}{2} \{ [\lambda_y \lambda_z (a_y b_z - a_z b_y)]^2 + [\lambda_z \lambda_x (a_z b_x - a_x b_z)]^2 + [\lambda_x \lambda_y (a_x b_y - a_y b_x)]^2 \}^{\frac{1}{2}} \quad (2.13)$$

The change of the surface area is:

$$\frac{A}{A_0} = \left[\frac{(\lambda_y \lambda_z C_x)^2 + (\lambda_x \lambda_z C_y)^2 + (\lambda_x \lambda_y C_z)^2}{|C|^2} \right]^{\frac{1}{2}} \quad (2.14)$$

Substituting the directional cosines of vector $\mathbf{c}$:

$$\frac{A}{A_0} = \left[\frac{\cos^2 \alpha}{\lambda_x^2} + \frac{\cos^2 \beta}{\lambda_y^2} + \frac{\cos^2 \gamma}{\lambda_z^2} \right]^{\frac{1}{2}} \quad (2.15)$$

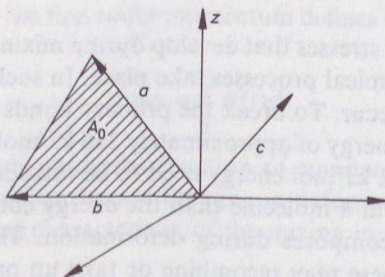


Fig. 2.2. One of the surface elements used for purposes of characterization of the mixing process [7]

Thus, mixing is characterized by the change of the surface area, which is a function of the major deformational ratios. The same results were obtained earlier by Mohr, Saxton and Jepson [8]. Based on equation (2.15), the mixing characteristics applicable to some simple types of deformation are given:

— elongation deformation on a plane, $\lambda_z = 1$; $\lambda_x = \lambda_0$; $\lambda_y = \frac{1}{\lambda_0}$

$$\frac{A}{A_0} = \left\{ 1 + \left(\frac{1}{\lambda_0^2} - 1 \right) \cos^2 \alpha + (\lambda_0^2 - 1) \cos^2 \beta \right\}^{\frac{1}{2}} \cong e^{\gamma/2} \approx \gamma_{\Sigma}; \quad (2.16)$$

— pure elongation, $\lambda_x = \lambda_0$; $\lambda_z = \lambda_y = \frac{1}{\lambda_0^{1/2}}$

$$\frac{A}{A_0} = \left[\lambda_0 + \cos^2 \alpha \left(\frac{1}{\lambda_0^2} - \lambda_0 \right) \right]^{\frac{1}{2}} \quad (2.17)$$

— simple shearing $\lambda_x = \left[1 + \frac{\gamma^2}{2} + \frac{\gamma^2}{2} (4 + \gamma^2)^{\frac{1}{2}} \right]^{\frac{1}{2}}$; $\lambda_z = 1$;

$$\lambda_y = \left[1 + \frac{\gamma^2}{2} + \frac{\gamma}{2} (4 + \gamma^2)^{\frac{1}{2}} \right]^{\frac{1}{2}}; \quad \frac{A}{A_0} \cong \gamma \cos \beta \approx \gamma_{\Sigma} \quad (2.18)$$

thus, the change of the area is proportional to the shearing deformation.

In general, the efficiency of laminar mixing depends on the magnitude of the total deformation. In addition to the parameters given in equation (2.15), several other parameters may also be employed to express the efficiency of mixing. For example, Fenner [9] utilized the following relationship to describe the intensity of mixing:

$$\frac{d\Gamma}{dt} = \sqrt{4\mathcal{I}_A} \quad (2.19)$$

where, $\mathcal{I}_A$ is the second invariant of the strain rate tensor. Other authors [10] utilized the invariant of deformation to describe mixing processes, thus:

$$\Gamma = \sqrt{\frac{2}{3}} \left[(\lambda_x - \lambda_y)^2 + (\lambda_y - \lambda_z)^2 + (\lambda_z - \lambda_x)^2 + \frac{3}{2} (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{xz}^2) \right]^{\frac{1}{2}} \quad (2.20)$$

The invariant derived from the strain rate tensor is used to describe the intensity of mixing.

On the effect of the high stresses that develop during mixing certain heating occurs, or certain mechanical-chemical processes take place. In such instances breaks in the polymer chain may also occur. To break the primary bonds of the polymer chains it is necessary to introduce energy of approximately 336 kJ/mol, while in order to break a secondary bond 12 to 42 kJ/mol energy need to be introduced. In instances where more energy accumulates in a molecule than the energy content of the C—C bond, the polymer molecule decomposes during deformation. The chain fragments may form free radicals, and these may recombine or take up oxygen which results in a decrease in the molecular weight. Where two different polymers are in the system,

mechanical-chemical copolymers may be formed. The above processes are mainly determined by the magnitude of the stresses developing.

The efficiency of the mixing processes are thus determined by:

- the magnitude of the stresses acting,
- the type and magnitude of the deformation,
- the residence time of the mixture and its time distribution, and also
- the heating of the mix.

In the plastic and rubber industries the mixing processes include the following physical, chemical and mechanical operations:

- reduction in size,
- the breaking up and milling of the initial raw materials,
- the decrease of viscosity on the polymer phase,
- the addition of materials in powder and/or in liquid form,
- the dispersion of the particles of the additives,
- the homogenization processes of the mix.

Apart from the first mentioned operation, in the mixing equipment all of these processes are invariably involved. The mixing processes themselves may be periodic or continuous. An important parameter of the processes taking place within the mixing and processing equipment is the residence time, and the distribution of the residence times of the individual elemental particles [10]. The function $f(t)dt$ defines the probability that the residence time falls in the time interval $(t, t + dt)$. $f(t)$ is a density function of residence time distribution. The cumulative distribution of residence time $F(t)$ expresses probability that the residence time of the particle in the equipment is less than t . Mathematically expressed:

$$F(t) = \int_{t_0}^t f(t') dt' \quad (2.21)$$

where t_0 is the minimum residence time.

The quantity defined by the relationship

$$\mu_n(t, t_0) = \int_{t_0}^t (t - t_0)^n f(t) dt \quad (2.22)$$

is called the n^{th} order momentum around time t_0 . The momentum around the origin is given by $t=0$.

The zero order momentum around the origin defines the distribution function of the residence time, while the first order momentum defines the average residence time, thus:

$$\bar{t} = \mu_1 = \int_0^t t f(t) dt \quad (2.23)$$

The 2nd order momentum yields the function of standard deviation. On the analogy of the residence time distribution function, a deformation distribution function can also be derived, being characteristic of the mixing in processing operations.

2.3 Non-continuously Operated Mixers

In the batch mixing equipment the components of the mix are randomly distributed, and the homogeneity of the mix is a function of the mixing time. Mixing takes place by the movement of the interfering surfaces. During mixing, the initially ordered distribution of the components constituting the mix gradually approaches a random distribution [11–15].

2.3.1 Blade and Rotor Mixers

2.3.1.1 Blade Mixers

Blade mixers are widely used in preparing various pastes and glue materials, since in these cases, in addition to mixing, heating or cooling of the material is also possible. The stirring components of blade mixers are two Z-shaped blades. In the cylindrical mixing space the two rotating blades rotate at different speeds. The blade mixers are intermittently operated, and the blades remain in the equipment right up to the end of the mixing cycle.

2.3.1.2 Internal Mixers

Those blade mixers in which the blades take up at least 60% of the vessel's internal space are called rotor or internal mixers, since the blades are called rotors. The most frequently utilized double rotor mixers are internal mixers often used for preparation of caoutchouc mixtures.

The structure of an internal mixer is shown in Figure 2.3. The working space of internal mixers consists of two half cylinders (2), the rotors (3) turn in this space. The equipment is mounted onto support (1). The components of the mix are added to the vessel via a hopper (5), or the door (6). After addition of the materials, piston (10) seals the mixing vessel. At the end of the mixing cycle the mix is discharged with the aid of the bottom piston (14). The driving motor (21) turns the rotors via a set of gears. The heat evolved during mixing is removed by cooling either the rotors (16), or the external walls of the vessel (17).

The main part of internal mixers is the rotor. The most important rotor types are (see Figure 2.4.):

- (a) Rotors with an oval shape. Rotors with an elliptical cross section, carry two spiral-shaped wings. The longer spiral runs on 0.6–0.7 of the length of the rotor with a pitch angle about 30° , while the shorter spiral runs on 0.35 to 0.4 of the length of the rotor with a pitch angle of some 45° .
- (b) Rotors with a triangular cross section, with pitch angles of about 30° .
- (c) Screw type rotors, with a pitch angle of some 42° .
- (d) Blade rotors. Several short blades protrude out of either a circular or elliptical rotor shaft.

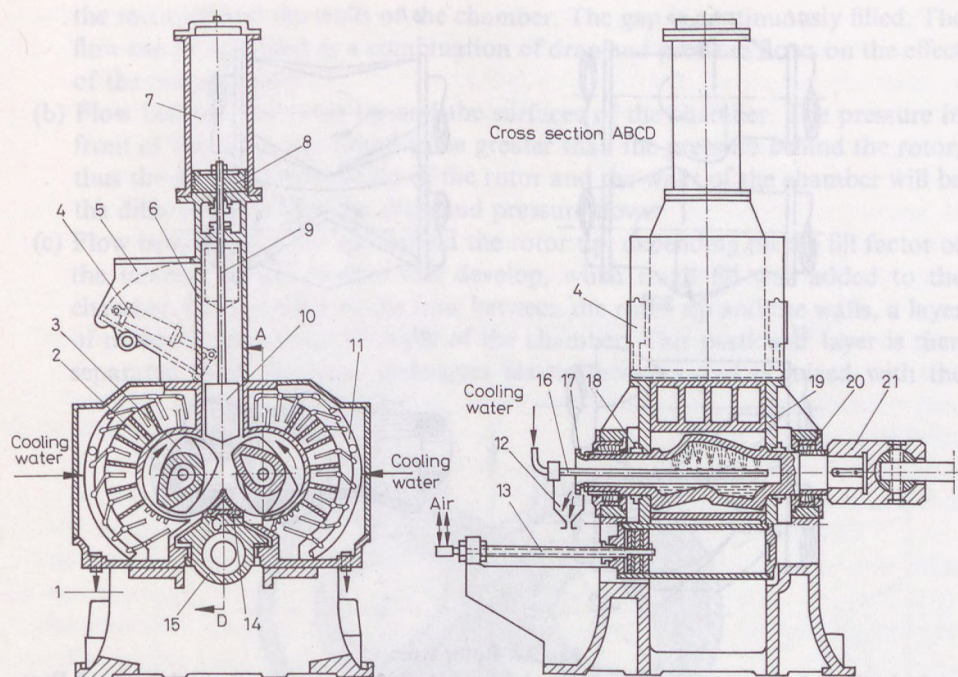


Fig. 2.3. Construction details of the internal mixers

1. machine supports, 2. mixing space, 3. rotor, 4. feeding piston, 5. hopper, 6. door, 7. pneumatics, 8. piston, 9. piston shaft, 10. piston closure, 11. main channel, 12. and 17. heating medium outlets, 13. piston employed to seal the bottom discharge outlet, 14. bottom sealing piston, 15. the cylinder of the bottom piston, 16. the cooling system assigned to the rotor, 18. rotor packing, 19. the side walls of the mixer, 20. the rotor bearings, 21. gear change

The processes that take place in the internal mixers are most readily followed with the aid of momentum–time curves (Figure 2.5.). The four phases of the mixing cycle are [16–21]:

- the incorporation or wetting phase; here the additives are incorporated into the main component of the mix,
- the dispersion phase, where the additives are gradually broken down into smaller particles and are dissolved in the main components,
- the main mixing phase, in which no further dispersion takes place, only distribution occurs, and
- the decomposition phase, in which the main component undergoes chemical changes and decomposes.

The effective phases of the mixing process are the second and the third phases. During the wetting stage, both the momentum and specific volume of the mix decrease with the time of mixing. In the practice the wetting phase is usually short compared with the dispersion phase. During the dispersion phase swelling of the mix increases with increasing mixing time, and it reaches the maximum at the second peak of the

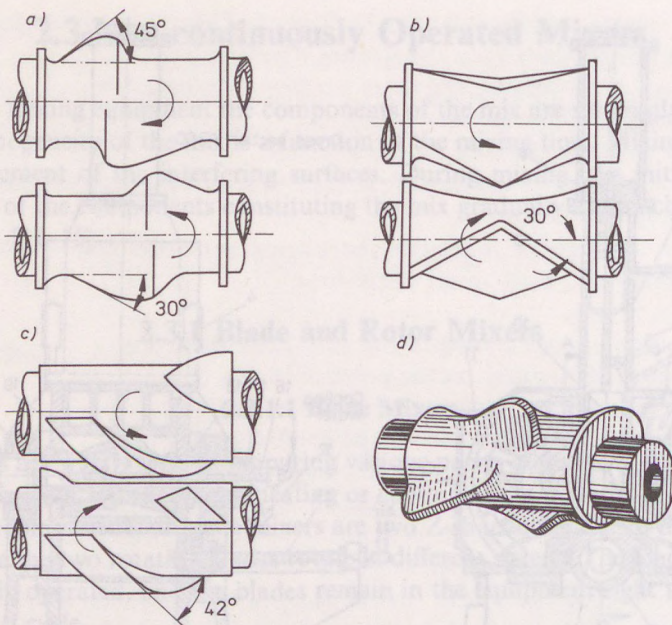


Fig. 2.4. Rotor types

a) Oval (elliptical) shape rotors, b) Triangular shape rotors, c) Rotor shapes with spiral shapes, d) Four-winged rotor

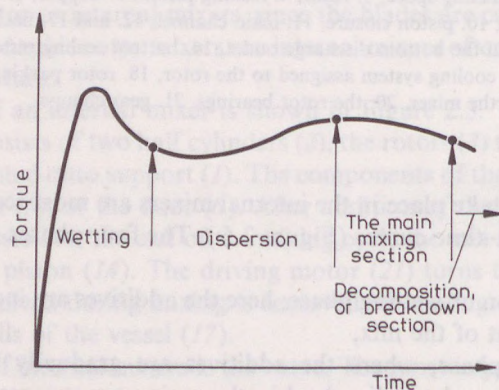


Fig. 2.5. A characteristic curve depicting processes taking place in an internal mixer; torque vs. time

efficiency of mixing or momentum. The efficiency of dispersion is determined by the maximum shearing force occurring.

The processes in an internal mixer were examined [16–17] by using a model device using a mixer with transparent external walls. In the mixing chamber the following processes could be distinguished:

(a) Flow in front of the rotor tip. This flow is depicted in Figure 2.6.a) in the space *I*. The flow space has the shape of a sickle with a minimum gap between

the rotor tip and the walls of the chamber. The gap is continuously filled. The flow can be regarded as a combination of drag and pressure flows on the effect of the moving rotor.

- (b) Flow between the rotor tip and the surfaces of the chamber. The pressure in front of the rotor was found to be greater than the pressure behind the rotor, thus the flow between the tip of the rotor and the walls of the chamber will be the difference between the drag and pressure flows.
- (c) Flow behind the rotor tip. Behind the rotor tip, depending on the fill factor of the internal mixer, cavities can develop, when small fill was added to the chamber. On the effect of the flow between the rotor tip and the walls, a layer of material adheres to the walls of the chamber. This particular layer is then separated from the wall, undergoes elastic recovery and is mixed with the

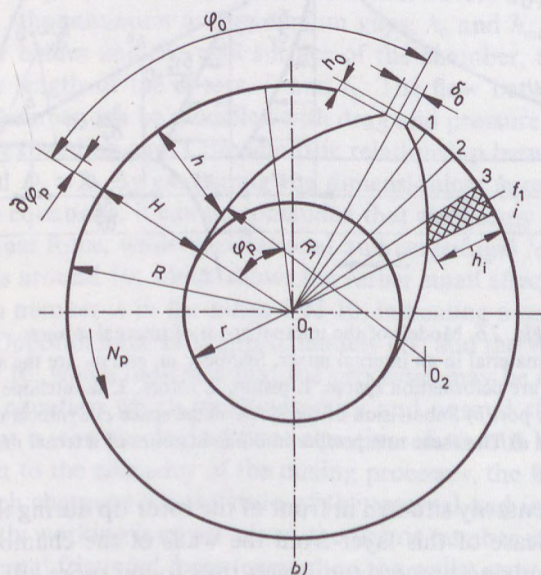
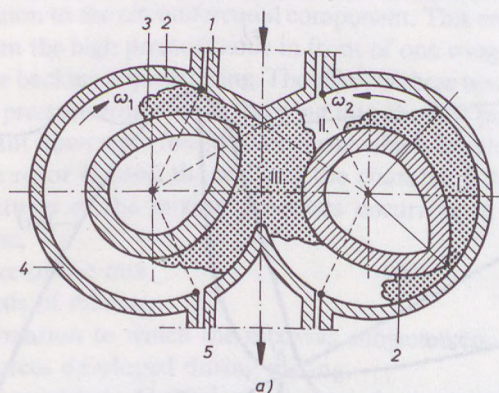


Fig. 2.6. a, b

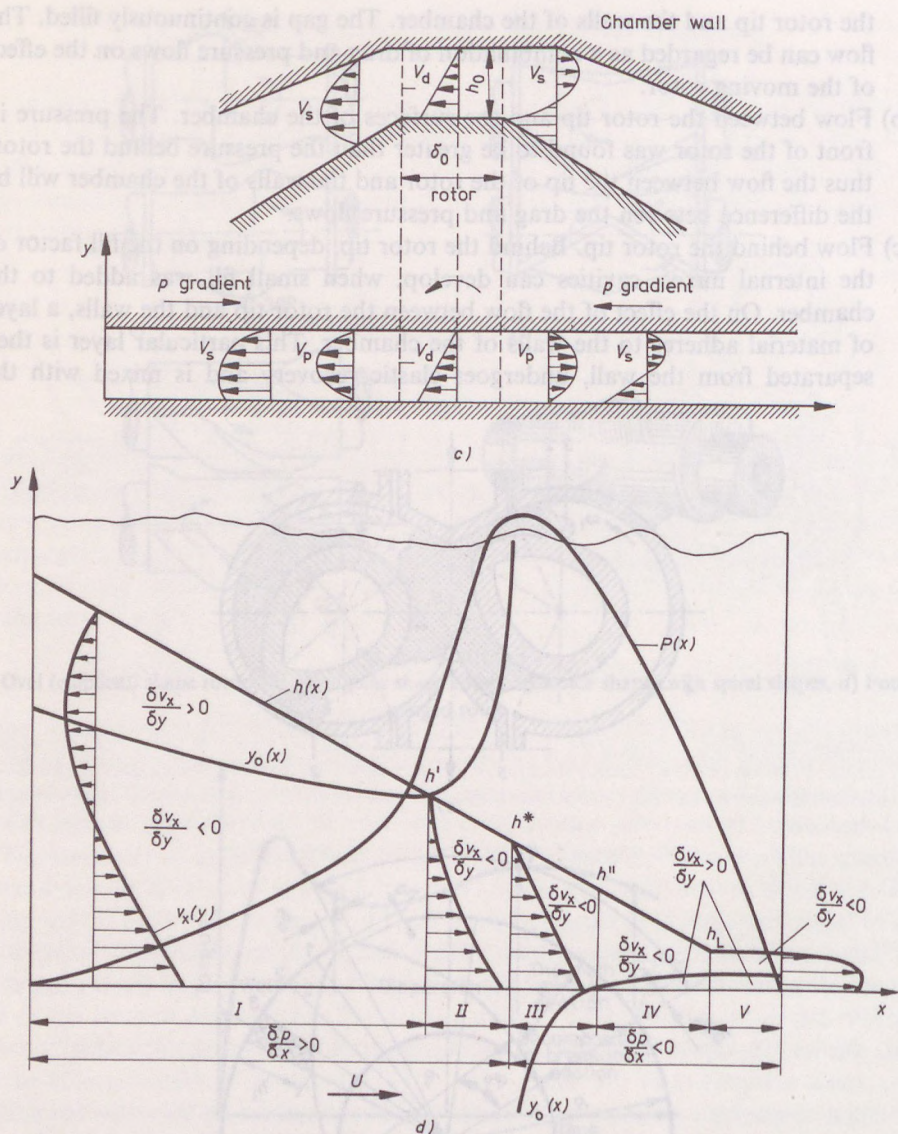


Fig. 2.6. Models of the internal space of internal mixers

a) Deformation of the material in an internal mixer. Symbols: ω_1 and ω_2 are the angular velocities of the rotors, I, II and III are deformation spaces, 1. piston, 2. rotors, 3. caoutchouc mix, 4. chamber, 5. the lock of the discharge port b) Subdivision of the sickle shape space c) Symbols used for a particular, single element d) The shear rate profiles in different zones of internal mixer's gap.

material momentarily situated in front of the rotor tip during the next turn. The continuous release of this layer from the walls of the chamber causes disturbances in the mixing process and it was thus found more advantageous if this layer of material remained adhered to the walls of the chamber.

(d) Flow in the space under the piston. The process in the space under the piston has to satisfy two requirements: firstly the components should be mixed into the main component as rapidly as possible, and secondly, passing of the material from one chamber into the other must be ensured. In cases where a higher fill factor was applied, a stagnant zone was observed in the space below the piston. In general, in addition to the applied fill factor, the ratio of revolution numbers of the rotors influences the flow developed in the space below the pistons. In proper mixing, one of the rotors pushes the material through the space under the piston to the other rotor, which, in turn, passes it to the sickle-shaped space of the second chamber.

(e) Flow in the space between the two rotors. The two rotors have altogether four rotor tips at 90° apart. At the middle portion of the rotors there are two wings at 180° apart, with a tip at each end. The rotor tips are angled to give an axial component of flow in addition to the circumferential component. This results in material being transferred from the high pressure zone in front of one wing into the low pressure zone behind the backing adjacent wing. The effect of these tips is to pass the material from the high pressure zone before the wing into the low pressure zone.

The most important flows were found to be those which developed before the rotor tip and between the rotor tip and the walls of the chamber [12–27].

The principal features of the mixing processes occurring in internal mixers are:

- the mixing time,
- the temperature of the mix,
- the energy needs of mixing,
- the total deformation to which the mix was subjected to,
- the shearing forces developed during mixing.

The characteristic geometric dimensions of internal mixers are the diameter of the mixing space, D_k , the minimum and maximum gaps, h_0 and $h_{\max}$, between the surfaces of the rotor blades and the wall surface of the chamber, the length, L of the chamber and the length of the rotors, l_1 and l_2 . The flow between the rotors and the walls of the chamber can be modelled with drag and pressure flows in an initially constricted, then expanding gap. Characteristic relationship between dimensions are $D_k \gg h_{\max} \gg h_0$ and $D_k \approx L$. By examining the dimensionless parameters characteristic of the balance equations, it can be concluded that the energy which brings about flow is the frictional force, while gravitational and centrifugal forces are negligible. The Gz number is around 10, which shows the rather small effect of heat transfer in one cycle, the Gn number is in the range 1 to 10, indicating a considerable effect of dissipation. The Deborah number is approximately 0.1, and the Weissenberg number is of the order of 10, which indicates that the processes may be described by such a rheological state equation which yields viscosity and normal stress for the simple shearing flow, that is, the rheological state equation of viscous liquids is applicable here. With respect to the efficiency of the mixing processes, the Bebris number must be examined which characterizes the ratio of the external and internal frictions. To obtain an efficiently working internal mixer, the Bebris number must be greater than 1, that is, the external frictional force (exerted on the walls) must exceed the internal frictional force. This may be achieved by cooling the walls or the rotor(s) of the mixer.

The rheological state equation and the balance equations applicable to a single turn of the rotor, based on the simplified geometrical illustration presented in Figure 2.6.d) can be as follows:

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_{xy}}{\partial y} \quad (2.24)$$

$$\frac{\partial P}{\partial y} = 0 \quad (2.25)$$

$$\frac{\partial \tau_{xy}}{\partial y} = \mu_1 \left| \frac{\partial v_x}{\partial y} \right|^{n-1} \left| \frac{\partial v_x}{\partial y} \right| \quad (2.26)$$

with boundary and initial conditions:

$$y=0, v_x=v_r; x=L_r, P=P_r, y=h, v_x=0 \quad (2.27)$$

$$x=0, P=P_0; h=h^*, \frac{\partial P}{\partial x} = 0 \quad (2.28)$$

$$x=L, P=P_0; y=y_0, \tau_{xy}=0$$

The individual zone limits are characterized by the following parameters:

$$\text{I/II. } h'; x' y_0=h$$

$$\text{II/III. } h^*; x^* \frac{dP}{dx} = 0$$

$$\text{III/IV. } h''; x'' y_0=0$$

$$\text{IV/V. } h_0 = \text{const.}$$

From the relationships (2.24) and (2.26) using the limiting and initial conditions (2.27–2.29) the change of the pressure gradient and the velocity profile may be determined in the sickle-shaped space. The pressure gradient may be expressed as:

$$\frac{\partial P}{\partial x} = \text{sgn}(H-H^*) V_r^n \mu_1 \left(\frac{n}{n+1} |H-Y_0|^{\frac{n+1}{n}} - |Y_0|^{\frac{n+1}{n}} \right)^{-n} \quad (2.30)$$

$$0 = \frac{(n+1) \left(|H-Y_0|^{\frac{2n+1}{n}} + \text{sgn } Y_0 |Y_0|^{\frac{2n+1}{n}} \right)}{(2n+1) \left(|H-Y_0|^{\frac{n+1}{n}} - |Y_0|^{\frac{n+1}{n}} \right)} + Y_0 - \frac{H^*}{2} \quad (2.31)$$

where $y=y/h_0$, $H=h/h_0$. The individual zone limits are:

$$h' = \frac{2n+1}{2n} h^* \quad (2.32)$$

$$h'' = \frac{2n+1}{2n+2} h^* \quad (2.33)$$

$$h^* = 2Y_0 + \frac{(2n+2) \left[(H-Y_0)^{\frac{2n+1}{n}} + Y_0^{\frac{2n+1}{n}} \right]}{(2n+1) \left[(H-Y_0)^{\frac{n+1}{n}} - Y_0^{\frac{n+1}{n}} \right]} \quad (2.34)$$

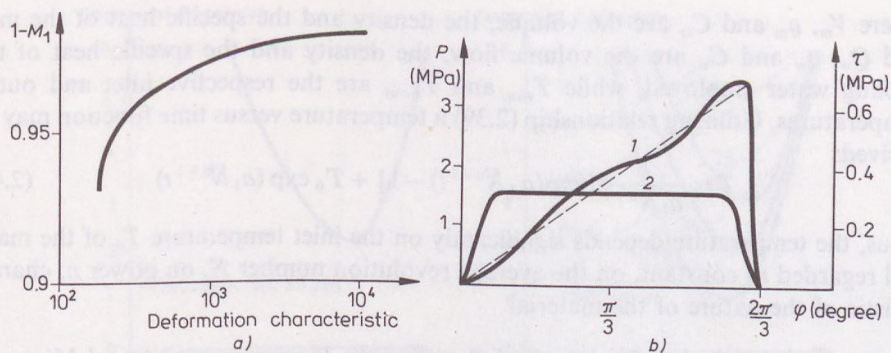


Fig. 2.7. Operational modes of internal mixers

a) The relationship between homogeneity ($1-M_1$) and deformation [20], b) Curve 1, calculated pressures (dotted line) and measured pressures (solid line) during a single revolution; curve 2 depicts the shearing stresses

Figure 2.7.b) shows the course of the pressure profile based on measured [14] and calculated data.

The efficiency of mixing can be described by the deformation that occurs in a single revolution, based on relationship (2.20). Figure 2.7.a) shows the homogenization characteristics as a function of total deformation. The entirety of the mixing process can be characterized by the average shearing stress and shearing strain rate calculated for one revolution.

$$\bar{\gamma} = \frac{\pi D_c \bar{N}}{60 h_0}, \quad (2.35)$$

where $\bar{N} = 1/2 (N_1 + N_2)$ represents the average number of revolutions of the rotors,

$$\bar{\tau} = \mu_1 \bar{\gamma}^n \quad (2.36)$$

yielding for the average power requirement:

$$P_T = \bar{\gamma} \bar{\tau} V = \mu_1 V \left(\frac{\pi}{60} \right)^{n+1} \left(\frac{D_c}{h_0} \right)^{n+1} \bar{N}^{n+1} \quad (2.37)$$

Having the mixing time, t_m , the entire deformation of the mix will be:

$$\gamma_t = t_m \bar{\gamma} = \pi \frac{D_c}{60} N^2 t_m \quad (2.38)$$

In the case of mixing caoutchouc it was observed that the average pressure in the internal mixer was directly proportional to the average shearing force, and this proportionality factor is around the value of three [14].

In the mixing cycle the temperature of the mix is increasing. This temperature increase may be derived from the integral energy equation, thus:

$$P_T \approx V_m \rho_m C_m \frac{dT(t)}{dt} - Q_w \rho_w C_w (T_{win} - T_{wout}) \quad (2.39)$$

where V_m , ϱ_m and C_m are the volume, the density and the specific heat of the mix, and Q_w , ϱ_w and C_w are the volume flow, the density and the specific heat of the cooling water employed, while T_{win} and T_{wout} are the respective inlet and outlet temperatures. Utilizing relationship (2.39) a temperature versus time function may be derived:

$$T = \frac{b}{a_1 N^{n+1}} [\exp(a_1 \bar{N}^{n+1} t) - 1] + T_0 \exp(a_1 \bar{N}^{n+1} t) \quad (2.40)$$

Thus, the temperature depends significantly on the inlet temperature T_0 of the material regarded as constant, on the average revolution number N , on power n , characteristic of the nature of the material.

Some Technological Parameters Influencing the Process in an Internal Mixer

The effects of the technological characteristics are summarized in Figure 2.8. [28–29].

(a) The effect of the load.

Optimum homogeneity of a mix is best achieved at a given fill factor, being around 0.75 of the capacity of the chamber (Figure 2.8.a)).

(b) The effect of the revolution number.

An increase in the number of revolutions increases the efficiency of mixing; this changes the optimum fill factor as indicated in Fig. 2.8.b).

In order to increase the intensity of the mixing one of the main possibilities is to increase the revolution number of the rotor. The average shearing rate is directly proportional to the revolution number. Usually a two-fold increase in the revolution number of the rotor reduces the necessary mixing time by 30 to 50%. However, concurrently, an increase in the revolution number greatly increases the temperature of the mix.

(c) The effect of mixing time.

The effect of mixing time is shown in Figure 2.8.c). Homogeneity of the mix improves with increasing mixing time.

(d) Pressure due to the effect of the piston.

The upper piston of the internal mixers exerts a pressure on the material in the chamber if this material occupies 60–70% of the available volume. The piston exerts its influence on the space directly under it. On the effect of the piston's movement the various powdered fillers and additives become more compact. The pressure applied at the beginning of the mixing cycle promotes dispersion in plastic or rubber materials. Usually the properties of the mix improve upon application of pressure. The optimal pressure lies in the range 0.3–0.6 MPa, any pressure applied above this does not influence the efficiency of the mixing but increases the temperature. Fig. 2.6.d) shows the correlation between pressure and the mixing time required.

(e) The effects of the temperatures of the rotors and the walls of the chamber.

The effect is shown in Figure 2.8.e). An increase in temperatures of the rotors and the walls of the chamber improves somewhat the efficiency of the mixing process, however, this effect is substantially smaller than the effect of the number of revolutions.

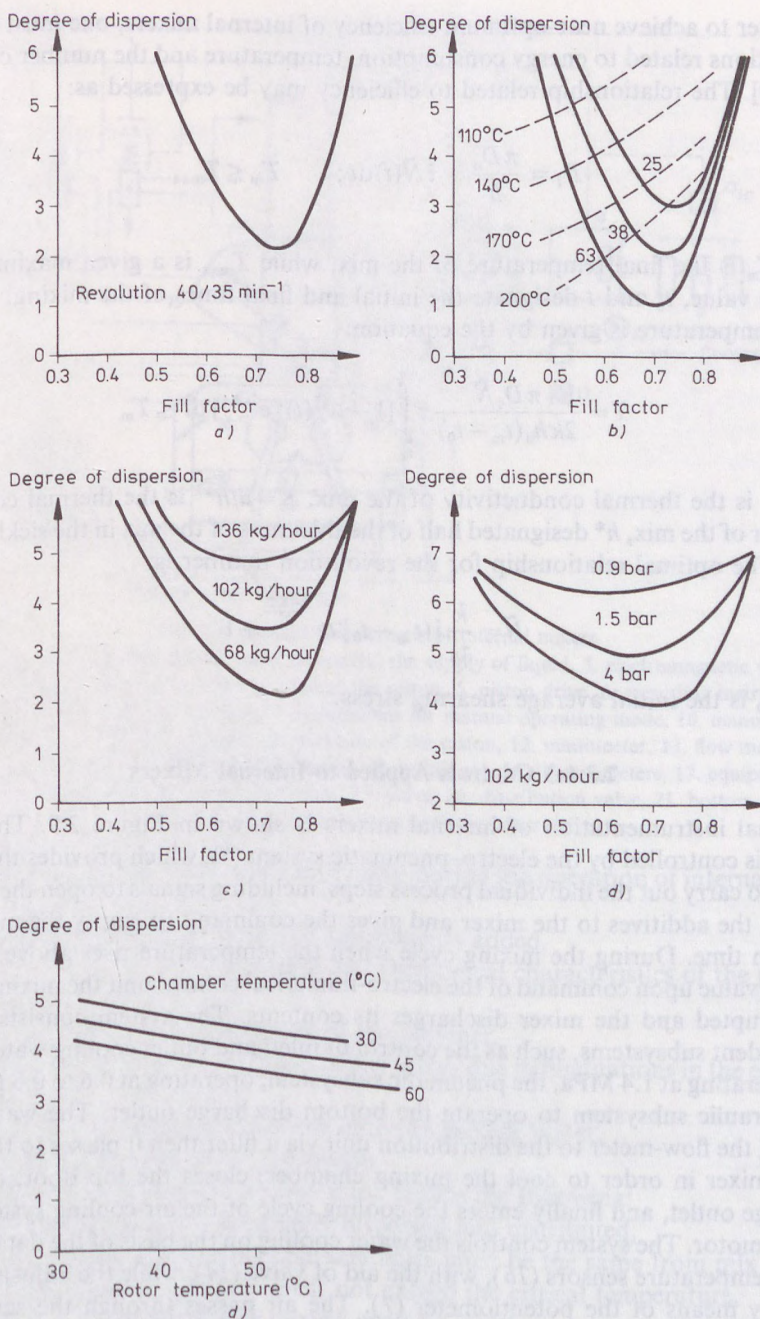


Fig. 2.8. The effects of the technological characteristics and the efficiency of internal mixers
a) The effects of the load, b) The effects of the revolution number, c) The effects of the mixing time,
d) The effects of the pressures applied by the piston, e) The effects of the rotor and the chamber (or
chamber wall) temperatures

In order to achieve near-optimum efficiency of internal mixers, one must establish the functions related to energy consumption, temperature and the number of revolutions [30]. The relationship related to efficiency may be expressed as:

$$P_T = \frac{\pi D_c}{h} \int_{t_0}^{t_m} \bar{\tau} \tilde{N}(t) dt; \quad T_m \leq T_{\max} \quad (2.41)$$

where T_m is the final temperature of the mix, while $T_{\max}$ is a given maximum temperature value, t_0 and t designate the initial and final times of the mixing.

The temperature is given by the equation:

$$T = \frac{\pi D_c \tilde{N}}{2k h_0 (t_m - t_0)} \bar{\tau} \int_{t_0}^{t_m} [1 - |\tilde{N}(t)| e^{-Kt}] dt \leq T_m \quad (2.42)$$

where k is the thermal conductivity of the mix, $K = a/h^{*2}$ is the thermal conductivity factor of the mix, h^* designated half of the thickness of the mix in the sickle-shaped space. The optimal relationship for the revolution number is:

$$\tilde{N} = \frac{k}{\tau_0} [(t_m - t_0)] te^{\frac{-Kt}{2}} + 1 \quad (2.43)$$

where τ_0 is the initial average shearing stress.

2.3.1.3 Controls Applied to Internal Mixers

The usual instrumentation of internal mixers is shown in Figure 2.9. The mixing process is controlled by the electro-pneumatic system (8), which provides the control signals to carry out the individual process steps, including signals to open the top door to fill in the additives to the mixer and gives the command to empty the mixer after a certain time. During the mixing cycle when the temperature rises above a certain limiting value upon command of the electro-numerical control unit the mixing process is interrupted and the mixer discharges its contents. The system consists of three independent subsystems, such as the control of inlet, and outlet cooling water subsystem, operating at 1.4 MPa, the pneumatic subsystem, operating at 0.6 to 0.8 MPa, and the hydraulic subsystem to operate the bottom discharge outlet. The water passes through the flow-meter to the distribution unit via a filter then it passes to the jackets of the mixer in order to cool the mixing chamber, closes the top door, opens the discharge outlet, and finally enters the cooling cycle of the air-cooling system of the driving motor. The system controls the water cooling on the basis of the data supplied by the temperature sensors (16), with the aid of valve (14), while the adjustments are made by means of the potentiometer (7). The air passes through the scrubber to remove any oil particles, then through the manometer (1); then enters the electro-pneumatic valves (2), (3) and (4), and controls the addition of the fluid components through the feeder ports and the operation of the locking device of the top door. The output requirement of the mixer is registered on the control panel continuously.

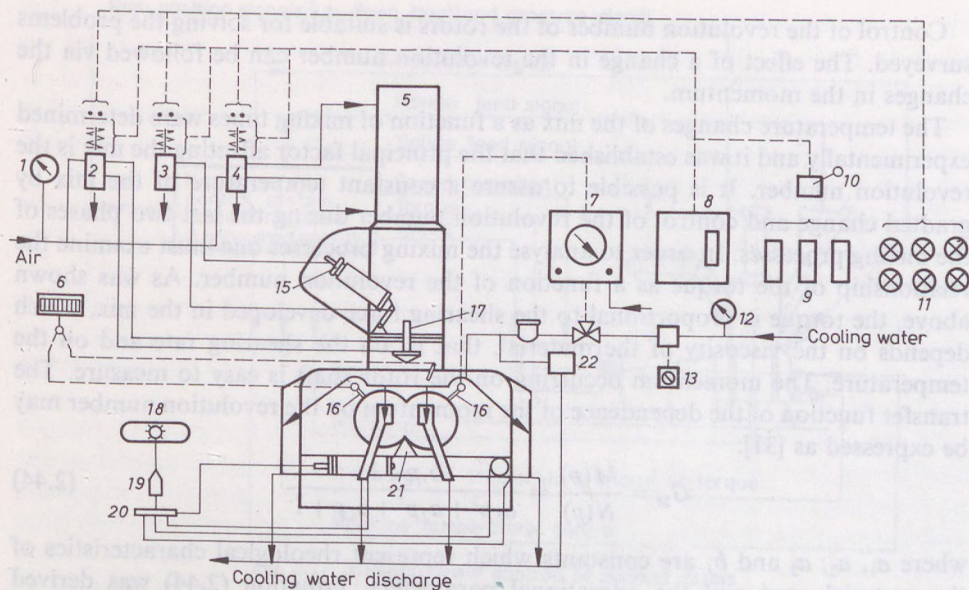


Fig. 2.9. Control installations of internal mixers

1. manometer, 2. electromagnetic valve to control the supply of liquid, 3. electromagnetic valve to control the door opening, 4. valve to control the piston, 5. piston drive, 6. recording instrument, 7. potentiometer, 8. control instrument, 9. installations for manual operating mode, 10. manual, remote control button, 11. lights to register the position of the piston, 12. manometer, 13. flow meter for water, 14. control valve, 15. the pneumatic piston of the hopper, 16. thermometers, 17. equipment used for addition of plasticizer, 18. water pipe joints, 19. valve, 20. distribution valve, 21. bottom discharge door, 22. the cooling system of the motor drive

The main disturbing factors that may occur during the operation of internal mixers are as follows:

- changes in the quantities of the components added,
- changes in the molecular weight and rheological characteristics of the polymer used,
- change in the inlet temperature of the polymer,
- change in the revolution number of the rotors due to fluctuations in the electrical network,
- change in the temperature of the entering cooling water,
- changes in the pressure of the piston.

Control modes of the internal mixers must ensure the following:

- the additives must be thoroughly dispersed and distributed,
- the rheological and heating characteristics must be the same from mix to mix,
- the temperature of the mix must not exceed the critical temperature,
- the energy consumption of mixing must be small,
- the mixing cycle should be short.

Thus, control of the internal mixers consists of the control of the revolution number, the cooling cycle, the penumatic cycle, the mixing time and finally, of the control of the addition of the components.

Control of the revolution number of the rotors is suitable for solving the problems surveyed. The effect of a change in the revolution number can be followed via the changes in the momentum.

The temperature changes of the mix as a function of mixing times were determined experimentally and it was established that the principal factor affecting the mix is the revolution number. It is possible to assure a constant temperature of the mix by gradual change and control of the revolution number during the last two phases of the mixing processes. In order to analyse the mixing processes one must examine the relationship of the torque as a function of the revolution number. As was shown above, the torque is proportional to the shearing force developed in the mix, which depends on the viscosity of the material, that is, on the shearing rate and on the temperature. The momentum occurring on the rotor shaft is easy to measure. The transfer function of the dependence of the momentum on the revolution number may be expressed as [31]:

$$G_M = \frac{M(p)}{N(p)} = \frac{b_1 p + 1}{a_3 p^3 + a_2 p^2 + a_1 p + 1} \quad (2.44)$$

where a_1 , a_2 , a_3 and b_1 are constants which represent rheological characteristics of the material used and the operational parameters. Equation (2.44) was derived experimentally. The torque-time relationship in case of a unit step disturbance is represented by the differential equation

$$a(M^*)'' + b(M^*)' + M^* = 1 + \delta e^{-\alpha_1 t} \quad (2.45)$$

where M^* is the initial torque, while the relationship between the constants is:

$$\delta = b_1 d_1 - 1; \quad a_1 = b + \frac{1}{d_1}; \quad a_2 = a + \frac{b}{d_1}; \quad a_3 = \frac{a}{1}$$

For the optimization of the revolution number versus time relationship, the procedure shown above and an empirical-numerical method [32] can be utilized.

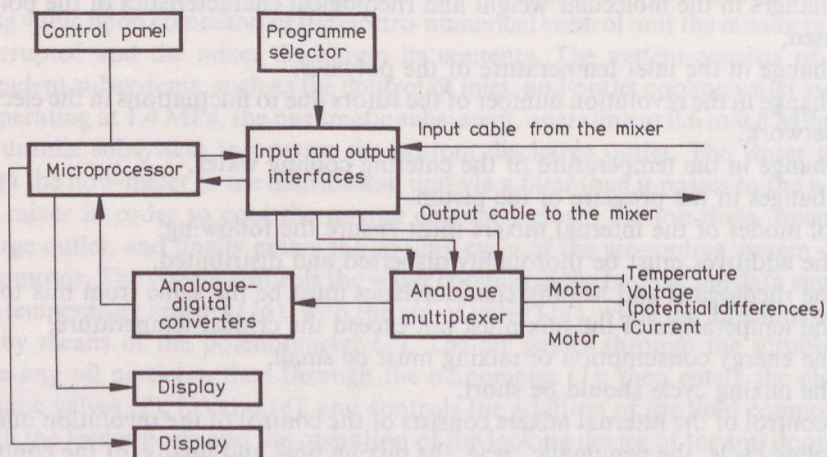


Fig. 2.10. Microprocessor controls applied to internal mixers

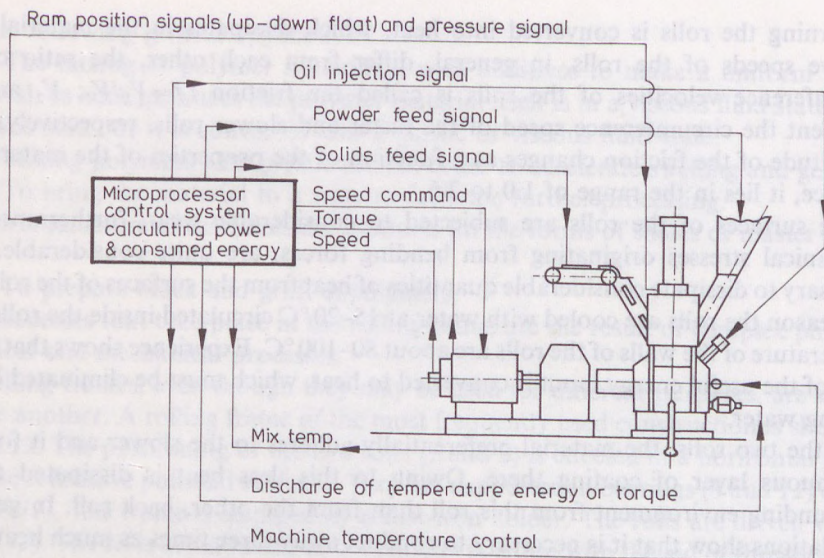


Fig. 2.11. Microprocessor controls of internal mixers

Figure 2.10. shows a microprocessor scheme used for control applications. A suitable searching programme can be chosen in the programming unit, this is fed into the microprocessor, which, via an input-output interface governs the running of the mixer, while the state of mixing is monitored by data received from the analogue-digital converter of the microprocessor. This system is suitable for the control of some eight to ten different types of mixing processes.

Figure 2.11. shows an internal mixer controlled by a microprocessor [33]. The mixing processes are monitored by momentum measurements, while revolution number, the flow of the cooling water, the addition of the components of the mix, and the pressure of the piston are controlled. The system also records the data.

2.3.2 Roll Mills

Roll mills are used for purposes of softening rubber materials, for preparation of gum mixes and polyvinyl chloride mixes etc. Such machines are batch mixers [34 to 36].

The main parts of roll mills are the rolls, positioned in a horizontal plane in parallel positions, which rotate in opposite directions with adjustable speeds. The material is transferred by the frictional forces of the rolls through the gap between the rolls. Due to the narrowing of the gap, pressure increases in the material. The material that sticks to the surfaces of the rolls moves at a faster rate compared with the total quantity of the same material present and, hence, strong shearing forces occur and laminar mixing develops. In the gap the pressure acts only on a certain proportion of the material, with a limiting angle of about 35–40°. Mixing and softening of the material is achieved by overcoming the shearing stresses in the material. The energy invested

by turning the rolls is converted into heat, which dissipates in the material. The relative speeds of the rolls, in general, differ from each other, the ratio of the circumference velocities of the rolls is called the friction ($f = V_2/V_1$; V_2 and V_1 represent the circumference speed of the faster and slower rolls, respectively). The magnitude of the friction changes as a function of the properties of the material, in practice, it lies in the range of 1.0 to 2.6.

The surfaces of the rolls are subjected to considerable wear, furthermore, the mechanical stresses originating from bending forces, are quite considerable. It is necessary to dissipate considerable quantities of heat from the surfaces of the rolls, for this reason the rolls are cooled with water at 15–20 °C circulated inside the rolls. The temperature of the walls of the rolls are about 80–100 °C. Experience shows that about 75% of the useful energy input is converted to heat, which must be eliminated by the cooling water.

Of the two rolls, the material preferentially adheres to the slower and it forms a continuous layer of coating there. Owing to this, less heat is dissipated to the surrounding environment from this roll than from the other, back roll. In general, calculations show that it is necessary to conduct away three times as much heat from the slower of the two rolls than from the other.

Types of Roll Mills

1) *Mixing* roll mills. The functional role of roll mills is to prepare plastic mixes (or rubber mixes) from polymer materials and additives. Their most common circumferential speed is around 0.05 m/s, with friction ratios of 1.08 to 1.2. The general phases of the preparation of the mixes are:

- plasticizing of the polymers (mastication),
- dispersion of the additives, and homogenization.

2) *Plasticating* or softening roll mills. These roll mills are employed for softening of polymer mixes; the material passed through such equipment is processed further by calendering or in an extrusion equipment. The characteristic speed is 0.08–0.16 m/s, with friction ratios of 1.2–1.3.

3) Rolling frames for *regenerate* refining. The milled and regenerated rubber is refined by means of these rolling frames. The highest relative speed is employed in these, (0.40–0.67 m/s), together with the highest friction ratios, 2.5 to 3.0.

4) Grinding mills. These produce finely ground, small particle size materials. These are employed to mill textile fabric wastes and to powder hard rubber. Their roll surfaces are smooth, their speed and friction ratios are approximately the same as for the frames mentioned in 3 above.

5) *Disintegrating rolling frames*. Employed to grind waste materials. Their speed and friction ratios are again as for 3, but the surfaces of the rolls are grooved.

6) *Washing* rolling frames. These are used to clean natural rubber from mechanical impurities. Their friction values range from 1.2 to 1.5. Either one or both of the rolls are grooved. Water is allowed to flow between the two rolls by gravity to remove the mechanical impurities liberated by the rolls.

The utilization of rolling mills. Rolling mills may be employed in polymer processing

for the following general applications:

- The mixing of polymer material(s) with additives to make a uniform plastic material. In such instances the polymer material itself is in a viscous fluid state, or in a plastic state, or it is converted into a plastic or viscous fluid state.
- Mixing polymers with plasticizers, in order to accelerate swelling and gelation.
- To bring the material to a state to facilitate further processing.
- Manufacture of semi-finished products (in the forms of sheets or master batches).
- To prepare block and graft copolymers.

The processes that take place in the rolling frame are the result of complex physical, chemical and mechanical processes.

All rolling frames, even though they may be used for different purposes, are similar to one another. A rolling frame of the most frequently used construction is shown in Fig. 2.12. The positioning of the two rolls (1 and 2) is effected in a horizontal plane, and the rolls have polished surfaces. They are supported in bearings (8 and 12) on the frame (11). The frame is clamped by a cast-iron holder. The rolls are driven via the shaft (15). The rolls are adjusted into a parallel position with the aid of threaded rods (10).

The rolls may be driven either by synchronous or asynchronous motors, either both rolls together or individually by two asynchronous motors. The friction between the

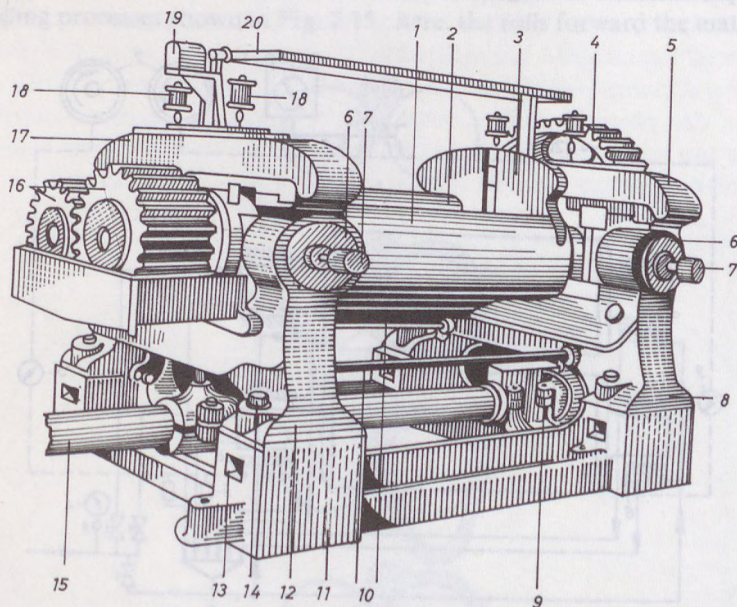


Fig. 2.12. A commonly used roll mill construction

1. front roll, 2. rear roll, 3. partition, 4. large cog-wheel drive, 5 and 17. machine supports, 6. distribution disc, 7. control screw, 8 and 12. machine supports, 9 and 14. bearings of the drive shaft, 10. reinforcing rods, 11. base plate, 13. access hole, 15. drive shaft, 16. frictional cog-wheels, 18. oiling device, 19. safety switch housing, 20. counter weight

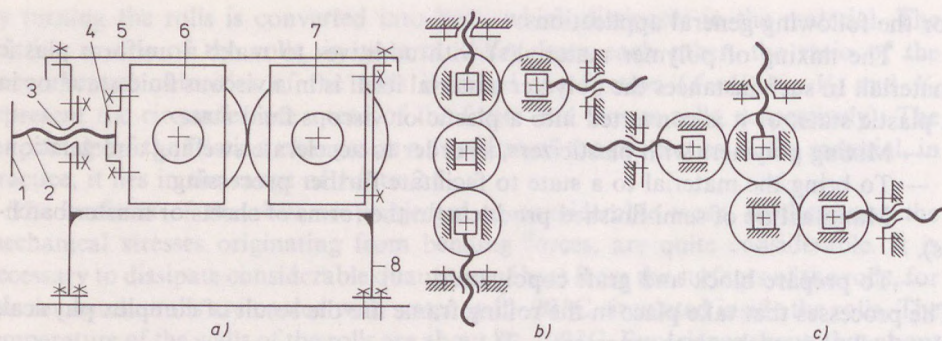


Fig. 2.13. Mechanism for adjusting the gap between the rolls, as applied to roll mills and L-calenders
a) For roll mills, b) and c) for L-calenders 1. crank, 2. clamping screw, 3. nut, 4. screw, 5. machine support, 6. bearings of the manouverable front roll, 7. bearings of the rear, stationary roll, 8. machine support

rolls is ensured by cog-wheels (16). The bearing of the roll in the rear (2) is fastened on the supporting frame, while the front roll (1) bearing is constructed in such a way that it can be moved, thus, the gap between the rolls is adjustable. The mechanism for adjusting the gap between the rolls is similar in the case of rolling frames to that of calenders, and it is shown in Figure 2.13. The rolling frames are equipped with a system to prevent overloading, thus, when the forces applied on the rolls exceed a

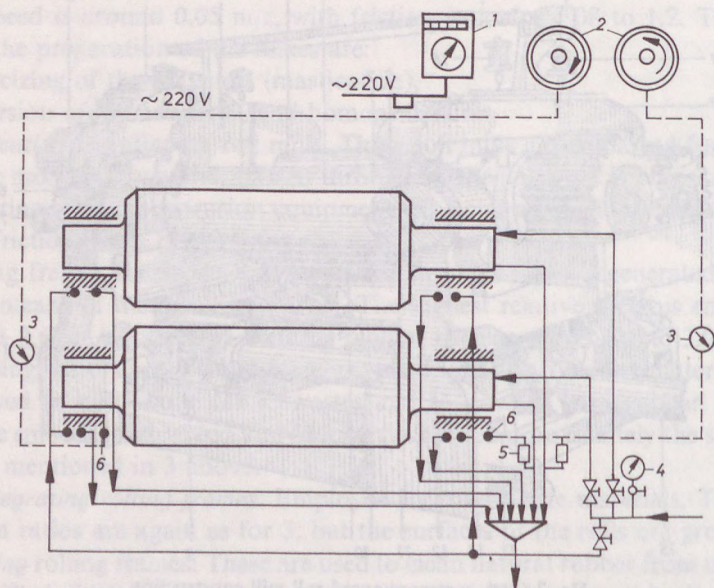


Fig. 2.14. Cooling system for roll mills

1. instrument dial, 2. recording manometers, 3. manometers, 4. pressure measuring devices of the cooling water cycle, 5. mercury manometers, 6. pressure measuring devices to measure the oil pressure in the bearings

certain value, a safety screw breaks and the distance between the rolls suddenly increases.

The rolling mill is also fitted with safety devices such as the bar (20), which stops the rotation of the rolls and rotates them in a reverse direction for one third of a turn when pressed.

For the rolling mills to work with the desired efficiency it is necessary to lubricate the bearings with oil in a suitable oil circuit. During processing the temperature of the rolls should be kept at an appropriate low temperature, ensured by the cooling system. The cooling system is shown in Figure 2.14.

2.3.2.1 Theory of Mixing on Roll Mills

Processing with the aid of roll mills involves a periodic mixing process. Taking the example of a multicomponent mix, the mix resides in the mill for a prolonged time, the same quantity of material may be passed through the gaps between the rolls several times, the material warms up and turns round and round adhering to the roll with the speed of rotation [32–42].

The first consideration must be the attitude of the material to rolling.

A considerable number of experiments were carried out using caoutchouc mixes, leading to the definition of various mixing phases (Figure 2.15.) [42]. The behaviour of a given polymer depends on the sizes of the rolls, the size of the gap between the rolls, the speed of rotation of the rolls and the temperature. Consider the first phase of the milling processes shown in Fig. 2.15.; here, the rolls forward the material to the

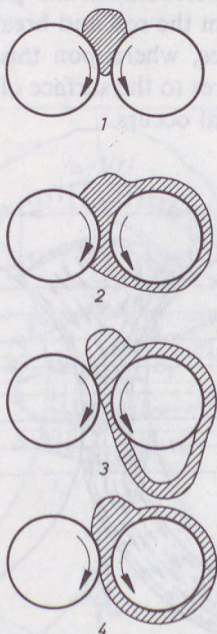


Fig. 2.15. Mixing phases of a roll mill

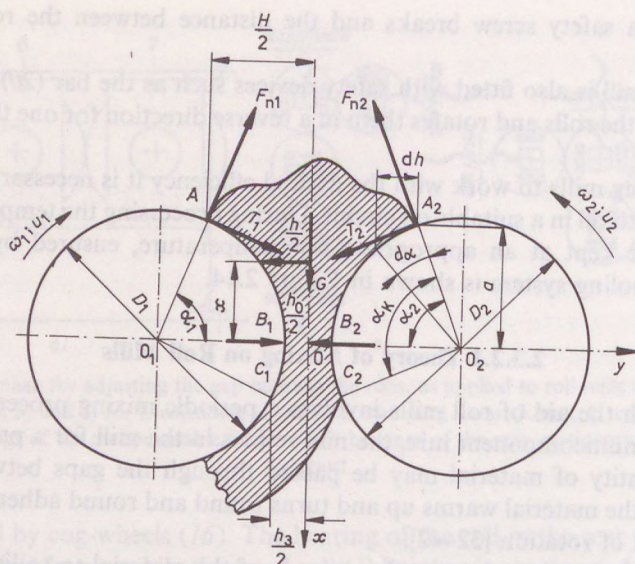


Fig. 2.16. Pressures applied in a roll mill

gap, and a thin layer of the material enters the gap. If the temperature of the material is high enough, it flows through between the rolls (and, hence, through the gap), a film of material adheres to the surface of the slower roll and phase 2 evolves. If the temperature of the material is increased further phase 3 develops, at this stage the polymer strip detaches itself from the roll and breaks up into pieces. With a further temperature rise phase 4 evolves, whereupon this viscous, elastic material passes through the gap and again adheres to the surface of the slower roll. At higher speeds unstable break-up of the material occurs.

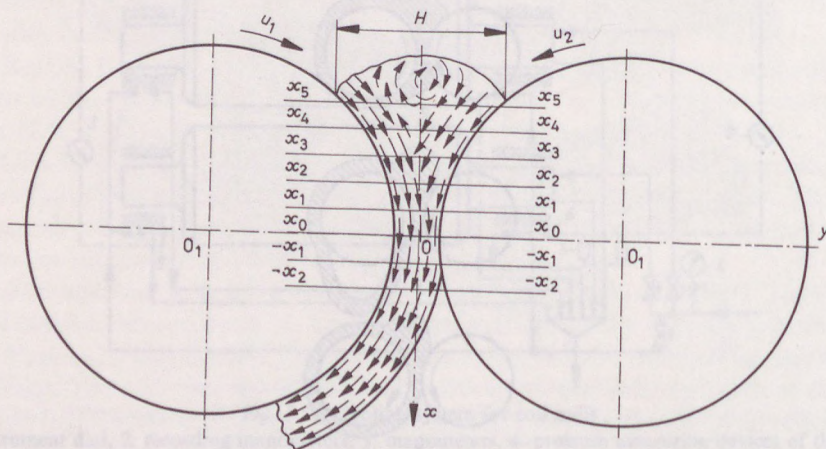


Fig. 2.17. Streamlines evolved in a deformation gap

The material at phase 2 may be regarded as an elastic strip wound onto one of the rolls. When the speed of rotation of the roll is increased, strips of material become detached from the roll and an uneven strip surface develops. By reduction of the size of the gap a more even strip of material is obtained. In a stable operational mode such an even strip of material is obtained, and the localised detachment of the material ceases. Material is detached from the roll only if the elastic energy content of the material exceeds a certain critical value. Materials with a broad range of molecular weights are more resistant to detachment compared with materials with a narrower range of molecular weights. Phase 3 is characterized by crumbling and breaking up of the material, and the material is unable to support its own weight. Further temperature increases achieve a stable, fluid-like state of the material (Phase 4).

[illegible]

99

shearing forces act on the material. The rolls of the mill can forward the material only at certain angles, these angles are $\alpha_1 = A_1 O_1 B_1$ and $\alpha_2 = A_2 O_2 B_2$. The material is stretched in the gap due to the adhering and shearing forces, and the streamlines developed are presented in Figure 2.17. Two main parts of the deformation zone are the forward flow and a reserve flow zones, as shown in Figure 2.18. The reverse flow zone is the area $A_1 N_1 N_2 A_2$, where the speed of reverse flow gradually decreases from the surfaces of the rolls to the middle line. The material at the moment of entry into the gap forms a rotating bank of stock between the rolls due to the reverse flow. At some distance from the point of entry of the material, the speed of rotation of the roll is the same as the average speed of the material. This corresponds to the cross-sectional area $N_1 N_2$, where the pressure curve exhibits a maximum, and the shearing force acquires a zero value. The position of this neutral zone depends on the rheological properties of the material, on the size of the gap between the rolls, the size of the bank of stock, the temperatures of the rolls and the speed of their rotation. In the zones bounded by arcs $N_1 B_1 C_1$ and $N_2 B_2 C_2$ the movement of the particles takes place in the forward direction and the pressure drops rapidly to atmospheric pressure. At the cross-section $C_1 C_2$ the material is forwarded by adhering to the roll of the higher temperature and slower rotational speed, and finally, the material makes a re-entry into the deformation zone.

Determination of the Characteristics of Roll Milling Processes

The frictional forces acting on the rotating rolls are:

$$\begin{aligned} F_1 &= F_{n1} f_1 = F_{n1} \operatorname{tg} \varphi_1 \\ F_2 &= F_{n2} f_2 = F_{n2} \operatorname{tg} \varphi_2 \end{aligned} \quad (2.46)$$

where F_{n1} and F_{n2} are the normal forces at the roll surfaces, f_1 and f_2 are the frictional constants, φ_1 and φ_2 are the friction angles. The mix is "pulled in" in between the rolls by a force expressed as:

$$F_b = mg - F_{n1} (\sin \alpha_1 - \cos \alpha_1 \operatorname{tg} \varphi_1) - F_{n2} (\sin \alpha_2 - \cos \alpha_2 \operatorname{tg} \varphi_2) \quad (2.47)$$

where α_1 and α_2 are the angles of entry of the material. Rearranging relationship (2.47) and assuming that $R_1 = R_2 = R$, $F_1 = F_2 = F$ and $\alpha_1 = \alpha_2 = \alpha$ and mg is negligibly small, then:

$$\frac{F_b}{\cos \alpha} = 2F_n (\operatorname{tg} \varphi - \operatorname{tg} \alpha) \quad (2.48)$$

that is, the material mix enters the gap between the rolls, when $\varphi > \alpha$. In practice, the angle of pull is between the values of 30 and 45°.

The processes that take place in the rolling mill and between the rolls of a calender are essentially the same. The feature of the former is that the material passes through the gap between the rolls several times, while in the case of calendering the material passes through the gap between the rolls only once.

The feature of the gap between the rolls is that both R_1 and R_2 are much great-

er than $h(x)$, thus, the geometry of the gap may be approximated by equation:

$$h(x) = h_0 + \frac{x^2}{2R} \quad (2.49)$$

The characteristic geometric dimensions of the gap are the minimum gap h_0 and the distance Δx between the values x_{in} and x_{out} . The characteristic speed of the material movement may be expressed as:

$$v = \frac{Q}{h_0} \quad (2.50)$$

where Q is the flow volume related to unit roll length. The characteristic shearing rate is $\dot{\gamma} = \frac{V}{h_0}$, where V designates the velocity at the circumference of the roll. The actual velocity of the material varies gradually with the size of the gap, and the value of the shearing rate varies similarly. Examination of the flow equation above leads to the conclusion that in a roll milling process the most important role is that played by the viscous forces. In the energy equation the x -directional Graetz number is derived and expressed as:

$$Gr_x = \frac{\rho C_p v \Delta x^2}{k} \cong \frac{\rho C_p v (2\pi R/3)^2}{k} \approx \frac{10^3 \times 2 \times 1 \times 8}{0.2} \approx 10^5 \quad (2.51)$$

which indicates that the effects of heat conduction are quite substantial. In the inlet and the outlet zones the velocities are substantially smaller, however, the Graetz number is still of the order of 10^4 . The Griffith number is:

$$Gn = \frac{b\bar{\tau}\bar{\gamma}}{k} h_0^2 = \frac{0.1 \times 5 \times 2.5}{0.2} 0.04 \approx 0.25 \quad (2.52)$$

which indicates that the effect of the dissipated energy is by no means negligible. The Deborah number and the Weissenberg number relate to the gap size via the characteristic velocities with maximum values of:

$$N_{De} = \frac{\lambda_1 v}{\Delta x} \cong 0.1 \lambda_1 \quad (2.53)$$

$$N_{We} = \frac{\lambda_1 v}{h_0} \cong 5 \lambda_1$$

which means that, depending on the speeds of the rollers, the elastic effects may be quite substantial and the use the rheological state equation of viscous liquids alone is not sufficient.

From the point of view of processing, the Bikerman number and the Bebris number are also important. The Bk criterion shows to what degree the material exhibits slippery characteristics on the surfaces of the roll, while the Bebris number indicates the attitude of the material to rolling.

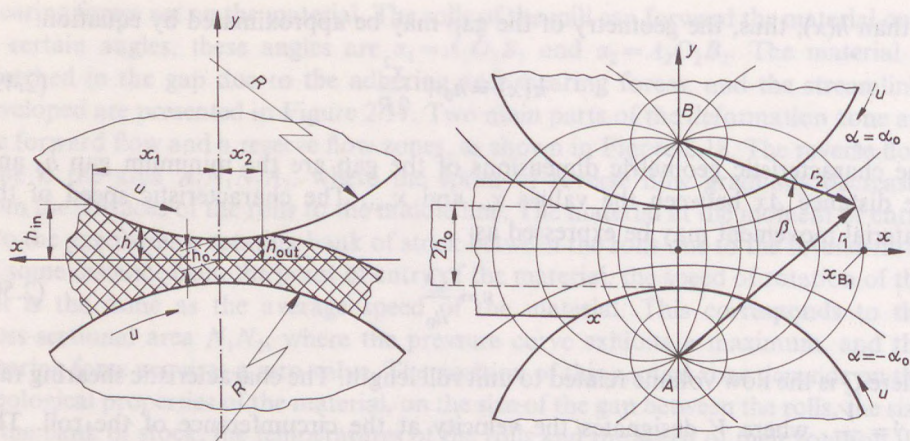


Fig. 2.19. The deformation space illustrated in a rectangular and a bipolar coordinate system

Parameters that characterize mixing by rolling mills may be listed as follows:

- the quantity of the material to be processed in one milling cycle,
- the mixing time,
- the magnitude of the forces on the rolls that tend to push the rolls apart,
- the energy needs of the rolling process (or, in relation to the energy, the magnitude of torque on the rolls),
- the warming of the material during the mixing process,
- the maximum shearing force that occurs during mixing, and
- the total deformation of the material during mixing.

The initial equations to determine the parameters are as follows. In the Cartesian coordinate system (Figure 2.19.) [14, 43, 44]:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \quad (2.54)$$

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_{xy}}{\partial y} \quad (2.55)$$

$$\tau_{xy} = \mu_0 [\exp - b(T - T_0)] \left| \frac{dv_x}{dy} \right|^{n-1} \frac{dv_x}{dy} \quad (2.56)$$

$$\rho C_p v_x \frac{\partial T}{\partial x} = k \frac{\partial^2 T}{\partial y^2} + \tau_{xy} \frac{\partial v_x}{\partial y} \quad (2.57)$$

In the bipolar coordinate system depicted in the second part of Fig. 2.19. these are:

$$\frac{\partial}{\partial \beta} (h v_x) + \frac{\partial}{\partial \alpha} (h v_y) = 0. \quad (2.58)$$

$$\frac{\partial P}{\partial \beta} = \frac{\partial}{\partial \alpha} \left\{ \mu_1 \left| \frac{\partial}{\partial \alpha} \left(\frac{v_x}{h} \right)^n \operatorname{sgn} \left[\frac{\partial}{\partial \alpha} \left(\frac{v_x}{h} \right) \right] \right\}. \quad (2.59)$$

$$\frac{k \partial^2 T}{h^2 \partial \alpha^2} = \frac{\rho C_p}{h} \left(v_x \frac{\partial T}{\partial \beta} + v_y \frac{\partial T}{\partial \alpha} \right) + \mu_1 \left| \frac{\partial}{\partial \alpha} \left(\frac{v_x}{h} \right) \right|^{n+1}. \quad (2.60)$$

The boundary conditions for solving the above system of equations are:

$$\begin{aligned}
 x = x_{\text{in}} \quad & P=0; \quad T=T_0 \\
 x = x_{\text{out}} \quad & P=0; \quad \tau_{xy}=0; \quad \bar{v}=\text{const.} \\
 y=0 \quad & \frac{\partial v_y}{\partial y}=0 \quad \frac{\partial T}{\partial y}=0 \\
 y = \pm \frac{h}{2} \quad & v_y=v_x=V_1=V_2; \quad T=T_w \quad T_0=T_w
 \end{aligned} \tag{2.61}$$

and

$$\begin{aligned}
 -\alpha_0 < \alpha < \alpha_0; \quad & \beta = \beta_+; \quad P=0, \quad T=T_0, \\
 \alpha = \pm \alpha_0; \quad & \beta \geq \beta_+; \quad P=0, \quad T=T_1 \\
 \beta = \beta_-; \quad & P=0, \quad \frac{\partial P}{\partial \beta}=0
 \end{aligned} \tag{2.62}$$

The equations (2.54–2.57) and (2.58–2.60) may be solved numerically. Characteristics of the roll mill processes are:

— the forces pushing the rolls apart:

$$F = L \int_{-x_2}^{x_1} P(x) dx \tag{2.63}$$

— and the torque:

$$M = 2RL \int_{-x_2}^{x_1} \tau_{xy_n}(x) dx \tag{2.64}$$

These may be determined from the pressure profile $P(x)$. Figure 2.20. shows the pressure curves calculated and determined experimentally. It may be observed that the pressure maximum is near the minimum nip, while the calculated curves are, in general, situated below the curves determined experimentally.

Figure 2.21. depicts the temperature distribution in the gap in symmetric (a), or asymmetric (b) rolling processes. According to this diagram two temperature maxima exist in the entry zone of the material. In the case of symmetrical milling these are nearly the same in magnitude, in asymmetric milling situation the maximum near the hotter roll is significantly higher than the maximum near the colder roll. Now, with the effect of mixing, temperature equalization takes place, thus, the temperature maximum occurs near the axis of the gap.

Thus, in symmetrical rolling a large gap exhibits a parabolic temperature curve, in the case of asymmetric rolling it yields a curve resembling a half parabola, while in cases of smaller gaps curves with maxima occur. The temperature maxima and minima shown on the temperature curves are related to the dissipation of energy. The maximum heat dissipation occurs at the surfaces of the rolls, however, the net effect of dissipation is somewhat reduced due to heat conduction of the rolls, so that the heat maxima occur some distance away from the roll surface. Temperature minima occur

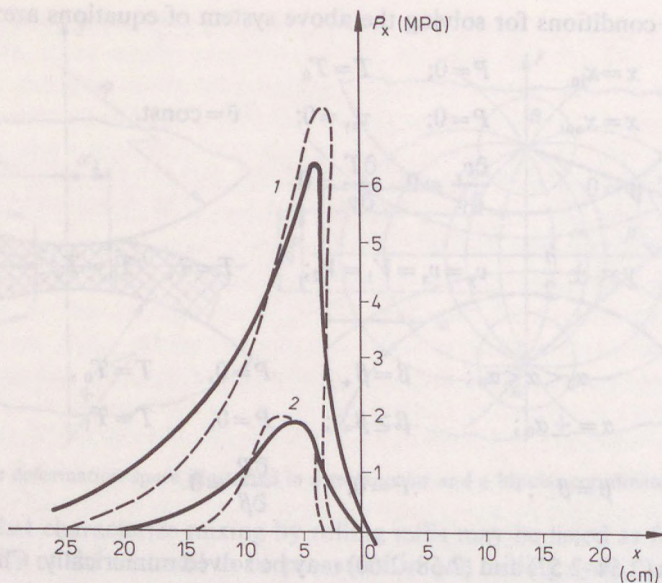


Fig. 2.20. Pressure distributions in the gap between the rolls
Symmetrical rolling of a natural caoutchouc mix. $\mu_0 = 4.16 \times 10^5$ Pa, $n = 0.25$, $b = 0.05$, $T_0 = T_1 = T_2 = 40^\circ\text{C}$, $R = 30$ cm, $h_0 = 0.01$ cm, $N = 40$ litres/min, and 10 litres/min
—: calculated, ---: measured

at equal distances from the rolls, in a plane between the rolls, since at these points the effects of heat dissipation is a minimum. In cases of asymmetric rolling the heat minimum is shifted towards the colder roll. A temperature increase is also observed along the middle line in the gap from the inlet point to the outlet point of the material; this phenomenon is due to heat conduction.

The parameters characteristic of the processes in the rolling mill may be calculated by considering a one-dimensional, quasi-isothermal case, where temperature distribution calculations are ignored and only the average temperatures are calculated. In such an instance the characteristics of rolling may involve [14]:

— the forces pushing the rolls apart:

$$F = 2\mu_1 LR \left(\frac{V}{h_0} \right)^n g_1 \quad (2.65)$$

— the energy consumption of rolling:

$$P_T = 2\mu_1 LV \left(\frac{V}{h_0} \right)^n \sqrt{2Rh_0} g_2 \quad (2.66)$$

— the average temperature of the mix, derived from the equation:

$$VLh_{\text{out}} \varrho C_p (T - T_{\text{in}}) = 2L\mu_0 \exp[-b(T - T_0)] V \sqrt{2Rh_0} \left(\frac{V}{h_0} \right)^n g_2 \quad (2.67)$$

Equation (2.67) may be solved by iteration. The empirical functions g_1 and g_2 are given by the relationships:

$$g_1 = 1.93 + 2.63n + 1.22n^2 \quad (2.68)$$

and

$$g_2 = 4.67 + 8.06n - 4.09n^2 \quad (2.69)$$

In the case of rolling mills the material passes through the gap between the rolls several times and the total heating during this process can be determined by changing the inlet temperature of the material (i.e. $T_{in2} = T_1$, $T_{in2} = T_2$, etc.), while the final average temperature of the material may be determined by equation (2.67), although this approach ignores the cooling effects that occur on the surfaces of the rolls. This, however, may be overcome by the introduction of a convectional term into the equation.

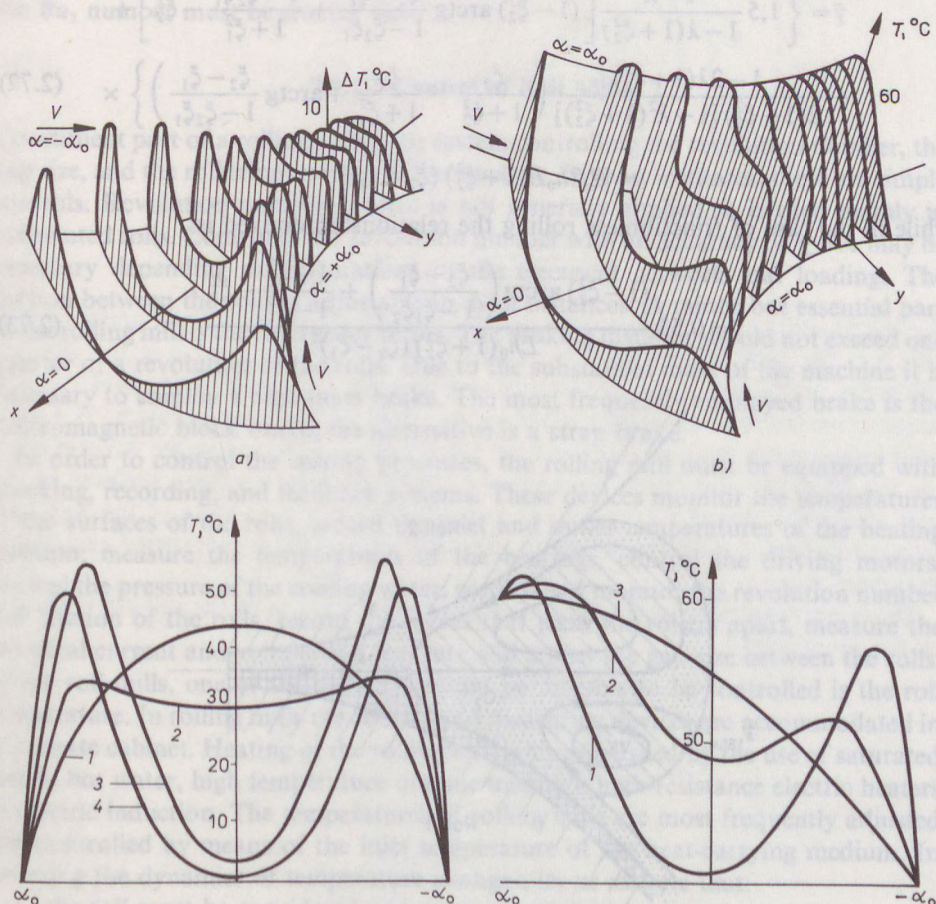


Fig. 2.21. Temperature distributions in the gap between the rolls

Let the total mixing time be t_m and during this the material passes through the gap i times. Mathematically:

$$i(t) = \frac{V(1 + \xi_2^2)t_m}{x_{out} - x_{in}} \quad (2.70)$$

where $\xi = \frac{x}{\sqrt{2Rh_0}}$

An important feature of mixing by means of a roll mill is the total deformation occurring. The total deformation is expressed as:

$$\bar{\gamma}_t = i(t)\bar{\gamma} \quad (2.71)$$

where $\bar{\gamma}$ is the average shear in the gap.

In cases of unequal roll speed and a material with Newtonian viscosity properties, the average shearing deformation related to a single revolution is expressed as [11–14]:

$$\begin{aligned} \bar{\gamma} = & \left\{ 1,5 \frac{1-\lambda}{1-\lambda(1+\xi_2^2)} \left[(1-\xi_2^2) \arctg \frac{\xi_2 - \xi_1}{1 - \xi_2 \xi_1} + \frac{1 - \xi_2^2 \xi_1}{1 + \xi_1^2} - \xi_2^2 \right] + \right. \\ & \left. + \frac{1 - 2\lambda(1 + \xi_2^2)}{2(1 + \xi_2^2)[1 - \lambda^2(1 + \xi_2^2)]} \left(\frac{\xi_2}{1 + \xi_2^2} - \frac{\xi_1}{1 + \xi_1^2} + \arctg \frac{\xi_2 - \xi_1}{1 - \xi_2 \xi_1} \right) \right\} \times \\ & \times [2,8h_0L(1 + \xi_2^2)(\xi_2 - \xi_1)]^{-1} \end{aligned} \quad (2.72)$$

while in the case of frictionless rolling the relationship derived is:

$$\bar{\gamma} = 0,53 \frac{(1 - \xi_2^2) \arctg \left(\frac{\xi_2 - \xi_1}{1 - \xi_1 \xi_2} \right) + \frac{1 + \xi_2^2}{1 - \xi_1^2} - \xi_2^2}{Lh_0(1 + \xi_2^2)(\xi_2 - \xi_1)} \quad (2.73)$$

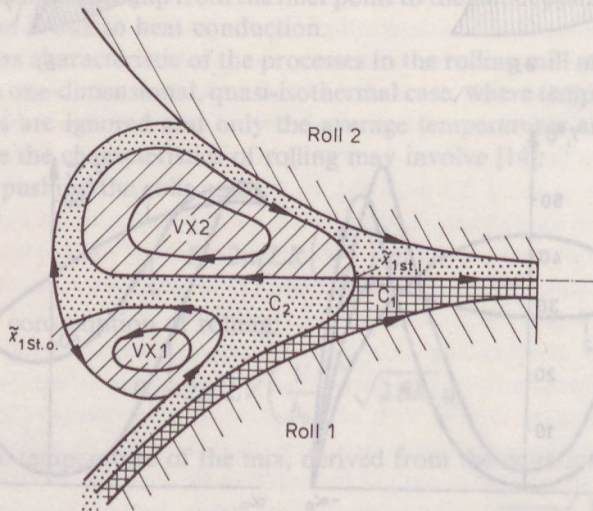


Fig. 2.22. Evolution of the bank at entry into the gap between the rolls

By comparing the two relationships it is seen that the deformation of the material is greater in the case of frictional rolling. In describing the processes related to rolling, two additional factors need to be considered. The first is the observed phenomenon, that, in certain conditions, the material tends to slip on the surface of the roll. In such instances, when solving the equations (2.58–2.60) the limiting values need to be modified so that the actual speed of the material on the surfaces of the rolls used. In this way, the pressure curve may be calculated with higher accuracy [45].

In the bank region (as shown in Figure 2.22.), a certain part of the material, by adhering to the roll's surface, enters the gap and passes through it. Another portion of the same material is detached from the surface of the roll at the point of stagnation (x_{1st}) and moves in the reverse direction along the central line, and reaching the external point of stagnation (x_{2st}) it leaves the bank. This bank plays an important role in mixing and in the equalisation of temperatures [46]. The stability of the bank is an important factor. One of the conditions for stability is that the stretching stresses that occur in the material should not exceed the tensile strength of the melt, that is, the Ba_2 number must be smaller than 1.

2.3.2.2 Control of Roll Mills

Constituent part of a rolling mill is the system controlling the revolution number, the gap size, and the roll temperatures of the machine. In most instances, these are simple controls. Revolution number control is not generally applied, it is used mainly in automated rolls. Control of the revolution number with an accuracy of $\pm 5\%$ may be necessary depending on fluctuations in the electrical network and loading. The friction between the rolls is adjustable in most instances. A minor but essential part of the rolling mill is the emergency brake. The braking distance should not exceed one quarter of a revolution of the rolls. Due to the substantial mass of the machine it is necessary to employ a high mass brake. The most frequently employed brake is the electromagnetic block brake; the alternative is a strap brake.

In order to control the mixing processes, the rolling mill must be equipped with checking, recording, and feedback systems. These devices monitor the temperatures of the surfaces of the rolls, record the inlet and outlet temperatures of the heating medium; measure the temperatures of the bearings, control the driving motors, control the pressure of the cooling water, control and monitor the revolution number and friction of the rolls, record the forces that push the rollers apart, measure the electrical current and voltage and measure and adjust the gap size between the rolls. In the roll mills, one of the most important parameters to be controlled is the roll temperature. In rolling mills the control and measuring devices are accommodated in a separate cabinet. Heating of the rolling mill is accomplished by the use of saturated steam, hot water, high temperature organic material, high-resistance electric heaters or electric induction. The temperatures of rolling mills are most frequently adjusted and controlled by means of the inlet temperature of the heat-carrying medium. In assessing the dynamics of temperature changes, let us assume that:

- the roll must be considered as a reservoir of the heat-carrying medium,
- the flow of the medium through the roll is constant,

- the distribution of temperature in the walls of the rolls can be described by temperature distribution in a flat plate,
- the wall thickness of the roll is the same along the entire length of the roll,
- the temperature gradient is calculated in a direction perpendicular to the wall,
- the heat exchange between the heat-carrying medium and the roll, as well as between the surfaces of the roll and the environment is convective,
- the properties of the rolls and the heat-carrying medium are constant.

The dynamic system of equations for roll temperatures is as follows:

$$K \frac{d\Delta T}{dFo} + \Delta T = b\Delta T_{in} + (1-b)\Delta T_r(y)_{y=1} \quad (2.74)$$

$$\frac{\partial \Delta T_r(y)}{\partial Fo} = \frac{\partial^2 \Delta T_r(y)}{\partial y^2} \quad (2.75)$$

$$\left. \frac{\partial \Delta T_r(y)}{\partial y} \right|_{y=0} + Bi\beta[\Delta T_r(y)|_{y=0} - \Delta T_1] = 0 \quad (2.76)$$

$$\left. \frac{\partial T_r(y)}{\partial v} \right|_{y=1} + Bi[\Delta T_r(y)|_{y=1} - \Delta T] = 0 \quad (2.77)$$

$$Fo = \frac{at}{\delta^2}; \quad Bi = \frac{\alpha\delta}{k}; \quad \beta = \frac{\alpha_1}{\alpha}; \quad y = \frac{x}{\delta}$$

where

$$K = \frac{GCa}{\delta^2(\alpha F + TC)}; \quad b = \frac{TC}{\alpha F + TC}$$

G is the quantity and C is the specific heat of the heat-carrying medium present in the roll, δ is the wall thickness, K is the thermal conductivity, and a is the thermal diffusivity of the roll. F designates the heat transfer surface, α is the heat transfer factor from the heat-carrying surface to the walls of the roller, while α_1 is a constant representing the heat transfer from the surfaces of the roll to the environment: t is the time, Q_{in} and Q are the temperatures of the heat-carrying surfaces at the inlet and outlet points of the roll, Q_r and Q_1 are the temperature of the wall and the temperature of the surrounding air. Δ depicts the differences compared against the stationary value.

The temperature changes in the heat-carrying medium and in the roll are expressed by the equations:

$$G_{\Theta_{in}-\Theta_r(0)}(p) = \frac{b}{Kp + 1 - (1-b)G_{\Theta-\Theta_r(1)}(p)} \quad (2.78)$$

$$G_{\Theta_1-\Theta_r(0)}(p) = \frac{(1-b)G_{\Theta_1-\Theta_r(1)}(p)}{Kp + 1 - (1-b)G_{\Theta-\Theta_r(1)}(p)} \quad (2.79)$$

where

$$G_{\Theta-\Theta_r(1)}(p) = \frac{Bi \left(Bi\beta \frac{sh\sqrt{p}}{\sqrt{p}} + ch\sqrt{p} \right)}{R(p)}; \quad (2.80)$$

$$G_{\Theta_1 - \Theta_r(1)}(p) = \frac{Bi\beta}{R(p)}; \quad (2.81)$$

$$R(p) = Bi(1 + \beta) \operatorname{ch} \sqrt{p} + Bi^2 \beta \frac{\operatorname{sh} \sqrt{p}}{\sqrt{p}} + \sqrt{p} \operatorname{sh} \sqrt{p} \quad (2.82)$$

Calculation of the transfer functions is cumbersome due to the transcendental functions. Approximations of the above are provided in the literature [47 and 48], while the curves obtained are shown in Figure 2.23.

The main parts of the temperature control system in the roll mixers are the sensing, the control and the supplementary devices. In the usual control system the control is

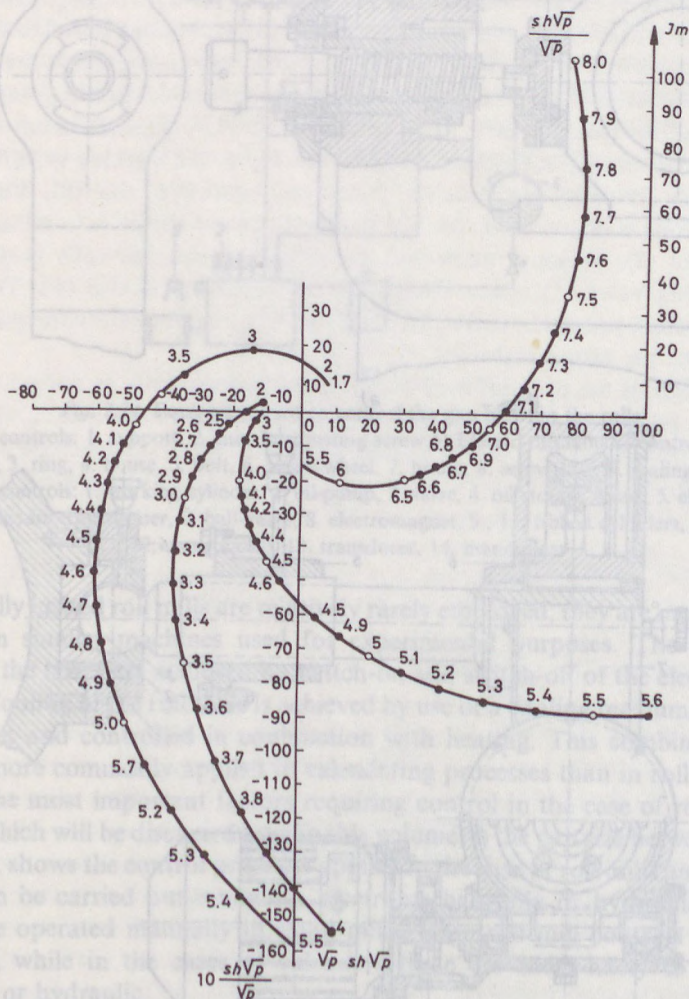
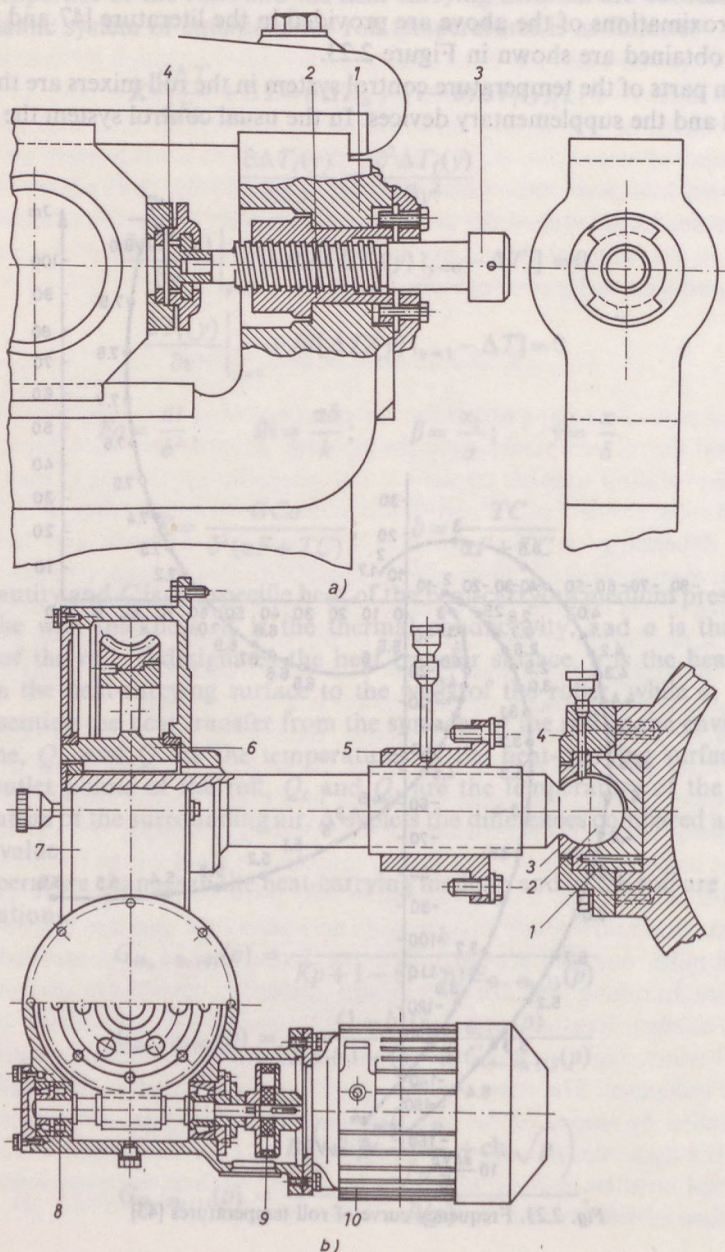


Fig. 2.23. Frequency curve of roll temperatures [43]

built into the condenser pipe after the roll and the amount of the heat-carrying medium is controlled with the aid of valves. As control media, pneumatical output dilatometers are employed. Continuous controls are seldom utilized; where they are used, the signal of a thermocouple, built into the surface of the roll, is transmitted to the control, where the PI control, fitted with an automatic potentiometer, moves the valve which controls the heat transmitting medium.



supporting frame (1) a nut is fitted (2) into which an adjusting screw (3) is inserted. By moving the screw outwards the gap between the rolls is enlarged, since the pressure of the material on the rolls push the rolls in an outward direction, until the casing of the bearing touches this screw.

In order to facilitate the adjustment, scales are fitted around the screw, fastened to the frame, giving an easily seen indication of the size of the gap between the rolls. In general, adjustment of the rolls is effected manually, although in large machines it is done with the aid of motors. In this case switches are fitted on the control shaft driven by the motor which allows coupling to the motor one side or the other side or both sides at the same time.

Adjustment of the gap size in the case of calendering is achieved in the following way: one of the rolls remains fixed, while the other can be moved by moving the bearing of the roll in the support frame. Adjustment of the size of the gap is performed with the aid of a pair of screws, where the nut of the screw is fastened to the support frame of the machine, while the screw itself is fitted onto the bearing case of the roll. The screw is driven by an electric motor, the screw moves the bearing, and hence the roll is moved. This mechanism is shown in Figure 2.24.b). Figure 2.24.c) illustrates a hydraulically driven gap adjustment mechanism. Here, the working roll (1) is mounted, fixed to the frame by fastening the piston rod bearing of the roll. When the gap between the rolls is of constant size, the pump (2) passes the oil into oil tank (4), via a safety valve (3). When a decreased gap size between the rolls is desired, the electromagnetic valve (5) opens the pressure-intensifying device (6). The oil with increased pressure opens the valve (7), and flows in the space before the piston which, in turn, moves the piston rod.

The efficiency of the roll mill may be increased substantially by subjecting the film of the mix in process to the cooling effect of air on a large surface area with the help of conveyor belting. With enhanced cooling the output of the machine is increased. To some extent the oxidising effect of air also plays a part in this process. Figure 2.25. is a sketch of this installation. From the roll mill (1) the material is transferred onto

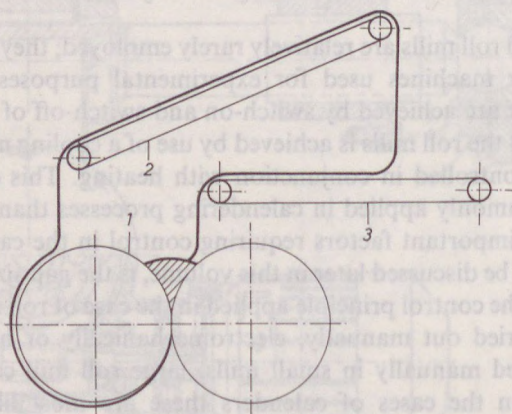


Fig. 2.25. Intensifying cooling with the aid of transport belts

1. slow roll, 2. and 3. transport belt

the belt (2), from the roll with the lower revolution number the material moves forward and falls onto the belt (3) by gravity. This belt returns the material back to the gap. This circulating material cools down in contact with air. Cooling is further enhanced, in such instances, by the fact that the slow-moving roll is not coated with the material processed thus the roll can more efficiently transmit heat to the surrounding atmosphere.

An equipment for similar purposes is shown in Figure 2.26. The material is peeled off from the slow-moving roll (1) in a controlled fashion by the pair of rolls (2) and turned the other way round. Now, the material re-enters the gap via the incline (3). The upper pair of rolls (2) is driven by a variable-speed motor (4), via the chain drive (5). Under this pair of rolls carriage (6) is situated, which moves backwards and forwards along the roll length during the machine's operation. This motion is brought about by means of a left-hand/right-hand revolving spindle (7), which is driven by the drive (4) via chain transmission (8). Two rolling rods are attached to the carriage (6), about 600 mm apart. The material leaving the slow roll gets between these two rods, it becomes puckered in a random pattern sidewise, and owing to the swinging motion of the rods it is deposited at different sites in the gap. Thus, mixing takes place, independently of the operator. The advantages of this machine are: more efficient

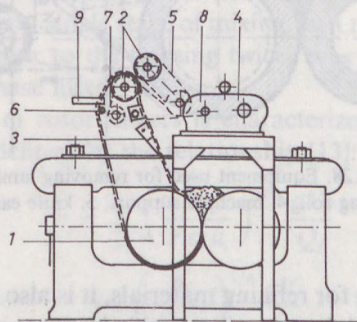


Fig. 2.26. Cooling and automatic mixing equipment for roll mills

1. roll mill, 2. pair of rolls, 3. return incline, 4. drive, 5. chain drive, 6. carriage, 7. left-hand, right-hand spindle, 8. chain transmission, 9. two units of rods with rollers

cooling, reduced manual labour, efficient crosswise mixing and reduced energy consumption.

The return transport of the materials in the case of regenerate refining machines is automated by the use of conveyor belts. Figure 2.27. shows such a unit. Here, belt (4) is tightened via the mobile roll (6), and controlled by the fixed rolls (5), supported by the rear roll (2), it picks up the material which has fallen through between the two rolls, presses it against the slow-rotating roll and transports to the top of the roll, and the material gets into the gap again.

In order to achieve the appropriate tightness of the belt, the tightening roll (6) is fitted in runner (7). To the other end of the runner a cable (10) is affixed. The cable is passed through control pulleys (8) and fastened to the air pressured piston (9). This type of roll mill works in a labour-saving continuous mode of operation. This type

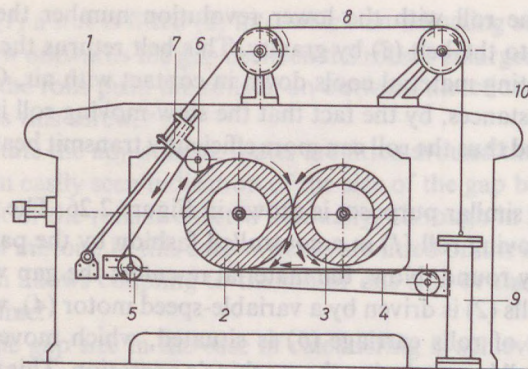


Fig. 2.27. Return transport system for a refine roll mill

1. support, 2. rear, large roll, 3. front, small roll, 4. belt, 5. diversion rollers, 6. tension rollers, 7. slide, 8. control rollers, 9. air pump, 10. cable

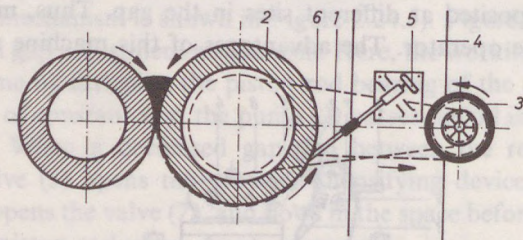


Fig. 2.28. Equipment used for removing laminate

1. knife, 2. roll, 3. receiving roll, 4. machine support, 5. knife case, 6. chain transmission

of machine is used not only for refining materials, it is also utilized in the preparation of rubber mixes, however, labour saving in this instance may be only marginal.

Upon completion of the refining operation, the fine veily regenerate sheet must be removed from the roll. As shown in Figure 2.28., this thin layer is removed from the roll (2) with the aid of the knife (1) so that the material is transferred to the pick-up roll (3) onto which the material is wound. The knife (1) is adjustable by means of adjusting screws in the knife box (5) fixed to the frame of the machine (4) at the surface of the roll. The pick-up roll (3) is driven by a chain transmission (6) from the roll neck.

2.4 Continuous Mixers

The output efficiency of mixing may be increased by a full automation of the mixing processes. Continuous mixers are generally single- or twin-screw machines. The continuous mixers have several advantageous features, compared with intermittent mixers. Their mixing intensities may be some three-four fold greater compared with the intermittent mixers, the temperature of the mix does not exceed 85–100 °C, unlike

the intermittent mixers where the temperatures often rise to 140–150°C, and the power requirement of continuous mixers is 30–40% lower than that of intermittent mixers. A disadvantage of continuous mixers is that the composition of the mix must be maintained constant and for this, accurate feeding is necessary.

2.4.1 Rotor Mixers

Examples of these are the Rotomill, manufactured by the Goodrich Company, or the Transfermixer, made by the Farrel Company. The former is fitted with one rotor, the latter is fitted with two rotors. These types can be regarded as continuous versions of internal mixers. The rotor blade of the Rotomill equipment has a conical shape, with thread and it rotates in a conical-shaped housing. The spacing between the housing and the rotor is adjustable by moving the rotor in the direction of its own axis. The rotors of the Transfermixer are more similar to the screws of the extruders. For the single phase variety, the depth of the screw channel decreases gradually from the hopper to the outlet orifice, while the depth of the channels in the walls of the housing increases gradually in the same direction. As a result, the mix is transferred from the screw channels to the channels made on the housing. During the mix's residence time a single transfer constitutes a single stage of mixing. In a two-phase Transfermixer the mix transfers from the rotor to the housing twice, thus this ensures a more intense mixing than the single phase mixer.

The mixing efficiency of rotor mixers is characterized by the total and average deformation, which are defined by the relationship [13]:

$$\gamma_j = \sum_{i=1}^j \left(\frac{P_{Ti}}{F_i \omega \mu_i} \right)^{1/n_i} \frac{\rho V_i}{Q_j} \quad (2.83)$$

$$\bar{\gamma} = \left(\frac{P_T}{F \omega \mu} \right)^{1/n} \frac{\rho V}{Q}$$

where j represents the number of zones, i is the sequential number of the zones, P_T represents the power consumption, μ is the viscosity, ω is the angular velocity of the rotor (or rotors), F_i is the area covered by the wing of the rotor, V_i is the volume of the material in the i^{th} zone, Q_j is the volume flow through the mixer, n is the power of the viscosity equation, and ρ is the density of the material.

Figure 2.29. illustrates a characteristic control scheme applicable to mixing equipment using continuous modes of operation [49]. The volume flow of continuous operation mixers, unlike the extruders with one or two screws is independent of the revolution number of the rotor. Inside the mixer the shearing rate is increasing or decreasing as a function of the speed of loading. The residence time of the mix in the mixer may be controlled by opening or closing the discharge outlet. In practice, during operation the revolution number is adjusted, then the discharge outlet is closed. During loading the torque increases first slowly then rapidly, the discharge outlet is slowly opened and after a short period of fluctuation a steady value of torque is attained. The control system consists of two control loops. One is a loop of constant

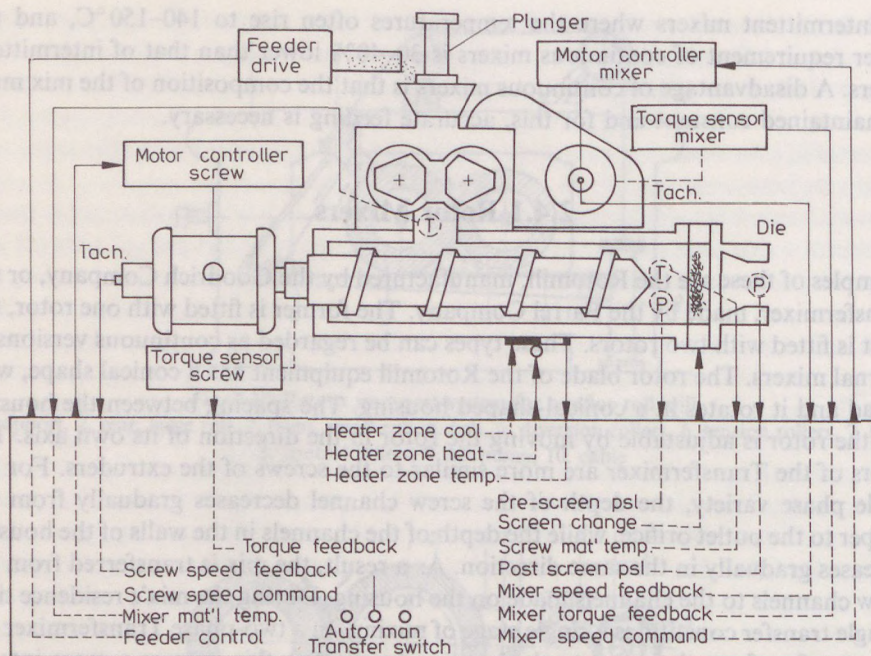


Fig. 2.29. Control system of a mixer with a continuous mode of operation

energy consumption, the other is the loop of constant outlet temperature. The required programme is selected on the control panel. A microprocessor calculates the necessary rotation number and torque. The size of the gap is determined with the aid of a PID algorithm. Initially, the programme adjusts the rotors to a certain revolution number, it closes the gap, and after a steady torque is attained the measured torque value is compared with the required value and the gap is opened in accordance with it. Where there is a constant outlet temperature programme, the temperature value desired is established and the microprocessor determines the specific power required. The measured temperature is compared with the required temperature, specific standard energy needs are repeatedly calculated which is adjusted by means of the torque, similarly to the first loop of the control.

2.4.2 Single-Screw Extruders

The material is fed into the single screw extruder in the solid state, the material melts and is passed to the metering section. The residence time of a given polymer particle is given by the relationship:

$$t = t_s + t_f + t_m \quad (2.84)$$

where t represents the residence time of the particle, with residence times t_s in the solid zone, t_f in the molten film and t_m in the melt. The residence time and the

deformation can be determined by subdividing the screw channel lengthwise and in height, thus, the residence time in each i^{th} section of the channel is to be calculated for the individual elemental layers. The transport zone of the solid material may be ignored view of deformation, the residence time is calculated from the relationship l_s/V_s , where l_s is the length of the solid material transport zone, while V_s is the average velocity of the solid polymer. This subdivision approach makes the calculation a rather extended and cumbersome procedure, however, the obtained value approximates reality better. This is especially the case if the depth of the screw channel varies, although the error involved by using an approach in which the entire length of the channel is considered a single entity is not too great either. At the moment when melting starts ($i=0$), the amount of the melt in the individual sections will be:

$$q_i = G \frac{W_s(i-1) - W_s(i)}{W} \quad (2.85)$$

where G is the total mass flow, $W_s(i-1)$ and $W_s(i)$ are the average width of the solid polymer in the $(i-1)^{\text{th}}$ and the i^{th} sections, respectively. The residence time of the just-molten material in the solid bed is expressed as:

$$t_s = \frac{q_s H W \left(i - \frac{1}{2} \right) \Delta z}{G} \quad (2.86)$$

where Δz is the length of the individual sections. The residence time distribution in the molten film on the barrel surfaces is [50]:

$$f(t)dt = \frac{2t_0 dt}{t^3} \quad (2.87)$$

where $t_0 = W_s(i)/2V_x$ is the minimum residence time necessary for a particle to move to half of the solid polymer width. The section filled with the molten material is divided into K sections with height ΔY (where $Y = y/H$) from the screw surface to $Y = 2/3$ and from the screw to the barrel. The ratio of the just-melted material in the k^{th} layer is given by:

$$f_i = \frac{q(i)}{G} \cdot \frac{H q_m (W - W_s(i)) (v_z(Y) \Delta Y + v_z(Y^*) \Delta Y^*)}{G(1 - W_s(i)/W)} \quad (2.88)$$

where $v_z(Y)$ and $v_z(Y^*)$ are the velocities in the z direction at the Y and Y^* supplementary coordinates. This can be calculated from the relevant rheological model.

In subsequent phases of the melting processes, when a melt layer develops also on the screw surfaces, until the molten layers still increase, similar relationships may be employed than in the case of the melt layers formed on the surfaces of the barrel, except that the following residence time should be used:

$$t_0 = \frac{W_s(i)}{2v_x} + \frac{W_s(i)}{2v_s} \quad (2.89)$$

Table 2.2. Mixing characteristics of Newtonian type fluid flow

Characteristic	Symbol	Expression
Residence time	t	$\frac{L}{3V \sin \Theta \cos \Theta (1 + \Phi)} \frac{3Y - 1 + 3\sqrt{1 + 2Y - 3Y^2}}{Y[1 - Y + \sqrt{1 + 2Y - 3Y^2}]}$
Residence time distribution	$f(t)dt$	$\frac{3Y}{\sqrt{1 + 2Y - 3Y^2}} (1 - Y + \sqrt{1 + 2Y - 3Y^2}) dY$
Accumulated time distribution	$F(t)$	$\frac{1}{2} [3Y^2 + 1 + (Y - 1)\sqrt{1 + 2Y - 3Y^2}]$
Total deformation	γ	$\frac{1}{3} \frac{L}{H} \frac{1}{1 + \Phi} \left[\frac{2F(Y, \Phi)}{\cos \Theta} + \frac{G(Y, \Phi)}{\sin \Theta} \right]$
Total average deformation	$\bar{\gamma}$	$\frac{L}{H} \frac{\cos \Theta}{\sin \Theta} \frac{6 - 4Y}{5 - 9Y} - \frac{L}{H} \frac{\sin \Theta}{\cos \Theta} \frac{1.08}{1 - Y}$

Explanations: $Y = \frac{y}{H}$; $\Phi = -\frac{H^2}{6\mu V} \frac{\partial P}{\partial z}$;

$$F(Y, \Phi) = \frac{f_i [(1 - 3Y^*)^2 + \frac{\text{ctg}^2 \Theta}{4} (1 + 3\Phi - 6Y^*\Phi)^2]^{\frac{1}{2}}}{(1 - Y)Y + f_i(Y^* - Y)(1 - Y^* - Y)}$$

$$G(Y, \Phi) = \frac{(1 - f_i)[4(1 - 3Y^*)^2 \text{tg}^2 \Theta + (1 + 3\Phi - 6Y^*\Phi)^2]^{\frac{1}{2}}}{(1 - Y)Y + f_i(Y^* - Y)(1 - Y^* - Y)}$$

$$f_i = \frac{1}{1 - \frac{Y^*(2 - Y^*)}{Y(2 - 3Y)}}; \quad Y^* = \frac{1 - Y + \sqrt{1 + 2Y - 3Y^2}}{2}$$

In the case where the melt layers surround the solid polymer completely, the appropriate approach to the melt layers is the parallel plate model [50–53].

The flow velocity, for each layer i , k is expressed separately for fractions f_1 , f_2 , etc. ... f_k . The total residence time in the individual sections is the sum of the residence times in the solid form, in the melt zone, and in the melt film. Thus, to each f_j portion a separate residence time distribution function can be assigned. The residence time of the material in the melt zone, for a Newtonian melt, will be:

$$t_m = A \frac{3Y - 1 + 3\sqrt{1 + 2Y - 3Y^2}}{Y(1 - Y + \sqrt{1 + 2Y - 3Y^2})} \quad (2.90)$$

where

$$A = \frac{(i-j)\Delta z}{3V_z(1+\Phi)}; \quad \Phi = \frac{H^2}{6\mu V_z} \left(-\frac{dP}{dz} \right)$$

$(i-j)\Delta z$ is the distance from that point where the portion is melted to the point at which the material is examined. The residence time of the entire screw plasticating unit is obtained by summing up the residence times in the various sections.

In calculating the shearing distribution function, it must be considered that the polymer particle undergoes shearing in the molten film stage and in the melt zone.

The mixing characteristics calculated for the molten film and the melt zone are given in Table 2.2. The shearing deformation distribution was calculated for each particular element and were summarized for the entire section filled by the melt.

Table 2.3. shows the effect of the melt film on the average residence time and on the average deformation. The data in this Table also reveal that taking into consideration the residence time in the film melt influences the values of the average residence time only to a small extent, however, this value is quite significant from the aspect of total deformation.

Table 2.3. Effects of the melt film on the residence time and on deformation in a single-screw extruder [50]

Diameter of barrel, cm	Mass flow, g/sec	Revolution per min.	Residence time, s		Deformation	
			(1)	(2)	(1)	(2)
2.54	3.15	80	50	49.8	435.8	324.2
6.35	12.60	80	112.6	111.7	3795.0	3583.0
15.24	50.40	30	278.8	273.8	4977.0	4649.0

It was found during examination of the technological data that at constant screw speed and increased mass flow, the residence time and the average deformation decrease. In the case of constant mass flow, the residence time decreases slightly with increasing screw speed, the average deformation increases with increasing screw speed, while the accumulated deformation distribution remains practically constant. An important requirement of screw plasticating is the homogeneous distribution of temperatures. This is primarily determined by the melting efficiency of the plasticating unit, and a constant length of the melting zone means an approximately constant melt temperature. If the average residence time and the average deformation are examined by maintaining the melting length at a constant value, in order to complete melting to the tip of the screw, then the average residence time decreases with a continuous increase of the speed of the screw. Thus, the G/N ratio will be a minimum, while the average shearing deformation reaches a maximum value.

In order to maintain constant quality of the melt the mixedness must also be kept constant. The efficiency of mixing is largely determined by the G/N ratio.

Up to now, isothermal flow of melts with Newtonian behaviour was discussed. A non-Newtonian behaviour influences the residence time distribution only slightly and it does not affect the average deformation, as shown in Figure 2.30., in which the mixing parameter represents practically the average deformation. Temperature affects both parameters. By taking into account the temperature space, it influences the deformation distribution function only slightly, and the function may be solved by the application of non-isothermal velocity distributions. In calculating the residence time, the temperature reduction applied [52] will be:

$$t_r = t \exp \left[\frac{E}{R} \left(\frac{1}{T_r} + \frac{1}{T} \right) \right] \quad (2.91)$$

where t_r is the reduced residence time corresponding to t , T_r is the reference temperature, T is the actual temperature, E is the activation energy of the viscous flow, and R is the gas constant.

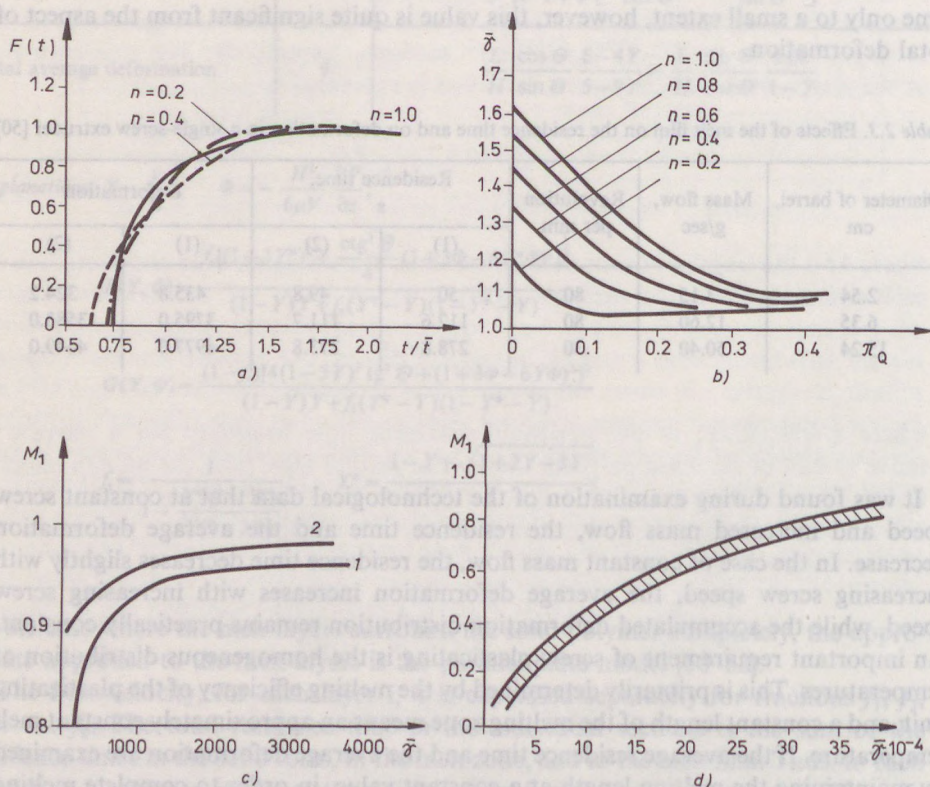


Fig. 2.30. Mixing characteristics of single- and twin-screw extruders

a) Residence time distribution function for single-screw extruders [47], b) Mixing parameters versus volume flow rate for single-screw extruders [47], c) Mixing extent versus deformation as applied to twin screw mixers 1. counter-rotating twin-screw mixer 2. co-rotating twin-screw mixer, d) Mixing extent versus deformation as applied to twin-screw mixers, derived from data of six augers of opposite rotation and four mixers of the same rotational direction

- By examining the mixing process and the residence time it can be concluded that:
- for a given plasticating unit the residence time is determined primarily by the mass flow; the greater the mass flow the shorter the residence time,
 - mixing is determined by the length of the melting and the G/N ratio; the efficiency of mixing is inversely proportional to the length of melting and the G/N ratio,
 - the largest deformations and the largest shearing stresses occur in the film on the surface of the barrel.

Thus, mixing is influenced to the greatest extent by disturbances through fluctuations in the length of the melting zone.

The brief analysis outlined above is applicable to the single screw, continuously operated plasticating units; the processes that take place in mixers with twin or multi-screws may be modelled in the same way.

The processes in twin-screw plasticating units are, to a certain extent, the same as the processes taking place in the twin-screw mixers, and in the two-rotor mixers. Characterisation of the mixing effect of the twin-screw plasticating units is usually achieved by using the deformation invariant according to equation (2.20) above [55–58]. In view of the mixing process the deformations taking place in a twin-screw plasticating unit can be divided into two parts: the deformation processes in the screw channel and those in the so-called calender gap between the screws with opposite rotational directions. Reference to equation (2.20) indicates that it is necessary to determine the individual components of deformation. The individual deformations can be determined from the average deformation, thus:

$$\bar{\gamma}_{ij} = \frac{1}{(Y_{ug} - Y_{dg})(X_{rg} - X_{lg})} \int_{Y_{dg}}^{Y_{dg}} \int_{X_{lg}}^{X_{rg}} \dot{\gamma}_{ij} dy dx \quad (2.92)$$

where Y_{ug} and Y_{dg} are the upper and lower coordinates of the section filled with melt, while X_{lg} and X_{rg} are the left-hand side and right-hand side coordinates of the section occupied by the melt. The individual components related to a particular section of the channel may be written as:

$$\begin{aligned} \dot{\gamma}_{xx} &= 2 \frac{\partial v_x}{\partial x}; & \dot{\gamma}_{yy} &= 2 \frac{\partial v_y}{\partial y}; & \dot{\gamma}_{zz} &= 0; \\ \dot{\gamma}_{xy} &= \dot{\gamma}_{yx} = \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}; & & & \\ \dot{\gamma}_{yz} &= \dot{\gamma}_{zy} = \frac{\partial v_z}{\partial y}; & \dot{\gamma}_{xz} &= \dot{\gamma}_{zx} = \frac{\partial v_z}{\partial x} \end{aligned} \quad (2.93)$$

The deformations are derived as the product of the residence times of the melt in the individual deformation spaces and the average shearing rates in the given space fraction, and the partial deformations must be summed. The corresponding relationships for describing the above will be discussed later in the text.

The relationship between the extent of mixing and the average deformation is shown in Fig. 2.30. The curves obtained are of similar course as in the case of single-screw plasticating units. The efficiency of mixing is dependent on the rheological parameters involved, on the revolution number and the temperature, in addition to the geometric dimensions of the unit.

Automation of extruders will be discussed later.

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3 Calendering Process Control

3.1. Introduction

Calendering plays an important role in the processing of thermoplastics. It is a continuous shaping process, in which the plastics acquire their final shapes after the material is passed through the nip between heated rolls rotating in counter directions. Sheets and films are the most frequent shapes produced by these processes. In the calendering processes proper the material passes through the nip of the rolls only once. This is the most important difference between the processes of calendering and roll-milling. Thus, in the case of the calendering procedures the material must pass between several rollers to obtain sheets or films of smooth surfaces.

In both the rubber and the plastics industries the calendering is utilized for any of the following purposes:

- to manufacture smooth rubber sheets,
- to manufacture rubber sheets with patterns on one side,
- to manufacture double-coated rubber surfaces,
- in the coating of textiles with rubber,
- in the production of plastic sheets,
- in plastic foil production.

The number of calender rolls may be two, three, four or five. The rolls of the two-roll calender may be arranged vertically or horizontally. The vertical arrangement of a battery of calender rolls consisting of four or five rolls is commonly employed. Frequently used configurations are the "L" and the inverted "L" shapes in the case of four- and five-roll calenders. Triangular configuration is applied in calenders with three rolls, while slanting configurations are usual in the four-roll calendering systems. The four-roll arrangement with a supplementary roll is employed in double coating and rubber coating processes.

When the calender rolls are arranged in a vertical plane, certain disadvantages become obvious, such as the cumbersome feeding of the material into the machine and the difficulties in accurate adjustment and control of the nip.

During operation the rolls become deformed on the effects of the load changing the gap, the deformations in the separate gaps influence each other which makes the formation of sheets of uniform thickness difficult. To reduce these problems, the arrangement of the rollers into "L" shaped configuration seems to be a promising solution. However, this does not eliminate the control difficulties due to the changes in the distances between the rollers on account of distortions. In this respect the arrangement of the rolls in a slanting configuration appears to be a better approach, since in this case the forces appearing during manufacturing distort the rolls so that

the previously adjusted nip and thus the thickness of the product are affected to a considerably lesser degree. A further advantage of this configuration is that the material can be fed from above, which makes automatic feeding more feasible. For a high-quality product, it is essential that the rolls have the smoothest possible surfaces. Therefore, in most instances the surfaces of the rolls are not only ground, but polished as well. A further important requirement is accurate temperature control. For this purpose a separate closed-circuit heating system is employed for each of the rolls, which makes possible the application of different independent temperature settings on each of the rolls.

In the calendering processes the previously well-mixed, homogeneous and occasionally preheated material is passed between pairs of rolls, yielding a product of uniform thickness with smooth or patterned surfaces. The plastic material in the gradually narrowing spacing between the rolls is subjected to compressive forces in the direction perpendicular to the flow of the material, and to stretching forces in the direction of the movement of the material. Strong shearing develops in the material between the rolls. On the effect of heating by the rolls and the dissipation of energy liberated during the deformation processes, the material in the roll-spacing transforms into a viscoelastic or viscously fluid (melt) state, depending on the nature of the material used and on the processing conditions. Calendering involves thus both melting and shaping processes in one step.

In most cases the end products of the calendering processes are either sheets, films, or coated textiles. The quality aspects of the material include size stability, the quality of the surface layers and the required level of mechanical characteristics. These characteristics are closely related to the technological parameters. The proper choice and maintenance of the technological parameters make the quality control of the product feasible.

The process of sheet calendering is shown in Figure 3.1. The material is stockpiled on the feed side of the machine to form what is often referred to as a rolling bank. This bank acts as a buffer material reservoir between the feed side and the exit side of the material flow. The rolling bank flow is usually asymmetrical, since the material enters only at one side of the two rollers. Thus, the material flow in the nip region will have to be essentially independent of the rolling bank. On the exit side (i.e. in the A_2' , B_2' , C_2' , C_3 , B_3 , A_3 region) it is essential that the calendered sheets separate smoothly from one surface and ultimately from the surfaces of both of the rolls. The technological parameters of calendering may involve the following attributes: the speed of the roll, the output/throughput, the temperatures of the rolls, the separating forces applied to the rolls and the input power of each roll. The resulting calendered sheets can be characterized by surface quality and by thickness tolerance.

One very important calendering process is that of textile coating, which is shown in Figure 3.2. Here the polymer entering the nip is distorted to form a sheet in the first region and is pressed into the lattice structure of the textile material as depicted in the second region. Ultimately, the product's quality depends on the uniform thickness of the polymer layer formed. Note: it is important to keep both the upper and lower polymer layers within the required tolerances.

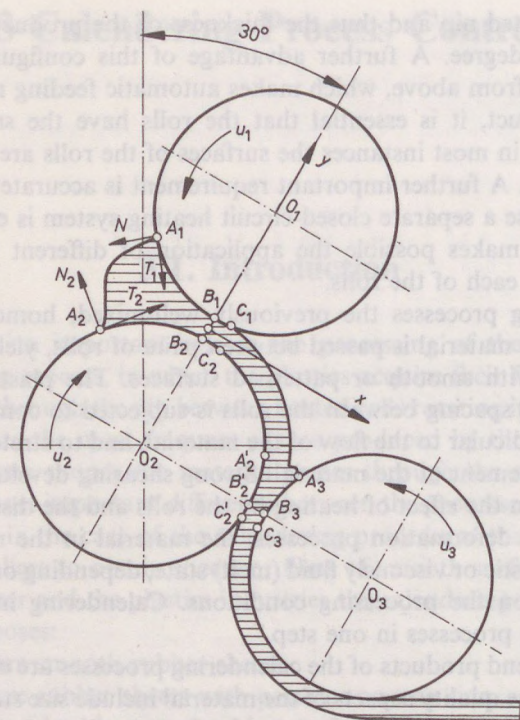


Fig. 3.1. Sheet calendaring

The following text considers the relationship between the parameters of the processes, the controls involved [1 to 3] and some automatic equipment employed in this field of manufacturing.

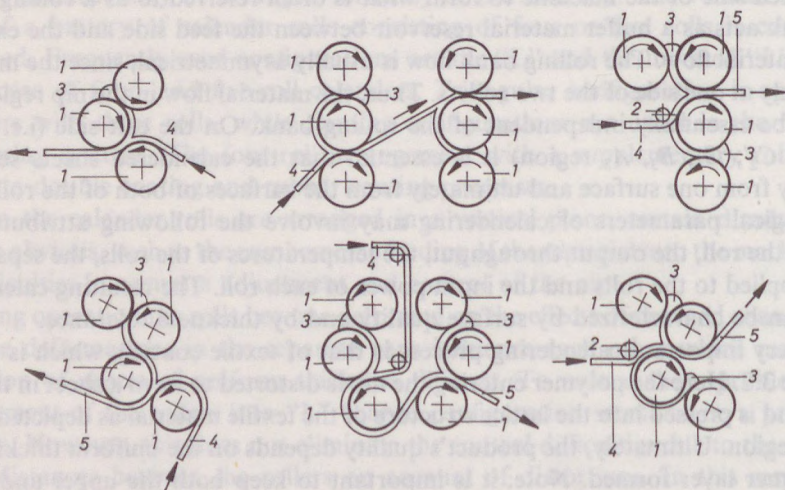


Fig. 3.2. Textile coating

1. rolls, 2. tension roll, 3. polymer, 4. web, 5. coated web

3.2 Deformation in the Gap

Before defining the relationships characterizing the calendering processes, it is advisable to examine the processes of deformation in a gap of the rolls [4 and 5].

In the symmetrical calendering process the polymer is passed over the surfaces of the rolls at speeds approaching the speed of rotation of the rolls, and further layers of the material move along closed streamlines, symmetrical about the axis of the gap. The flow rates in the reverse direction are lower than the speed of the roll. In the rotating "bank" the motion of the polymer is directed towards the surfaces of the rolls, the polymer stretches, the relatively weak intermolecular bonds break, and the polymer separates from the "bank". The adhesion between the polymer and the roll influences the type and flow of the material to some extent, but it does not change it fundamentally. The flow of material in the gap is hindered by the strong intermolecular bonds in the upper layer of the bank.

In cases of non-symmetrical calendering processes the streamlines are displaced toward the slower roll. The surface temperature of the rolls strongly affects the degree of adhesion. Changes in both the adhesion and friction are accompanied by changes in the streamline profile. It was observed during the calendering of certain filled caoutchouc materials that shearing developed to a lesser extent owing to the surface sliding, and the material suffered deformation in the gap.

In a steady calendering process, when a continuous sheet of material is formed on the surface of one of the rolls, a rotating portion of the material appears at the entry to the gap. The material leaves the gap in the cross-section $h_2 \approx (1.1 \dots 1.3)h_0$ and it moves with the rotating roll, adhering to it. On entering the gap a layer of the material with a thickness of $(0.7 \dots 0.8)h_0$ moves with the roll owing to adhesion with a speed equal to that of the external circumference of the roll. A further quantity of material adds to the total quantity of the material that rotates and adheres to the roll on the entry side zone, thus resulting in the rotation of additional quantities of material. Another layer of material, with a thickness of $(0.2 \dots 0.3)h_0$, adheres to the other roll of the pair and rotates with the speed of the circumference of the roll. Thus, the surface of the calendered sheet is determined by these layers of the material adhering to both of these rolls. In the centre of the entry zone two reverse flow zones occur. With increasing friction between the rolls, the zone of the reversed flow is gradually eliminated at the roll to which the material adheres (active roll). This zone can disappear altogether at a given roll friction and only a single zone of reversed flow remains, which increases the rotating velocity of the rolls. If the speed of rotation of the active roll is the higher, than the reversed flow increases in the direction of the active roll in the entry zone. Such behaviour may be observed in the case of rubber materials containing a small quantity of additives. In the case of other materials, the rotating velocity of the material in the entry zone decreases when the speed of the roll decreases, and the direction of rotation remains the same. In the case of symmetrical calendering of plasticized natural rubber, the reversed zone does not develop in the rotating entry zone next to the active roll. In the case of symmetrical calendering of natural rubber material containing a considerable quantity of fillers, no rotating zone evolves, while the mode of deformation becomes plastic in character.

In the calendering processes deformational behaviour of the materials was found to be extremely different depending on the properties of the materials employed and on the operational conditions. The adhesive and cohesive properties of the material, the state, the temperature etc. of the roll surfaces affect the deformation mechanism observed.

The two most characteristic types of deformation are:

- shearing deformation (consisting of both steady-state and non-steady-state deformations),
- elongational deformation.

Shearing deformation is characteristic of the calendering of rubber mixtures and PVC rubber blends containing small amounts of fillers. Elongation deformation is typical of calendering of rubbers containing large amounts of fillers and PVC blends containing lubricants.

3.3 Characteristics of Calendering

In the calendering processes the aim is to manufacture foils, sheets or coated products.

Calendering processes are never used on their own; they are constituent parts of a production line in conjunction with other equipment. Figure 3.3. shows an arrangement with four rolls for the rubber coating of corduroy material on both sides. The corduroy material, previously wetted, is wound on an auxiliary textile and positioned on one of the axles of the unwind stand (1). The roll of material is usually fixed by a rectangular axle slid through a wooden cylinder. This axle is fastened in a disc chunk with bearing having a rectangular slot. A better arrangement is to fix the wooden cylinder in conical-shaped clamps which can be moved by means of compressed air operated rolls. One end of the corduroy textile material is vulcanized to the end of the previous roll of textile with the press (2), thus avoiding the need to adjust the material each time after a roll of material is used. When one of the rolls of textile is unwound and used up, the next roll is vulcanized onto the end of the previous roll, and until

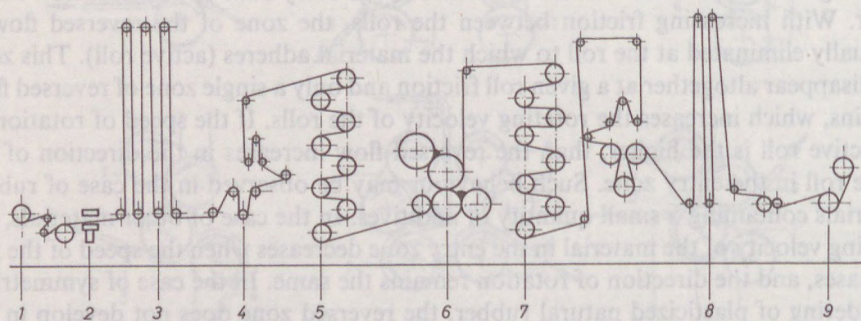


Fig. 3.3. A four-rolls calendering group of machines

1. discharge equipment, 2. splicing press, 3. compensator, 4. tension roll, 5. drying drums, 6. calender,
7. cooling drums, 8. compensator, 9. winding equipment

this is accomplished, the addition of more material is suspended. In order to minimize idling time, a compensator (3) is employed to keep a length of the textile material in reserve. During the joining of the ends of the corduroy textile material, feeding of the calenders is accomplished from this compensator. The compensator consists of fixed upper rolls and mobile bottom rolls in a vertical plane. Drawing of the material is effected by running the corduroy material over the stationary upper rolls and the lower part of the bottom rolls. The mobile rolls are positioned near the lowest extremity of the compensator before the change. When the unwind stand is out of operation, the calenders draw the textile from the compensator, while the dancing rolls move upwards. The parallel movement of the rolls is assured by a chain or cog-wheel parallel lead. It is also customary to include a breaking mechanism (4), which produces a slight tension in the material to pull it tight.

The corduroy material is now passed to the preheating drums (5), heated by means of steam. The preheating drums are rated so that even at the highest speed of calender run, the moisture content of the material is reduced to a minimum of 1.5% and the material is heated to the temperature at which it has a favourable adherence. In up-to-date machinery, automatic temperature controls are employed for the preheating drums. From the drums the corduroy material is passed to the rolls of the calender (6) via a widener equipment. After the calenders the material is passed over cooling drums (7) and through another compensator, and is finally wound in between an auxiliary textile material with the aid of the winding equipment (9).

Thus, calendering may be regarded as a process consisting of:

- a shaping process between the rolls,
- a unifying process between the rolls and
- a cooling process over a series of cooling drums.

3.3.1 Film and Sheet Calendering Processes

In film and sheet calendering the shaping process is analogous with the processes discussed in the previous chapter with respect to the roll mills.

During calendering, the material is passed through two or more gaps until it acquires its final form. In the discussion below the thickness of films and sheets will be considered.

The volume flow of the multiroll calenders is defined as:

$$Q_n = \delta_{1n} h_{0n} L_n \frac{V_n(1+f_n)}{2} \quad (3.1)$$

where $\delta_{1n} = \frac{h_{1n}}{h_{0n}}$; L_n is the width of the material running between the n^{th} pair of rolls, h_{0n} is the gap between the same pair of rolls, V_n is the peripheral velocity of the slow roll, while f_n is the friction between the n^{th} pair of rolls.

The volume flow of the material at the exit point is:

$$Q = hLV \quad (3.2)$$

where h is the thickness of the calendered sheet, V is the rotation velocity of the roll (its peripheral velocity), while L is the width of the sheet. The conservation of mass flow is thus

$$Q_1 = Q_2 = \dots Q_n = Q = \text{const.} \quad (3.3)$$

The thickness of the calendered sheet is given by:

$$h = \alpha \delta_{1n} h_{0n} \frac{V_h}{V} \cdot \frac{1+f_h}{2} \quad (3.4)$$

where $\alpha = L_n/L$. The relationship between the gaps of a multiroll calender system is derived from equations (3.1) and (3.3) as

$$\delta_{11} h_{01} L_1 V_1 (1+f_1) = \delta_{12} h_{02} L_2 V_2 (1+f_2) = \dots \quad (3.5)$$

Thus, relationship between the first and the n^{th} gap is as follows:

$$h_{01} = \alpha_1 h_{0n} \frac{\delta_{1n}}{\delta_{11}} \frac{V_n}{V_1} \frac{1+f_n}{1+f_1} \quad (3.6)$$

The parameter δ_{1i} is a function of the operating parameters.

The transfer of the sheet from one roll to the other is dependent on the velocity, the temperature, the surface properties of the rolls and on the properties of the material being processed. When the material is passed to the fast rolls, the nip, at the exit, may be expressed by the relationship:

$$h_{2n} = \delta_{1n} h_{0n} \frac{1+f_n}{2f_n} \quad (3.7)$$

similarly, when the material is passed to the slow rolls, the relationship is:

$$h_{2n} = \delta_{1n} h_{0n} \frac{1+f_n}{2} \quad (3.8)$$

The thickness of the sheet at the exit may be defined by the equations (3.7) and (3.8). Solving these equations by approximating, one can obtain the equation expressing the relationship relevant to the situation where the sheet is passed to the fast rolls. This is given by:

$$h = \alpha \frac{(1+f_n)}{f_n} \left[-0.13 \times 10^{-3} \frac{h_{1n}^2}{h_{0n}} + 0.365 \times 10^{-2} h_{1n} + \right. \\ \left. + h_{0n} (0.072 f_n^2 - 0.148 f_n + 0.66) \right] \quad (3.9)$$

and for the case when the sheet is passed to the slow rolls, the relationship obtained is:

$$h = \alpha (1+f_n) \left[-0.13 \times 10^{-3} \frac{h_{1n}^2}{h_{0n}} + 0.365 \times 10^{-2} h_{1n} + \right. \\ \left. + h_{0n} (0.016 f_n^2 + 0.026 f_n + 0.594) \right] \quad (3.10)$$

The above relationship holds in cases where swelling or elastic after-effects do not occur. In all cases, where the Weissenberg number is not negligible, swelling of the material must be taken into account. The degree of swelling is dependent on the normal stresses occurring. In such cases the thickness of the calendered sheet is given by the relationship:

$$h_d = h \left[\frac{\sigma_1 + (\sigma_1^2 + 4G)^{\frac{1}{2}}}{2G} \right]^{\frac{1}{2}} \quad (3.11)$$

where σ_1 is the first normal stress difference and G is the shearing modulus of the material. The normal stress difference may be expressed by a power function, similar to the viscosity equation, thus, swelling is a function of the swelling speed and the shearing modulus.

3.3.2 Textile Coating by Calendering

The production of coated textile materials is an important area of application where calendering processes are utilized. Let us briefly analyse the processes of coating quantitatively [6].

Figure 3.4. shows the parameters involved in textile coating, in Cartesian coordinates [3] and in a bipolar coordinate system [9]. Considering first the Cartesian coordinates, we use a fairly simple method of approximation to calculate the thickness of coating. Let δ be the thickness of the textile, and consider the textile pores as simple capillaries so that the penetration of the polymer into the textile material is regarded as the flow of the polymer in a capillary. The average flow speed is given by the equation:

$$\bar{v} = \left(\frac{P}{h_\delta} \right)^n \frac{r^{1+n}}{\mu_0 2^n (3+n) \pi} \quad (3.12)$$

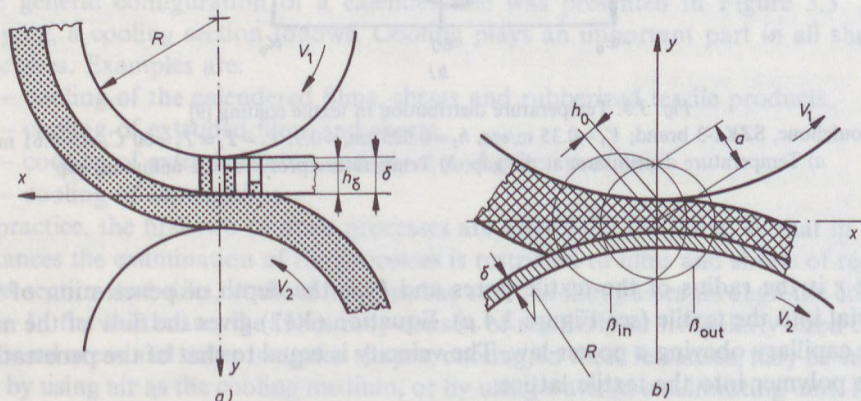


Fig. 3.4. Markings applied in textile coating

a) Cartesian coordinate system [3], b) Bipolar coordinate system [9]

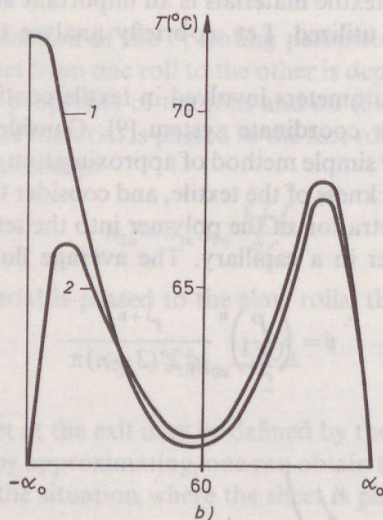
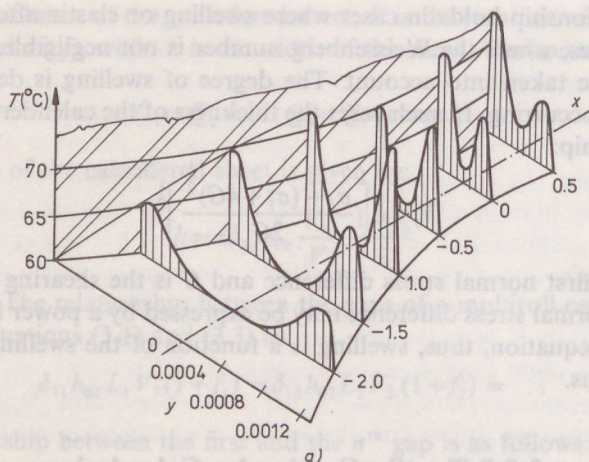


Fig. 3.5. Temperature distribution in textile coating [9]

Caoutchouc, SZKI-3 brand; $V_1 = 0.35$ m/sec, $h_0 = 0.025$ cm, $\alpha = 0.9$, $T_0 = T_1 = T_2 = 60^\circ\text{C}$, $R = 0.61$ m,

a) Temperature distribution at the gap, b) Temperature profile at the minimum gap

where r is the radius of the textile pores and h_δ is the depth of penetration of the material into the textile (see Figure 3.4.a). Equation (3.12) gives the flow of the melt in the capillary obeying a power law. The velocity is equal to that of the penetration of the polymer into the textile lattice:

$$\bar{v} = \frac{dh_\delta}{dt} \quad (3.13)$$

and it follows that

$$h_{\delta}^{1+n} = \frac{1+n}{3+n} \cdot \frac{r^{1+n}}{\mu_0^n 2^n \pi V (2Rh_0)^{\frac{1}{2}}} \int_{\xi_1}^{\xi_2} P^n(\xi) d\xi \quad (3.14)$$

Using the expression for pressure, the thickness of the calendered layer is given by

$$h_{\delta}(\xi_2) = \sqrt{\frac{R}{h_0}} r \left\{ \frac{3^n(1+n)}{(n+2)2^{\frac{7n-1}{2}}} \int_{\xi_2}^{\xi_1} \frac{[g(\xi_2, \xi_1) + 5\xi_2^3]^4 d\xi}{(1+\xi^2)} \right\}^{1+1/n} \quad (3.15)$$

This relationship shows that the depth of penetration strongly depends on the thickness of the gap.

The results obtained show that the depth of penetration depends neither on the velocity nor on the temperature of the rolls. This is not entirely true as both of these criteria affect the exponent of the equation above. However, the effects of these two factors may be regarded as small, since an increase of the roll speed lowers the viscosity of the melt and reduces the time of penetration into the textile structure. A higher temperature lowers the value of μ_0 as well as the viscosity and the pressure, both of which again exert contrary effects. Non-isothermal coating application was investigated by the above method using the coordinate system in Figure 3.5.b) [9].

Figure 3.5. shows the temperature profile developed during the process of textile coating. Part *a* shows the temperature distribution, and part *b* gives the temperature profile at the minimum nip size, h_0 . The first curve of Figure 3.5.b) represents an adiabatic textile surface, while the second curve is for an isothermal state. The actual textile surface shows a behaviour between these two curves.

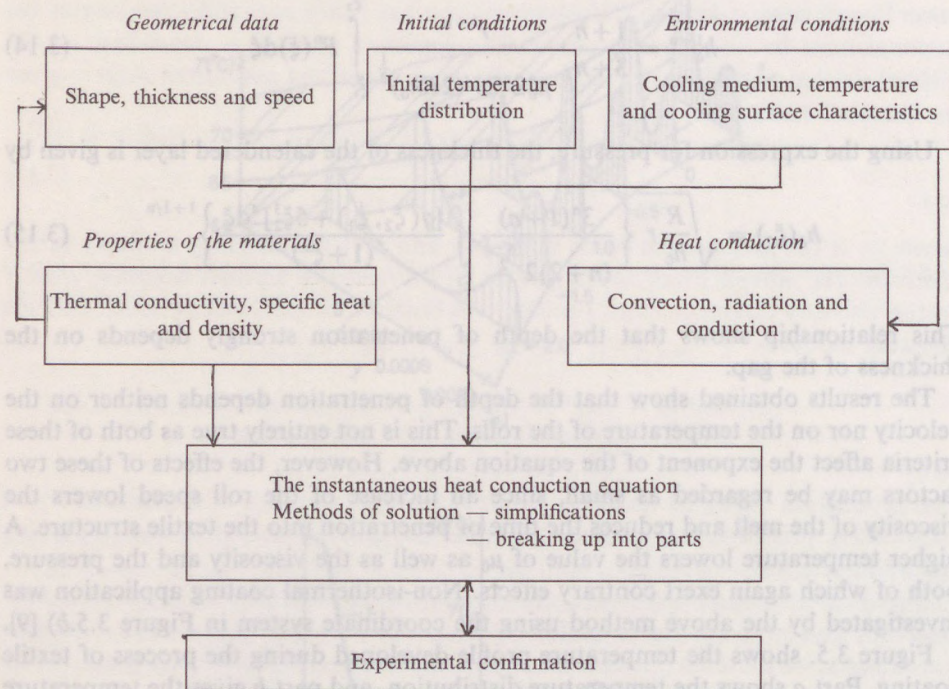
3.3.3. Cooling of the Calendered Products

The general configuration of a calender line was presented in Figure 3.3. After shaping, a cooling section follows. Cooling plays an important part in all shaping processes. Examples are:

- cooling of the calendered films, sheets and rubberized textile products,
- cooling of extruded films and sheets,
- cooling of extruded tubes and pipes and other profiles,
- cooling of blown films.

In practice, the first two of these processes are essentially the same, so that in these instances the examination of the processes is restricted to films and sheets of regular cross section and sizes, at the time when the sheet or film passes through the cooling rolls. In the third case, the tubes may consist of regularly or irregularly sized cross-sectional areas and other irregular shapes; cooling, in these instances, may be carried out by using air as the cooling medium, or by using water in a calibrating unit. In the case of a blown film, cooling is achieved by a flow of air applied to both the inside and outside of the bubble.

Table 3.1. General scheme for the study of product cooling processes



The cooling processes may be approached by a generally applied scheme as in Table 3.1. Cooling should be effected on the basis of the energy equation:

$$\rho C_p \frac{\partial T}{\partial t} = \text{div} (-k \text{ grad } T) \quad (3.16)$$

solved by the application of the initial and boundary values described in Chapter 1.

The various possibilities for solving the equation may be grouped as follows:

- analytical solutions,
- approximations,
- solutions arrived at by following analytical steps,
- methods of finite differences,
- the method of finite elements.

In cases of fairly complicated shapes only numerical methods may be employed [7–12].

For films and sheets a general analytical solution is given by the equation:

$$\pi_T(y, t) = \sum_{i=1}^{\infty} \frac{2 \sin \delta_i}{\delta_i + \sin \delta_i \cos \delta_i} \exp(-\delta_i^2 Fo) \cos\left(\delta_i \frac{Y}{H}\right) \quad (3.17)$$

where y is the thickness coordinate, H is the half thickness of the film or sheet, π_T

is the dimensionless temperature $\frac{T-T_k}{T_0-T_k}$; the Fourier number is: $Fo = \frac{at}{H^2}$, and δ_i is the root of the transcendental equation:

$$\cot \delta_i = \frac{\delta_i}{Bi} \quad (3.18)$$

where Bi is the Biot number. For cooling of calendered films and sheets, equation (3.17) can be approximated by the equation:

$$\pi_T = \exp(-Bi Fo) \quad (3.19)$$

In instances where numerical methods are applied it is possible to include the properties of the material and the interdependent relationships of the heat conduction constant and temperature, so that more accurate solutions are obtained.

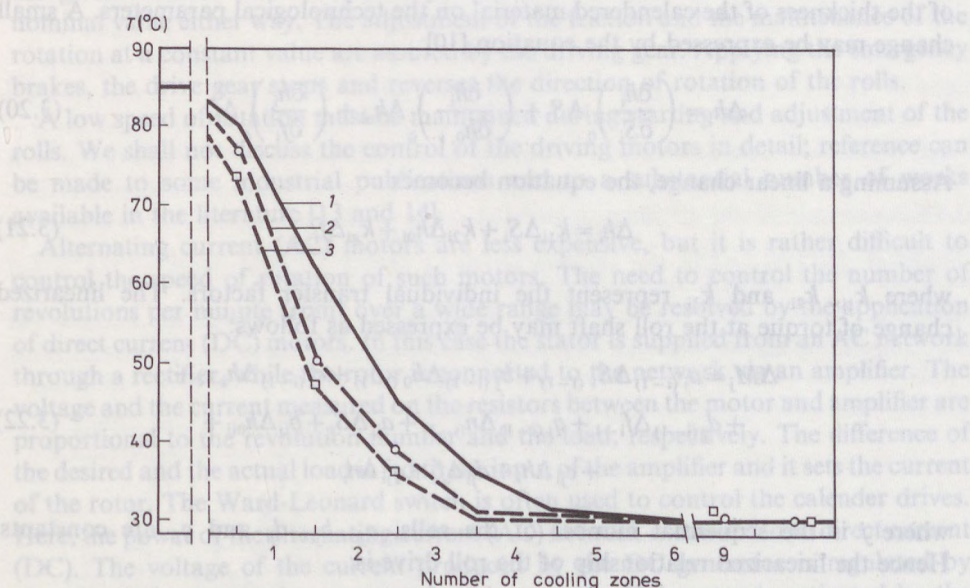


Fig. 3.6. Cooling curves of calendered coated textile. Thickness: 1.5 mm; the temperature of the cooling roll = 26°C; speeds 1: 1.3 m/sec; 2: 0.8 m/s; 3: 0.5 m/s
—: calculated, ---: measured

Figure 3.6. depicts the cooling curves obtained for a textile material coated with natural caoutchouc in a thickness of 1.5 mm. The cooling curves obtained by the method of finite differences provide a better approximation of the cooling process than the curve obtained by using the approximation equation, however, this latter approach suffices for calculations concerning technological processes.

3.3.4 Dynamics of the Calendering Processes

The quality of the products obtained by calendering is characterized by the even thickness of the sheets, the even thickness of an applied rubber coating, the homogeneous nature of the sheets and the rubber coating, and their surface qualities. These parameters are, in turn, influenced by the following parameters:

- the uniform feeding rate of the calenders,
- the thermodynamic and rheological homogeneity of the materials used,
- the uniformity or the fluctuation of the size of the gap between the rolls,
- fluctuations in the revolution number of the rolls and
- changes in the temperature of the rolls.

We now consider the dynamic equations related to the thickness of the calendered product and the characteristic features of the machinery, such as the torque, drive, friction and the gap between the rolls. Equations (3.9) and (3.10) show the dependence of the thickness of the calendered material on the technological parameters. A small change may be expressed by the equation [10]:

$$\Delta h_i = \left(\frac{\partial h_i}{\partial S_i} \right)_0 \Delta S_i + \left(\frac{\partial h_i}{\partial h_{0,i}} \right)_0 \Delta h_{0i} + \left(\frac{\partial h_i}{\partial f_i} \right)_0 \Delta f_i \quad (3.20)$$

Assuming a linear change, the equation becomes

$$\Delta h_i = k_{1i} \Delta S_i + k_{2i} \Delta h_{0i} + k_{3i} \Delta f_i \quad (3.21)$$

where k_{1i} , k_{2i} and k_{3i} represent the individual transfer factors. The linearized change of torque at the roll shaft may be expressed as follows:

$$\begin{aligned} \Delta M_j = & a_{j(i-1)} \Delta S_{i(i-1)} + b_{j(i-1)} \Delta h_{0(i-1)} + c_{j(i-1)} \Delta h_{i-1} + \\ & + d_{j(i-1)} \Delta f_{i-1} + g_{j(i-1)} \Delta n_{(i-1)} + a_{ji} \Delta S_i + b_{ji} \Delta h_{0ij} + \\ & + c_{ji} \Delta h_i + d_{ji} \Delta f_i + g_{ji} \Delta n_i \end{aligned} \quad (3.22)$$

where j is the sequential number of the rolls, a_{ji} , b_{ji} , d_{ji} and g_{ji} are constants. Hence the linearized relationship of the roll drive is:

$$\frac{k_{Mj}}{R_j} \Delta U_j + \beta_j \Delta m_j = \Delta M_j \quad (3.23)$$

where $\beta_j = \frac{k_{Ej} k_{Mj}}{R_j}$ represents the strength of the driving gear.

The change in friction between the rolls is given by:

$$\Delta n_i = k_{4i} \Delta n_i + k_{5i} \Delta f_i \quad (3.24)$$

where k_{4i} and k_{5i} are the corresponding partial derivatives. Due to the changes in the thickness of the material leaving the previous gap, the change in the load of the i^{th} gap will be:

$$\Delta h_{1i} = k_{6i} \Delta h_{i-1} \quad (3.25)$$

where $k_{6i} = v_{j-1}/v(S_i)$ and v_{si} represent the average rate at which the material passes through cross-section S_i . This system of equations expresses the changes occurring in the technological parameters for the $(j-1)^{\text{th}}$ and the j^{th} calender rolls. The solution of the equation gives the change in the layer thickness of the sheet produced as a function of the alteration of the width of the nip, designated by δh_{0i} and of the change in the number of revolutions, Δn_j .

3.4 General Construction of Calenders

3.4.1 The Drive Systems of Calenders

The driving motors of the calender have an output in the wide range 25 to 500 kW. The speed of rotation may be controlled in a limiting range of 1 : 10. The accuracy of the given number of revolution adjusted must be maintained within 3% of the nominal value either way. The adjustment of the friction and the maintenance of the rotation at a constant value are assured by the driving gear. Applying the emergency brakes, the drive gear stops and reverses the direction of rotation of the rolls.

A low speed of rotation must be maintained during starting and adjustment of the rolls. We shall not discuss the control of the driving motors in detail; reference can be made to some industrial publications and to a substantial number of works available in the literature [13 and 14].

Alternating current (AC) motors are less expensive, but it is rather difficult to control the speed of rotation of such motors. The need to control the number of revolutions per minute (rpm) over a wide range may be resolved by the application of direct current (DC) motors. In this case the stator is supplied from an AC network through a rectifier, while the rotor is connected to the network via an amplifier. The voltage and the current measured on the resistors between the motor and amplifier are proportional to the revolution number and the load, respectively. The difference of the desired and the actual load is fed to the input of the amplifier and it sets the current of the rotor. The Ward-Leonard switch is often used to control the calender drives. Here, the power of the alternating current (AC) network is converted to direct current (DC). The voltage of the current produced by the DC generator is regulated by alteration of its excitation current. In this way, the DC motor is activated by the induced DC.

The rolls are coupled to the driving motor by means of a gear drive or separate driving motors are employed. The supplementary equipment, the compensating and cooling rolls and the take up equipment are driven by separate drivers. The take-up equipment require simultaneous drive, so that the calendered film or coated textile is prevented from being damaged or permanently deformed.

Systems with Continuously Moving Webs

Let us now examine the arrangement shown in Figure 3.7., and suppose that the angular velocity of the second pair of rolls is greater than the velocity of the first pair. This, inevitably must result in a stretch of the product between the rolls, thus, the

quantity of the material passing through the first pair and the second pair of rolls differs as is derived by the following equation:

$$\frac{dG_{12}}{dt} = \gamma_1 F_1 v_1 - \gamma_2 F_2 v_2 = \frac{d(\gamma_2 F_2 v_2)}{dt} \quad (3.26)$$

The elongation due to stretching is given by:

$$\frac{d}{dt} \left(\frac{1}{1+\varepsilon_2} \right) + \frac{v_2}{L} \frac{1}{1+\varepsilon_2} - \frac{v_1}{L} = 0 \quad (3.27)$$

Solving the equation gives:

$$\varepsilon_2 = \frac{1}{\frac{v_1}{v_2} + \left(1 - \frac{v_1}{v_2} \right) e^{\frac{1}{T}}} \quad (3.28)$$

which may be approximated by the equation:

$$\varepsilon_2 = \left(\frac{v_2}{v_1} - 1 \right) (1 - e^{\frac{1}{T}}) \quad (3.29)$$

and this holds true between the limiting values of $1 > N_1/N_2 > 0.9$. From this it follows that if the speed of the second pair of rolls increases suddenly, then the relative stretch of the product, expressed as (ε_2) will also increase with the time constant $T=L/v_2$, while the relative stretch $\left(\frac{v_2}{v_1} - 1 \right)$ corresponds to the speed deviation between the rolls at a steady state. Owing to the elongation effect stress develops in the elastic material. Conversely, if the speed of the first pair of rolls is the

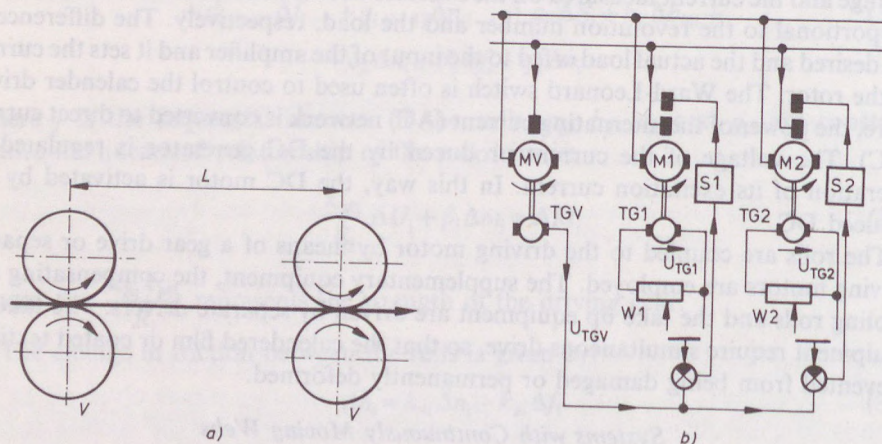


Fig. 3.7. Synchronous runs

a) Markings, b) Speed-controlled synchronously running system: main motor drive (MV), tachogenerator (TGV), controls (S1) and (S2), tachogenerators (TG1) and (TG2), sliding resistances (W1) and (W2)

greater, then the material becomes loose and the increase in length of the product is given by $\Delta L = \Delta vt$.

A great number of thoroughly tested methods are available in the literature, which describes experiments to produce a simultaneous run of the rolls. There are two general methods of applying driving controls. One is based on the measurement of the differences in speed of the rollers, while the other is based on angular differences. In the latter, the angular displacement is measured between the various groups of machinery and the main motor drive, and the control processes are based on the angular differences. This is made possible with the aid of differential gears working on principles of either mechanical, electro-mechanical or electric modes of operation. In the above instances the differences between a rotating field and a rotating shaft, or the differences in the number of revolutions of the two shafts, or the differences between two fields are compared for control. The torque produced by differences in the number of revolutions moves the control resistance which intervenes via the generator coils of their driving motor in such a way that the difference will decrease. The effect of these controls is that the two shafts will turn in relation to each other by angle, the magnitude of which will correspond to the magnitude of the interference of the controls. This means in essence that a certain long-term deviation of the angles is necessary to eliminate the previously existing error (called P-type controls).

Speed control is applied when the purpose of control is not to achieve exactly simultaneous running. In such a case (see Figure 3.7.b)), in order to be able to compare the number of revolutions made by the rolls, the revolution numbers are converted to equivalent voltages by a tachogenerator. The potentials of the joint driving motors (TG1) and (TG2) are compared with potentials set by the tachogenerator (TGV) of the main motor (MV). If the two voltages differ from each other, the error signal influences the motor excitation via the controls (S1) and (S2). The adjustments of the revolution numbers of the group motor drives related to that of the main motor can be made by means of the sliding resistances (W1) and (W2). The synchronous drives were examined in detail in Chapter 1.

3.4.2 The Construction of the Calender Rolls

For normal use the calender rolls are made from chilled cast iron. The hardness of their external surfaces, of about 25 mm thickness, is approximately 500 Brinnel units. Where a particularly high durability is required with extraordinarily high surface hardness, the rolls may be made of steel. Rolls may also be made of chrome steel material followed by a special hardening procedure. In such instances, a hardness of the surface layer, to a depth of some 2.5–8.0 mm, 600 Brinnel units (600 HB) can be achieved.

Apart from the fact that the hardness and the strength of rolls made of steel is higher, an added advantage is that the deformation of such rolls is smaller. Since the hardness modulus of a steel roll is more than about twice the hardness modulus of cast iron, the deformation of the steel rolls is proportionately smaller than that of the cast iron rolls used under the same conditions.

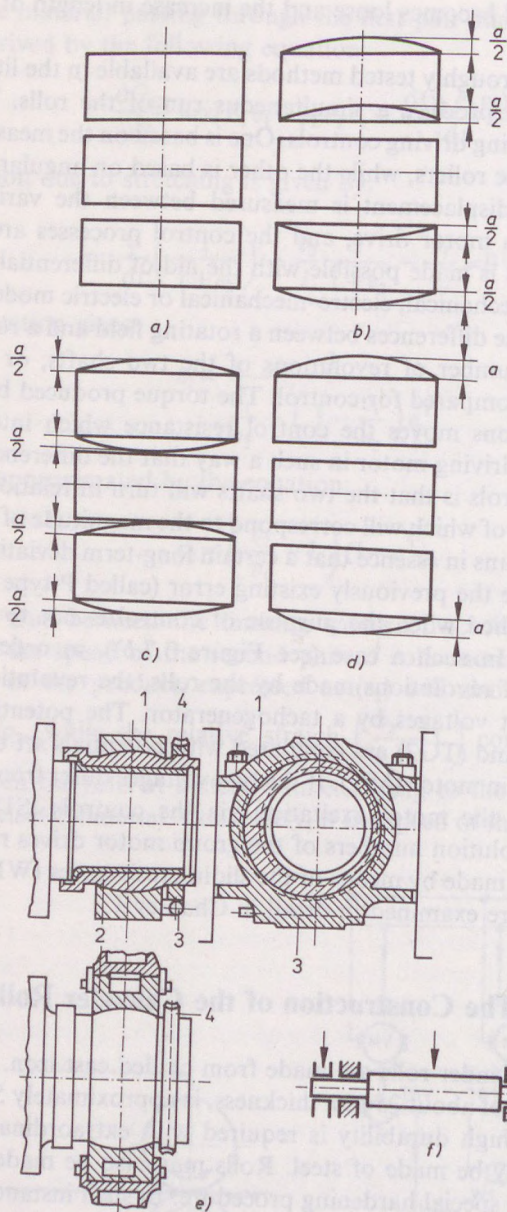


Fig. 3.8. a), b) c) and d) are sketches of calendar roll deformations, e) calendar roll deformation in the case of slanting adjustment made with an eccentric ball bearing casing.
1. ball bearing casing, 2. spherical shape insert, 3. block adjustment, 4. pulley wheel, f) deformation equalization by method of "roll bending".

The force that pushes calender rolls apart is of the order of 4–6 kN/cm. Due to the force between the rolls they tend to bend outwards. If, for example, a three-roll calender as depicted in Figure 3.8. is examined, where both the bottom gap and the top gap are evenly loaded, the following conclusions may be drawn. Part *b*) of the diagram shows the effects of the forces considerably exaggerated, for purposes of illustration. Under no-load conditions the cross-section of the rolls shows perfect symmetry, *a*). Referring to diagram *b*), here, the gaps when under load are not uniform in size, the gap in the centre of the roll being wider than that towards the ends of the rolls; as a result, the sheet produced will not be of uniform thickness. This error may be corrected by making the roll surfaces, both of the upper and the lower roll, convex in shape, as shown in diagram *c*). The elevations of these surfaces may be a few tenths of a millimeter. Due to the applied forces the deformation of the rolls is increased two-fold, which equalizes the effects of the convex surfaces of the rolls to the extent that the differences disappear, as shown in diagram *d*).

In actual practice, of course, this is not so simple. The forces occurring in the gap are not of uniform distribution. In the upper gap the forces that develop are greater in magnitude, since the material is loaded to the gap. This means that the degree of deformation on the upper roll will differ from that of the lower roll, and it might happen that the lower roll's surface should be made concave, rather than convex. This situation is complicated still further, where a four-roll arrangement is employed. Even more difficulties occur when the mixes used vary substantially, and the required performance of the rolls and the calendering processes may also vary. This means that the surfaces developed for one purpose may not be applicable for another purpose.

In practice, the convex surfaces on the rolls are developed just on the calendars. During grinding of the rolls a trial run is made with an average mix, and the thicknesses of the sheets produced are measured. Depending on the measurements obtained, grinding of the roll (or rolls) is continued until an even-thickness sheet is produced.

A more up-to-date method of calendering is to use rolls which are adjusted at a slant, relative to each other. If one of the two rolls is built into a bearing's casing, the shape of the roll gap is adjustable within limits. Let us now consider two rolls positioned parallel to each other. Assume that the gap between these two rolls, that is the gap size, is the same along the rolls' entire length. Now, if one of the two rolls is adjusted in a plane parallel with the axis of the other roll, the gap at the centre of the rolls remains the same size, however, it increases towards the ends of the rolls, thus, the same net result is achieved as would have had been the case by making the centre of one or both of the rolls convex in shape. Such movement of one of the rolls is only possible where the roll is driven via a universal joint. Where a pin gear is to be employed, the above arrangement would not be possible, since in this case the spur wheels would run at an angle, not fully fitting into the teeth of the spurs, thus, their wear would become excessive. One of the rolls can be adjusted out of the parallel plane with the aid of a motor drive via a suitable transmission. Where the rolls are adjusted at an angle, relative to each other as described, a greater degree of bending of the rolls is permissible. This, in turn, allows the use of a lighter construction.

The required adjustment of the rolls at an angle to each other may be done in one

of the two following alternative ways. The first solution is to move the screw-shafts simultaneously, which turn moves the bearings in the opposite directions. A second solution is provided by the use of spherical eccentric inserts into which the bearing is imbedded. By moving these eccentrically-positioned pieces the spatial arrangements of the rolls are changed, as shown in Figure 3.8.e).

Another method still is the so-called "Roll-Bending" method. In this case, as is shown in Figure 3.8.f), pressure is applied on the roll neck extended beyond the bearings with the use of a specifically assigned roll operated by hydraulics. The deformation with opposite direction produced in this way compensates the deformation due to the load, that manifests itself in bending of the rolls. If the rolls are manufactured with a specified basic roll camber, it may also occur that opposite pressure needs to be applied on the roll necks to compensate the effects of too excessive roll cambering. In the literature this latter approach is regarded very highly, however, one disadvantage must be mentioned; the force applied to reduce deformation increases the applied loading on the bearings, because this loading is added to the reaction force produced by the normal operational loading on the working surfaces of the rolls. The calender rolls are usually equipped with sliding bearings. Due to the considerable stresses present, high quality brass bushes are employed; recently, bushes made of plastic materials have also been utilized.

In up-to-date calenders, rolling bearing casings are also employed. The great advantage of these is their relative ease of maintenance, and the power requirement necessary for their drive is at the same time reduced by some 20–30%.

The application of rolling bearings gained ground particularly because axial clearance and play-free runs are possible with the application of accurately-made ball bearings with minimal play.

The oil used for lubrication of the bearings is transported by pumps to the points of application. The overflow oil is passed through filters, and, where necessary, passed through a cooling cycle before re-entry into the reservoir. In order to avoid any possibility of running a calender without oiling, the motor of the oil pump is electrically linked to the main drive motor. If the oil pump is not functioning, the calendering processes come to a halt; conversely, until the oil pump is switched on, it is not possible to start the calender's motor.

In the large calenders a safety relay system is built into each of the bearing cases. If the temperature reaches a certain predetermined value and in the absence of external interference the relay will stop the main drive of the machine. A certain degree of play is present in all bearings. This play may induce a resonance in the rolls and it can induce "floats" of the rolls, which may, in turn, adversely affect the dimensions of the product. Floating of the rolls occurs where the gravitational pull on the rolls and the forces pushing the rolls apart do not coincide in direction. For example, consider the upper roll; the gravitational force pulls it down in a vertical plane, while the forces applied on the roll's surface pushes it in an upward direction on the same plane. If the pressure applied to the surface layer of the roll suddenly ceases, such as may occur if the material mix runs out, gravity remains the only force applied on the roll, and the roll may move out of position, in a downward direction, followed by an upward movement at the moment more material is passed through the

gap between the rolls and the upward pressures applied on the roll's surface is renewed. The effect of floating along the line means that additional dynamic loading is exerted on the bearings, the screw shafts supporting the bearings and on the nuts and pipes. Due to this floating effect, the production of precisely uniform material thickness is not attainable in practice, furthermore, floating may also affect quite adversely the functioning of the loops designed to control the thickness of the material.

In order to reduce floating and hence to ensure a better maintenance of the positions of the working rolls, a floating damper device is employed at the bearings of the rolls, carrying the loads of changing directional modes. The principal features of this are hydraulic roll elements, which continuously press the clamps of the rolls against to that surface of the bearings which carry the load in the case of pressure on the roll, too. It must be noted that the forces developed in this way can also deform the rolls themselves, similarly to the "Roll-Bending" procedure. Thus the floating damper device, to some extent, assists in equalizing the bending of the rolls.

3.4.3 Heating and Cooling of the Rolls

Normal calendering processes require constant temperatures along the entire length of the rolls. Occasionally, however, the temperature differences along the full length of the rolls may be as much as 8–10 °C. Such differences result in a non-uniform thermal expansion of the rolls, which cause localized changes in the diameter of the rolls, and, due to this, variations in the thickness of the calendered product are also likely to occur. In order to achieve some degree of compensation, the calender rolls are heated to the required temperatures during slow rotational movement of the rolls.

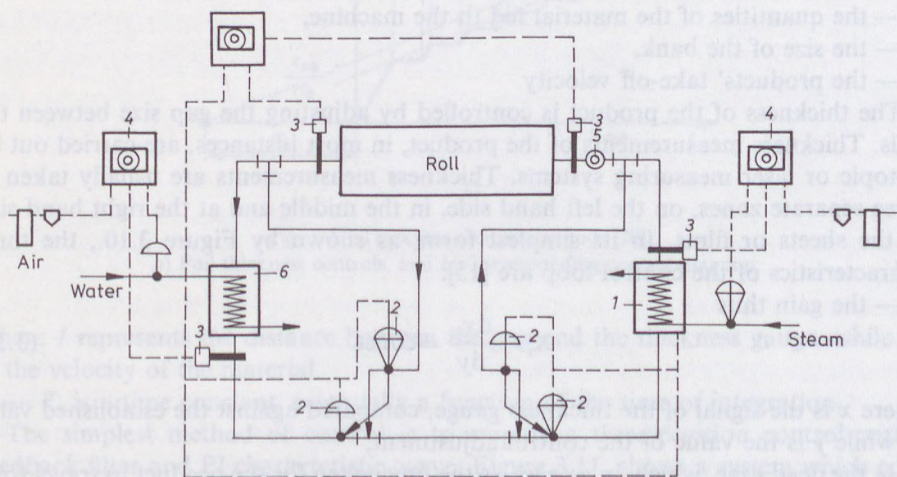


Fig. 3.9. Calender roll temperature control system

1. heat exchanger, 2. membrane valve, 3. thermometers, 4. temperature controls, 5. pump, 6. heat exchanger

Figure 3.9. shows a modern roll temperature control system. The system works as follows: the rolls are heated by the hot water coming from the heat exchanger (1). Temperature control of the hot water itself is achieved by the controls (4), which switch the steam, entering the heat exchanger, on and off. The temperature of the water is monitored by the thermometer (3). The rolls are cooled by a constant-temperature cold water circulation in the heat exchanger (6). All the rolls are supplied with both hot and cold water, as required, via a separate feed pump (5). These two temperature control devices operate in a range of some $\pm 3^\circ\text{C}$.

The respective heating and cooling systems of the rolls may be connected to a single machine or to a group of machines. In some instances supplementary electric heating units are also built into the rolls, below the rolls' surfaces, or, more precisely, inside the rolls. It is fairly difficult to achieve accurate temperature measurements of the rotating rolls. However, in most cases a heat sensor is built into the surface of the roll by the roll manufacturers. The dynamics of the heating of the rolls is similar to that described for the rolling mills or roll mixers mentioned in Chapter 2.

3.5 Control Methods Employed in Calendering

The basic requirements of control in calendering are to ensure the uniform thickness and homogeneity of the foil or sheet produced. Apart from producing sheets of uniform thickness, it is also important to maintain the width of the product within certain limiting values. In order to achieve these objectives it is necessary to control the following parameters:

- a gap size between the rolls,
- the temperatures of the rolls,
- the speed of rotation of the rolls,
- the quantities of the material fed to the machine,
- the size of the bank,
- the products' take-off velocity.

The thickness of the product is controlled by adjusting the gap size between the rolls. Thickness measurements of the product, in most instances, are carried out by isotopic or laser measuring systems. Thickness measurements are usually taken in three separate zones, on the left hand side, in the middle and at the right hand side of the sheets or films. In its simplest form, as shown by Figure 3.10., the three characteristics of the control loop are [15]:

- the gain thus

$$K_s = \frac{dx_w}{dy} = \text{const.} \quad (3.30)$$

where x is the signal of the thickness gauge, compared against the established value w , while y is the value of the control adjustment,

- the dead time, which, in essence, is the time taken for the product to travel from the gap to the thickness measuring device, given by:

$$T_h = \frac{1}{V_m} \quad (3.31)$$

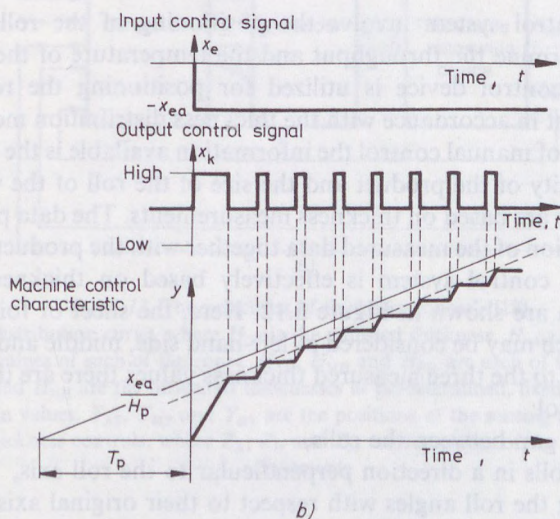
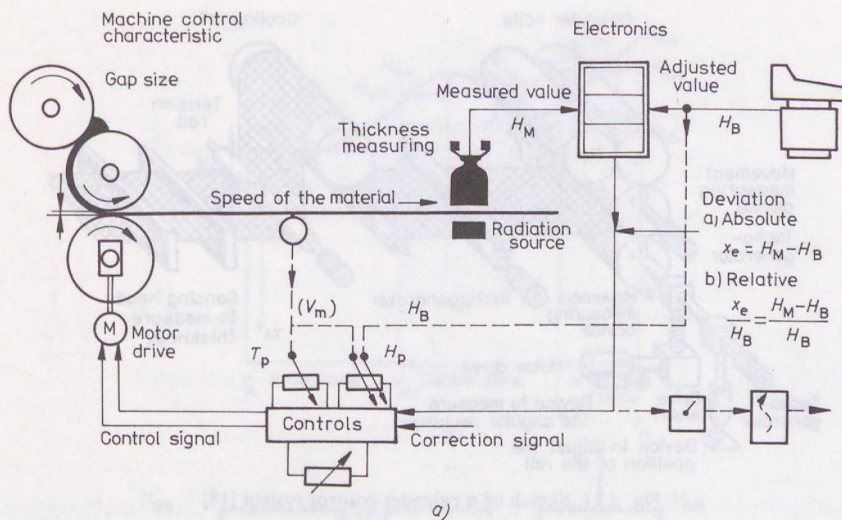


Fig. 3.10. Thickness control methods [20]

a) Foil thickness controls, and b) Corresponding control diagram.

where l represents the distance between the gap and the thickness gauge, while V_m is the velocity of the material.

— T_s is a time constant, essentially a function of the time of integration.

The simplest method of control is to employ a three-position control with a feedback filter and PI characteristic curve. Figure 3.11. shows a system which compares the integrated average of the thickness profile, measured in the three zones, against the desired value [16, 17]. The control of such a four-roll calender system is accomplished partly manually and partly automatically. The manually controlled

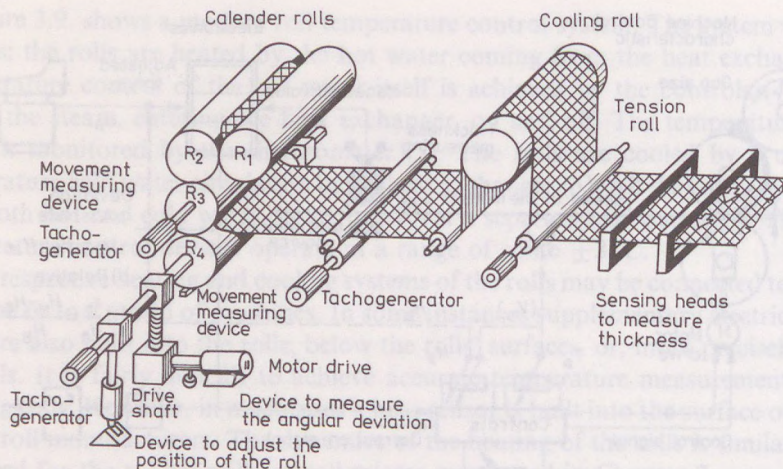


Fig. 3.11. Sketch of a calender control system [18]

aspects of the control system involve the positioning of the rolls, W_2 and W_3 , which directly determine the throughput and the temperature of the material.

The automatic control device is utilized for positioning the roll W_4 , and its crosswise movement in accordance with the thickness distribution measured. For the proper application of manual control the information available is the width of the foil produced, the quality of the product and the size of the roll of the wound product. Automatic controls are based on thickness measurements. The data processor system provides an indication of the measured data together with the production parameters. The whole of the control system is effectively based on thickness controls, the principles of which are shown in Figure 3.12. Here, the sheet or foil is divided into three sections, which may be considered as left-hand side, middle and right-hand side section. According to the three measured thickness values there are three possibilities for thickness control:

- changing the gap between the rolls,
- moving the rolls in a direction perpendicular to the roll axis,
- and changing the roll angles with respect to their original axis.

The controlled variables employed are the mean zone-thicknesses. For example, the value obtained for the left-hand side zone shown in Figure 3.12.a) is given by the equation:

$$H_{AM} = \frac{1}{Y_{AM} - Y_A} \int_{Y_A}^{Y_{AM}} H(Y) dY \quad (3.32)$$

Two further controlled values are H_{HM} and H_{MM} . Figure 3.12.b) is the flow-sheet of the control system. The measuring heads are registering initially the thicknesses H_{A4} , H_{M4} , H_{H4} at the transverse profile locations Y_{AT} , Y_{MT} , Y_{HT} . The setted thickness value H_{GS} and the deviation (H_{GD}) are calculated from measured thickness profiles. The controller forms calender setting values Z_{AS} , Z_{MS} and Z_{HS} for

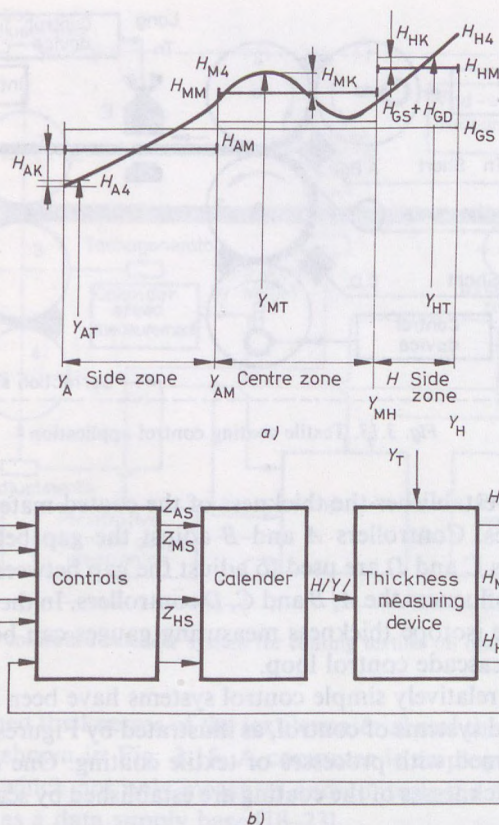


Fig. 3.12. The principles of thickness controls [18]

a) Foil thickness distribution curve, where H_{GS} is the adjusted thickness, H_{AM} , H_{MM} and H_{HM} are the average thickness values of each of the zones, H_{AH} , H_{MH} and H_{HH} are each of the measured thickness values, H_{AK} , H_{MK} and H_{HK} are the measured thicknesses at predetermined, fixed points, H_{AK} , H_{MK} and H_{HK} are correction values, Y_{AT} , Y_{MT} and Y_{HT} are the positions of the sensing device heads, b) Flow diagram of thickness controls, where Z_A , Z_H and Z_M are the values of the calender position adjustments

the given thickness parameters. The average thickness of the product is determined from at least 20 measurements/metre length of the material, according to equation (3.32). The thickness gauge makes three measurements simultaneously by means of three separate sensor heads in each of the three zones defined above. The three sensors take thickness measurements in the zones crosswise in the product at a suitable rate.

Where the calender is used for coating a textile material, as in Figure 3.13. [15], two gauges are employed to measure the backscatter, together with another gauge measuring the transmission. The backscatter devices, designated by the letters AB , measure the thickness of the chaoutchouc layer on the textile, device C measures the thickness of the chaoutchouc on the underside of the material at the left-hand side, while gauge D measures the thickness of the chaoutchouc at the right-hand side. The thickness

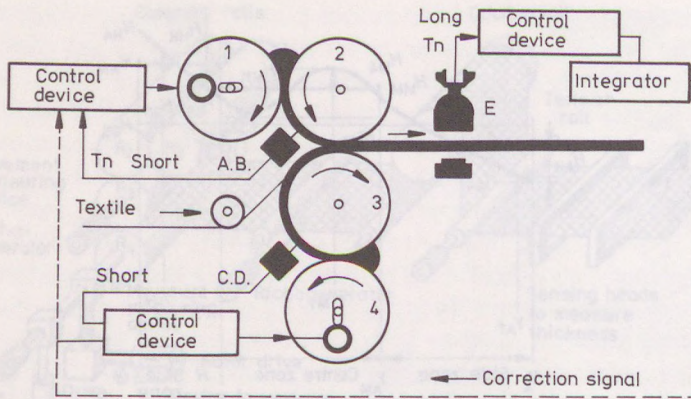


Fig. 3.13. Textile coating control application

measuring device E establishes the thickness of the coated material on both the left- and right-hand sides. Controllers A and B adjust the gap between rolls 1 and 2, similarly, controllers C and D are used to adjust the gap between rolls 3 and 4, while the control loop E influences the A, B and C, D controllers. In the above combinations certain errors of the isotope thickness measuring gauges can be compensated. This system is termed a cascade control loop.

Up to this point, relatively simple control systems have been considered. We now turn to computerized systems of control, as illustrated by Figures 3.14. and 3.15. both of which are concerned with processes of textile coating. One of them is the DDC system. Here, the thicknesses of the coating are established by scatter/capture devices,

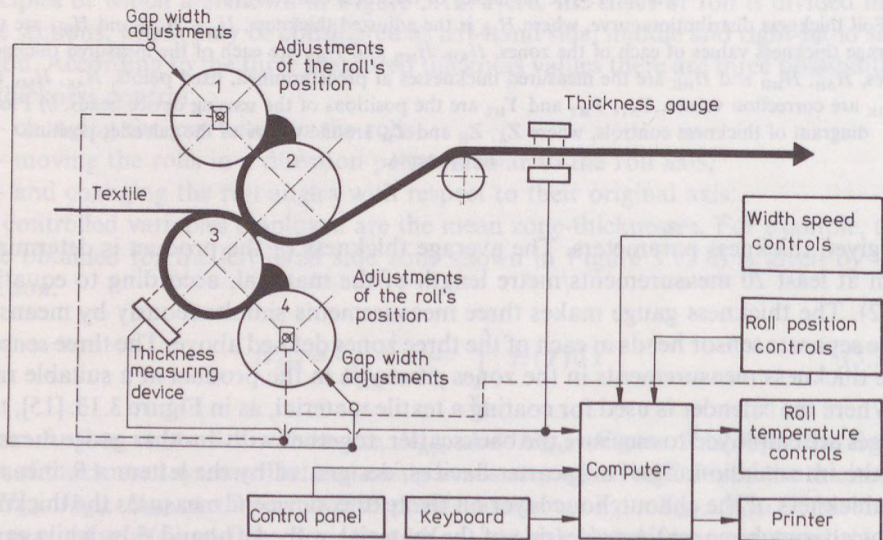


Fig. 3.14. Computer controlled textile coating calender control system [21]

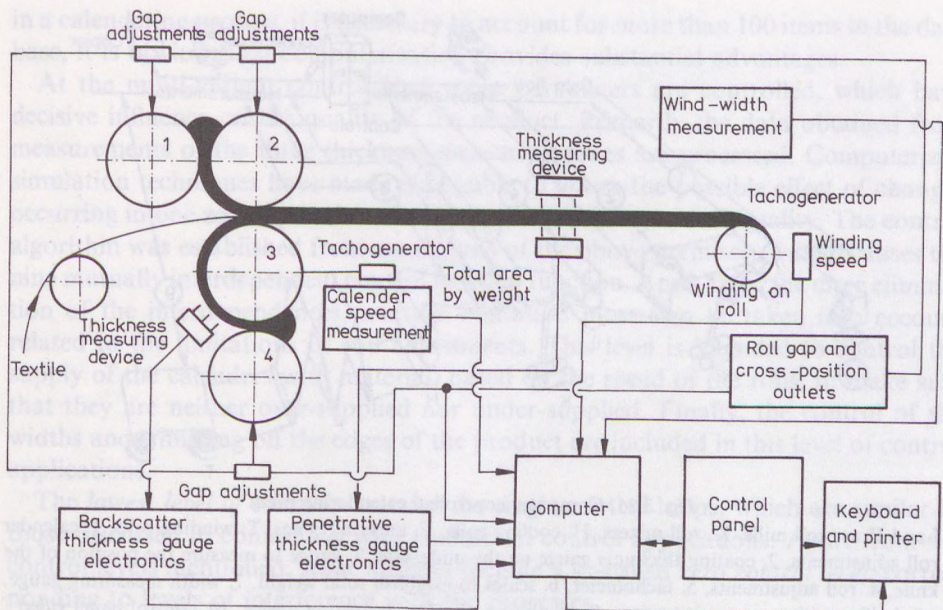


Fig. 3.15. Computer controlled calender system for coating textiles on one or both sides [23]

measuring the combined thicknesses of the textile material and the coating(s) applied. The whole system is shown in Fig. 3.15. A computer is employed as the centre of control applications, which not only measures and controls the temperatures of the rolls, but also serves as a data supply base [18–23].

A specific example of such control methods is shown in Figure 3.16.; this system measures the following parameters:

- the net weight per square meter,
- the width of the coated material,
- the width of the textile material,
- the weights of the bottom and the top layers of the coating applied, converted and expressed as per square meters unit measurements,
- the width and the speed of the calendering processes,
- the distances of the rolls from each other, and
- the positions of the rolls.

The thickness of the film or foil may be measured in three distinct zones as in the control system mentioned above. Apart from this method, the thickness of the bottom layer may be measured by the method of backscatter. The three sensors are positioned to provide information on the position of each of the rolls, 1, 2 and 3 (Figure 3.15.). The tachometer measures the speed of rotation of the calender rolls and that of the winding of the product onto a roll core. The rate of winding of the uncoated textile material and that of the coated textile are registered by sensor units. The data thus obtained is compiled and collated by the computerized system, which provides feedback information to the digital controls.

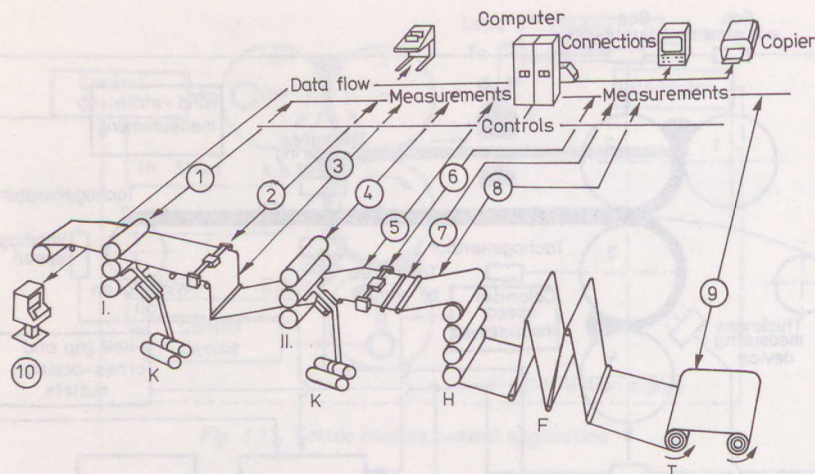


Fig. 3.16. Computer controlled calendering plant

I and II are roll mills, K. roll mixers, H. cooling rolls, F. tension frames, T. winding rolls, 1. calender roll adjustments, 2. coating thickness gauge on the underside, 3. gauge to measure the position of the knife, 4. roll adjustments, 5. tachometer, 6. scales to establish total weight, 7. width measuring gauge, 8. knife position measuring gauge, 9. revolution number measuring device, 10. control panel video terminal

A hierarchical system is shown in Figure 3.17., depicting the entire control system of a calendering plant.

The highest level is that of *production planning*, which assigns production plans to each of the production lines.

The *production programming level* requests from planning and gathers other information from the various production areas, such as from the mixing plant, the extruder section, the calendering division, and so on. From these data a plant programme is devised and sent to the next level.

Production controls receive the production quality code, and, based on this information, the production lines are prepared accordingly. The control system adjusts the machinery to the optimum temperatures, gap sizes, speeds and stretching modes, etc., as required partly by adjusting the base signals of the DDC loops. The second module of the programme system performs adaptive control, which entails adjustments to the limiting values of quality requirements and tolerances as set out in the production programme, and thus, preparations are made to produce near optimum capacity.

A special algorithm has been established for control purposes, which also takes into account the changes in dimensions during cooling after the calendering process. The base signal utilized for controls should be calculated from the final surface, mass and size data, but would mean a too high time constant. The computer adjusts the calender parameters from the width and the speed data.

Moreover, on the level of production control the operational parameters of the next, *multi-variant control* level are calculated, as well as the transitional production strategies, and the control data necessary for manufacturing new product code. Since,

in a calendering process, it is necessary to account for more than 100 items in the data base, it is obvious that computerization provides substantial advantages.

At the multi-variant control level those parameters are controlled, which have decisive influence on the quality of the product. Primarily the data obtained from measurements of the three thickness measuring zones are processed. Computerized simulation techniques have made it possible to assess the possible effect of changes occurring in one zone upon the other two zones and on product quality. The control algorithm was established from an analysis of the above premisses, which causes the nine mutually interdependent control loops to function. Apart from the mere elimination of the interdependences, another limitation must also be taken into account related to the limitations of roll adjustments. This level is intended to control the supply of the calenders with material, based on the speed of the rolls, to make sure that they are neither over-supplied nor under-supplied. Finally, the control of the widths and trimming off the edges of the product are included in this level of control applications.

The *lowest level of controls* contains the single control loops, which are similar to those discussed in connection with traditional control applications. Apart from the control levels mentioned, some authors include a so-called *zero control level*, corresponding to levels of interference with the processes.

The advantages of the computerized control system may be summarized as follows:

- due to better thickness control(s) the need for high quality of raw materials is reduced, together with material wastage,
- with increased calender speed the productivity and output of the calender unit is increased,
- both start-up times and time consumed in product change-over are reduced, due to the automatic adjustment of the working parameters of the machinery, utilizing computer feedback information,
- the quality of the product manufactured by the calender unit, or units, is improved, since the calender operators have more time for the quality control of the end product(s),
- an accurate assessment of the production processes is made possible by use of a computer.

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4 Operation and Control of Screw Plasticating Units

4.1 General Characterization of Screw Plasticating Units

Polymer processing is a combined procedure of melt-producing, shaping and heat treatment processes. The most important entity of melt production is the screw plasticating unit. This machinery is employed in profile, sheet, foil and pipe extrusion processes, in film and bottle blowing processes and in injection moulding. The materials processed are thermoplastic and thermosetting materials and caoutchouc mixtures.

Based on their modes of operation, the screw plasticating units may be subdivided into continuously and non-continuously operated units. The extruders are included in the former group, while injection moulding machines are included into the latter. In the extruders the plasticating processes take place continuously; the injection moulding processes are cyclic. In the cyclic mode of operation, the screw also induces a movement in the direction of the longitudinal axis, beyond rotation, which results in the shortening of the real screw length. The continuously-operating plasticating units are used for processing thermoplastics and elastomer materials which soften upon heating. The cyclic mode of operation is employed in plasticating of thermoplastics and thermosetting plastics and caoutchouc mixtures.

The continuously operating units may be subdivided into groups of single or twin-screw units. These two basic units may be further categorized according to the types of screws employed, as follows:

Conventional screws. These are generally divided into three zones, the solid-conveying zone is the section with the deepest channel, the melting zone is made with decreasing channel depths, while the metering zone has a constant, shallow channel depth. The positioning of the various zones depends on the type of the material being processed.

Mixing screws. These are screw types developed primarily to increase the efficiency of the melt processes. They contain mixing elements in the melting zone.

Screws with a mixing element in the metering zone. By the application of such screws a lower melt temperature and a more even temperature distribution are achieved.

Vented screws. These, together with the barrel of the screws form a devolatilizing plasticating unit. Here, the screws are of similar construction as that of the conventional screws, but following the devolatilizing zone there is another three-zone screw section thus, their overall construction resembles a two-screw construction.

The most essential part of a plasticating unit is the screws. The geometrical construction of a plasticating unit with a single screw is shown in Figure 4.1.

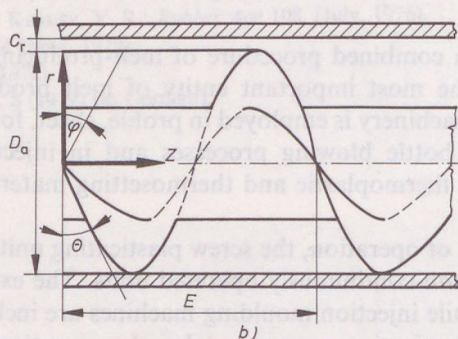
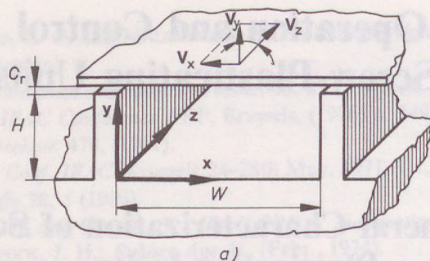


Fig. 4.1. The geometry of the screw

a) Rectangular channel, positioning of the Cartesian coordinate system, b) Positioning of the cylindrical coordinate system

The geometry of the flight along the screw surface may be constructed so that the flight is unrolled onto a flat plane. On the flat surface, the flight along the screw surface forms a right-angle triangle. The base of the triangle represents one half of the flight pitch provided that the height of the triangle is equivalent to half of the circumference at the screw surface. The flight pitch E is the axial distance between two points on the flight, separated by a full turn. This screw geometry is illustrated in Figure 4.1.

D represents the internal diameter of the barrel, H is the depth of the screw channel, θ is the helix angle of the screw, W is the channel width, E is the pitch of the screw, e is the flight width parallel to the screw axis, C_r represents the clearance between the internal surface of the barrel and the flight of the screw. W and θ change in the direction of the radius from the root of the screw towards the surface of the barrel. The relationships between these geometrical dimensions are given by:

$$\theta = \arctg \frac{E}{(D - 2C_r)} \quad (4.1)$$

$$W_b = \frac{E - e}{i} \cos \theta \quad (4.2)$$

Various screw sizes are needed for processing different materials. The most frequently used diameter sizes of the screw plasticating units are 20, 25, 32, 45, 63, 90, 125, 160, 200, 250, 320 and 400 mm. The screw length-to-diameter ratios in cases of thermoplas-

tics are: 15, 20, 25, 30 and 35, while for machines processing caoutchouc mixtures these ratios are 5, 8, 10 and 12.

The screws used in continuous plasticating with thermoplastics are the traditional three-zone screws divided into three functional sections, the zone assigned to conveying of the solid material, the melting zone and the melt transport zone. The lengths, the channel depth and the compression ratios of the individual zones are constructed according to the type of materials used.

For thermoplastics, the length of the solid-conveying zone is $(4-6) D$, the length of the melting zone is $(7-14) D$, while the length of the metering zone is $(4-8) D$. The screw pitch is $(1.1-1.5) D$, and the screw pitch angles are $17-24^\circ$. The channel depth in general, lie between the values of $(0.1-0.2) D$. The screws employed in working with thermoplastics may be grouped into three categories.

1. Screws used with materials of wide softening ranges. Their characteristic features are the length of the solid-conveying zone, $(4-6) D$, the length of the melting zone, $(7-13) D$, while the length of the metering zone is $(3-8) D$. The compression ratio of the screw is 2.5-3.

2. Screws used with materials of wide softening ranges and low heat stability.

The length of the solid-conveying zone is the same as in 1. above, the length of the melting zone is $(12-18) D$, the metering zone, is usually missing, or is $(2-3) D$ in length. The compression ratios of the screws are 1.5-2.0.

3. Screws used in plasticating materials with a narrow softening rage (crystalline materials).

The length of the solid-conveying zone is $(14-16) D$, the melting zone is extremely short, at $(1.5-2.0) D$, the length of the metering zone is $(4-7) D$, the compression ratios are 3.0-4.5.

The flight width of the screws are $(0.08-0.12) D$ in general, while the clearance between the surface of the barrel and the flight is $(0.002-0.005) D$.

For plasticating units with a cyclic mode of operation (e.g. injection moulding equipment), the screw length is generally 40-50% shorter. The characteristic screw sizes of the screw type injection moulding units are given in Table 4.1.

In processing thermosetting polymers, the depth of the screw channel is normally uniform. The end of these screws are of conical shape and, in some instances, fitted with blades in order to facilitate removal of the material from the barrel surfaces.

In the plasticating of chaoutchouc mixtures using cold feed equipment the screw lengths are $(5-6) D$, in case of hot feed equipment the screw length is $12 D$. The

Table 4.1. The screw types used in various injection moulding units

Screw types	Length (L)	Compression ratio	L_s	L_k	L_m	H_s	H_m
I.	$(11-15) D$	2.0-3.0	$(4-6) D$	$4-5 D$	$(2-4) D$	$(0.11-0.18) D$	$(0.04-0.05) D$
II.	$(15-18) D$	1.5-2.0	$(4-5) D$	$(11-13) D$	—	$(0.11-0.13) D$	—
III.	$(13-18) D$	2.5-3.0	$(7.5-11.5) D$	$2.5 D$	$(3-4) D$	$(0.11-0.13) D$	$(0.04-0.06) D$
IV.	$(12-16) D$	0.8-1.0	—	—	—	$(0.10-0.13) D$	$(0.1-0.16) D$

solid-conveying zone is shorter, $(1.2-1.5) D$, and the rest of the screw functions as an metering zone. The screw pitch is $(1-1.5) D$ for double flighted screws and $(0.6-0.8) D$ in the case of single flighted screws.

4.1.1 Description of a Single-Screw Plasticating Unit

Examining the operation of the screw plasticating units, the following constituent parts can be distinguished:

- solid-conveying zone,
- melting zone,
- melt transport and mixing zone,
- connection zone towards the die.

The solid-conveying zone starts at the hopper and extends to the formation of the melt at the barrel surface. The two characteristic sections are the feeding section, which includes the movement of the material on the hopper and filling of the screw channel, and the conveying section, constituting the transport of the solid material in the screw channel. In the melting zone the polymer is transformed to a polymer melt, or a state of melt-like consistency. The starting point of the melting zone is the point at which the melt appears on the surfaces of the barrel or the screw, its end point is where the last traces of the solid polymer disappear. The interesting sections are the so-called delay zone, the main melt section, the section where the solid bed breaks up. In the metering zone the conveying and mixing of the melt take place. The characteristic feature of this zone is the melt flow. The connection zone contains the system of channels following the end of the screw and the breaking plate. This section serves to cause the melt to enter the shaping part of the die. The duration of the above processes is governed to a substantial extent by the type of material used and this may modify the specific part processes. The above description has concerned the traditional screw plasticating units for processing thermoplastics.

In the processing of caoutchouc mixtures two kinds of plasticating units may be utilized, one is the cold feed plasticating unit, the other is the hot feed plasticating unit. The cold feed plasticating units, nowadays, do not differ too much from the thermoplastic plasticating units. The viscosity of rubbers is generally very high, compared to most thermoplastics, as much as about ten-fold higher. Consequently, a substantial amount of heat is generated in this plasticating process. The length of the plasticating unit used is reduced. The specific energy requirement for rubbers is generally low, this is partly due to the fact that they are usually plasticated at relatively low temperatures. This is another reason for the short plasticating unit length. The feed section of the rubber plasticating units is specifically designed to suit the properties of the feed-stock material(s). The plasticating unit may be fed with either strips, large pieces (chunks), or pellets. Where the material is supplied in the form of strips, the hopper is often equipped with a driven roll in parallel with the screw.

The screws for rubber have constant and longer channel depth than those for plastics. Many rubber screws have double-flight design.

During the plasticating of caoutchouc mixes the differences between the operational zones are not so significant than in the plasticating of thermoplastics. In the plasticating processes the caoutchouc mixtures behave as materials of high viscosity, and their movement resembles the melt flow of thermoplastics observable in the metering zone.

The behaviour of processing of thermosetting plastics in the solid-conveying zone is the same as the behaviour of thermoplastics. However, their behaviour pattern in the melting zone and in the metering zone differ from the thermoplastic materials. The filled thermosetting materials, upon entry into the melting zone, melt at the surfaces of the barrel and on the surfaces of the screw. During the resin is transformed into a thin, low-viscosity layer of melt. This layer of melt behaves as a lubricating layer. The thermosetting materials move in the plasticating unit in a plug-like manner, since the main form of movement is sliding on the melt film. In the melting process the heat introduced via the surfaces of the barrel and of the screw play the major part, and heat dissipation in the melt layer also exerts an influence. Following completion of the melting process shearing flow do not develop, the melt continues its progress on the surfaces of the melt layer previously formed. The effects of heat dissipation upon the movement of the material are negligible. Heating of the material takes place by heat conduction from the surfaces of the barrel, and by means of conduction to the main mass of the polymer across the moving surfaces.

For thermosetting materials, due to the inherent dangers of the overheating the screw threads employed in the melt transport zone are generally of uniform depth.

The processes in the plasticating units of cyclic operational mode are similar to those described above. The differences lie in the axial movement of the screws, and in the heat transfer processes in the static sections interrupting the dynamic sections. Due to the combined effects of these two factors, in the plasticating section the screw is gradually shortened, the boundary lines of the functional zones change, the static section induces uneven temperature distribution and this in turn introduces changes in the course of the melting process.

Vented plasticating units are significantly different from the conventional units. A vented unit is equipped with one or more openings in the barrel, through which volatile components can escape. Such a unit can extract volatile components from the polymer in a continuous fashion. The screw has to be designed in such a way that there will be no positive pressure in the polymer under the vent port. This has led to the development of the two-stage screws, having two compression sections separated by a decompression section. This is somewhat like two single-stage screws coupled in series along one shaft. Single screw vented plasticating units of conventional design usually cannot handle volatile contents in excess of five per cent, at this upper limit they would require multiple vent ports.

4.1.2 Description of Twin-Screw Plasticating Units

A large variety of twin-screw plasticating units exists, vastly different in design, operating principles and fields of application. It is thus rather difficult to make general comments about twin-screw plasticating units. The differences between the various

twin-screw units are much greater than the differences between single-screw plasticating units. This is to be expected, since the twin-screw construction substantially increases the number of design variables, such as the direction of rotation, the degree of intermeshing and so on. The classification of the twin-screw plasticating units is shown in Figure 4.2. The most important subdivision is based on the position of the screws in relation to one another. Plasticating units may be constructed with:

- non-intermeshing screws, where the screws are positioned close to each other, but, as the name implies, the screws do not mesh, or engage each other's threads, and are thus positioned tangentially,
- intermeshing screws; here, the screws are also positioned close to each other, but the distance between their centres is less than twice their external radius and, therefore, the flight of one screw penetrates the channel of the other or one screw engages the other.

Another possible subdivision of the plasticating units may be according to shape and size of the flights and channels of the screws, these are:

- non-conjugated screws, where the flights are constructed to fit loosely into the channels of the other screw and to leave ample passages all around,
- conjugated screws with flights of the same shapes and dimensions, but constructed in such a way as to fit tightly into the channels of the other screw with a minimum of clearance.

Plasticating units with intermeshing screws are again divided into two groups on the basis of the screws' direction of rotation, thus:

- co-rotating screws, where both screws rotate in the same direction and
- counter-rotating screws, where the two screws rotate in opposite directions.

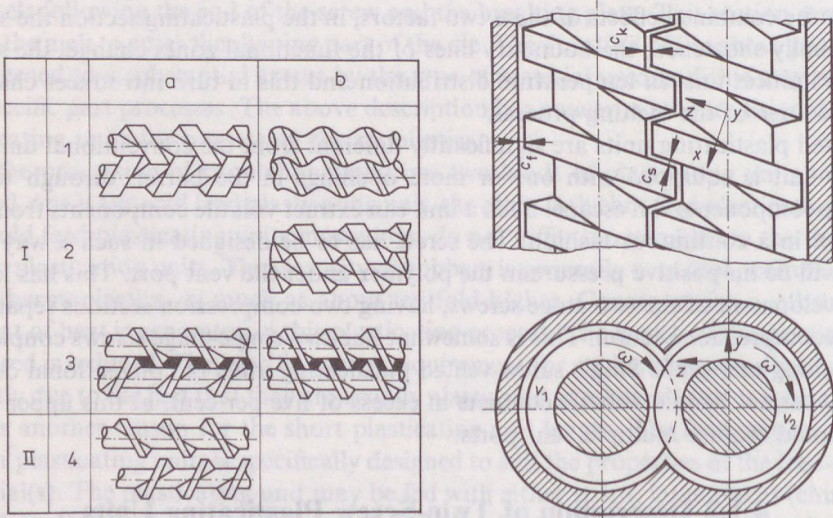


Fig. 4.2. Classification of twin screw plasticating units

I. Intermeshing screws, II. Non-intermeshing screws, a) Screws rotating in counter directions relative to each other, b) Screws rotating in the same direction, 1. and 2. completely conjugated screws, 3. incompletely conjugated screws, 4. non-conjugated screws

Machines with non-intermeshing screws operate very similarly to the single-screw plasticating units. Along the peripheries of each of the screws the relationship between the screw, the barrel and the material is the same, the main factor controlling plastication being the frictional coefficient of the material against the metal. Where the screws are in tangential positions the material has a free passage from one screw to the other, but nothing really forces the material to move from one screw to the other. A high backflow is always present, since the situation resembles the operation of a single-screw plasticating unit.

Machines with intermeshing screws do not function in the same way. Here there is an actual interaction of one screw on the material contained in the channels of the other screw in the intermeshing region of the flights, thus, one screw penetrates the channels of the other screw. Where the screws intermesh, the very presence of the flight of one screw within the channel of the other limits the rotational motion of the material around each screw so that a forward motion is achieved. With the rotation of the screws the material contained in the channels is forced to proceed forward axially along the barrel. This action is positive and does not depend on the operating conditions, it is due only to the geometric characteristics of this type of machine.

The L/D ratio is not of significant importance for the propulsion of the material since the forwarding action is not affected significantly by differences in head pressures, thus, a long metering zone is not necessary.

The screws employed in twin-screw extruders are manufactured with diameters in the order of 60–160 mm, and screws with less than 100 mm diameter are seldom used.

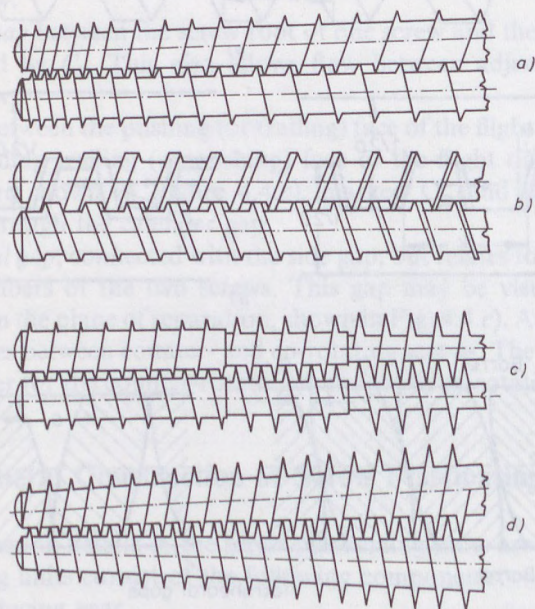


Fig. 4.3. Frequently employed screw types in twin-screw extruders

- a) Continuously decreasing pitch, b) Continuously decreasing screw channel widths, c) Channel of decreasing depths in a stepwise fashion, d) Conical shape screws (the diameter of the screw gradually decreases)

The L/D ratios lie between the values of 16–22, the most frequently used is the 20D length screw. Figure 4.3. illustrates some characteristic screw shapes. The screws with conical shapes seem to be increasing in use. The axes of these gradually deviate from one another in the direction of the drive, and this arrangement leaves more room for positioning the bearings of the screws. For the bearings of the cylindrical-shaped screws, with respect to the limited space available, the so-called tandem arrangement is recently employed. From the drive shaft the momentum is transferred to the shaft of the other screw by helical gears. In operating the helical gear drives, forces also occur in direction of the axis. The angle of the cogs is therefore chosen so that the

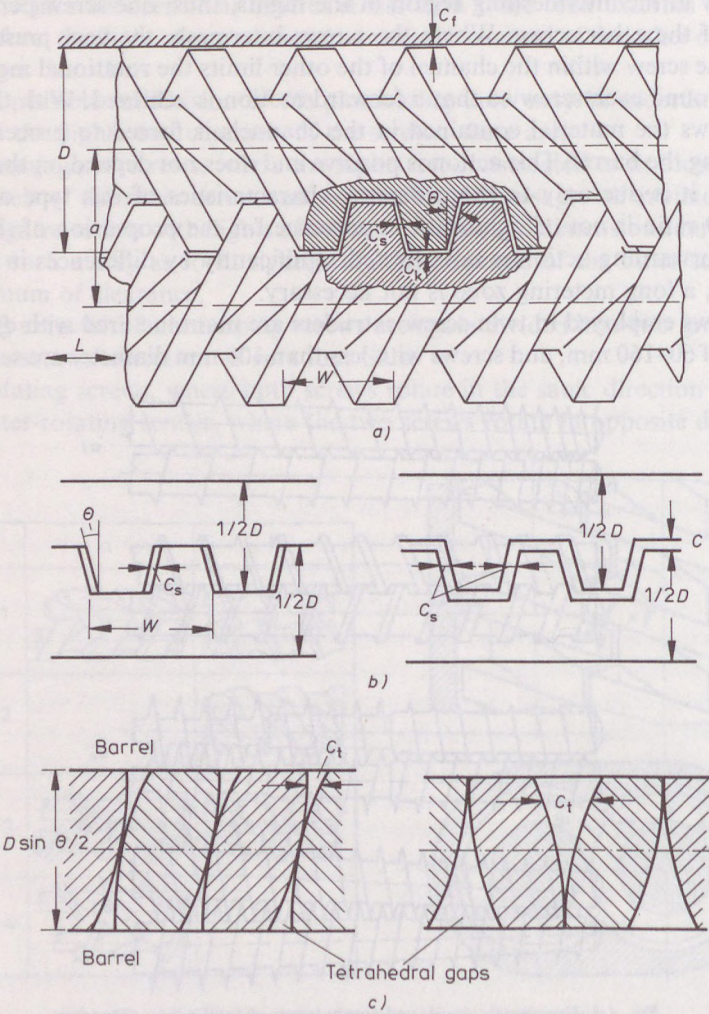


Fig. 4.4. The geometry of twin-screw plasticating units

- a) Screw geometry, b) Geometry of clearances in close-meshing and with radial clearance, conjugated twin-screw plasticating unit, c) The tetrahedral gap

forces developed in the axial direction in the screws and in the gears are of opposite directions.

The material in the feeding zone proceeds in the direction of the extruder head due to the forced flow mentioned before. Because of this forced flow the material, unlike in the single-screw plasticating unit, is transported forward even when the channels between the flights are not completely packed with the material. Note that it is only possible to obtain a homogeneous, good-quality melt if the channels near the head of the metering zone are completely filled with material in the molten state. Where the quality or the kind of material to be processed by a twin-screw plasticating unit is changed, the deviation between the density and the compression ratio can be managed by adjusting the rate of feed of the new material. In these instances it may occur that the channels of the screws in the feeding zone are not filled completely.

Figure 4.4. shows the geometric dimensions of a twin-screw plasticating unit. Section *a*) outlines the basic geometry of the plasticating unit, while section *b*) shows the positions of the gaps. Compared with single-screw plasticating, a new parameter is here the distance between the axles of the screws, marked *a*) and the angle of the flight (θ). Section *b*) of the diagram shows plasticating units with and without gaps between the two screws. It is convenient here to distinguish between four separate clearance regions:

- The *flight gap* between the barrel and the flight land, exactly analogous to that which arises in a single-screw extruder. This is marked C_f in Figure 4.4.*a*), and is responsible for the melt leaking backwards from chamber to chamber on the same screw.
- The *calender gap* between the screw root of one screw and the flight land of the other, denoted by C_k . This also allows flow between adjacent chambers on the same screw.
- The *side gap* between the pushing (or trailing) face of the flight on one screw and the corresponding trailing (or pushing) face of the flight on the other screw. These gaps are shown in Figure 4.4.*b*), marked C_s , and the relevant flows add to that through the calender gap.
- The *tetrahedral gap*, connected with the side gap, but relates to the flow between opposite chambers of the two screws. This gap may be visualized best from cross-section in the plane of separation, shown in Fig. 4.4.*c*). At this point a clear difference arises between counter- and co-rotating screws. The intermeshing can be much tighter for the counter-rotating than for the co-rotating configuration.

4.1.3 General Construction of Screw Plasticating Units

The general construction details of the screw plasticating units are shown by Figure 4.5. The plasticating units consist of the following components:

- motor and reducing gear,
- thrust bearings,
- barrel and feed throat,
- feed hopper,

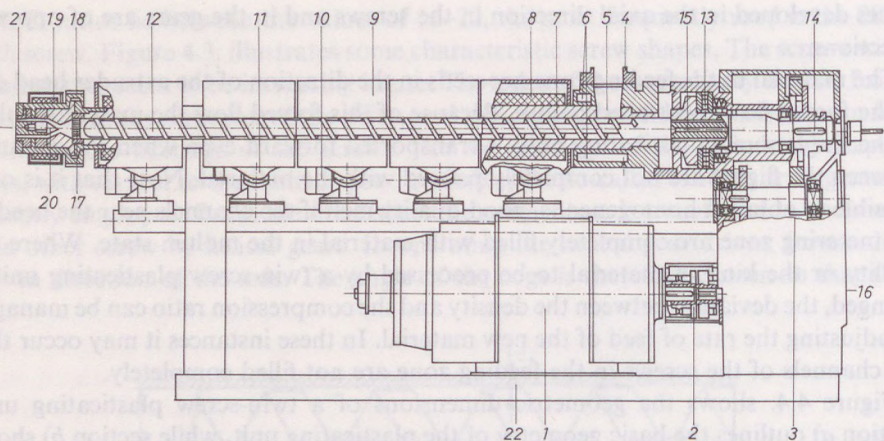


Fig. 4.5. The general construction of screw plasticating units

1. motor, 2. clutch drive, 3. gear system, 4. feedport, 5. feedthroat, 6. cooling channel, 7. barrel, 8. heaters, 9. cooling zone, 10. blower motor, 11. blower, 12. screw, 13. thrust bearing assembly, 14. screw shank connection, 15. cooling channel, 16. screen, 17. filter, 18. die assembly 19. cooling system, 20. torpille, 21. die, 22. stand

- screw,
- heating and cooling systems,
- die assembly,
- control and monitoring devices.

4.1.3.1 Motor and Gear Reducer

The drive has to turn the screw at the desired speed. It should be capable of maintaining a constant screw speed since fluctuations in the screw speed would result in throughput fluctuations, which, in turn would cause fluctuations in the dimensions of the extrudate. Thus, constancy of speed is a very important requirement for a drive. The drive must also be capable of supplying the required amount of torque to the shank of the extruder screw. A third requirement for most drives is the ability to vary the speed over a relatively wide range. In most cases a screw speed that is continuously adjustable, from almost zero to a maximum screw speed is desirable. The main drive systems are: AC motor drive systems, DC motor drive systems and hydraulic drives.

AC Motor Drive System

The two AC drive systems used in plasticating units are the adjustable transmission ratio drive and the adjustable frequency drive. The adjustable transmission ratio drive may consist either of a mechanical adjustable speed drive, or an electric friction clutch drive.

Mechanical Adjustable Speed Drive

Four basic types of mechanical adjustable (MAS) drives exist: belt, chain, wooden block and traction types. The latter two are not used in extruders since they are limited to low input speeds and are easily damaged by shock loads.

Mechanical adjustable speed drives, these days are seldom used in plasticating units due to their intensive maintenance needs, further, they have limited speed control, limited speed ratios, and their power efficiency is not very good.

Electric Friction Clutch Drives

In an electric clutch drive, there is no direct mechanical connection between input and output shaft and this eliminates mechanical friction and wear. Electrical forces are used to engage the input and output shafts. The three main types are hysteresis, eddy-current and magnetic particle clutches. In the extrusion industry, the eddy-current drive was widely applied in the past; the majority of the older extruders were equipped with such drives.

Adjustable Frequency Drives

Adjustable frequency drives use an AC squirrel cage induction motor connected to a solid state power supply capable of providing an adjustable frequency to the AC motor. The power supply converts AC power to DC power, then it inverts the DC energy in order to provide the required frequency and voltage for the AC motor. Thus, full power is handled through two sets of solid state devices, unlike the single conversion used in the DC-thyristor system. Therefore, the cost of an adjustable frequency drive is higher than that of a comparable DC drive, even though the DC motor itself is more expensive than an AC motor.

DC Motor Drive System

Most modern plasticating units are equipped with a variable speed DC drive. The torque requirement of the plasticating process generally decreases slightly with increased r.p.m., since most plasticated materials behave as non-Newtonian materials. The DC motors can handle either a constant torque or constant load, while field weakening motors can handle both. The DC drive can provide a speed range of up to 100 : 1. The horsepower requirements are of the order of 0.5 horsepower per kg of material to be plasticized.

Hydraulic Drive System

A hydraulic drive generally consists of a constant speed AC motor driving a hydraulic pump, which in turn, drives a hydraulic motor, and, of course, the associated controls. The entire system is often referred to as a hydrostatic drive. Some of the advantages of this drive are stepless adjustment of speed, torque and power; smooth and controllable acceleration; the ability to be stalled without damage; and the ease of controllability. With AC and DC drives, generally, a reducer is required to match

the low speed of the screw to the high speed of the drive. A typical reduction ratio would be in the range from 15:1 to 20:1. The most frequently used type of reducer is the spur-gear reducer, often used in a two-step configuration. A popular type of spur gear is the herringbone gear.

4.1.3.2 Thrust Bearings

The thrust bearing is usually located at the point where the screw shank connects with the output of the drive, which generally means a connection with the output shaft of the gear box. The back pressure generated by the material being forced through the die presses the screw against the thrust bearing. The useful life span of the thrust bearing is of the order of 100 000, that is, in excess of 10 years.

4.1.3.3 Barrel and Feed Throat

The extruder barrel is the cylinder that surrounds the extruder screw. The feed throat is that section of the extruder where the material is introduced into the screw channel, it fits around the first few flights of the extruder screw. Some extruders are built without a separate feed throat unit, in these machines the feed throat is an integral part of the extruder barrel. However, this type of design has some drawbacks. In most cases the feed throat casting is water cooled, in order to prevent an early temperature rise of the polymer. If the polymer temperature rises to a too high level, the polymer may stick to the surface of the feed opening, causing a restriction to the flow into the extruder. The polymer, by sticking to the screw surface also causes forwarding problems for the solid, since the polymer particles adhering to the screw do not move forward and restrict the forward movement of the other polymer particles.

At the point where the feed throat casting connects with the barrel, a thermal barrier should be incorporated to prevent the escape of heat from the barrel to the feed throat unit. In a barrel with an integral feed opening this is not possible. As a result the heat losses are greater and overheating of the feed throat may occur.

4.1.3.4 Feed Hopper

The feed hopper feeds the granular material to the plasticating unit. In most cases the material flows by gravity from the hopper to the plasticating unit, unaided. Some bulk materials have very poor flow characteristics and additional devices may be required to ensure a steady flow into the plasticating unit.

Figure 4.6. illustrates the feeding methods frequently used in practice [20]. Feeding methods may be grouped into three categories. These are:

- gravity feed (solution 1);
- gravity feed supplemented by devices to assist in dragging of the material (solutions 4 and 5, the former method consists of a grooved, conical barrel section, the latter represents a vacuum feed method);
- forced feed (solutions 2, 3 and 6). Solution 2 shows a feed hopper with an auger,

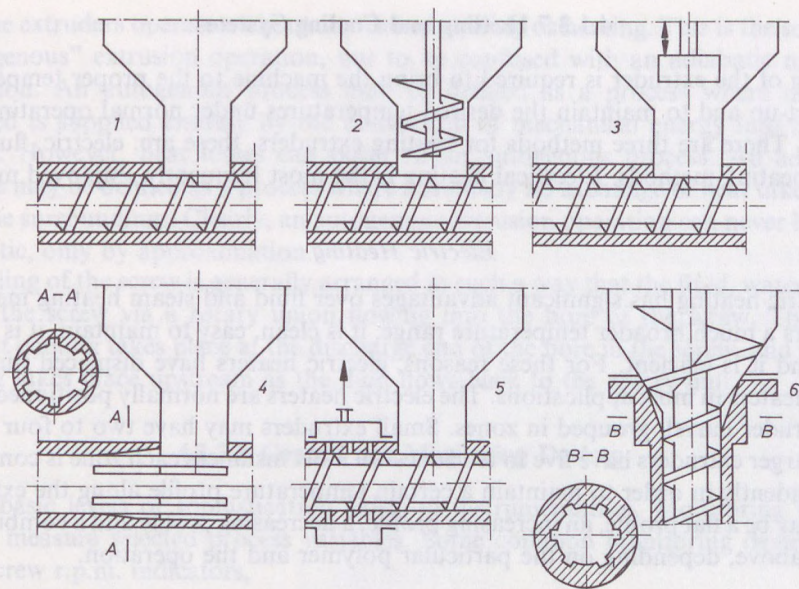


Fig. 4.6. Various hopper feed solutions

1. feeding by gravity, 2. a screw feed type of solution, 3. piston feed, 4. conical shape, grooved feed zone, 5. vacuum feed, 6. vertical positioning of screws

3 represents a method using a piston feed solution, while 6 depicts a conical shape dragging device in a vertical plane.

In practice, solution 1 shown above is the most wide-spread; all the other methods are utilized in processing of materials with bad flow properties.

4.1.3.5 The Screw

The screw is the heart of the plasticating unit. The rotation of the screw brings about forward transport of the material together with melting and homogenisation. The screws have already been discussed in detail.

4.1.3.6 The Die Assembly

The die assembly consists of the breaker plate, screens and the shaping systems. The breaker plate is a thick metal disc with a large number of closely spaced parallel holes, and it is used for two main reasons. The first reason is to arrest the spiral motion of the polymer melt and to force the polymer melt to flow in a straight line. Without the breaker plate the spiral motion could extend right to the die exit and cause distortion of the extrudate. The other reason is to support the screens positioned in front of the breaker plate. The function of the screens is, in general, to filter off contaminants that may be present in the polymer. In some instances the screens are used for the sole purpose of raising the diehead pressure in order to improve mixing efficiency.

4.1.3.7 Heating and Cooling Systems

Heating of the extruder is required to bring the machine to the proper temperature for start-up and to maintain the desired temperatures under normal operating conditions. There are three methods for heating extruders, these are: electric, fluid and steam heating methods. Electrical heating is the most frequently employed method.

Electric Heating

Electric heating has significant advantages over fluid and steam heating methods. It covers a much broader temperature range, it is clean, easy to maintain, it is of low cost, and it is efficient. For these reasons, electric heaters have displaced fluid and steam heaters in most applications. The electric heaters are normally positioned along the extruder barrel, grouped in zones. Small extruders may have two to four zones, while larger extruders have five to ten zones. In most instances each zone is controlled independently in order to maintain a certain temperature profile along the extruder. This may be a flat profile, an increasing profile, a decreasing profile and a combination of the above, depending on the particular polymer and the operation.

Resistance Heating

The most frequently used barrel heaters are electric resistance heaters. Heating is based on the principle that if a current is passed through a conductor, a certain amount of heat is generated, depending on the resistance of the conductor and on the magnitude of the current.

Induction Heating

In induction heating an alternating electric current is passed through a primary coil that surrounds the extruder barrel. The alternating current induces an alternating magnetic field of the same frequency. This magnetic field induces an electromotive force in the barrel, giving rise to eddy current.

Fluid Heating

Fluid heating allows even temperatures over the entire heat transfer area, avoiding local overheating. Where the same heat transfer fluid is used for cooling, an even temperature reduction can be achieved. The maximum operating temperature of most fluids is relatively low, generally below 250 °C.

Cooling

The external surface of the heaters or spacers between the heaters is often constructed with cooling ribs to increase the heat transfer area and cooling efficiency. Small extruders can often do without forced-air cooling, since here the surface area of the barrel is still quite large compared to the channel volume, giving rise to relatively large heat losses due to heat radiation.

Some extruders operate without any forced cooling or heating. This is the so-called "autogenous" extrusion operation, not to be confused with an adiabatic mode of operation. An autogenous process may be defined as a process where the heat required is supplied entirely by the conversion of mechanical energy into thermal energy. However, heat losses can occur in an autogenous process. An adiabatic process may be defined as a process where absolutely no exchange of heat takes place with the surroundings. Clearly, an autogenous extrusion operation can never be truly adiabatic, only by approximation.

Cooling of the screw is generally arranged in such a way that the fluid, water or oil, enters the screw via a rotary union flowing into the bore of the screw. The most efficient cooling takes place at the discharge end of the bore in the screw, and further cooling takes place upstream as the fluid flows back to the rotary unit.

4.1.3.8 Control and Monitoring Devices

Three basic levels of sophistication exists in instrumentation. Monitoring devices simply measure selected process variables. Some common monitoring devices are:

- screw r.p.m. indicators,
- current indicators,
- head pressure gauges,
- thermocouples inserted in barrel zones, in screws and heads,
- dimension scanners,
- chart recorders,
- feed monitor and alarm.

The next level of sophistication involves monitors used in conjunction with control units; for example, temperature control units inserted in each of the zones.

The highest level of sophistication is achieved by the use of microprocessors. These interfaced with sensors may be used for recording, process control and process diagnosis.

4.2 Processes Occurring in a Single-Screw, Continuously Operating Plasticating Unit

The task of the plasticating unit is to produce a homogeneous melt and to forward it to the shaping die. By the term "homogeneous melt", thermal, rheological, local and temporal homogeneity is understood. A melt of optimal properties will possess the following characteristics:

- an optimal temperature,
- minimum temperature fluctuations,
- optimal rheological characteristics (such as viscosity and elasticity modulus),
- optimal pressure,
- small pressure variations,
- freedom from impurities,

- a large mass flow, and
- minimum mass flow fluctuations.

The specific values depend on the materials used and the nature of the processing machinery employed. In order to optimize the shaping process it is necessary to supply the shaping die with a melt of optimal properties.

In examining a plasticating unit the most essential characteristic features are:

- the mass flow,
- the pressure distribution,
- the pressure and temperature of the melt upon exit,
- the length of the melt zone,
- the output requirement of the plasticating unit,
- the residence time of the material,
- the homogeneous nature of the material, and
- the energy needs of the plasticating process

4.2.1 The Plastication Processes of Thermoplastic Materials

During the plasticating of thermoplastics the following processes may be observed:

- feeding of a solid material to the screw channel,
- conveying of the solid material,
- melting, and
- homogenization and discharge of the melt.

4.2.1.1 The Movements of Solid Material in the Hopper and the Fill of the Channel

Movement of the solid material commences with feeding of the material into the plasticating unit and continues until the melting process is terminated. From these, the solid conveying phase continues until the beginning of the melting process. The initial phase of material movement is constituted by the movement of the material in the hopper and filling of the space under the stem of the hopper. The most important aspects of this phase involve the examination of the filling of the screw channel and the determination of the pressure that exists in the first few turns of the screw. In the study of material movement in the feeding hopper, the pressure distribution in the hopper, the pressure distribution at the point of free flow of the material and the mass flow across the vent port were determined. The most important work in this field is associated with the names of Janssen [13], Walker [14], Richmond and Gardner [15], Shirai [16] and Hoch [17].

Janssen calculated the pressure distribution in a cylindrical hopper. Walker, assuming a plastic state of equilibrium, calculated the pressure distribution in a conical-cylindrical hopper. The exit of the material from the hopper was examined by Richmond and Gardner, as well as by Shirai experimentally using radiographic techniques. The characteristic features of the outflow processes were established.

During free flow of a material from a hopper, two types of movement were distinguished, the so-called "plug movement" and the so-called "channel movement". In the former case the whole mass of particles moves, while in the latter case movement occurs in the channel formed in the centre of the mass of particles. For the pressure processes in the hopper an exponential function was obtained. For the dynamic pressure (occurring at the time when material leaves the hopper), in general, a smaller value was obtained than in the case of static pressures. The pressure developed in the polymer in the screw channel just below the hopper was influenced by the rotation of the screw. Pressure fluctuations take place due to the movement of the flight of the screw in the space under the feed hopper. Figure 4.7. shows the pressure distribution in the channel section below the hopper [19].

The curve $t=0$ describes the state when the screw is stationary. As a first approximation the pressure is equivalent to $\rho_0 g D$. When the barrel begins to rotate with angular velocity, ω , the pressure distribution becomes $P_0(z)$, while the curve $t=\pi/\omega$ represents the state when the screw has turned through 180° .

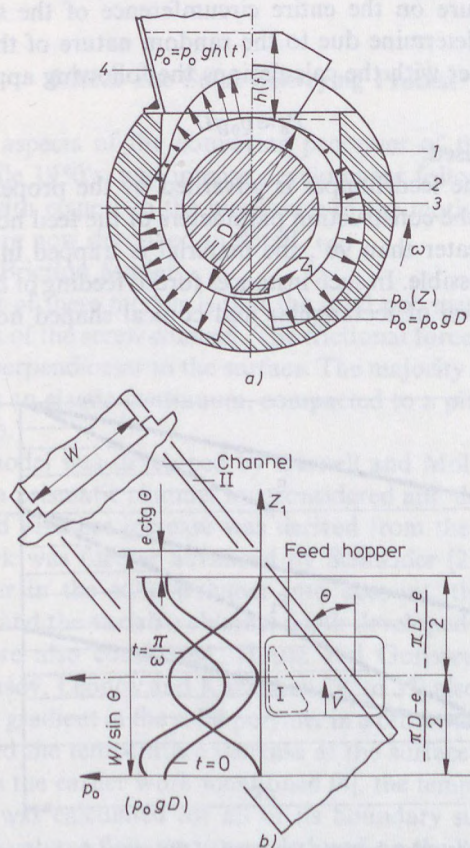


Fig. 4.7. Pressure distribution under the hopper
a) Cross section b) Analytical diagram of the screw channel

During this rotation a centrifugal force also develops, with a magnitude of $\varrho_0 \omega D/2$. The characteristic diameter region of the plasticating units is $2 \times 10^{-2} < D < 8 \times 10^{-2}$ m; in this region the ratio between the centrifugal force and the force of gravity above 20 r.p.m. is approaching unity, so the centrifugal force must also be taken into account. Pressure fluctuations in the region under the hopper are reflected in the pressure of the solid material, too, and affect the flow velocity of the solid material. The magnitude of pulsation is of the order of 0.02–0.05 MPa. Let the height of the material layer in the hopper be $h(t)$; taking this into account the pressure under the hopper is given by [19]:

$$P_0(z_1, t) = \varrho_0 g \frac{D}{2} \left[1 + \cos \left(\omega t + \frac{2z_1}{D} \right) \right] + \varrho g h \quad (4.3)$$

where ϱ_0 represents the bulk density of the polymer, g is the gravitational acceleration, D is the screw diameter, ω the rotational angular frequency of the screw, and z_1 is a random coordinate, representing the entry of the polymer into the screw channel. The wedge-shaped gap under the hopper prevents the material of height $h(t)$ from exerting a pressure on the entire circumference of the screw. The function $P_0(z, t)$ is difficult to determine due to the random nature of the coordinate, z_1 . In order to proceed further with the calculations the following approximation

$$P_0 \approx \varrho_0 g D \quad (4.4)$$

for the value of P_0 is used.

The movement in the feed hopper is governed by the properties of the mass of polymer particles and the construction parameters of the feed hopper. If the internal angle of friction is greater than 90° , the material is trapped in the hopper and no further movement is possible. In such instances forced feeding of the material becomes necessary. A comparison of rectangular and conical shaped hoppers shows that a

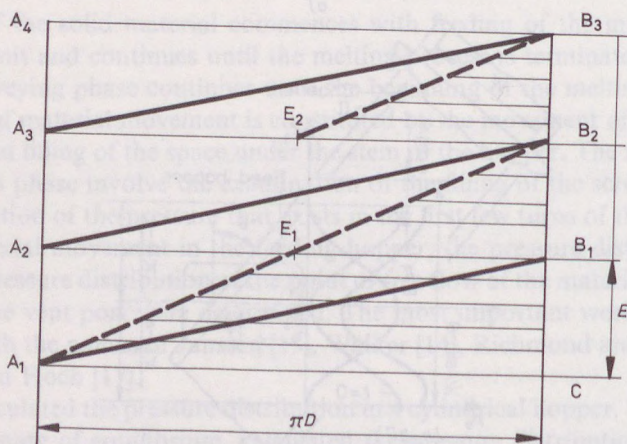


Fig. 4.8. Filling of the space between the turns of the screw channel under the hopper
A. Screw plasticating units with continuous mode of operation B. Screw plasticating units with cyclic mode of operation

hopper with a rectangular cross-section prevents the compaction and entrapment of a granular material better than a conical hopper of the same angle. The normal operation of plasticating units depends on the dimensions of the feed hopper and on the dimensions of the lower part of the opening of the hopper, and it is subject to the way the granular material fills the screw channel. The optimum length of the feed hopper to ensure a maximum volume flow lies between the values of $(1.2-1.5) E$, where E is the pitch of the screw. The first three pitches of the screw are studied in Figure 4.8. The material in front of the pitch $A_1A_2B_1$, is moved upon one rotation by one pitch and is forwarded to screw pitch $A_2A_3B_2$. Half of the material which stayed behind the screw pitch A_1B_1C is moved forward to the middle of the next pitch $E_1B_2B_1$, while the other half of the material remains in the first pitch of the screw at $A_1E_1B_1$. This means that of the initial quantity of material, 100%, 75% is now moved into the next pitch, while 25% of the material remained in the first pitch. Therefore, in order to obtain a 100% full pitch, the 25% vacancy in the second pitch must be filled from the hopper, and this means that the length of the hopper cannot be less than $1.25 E$. As a general rule the width of the hopper is three quarters of the screw diameter.

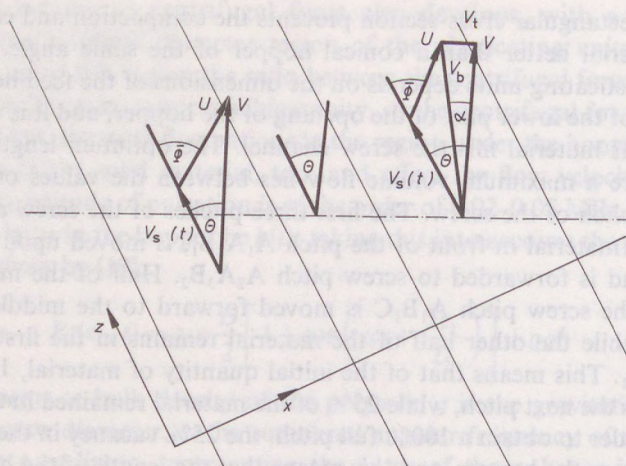
4.2.1.2 The Solid-Conveying Process

Investigations into aspects of the conveying processes of the solid material commenced in the middle 1950's, and intense development followed in the 1970's. The models developed with respect to the mechanics of the motion may be divided into two groups which are now described in detail.

a) Solid-to-Solid Friction Models

The basic concept of these models is that the solid polymer slides along the screw channel on the walls of the screw channel. The frictional forces are linearly related to the pressure forces perpendicular to the surface. The majority of the models regarded the solid polymer as an elastic continuum, compacted to a plug. The models [23-37] belong to this group.

One such basic model was developed by Darnell and Mol [22]. A plug-like solid polymer moving in a prismatic channel was considered and the relationship between the volume flow and pressure increase was derived from the force and momentum equilibria. This work was further advanced by Schneider [25], taking the pressure isotropies that occur in the solid polymer into account; the effects of the screw channel's curvature and the variable channel depth developed by Tadmor, Klein and Broyer [26, 37], were also considered. Housz and Gorissen [27], Lovegrove and Williams [28, 29], Basov, Leonov and Kazankov [30 to 33] also took into account the effect of the pressure gradient in the solid polymer in a crosswise direction. Broyer and Tadmor [37] included the temperature increase at the surface of the barrel, brought about by friction. In the earlier work mentioned [4], the temperature increase of the solid polymer plug was calculated for all of its boundary surfaces. The velocities, needed to derive the volume flow rate, were deduced on the basis of velocity vectors introduced for the polymer plug. Figure 4.9. shows the velocity vector diagram applicable to both continuous and intermittent operation screw plasticating units. In



$$V_s(z) = V \cos \theta (1 - \tan \theta \tan \bar{\phi})$$

$$U = V \frac{\sin \theta}{\sin \bar{\phi}}$$

$$V_s(z) = \frac{V \cos(\theta - \alpha) (1 - \tan(\theta - \alpha) \tan \bar{\phi})}{\cos \alpha}$$

$$U = V \frac{\sin(\theta - \alpha)}{\cos \alpha \sin \bar{\phi}}$$

$$V_b = V / \cos \alpha$$

$$\alpha = \arctan \left(\frac{V_b}{V} \right)$$

Fig. 4.9. Solid material velocity vectors in continuous and cyclic modes of operation

the intermittent plasticating units the movement of the screw in a reverse direction along its axis defines an angle. If this angle is small, the velocities, for the intermittent mode, do not differ significantly from those in continuous operation.

In respect to the flow volume rate, the theories included in this particular group lead to the equation:

$$Q = \int_{\frac{D-H}{2}}^{\frac{D}{2}} v_{\lambda} \left(2\pi r - \frac{ie}{\sin \Theta} \right) dr = \quad (4.5)$$

$$= \pi^2 D(D-H)NH \frac{\sin(\Phi - \Theta) \sin \Theta}{\sin \Phi} \left[1 - \frac{ie}{\pi(D-H) \sin \Theta} \right]$$

where v_{λ} represents the axial velocity of the solid polymer, r is the cylindrical coordinate from the surface of the screw to the surface of the barrel and i represents the number of flights. Equation (4.5) establishes an unambiguous relationship between the volume flow rate (Q) and the angle of the movement Φ , which depends only on the geometry of the screw (D , H and e) and on the r.p.m. number (N). The angle of movement may be determined on the basis of the momentum balance, and the various models may be summarized by the equation:

$$\cos \Phi = B_1 \sin \Phi - B_2 - B_3(P) \quad (4.6)$$

where B_1 and B_2 are parameters that include the geometry of the screw channel, the frictional coefficients and the side pressure factors, while B_3 is the pressure increase. The various elements are summarized in Table 4.2. for each model. By rearrangement of the equation the pressure increase during the movement of the solid material may be expressed as:

$$\frac{dP}{dz} - [A_1 f_b \cos \Phi - A_2 f_b f_s g_1(\Phi) \sin \Phi - A_3 f_s] P = 0 \quad (4.7)$$

The constants A_1 , A_2 and A_3 and the function $g_1(\Phi)$ are listed in Table 4.2.

The main conclusions derived from these models of solid conveying are as follows:

- the solid material transport is basically dependent on the ratio of frictional coefficients between the surfaces of the screw and on the surfaces of the barrel, the smaller is this ratio the greater is the volume flow of the material;
- a small helix angle and deep channel are advantageous for the transport of the solid material;
- a pressure increase decreases the volume flow rate of the solid material transport; and
- the pressure increase is more pronounced, the greater is the frictional coefficient at the surface of the barrel.

Some experiments were carried out to check the validity of these models.

Schneider [25] proved the applicability of his model by experimental means. Klein and Klein [38] demonstrated the applicability of the Tadmor-Klein model via considerable experimental work, provided that the dependence of the frictional coefficients on temperature, pressure and on the sliding velocity is known.

Problems associated with application of these models are:

- few data are available for experimental verification of the models;
- the state parameter dependence of the material constants applied in the models are yet to be derived;
- in determining the relationship between the transport angle and the drop in pressure, the compressibility of the solid polymer should also be taken into account;
- the effect of temperature on transport.

A review of the above theories shows that plasticating units with grooved, conical-shaped conveying zones, ensure a substantial solid material flow, by increasing significantly the frictional coefficient on the surface of the barrel. The model representing the plug-movement type of concept is also applicable to these plasticating units, with the difference that the frictional coefficient arising from friction against the surfaces of the barrel had to be derived in the iteration cycle [34–36].

b) Solid Conveying when Melt Films Cover Some or All Surfaces of Solid Plug

As soon as the temperature of one of the walls of the screw channel reaches the melting point of the polymer, a thin layer of melt is formed, smeared onto the metal surfaces. The moment a melt layer is formed, the force acting on the solid polymer will be the shearing force existing on the boundary surface of the melt layer. The mechanism of this solid material transport was studied and presented in references

Table 4.2. Solid material

Models	A_1	A_2	A_3
Darnell-Mol [22]	$\frac{1}{H}$	$\frac{A_0}{f_s H}$	$f_s \left(\frac{1}{H} + \frac{2H}{\bar{W}} \right)$
Schneider [25]	$\frac{p_b}{w_1 H}$	$\frac{p_b A_0}{w_1 f_s H}$	$f_s \left(\frac{p_s w_1}{H} + \frac{2p_s H w_2}{\bar{W}} \right)$
Tadmor-Klein [26]	$\frac{1}{w_1 H}$	$\frac{A_0}{w_1 f_s H}$	$f_s \left(\frac{w_2}{w_1 H} + \frac{2H}{w_3 \bar{W}} \right)$
Halász-Mondvai [4]	$\frac{p_b}{w_1 H}$	$\frac{p_b A_0}{w_1 f_b H}$	$f_s \left(\frac{p_s w_2}{w_1 H} + \frac{2p_s H}{w_3 \bar{W}} \right)$
Basov-Kazankov [19]	$\frac{p_b D(1-2 \ln R_0)}{2 \ln 1/R_0}$	$\frac{p_b D(1-\ln R_0)}{2 \ln 1/R_0}$	$\frac{D R_0^{1/k-1}}{2 \ln 1/R_0} p_b$
Basov-Kazankov [21]	$\frac{p_b}{H}$	0	$\left(p_b R_0^{1/k} - \frac{2kH(D-H)}{WD} \right)$
Leonov-Basov-Kazankov [31]	$\frac{1}{H}$	$\frac{1}{H}$	f_s

$$\text{Legend: } R_0 = \frac{D-2H}{D}$$

$$A_0 = \frac{D-H}{D} \frac{\sin \bar{\Theta} + f_s \cos \bar{\Theta}}{\cos \bar{\Theta} - f_s \sin \bar{\Theta}}$$

$$w_1 = \frac{w_s}{w_b} A_0 \sin \Theta + \frac{D-2H}{D} \cos \Theta$$

$$w_2 = \left(\frac{D-2H}{D} \right) A_0 \operatorname{ctg} \Theta + \left(\frac{D-H}{D} \right)^2$$

[39–43]. The complex model describing the movement of the solid material is now examined, based on the investigations described in [1].

The H_s/D ratio of the screw channel in the solid-conveying zone is in the range of 0.1–0.2, while the length to diameter ratio of this zone is 4 to 6. From the geometric dimensions it follows that the curvatures of the solid-conveying section cannot be neglected. The solid-conveying section extends from the feed hopper to the completion of melting, and the actual solid-conveying zone extends to the point where melting begins on the surface of the solid material being in contact with the barrel. This is followed by a short section, where the melting processes occur, the melt layer is formed and the width and the thickness of the solid material begins to decrease. From the point of view of the relevant parameters this section is considered as part of the solid-conveying zone as was derived earlier [39 to 41], however, the characteristic features of the formation of the melt layer must also be taken into account.

$g_1(\Phi)$	B_1	B_2	B_3
1	A_0	$w_1 + w_2 \frac{2H}{E}$	$\frac{w_3 H}{f_b \Delta z} \frac{\ln P_2}{P_1}$
1	A_0	$w_1 + w_2 \frac{2H}{E}$	$\frac{H}{p_b f_b \Delta z} \ln P_2/P_1$
1	A_0	$w_1 + w_2 \frac{2H}{E}$	$\frac{w_3 H}{f_b \Delta z} \ln P_2/P_1$
1	A_0	$\frac{p_s f_s}{p_b f_h} \left(w_4 + \frac{w_5 2H}{W} \right)$	$\frac{H}{p_b f_b w_6 \Delta z} \ln P_2/P_1$
$\text{cth} \left(\frac{p_b f_b w \sin \Theta}{2kD} \right)$	$f_s \left(\frac{1 - \ln R_0}{1 - 2 \ln R_0} \right)$	$\frac{f_h R_0^{1/k-1}}{1 - 2 \ln R_0}$	$\frac{D(1 - 2 \ln R_0)}{p_b f_b \ln 1/R_0} \frac{dP}{Pd z}$
1	0	$R_0^{1/k} + \frac{2KH(D-H)}{WD}$	$\frac{H}{p_b f_b \Delta z} \ln P_2/P_1$
$\text{cth} \left(\frac{f_b w \sin \Theta}{2H} \right)$	—	—	—

$$w_3 = \frac{D-H}{D} \left[A_0 \sin \Theta + \frac{D-H}{D} \cos \Theta \right]$$

$$w_4 = \left(\frac{\bar{w}}{w_b} \right) \frac{D-H}{D} \left[A_0 \left(\frac{D}{D-H} \right)^2 \sin \Theta + \cos \Theta \right]$$

$$w_5 = \frac{w_b}{w} w_1$$

$$w_6 = A_0 \sin \Theta + \left(\frac{D-H}{D} \right)^2 \cos \Theta$$

In order to discuss the conveying process of the solid material the dimensionless quantities must be re-evaluated; the Reynolds number is defined so that the inertia is compared with the external frictional force, then the centrifugal force is compared with the external frictional force, in order to determine each member of the momentum equation. The defined parameters with their range of values are collated in Table 4.3.

From the data presented in the Table the conclusion can be drawn that both the gravitational force and the centrifugal force can be neglected, compared with the magnitude of the frictional forces along the major part of the solids conveying zone, although, in some large-size machines the centrifugal force, in the vicinity of the feed hopper, must be taken into consideration. Furthermore, the Bebris number may be defined as the ratio of the external and the internal frictional forces, which, according to the data in Table 4.3, is of the order of 0.4 in that part of the channel around the

Table 4.3. Dimensionless criteria parameters of the solid material conveying zones

Dimensionless parameters		Calculated range values
$Re_1 = \frac{v^2 \varrho}{f_b P}$	first section second section	$10^{-4} \dots 10^{-1}$ $6 \cdot 10^{-6} \dots 1 \cdot 10^{-4}$
$Re_2 = \frac{\varrho r \omega^2}{f_b P}$	first section second section	$10^{-2} \dots 0.5$ $10^{-4} \dots 10^{-1}$
$Be = \frac{f_{wall}}{f_{internal}}$	first section second section	$0.3 \dots 0.1$ $> 10^{-2}$
$Br = \frac{fP \bar{v}}{k(T_b - T_d)}$		$0.3 \dots 70$
$Gr = \frac{C_p \bar{v} H^2}{kL}$		$10^{-3} \dots 10^{-1}$

hopper which is only partially filled, and it gradually decreases afterwards. The characteristic movement of the solid material is, indeed, plug-like, as suggested earlier. It is to be established whether the plug undergoes deformation during the movement or it behaves like a rigid body. For this purpose, the following dimensionless parameters are defined:

$$\begin{aligned}
 Ba_1 &= \frac{\text{applied force}}{\text{deformation force}} = \frac{\sigma \cdot A}{E \cdot A} \\
 Ba_2 &= \frac{\text{deformation force}}{\text{cohesive strength}} = \frac{E \cdot A}{\sigma_c \cdot A}
 \end{aligned}
 \tag{4.7}$$

where A is the surface area, E is Young's modulus, σ is the applied stress and σ_c is the cohesive strength. The first parameter compares the stresses applied on the solid plug with the elastic stresses developed in the plug, provided that these two can be compared; if the contrary is the case then the deformation of the solid polymer must also be taken into account, provided that the value of Ba_1 is small and, thus, the polymer behaves as a rigid body. The second number compares the deformation stress with the cohesive strength. This value shows whether the solid material is capable of being deformed, or whether it has a tendency to break up. The relationship between these two numbers provides the ratio of the applied forces versus the strength of the polymer. The latter plays an important part in predicting the tendency of the polymer to break up in the melting zone. According to the data in Table 4.3, the polymer behaves as a rigid continuum in the solid-conveying zone.

Upon examination of the energy equation, apart from the heat conduction terms included in the equation, convection occurs in the direction of the axis of the channel, and sliding friction appears as a heat source on the surfaces. This is accounted for by the modified Brinkman number. From Table 4.3, it is also concluded that the effects of surface dissipation also substantially affect the temperature of the solid polymer.

The compression number is of significant magnitude, so that the density changes of the solid polymer must also be considered.

Summarizing the above, based on the criteria parameters it may be concluded that:

— solid material transport resembles the movement of a rigid body under friction,

- the solid polymer heats up and is compressed during the movement,
- the movement of the solid material is influenced by the curvatures of the channel.

The complex movement model of the solid material based on [1] is as follows:

The plasticating units, whether cyclically operated, or operated continuously may be considered together, provided that it is taken into account that during the cyclic operation, the displacement of the screw in the direction of its own axis to some extent alters the direction of the movement of the solid material by a certain angle. Also, due to the cyclic nature of the intermittent mode of operation, the movement of the solid material is divided into three distinct sections, characterized in the first section by movement in absence of a reverse pressure, the second section is characterized by density variations, while the third section is characterized by a pressure-dependent density. In order to maintain the consistency of the argument, first transportation in a continuously operated plasticating unit is examined.

Based on the criteria parameters, the continuity, momentum and energy equations are examined in a cylindrical coordinate system, thus:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho v_z) = 0 \quad (4.8)$$

$$\frac{\sigma_{\varphi\varphi} - \sigma_{rr}}{r} - \frac{\partial \sigma_{rr}}{\partial r} - \frac{\partial \sigma_{zz}}{\partial z} = 0 \quad (4.9)$$

$$2 \frac{\sigma_{r\varphi}}{r} + \frac{\partial \sigma_{r\varphi}}{\partial r} + \frac{1}{r} \frac{\sigma_{\varphi\varphi}}{\partial \varphi} + \frac{\partial \sigma_{z\varphi}}{\partial z} = 0 \quad (4.10)$$

$$\frac{\sigma_{rz}}{r} + \frac{\sigma_{rz}}{\partial r} + \frac{\sigma_{zz}}{\partial z} = 0 \quad (4.11)$$

$$\frac{\partial T}{\partial t} = V(a \nabla T) + q \quad (4.12)$$

First, the momentum equation is examined to show that the analysis conducted in a cylindrical coordinate system leads to similar conclusions as was the case with equations based on the force equilibrium theory using correction factors.

The momentum equation may be simplified by taking into account the pressure anisotropy

$$\sigma_{zz} = \sigma_{rr} = k \sigma_{\varphi\varphi} \quad (4.13)$$

Dependence on r is eliminated by the approximations:

$$\sigma_{r\varphi}(r, z, \varphi) \approx \sigma_{r\varphi}(z, \varphi) \Big|_{r=\frac{D}{2}} \quad (4.14)$$

$$\sigma_{rz}(r, z, \varphi) \approx \sigma_{rz}(z, \varphi) \Big|_{r=\frac{D}{2}} \quad (4.15)$$

$$\frac{1}{H} \int_{\frac{D-2H}{2}}^{\frac{D}{2}} \frac{\partial \sigma_{\varphi\varphi}}{\partial \varphi} dr \approx \frac{2|n| \frac{D}{D-2H}}{H} \frac{\partial \sigma_{\varphi\varphi}}{\partial \varphi} \quad (4.16)$$

Converting to a dimensionless coordinate system:

$$R = \frac{2r}{D}; \quad \bar{r} = \frac{D-2H}{D}; \quad \sigma_1 = \frac{\partial}{\partial z} \bar{\sigma}_{zr}(z) \quad (4.17)$$

$$\sigma_2 = \sigma_{\varphi\varphi}|_{R=1}; \quad K_r = \frac{1-\bar{r}}{k(1-\bar{r}^{\frac{1}{k}})}$$

$$F(r) = \sigma_1 \frac{D}{2(2k-1)} \left[\frac{1}{1-\bar{r}^{\frac{1}{k}}} \left[k(1-\bar{r}^{\frac{1}{k}}) - \frac{1}{2}(1-\bar{r}^2) \right] \frac{1}{k} - (1-R^{2-\frac{1}{k}}) \right] \quad (4.18)$$

Thus, the momentum equation is:

$$= \frac{1}{1-\bar{r}} \left[\sigma_2 k(1-\bar{r}^{\frac{1}{k}}) - \sigma_1 \frac{D}{2(2k-1)} \left[k(1-\bar{r}^{\frac{1}{k}}) - \frac{1}{2}(1-\bar{r}^2) \right] \right] \quad (4.19)$$

$$\sigma_{\varphi\varphi}(R) = R^{\frac{1-k}{k}} [K_r \bar{\sigma}_{\varphi\varphi} + F(\bar{r})] \quad (4.20)$$

$$\frac{2}{D} \frac{1}{1-\bar{r}} \left[(1-2 \ln r) \sigma_{r\varphi} \Big|_{\frac{D}{2}} - \sigma_{r\varphi} \Big|_{\frac{D-2H}{2}} \right] - \frac{\ln \bar{r}}{1-\bar{r}} \frac{2}{D} \frac{\partial \sigma_{\varphi\varphi}}{\partial \varphi} + \frac{\partial \bar{\sigma}_{r\varphi}}{\partial z} = 0 \quad (4.21)$$

$$\frac{2}{D} \frac{1}{1-\bar{r}} \left[(1-\ln \bar{r}) \sigma_{rz} \Big|_{\frac{D}{2}} - \sigma_{rz} \Big|_{\frac{D-2H}{2}} \right] + \frac{\partial \bar{\sigma}_{zz}}{\partial z} = 0 \quad (4.22)$$

Obtaining further solutions in the cylindrical coordinate system becomes cumbersome due to difficulties in stating the boundary conditions. Where the screw helix angle is small, the rectangular coordinate system can be applied. Here the momentum equation is:

$$\sigma_{zz}(y, x) = \left(\bar{r} + \frac{2y}{D} \right)^{\frac{1}{k}-1} [K_r \bar{\sigma}_{zz}(x, z) + F(x)] \quad (4.23)$$

$$\bar{\sigma}_{zz} = \frac{1}{1-\bar{r}} \left[\sigma_2 k(1-\bar{r}^{\frac{1}{k}}) - \sigma_1 \left(\frac{D/2}{2k-1} \right) \left\{ k(1-\bar{r}^{\frac{1}{k}}) - \frac{1}{2}(1-\bar{r}^2) \right\} \right] \quad (4.24)$$

$$\frac{2}{D} \frac{1}{1-\bar{r}} [(1-\ln \bar{r}) \sigma_{yx}|_{y=H} - \sigma_{yx}|_{y=0}] + \frac{\partial \sigma_{xx}}{\partial x} = 0 \quad (4.25)$$

$$\frac{2}{D} \frac{1}{1-\bar{r}} [(1-2 \ln \bar{r}) \sigma_{yz}|_{y=H} - \sigma_{yz}|_{y=0}] - \frac{\ln \bar{r}}{1-\bar{r}} \frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{xz}}{\partial x} = 0 \quad (4.26)$$

The boundary conditions are:

$$\begin{aligned} y=0 & \quad \sigma_{yx|_0} = 0; \quad \sigma_{yz|_0} = -f_s \sigma_{yy|_0} \\ y=H & \quad \sigma_{yx|_H} = f_b \sigma_{yy|_H} \sin \Phi; \quad \sigma_{yz|_H} = f_b \sigma_{yy|_H} \cos \Phi \\ x=0 & \quad \sigma_{yx|_0} = 0; \quad \sigma_{xz|_0} = -f_s \sigma_{xx|_0} \\ x=W & \quad \sigma_{xy|_W} = 0; \quad \sigma_{xz|_W} = -f_b \sigma_{xx|_W} \end{aligned} \quad (4.27)$$

Continuing this approach, the x-directional components are integrated, the average pressure is expressed, substituting this into the equation for component of the z-direction, equation (4.6) is obtained. If the averaged stress components in the cross section of the channel are taken into account, the momentum equation leads to force equilibrium and inertia equilibrium. From the two relationships it is possible to derive the relationship with respect to pressure increase as indicated in [4]. By taking the pressure anisotropy into account, a similar A value is obtained than from the momentum equation. For the pressure increase, the relationship

$$P = P_0 \exp(-Az) \quad (4.28)$$

seems obvious as applied to the model based on stress and inertia equilibria, where P_0 is the pressure at the point $z=0$. (Note: by simplification of the momentum equation, it is possible to arrive at the same form.) When taking $z=0$ for the point directly under the hopper, at this site, on the basis of the criterium parameter procedure, the gravitational force cannot be ignored, this introduces a periodic pressure fluctuation as shown by equation (4.3).

The continuity equation may be rewritten in the form:

$$\frac{1}{\rho} \frac{\partial \rho}{\partial t} = \frac{1}{v_z} \frac{\partial v_z}{\partial z} \quad (4.29)$$

Density is usually a function of pressure and temperature. If a linear pressure dependence is assumed, in accordance with equation (4.28), the increase in density is exponential in character, which results in a corresponding decrease of velocity. According to observations, the velocity of the solid polymer directly under the feed hopper rapidly decreases and then assumes a near-constant value. Thus, the density during the compaction phase rapidly increases, followed by a slow rate of change.

In the expression of pressure the angle Φ is included, representing the angle of movement. This was introduced via the boundary conditions. Figure 4.9 shows the velocity vectors characteristic of the movement of the solid polymer plug. The screw is rotating with a linear (circumference) velocity of $V = 2\pi N$. The rotation of the screw moves the polymer with velocity v_z in the direction of the axis of the screw channel. The resultant of the two velocity vectors yields the apparent velocity of the polymer

$$\bar{v} = \bar{v}_z = \bar{V} \quad (4.30)$$

In the case $\bar{v}_z = 0$, the polymer rotates together with the screw and the material does not move in the direction of the axis of the screw. At an angle of $\Phi = 90^\circ + \Theta$ the polymer possesses only an axial velocity component, this is the maximum transport angle, at which the polymer's volume flow reaches its maximum possible value. Based on Fig. 4.9. the velocity vector $\mathbf{v}$ is:

$$\mathbf{v} = V \sin \Theta / \sin \Phi \quad (4.31)$$

The polymer's velocity relative to the surface of the screw is given by:

$$v_z = V \cos \Theta / v \cos \Phi \quad (4.32)$$

The polymer's velocity in direction of the axis, v_λ is given by

$$v_\lambda = V(1 - \tan \Theta \cotan \Phi) \sin \Theta \cos \Theta \quad (4.33)$$

The volume flow rate is:

$$Q = \int_{\frac{D-H}{2}}^{\frac{D}{2}} v_\lambda \left(2\pi r - \frac{ie}{\sin \Theta} \right) dr \quad (4.34)$$

Integrating:

$$Q = \pi^2 D(D-H) NH \frac{\sin(\Phi - \Theta) \sin \Theta}{\sin \Phi} \left[1 - \frac{ie}{\pi(D-H) \sin \Theta} \right] \quad (4.35)$$

Introducing the dimensionless expression of the volume flow rate $\pi_Q = Q/VWH$, the angle of the movement may be expressed from equation (4.35):

$$\sin \Phi = \frac{\sin \Theta}{(1 + \pi_Q^2 - 2\pi_Q \cos \Theta)^{\frac{1}{2}}} \quad (4.36)$$

Equations (4.35) and (4.6) connect the density pressure junction into a single relationship.

Thus far, isothermal solid material transport has been considered. Evolution of heat on the surfaces of the solid polymer is considerable, which is also revealed by the large Brinkman number, hence the effects of temperature must also be taken into account. The quantity of heat evolved on the friction surfaces is given by the relationship:

$$q = f \cdot P \cdot v \cdot A \quad (4.37)$$

where f is the frictional coefficient, P is the pressure acting on the surface, v is the relative velocity of the surfaces, and A is the surface area on which friction occurs. Part of this heat flow warms the metal surfaces, the other part warms the polymer, hence:

$$\alpha = \frac{(k_p \varrho_p C_p)^{\frac{1}{2}}}{(k_p \varrho_p C_p)^{\frac{1}{2}} + (k_f \varrho_f C_f)^{\frac{1}{2}}} \quad (4.38)$$

Equation (4.37) must therefore be multiplied by the heat absorption coefficient α , where k_p and k_f are the thermal conductivities, ϱ_p and ϱ_f are the density, C_p and C_f are the specific heat of the polymer and the metal, respectively.

The thermal conductivity of the polymer is given by:

$$k_{pg} = 2k_p \varrho_g (3\varrho - \varrho_g) \quad (4.39)$$

where k_p is the thermal conductivity of the solid polymer, ϱ is the density of the melt, while ϱ_g is the granule density.

Temperature distribution may be determined by solving the energy equation numerically. The quantity of heat generated per unit surface area of the barrel is given

by:

$$q_b = f_b p_b P \pi D N \frac{\sin \Theta}{\sin (\Theta + \Phi)} \quad (4.40)$$

while the quantity of heat per unit area of the screw is given by:

$$q_s = f_s p_s P \pi D N \frac{\sin \Phi \sin \Theta}{\sin (\Theta + \Phi) \sin \Theta_s} \quad (4.41)$$

The temperature distribution in the solid polymer may be obtained by solving the energy equation (4.12), taking the following boundary conditions into account:

$$\begin{aligned} q_b &= -k_p \left(\frac{\partial T}{\partial y} \right)_{y=0} + k_b \left(\frac{\partial T_b}{\partial y} \right)_{y=0} \\ q_s &= -k_p \left(\frac{\partial T}{\partial y} \right)_{y=H} \\ (T_p^b)_{y=0} &= T_b; \quad (T_p^s)_{y=H} = T_s \end{aligned} \quad (4.42)$$

thus, the heat flow partly warms the polymer in contact with the surfaces of the barrel, while part of the heat flow warms the surface of the barrel and leaves it in the cooling system. In the case where heating is not applied, $q=0$; if heating is applied, q is the heat flow of heating. The quantity of heat evolved on the surface of the screw heats partly the polymer, and partly the screw. Since the thermal conductivity of the screw is by some orders of magnitude greater than that of the polymer, it is assumed that in a steady state of the process an elemental part of the screw has a constant temperature and this temperature is the same as the temperature of the polymer in direct contact with the surface of the screw. Now, writing the energy equation by the method of finite differences

$$\frac{T(k, n+1) - T(k, n)}{\Delta t} = a_p \frac{T(k+1, n) - 2T(k, n) + T(k-1, n)}{\Delta y^2} \quad (4.43)$$

where k is the number of channel depth increments and n is the number of time increment. In choosing the values of Δt and Δy it is reasonable to write

$$a_p \frac{\Delta t}{\Delta y^2} = \frac{1}{2} \quad (4.44)$$

Hence, the form of equation (4.43) becomes:

$$T(k, n+1) = \frac{1}{2} [T(k+1, n) + T(k-1, n)] \quad (4.45)$$

Similarly, in the case of cooling, the temperature at the barrel surfaces becomes:

$$T(0, n) = \frac{\alpha_1 \frac{\Delta y}{k_p} q_b + T(1, n) + \frac{k_b}{k_p} \frac{\Delta y}{b} T_b}{1 + \frac{k_b}{k_p} \frac{\Delta y}{b}} \quad (4.46)$$

where b represents the thickness of the barrel. Likewise, the temperature of the screw surface is expressed as:

$$T(k, n) = \alpha_2 \frac{\Delta y}{k_p} q_s + T(k-1, n) \quad (4.47)$$

where α_1 is the ratio of the heat quantity entering the polymer from the surface of the barrel, while α_2 is the ratio of the heat quantity entering the polymer from the surface of the screw.

The above system of equations may be solved numerically by the introduction of velocity and transfer to the increment Δz . Here, the surface temperatures must also be taken into account in calculating the effective frictional coefficient. This means that in practice an iterative cycle must be employed to calculate the pressure, the temperature and the frictional coefficients.

So far we have considered the traditional plasticating units operating in the classical sense. Recently a plasticating unit has come into general use, in which the solid material transport zone is grooved. Due to the effect of grooving the mass flow of the polymer is greater, and the pressure at the end of the solid-conveying zone is higher. The theory put forward to this point is equally applicable to plasticating units fitted with such a grooved zone, except that the frictional coefficient must be recalculated by taking into account the geometry of the grooved section and the number of grooves. Thus

$$f = \frac{f_w(\pi D - Nb) + f_i Nb}{\pi D} \quad (4.48)$$

where N is the number of grooves, b is the width of the groove, f_w is the frictional coefficient of the polymer against the walls, and f_i represents its internal frictional coefficient.

Thermosetting materials conveyed as solids can be treated in the same way as the thermoplastics described above.

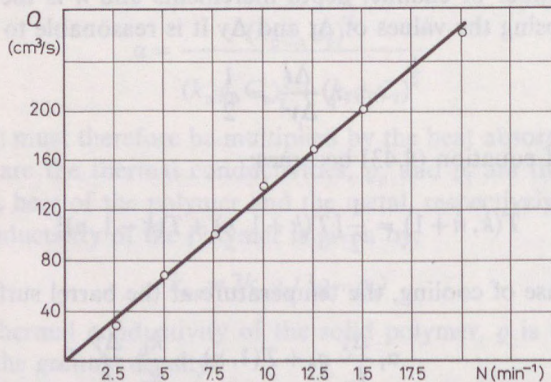


Fig. 4.10. The relationship between volume flow versus revolution numbers using PVC material
 $D = 60 \text{ mm}$, $H = 7.5 \text{ mm}$, $\Theta = 17.7^\circ$, $T = 60^\circ \text{C}$

Table 4.4. Calculated and experimentally determined values of movement angles for PE-1 material at 60 °C material temperatures

N 1/min	Q cm^3/s	π_Q	Φ	$\Phi_{\text{calculated}}$
2.5	0.46	0.15	20.8	21.7
5.0	0.64	0.11	19.7	19.4
7.5	0.95	0.10	19.7	19.2
10.0	1.07	0.09	19.4	19.1
12.5	1.23	0.08	19.2	19.1
15.0	1.38	0.08	19.1	19.0

The pressure, surface temperature and the density can be determined in an iterative cycle as follows:

- establish frictional coefficients appropriate for the barrel surface temperature and the surface velocity of the polymer on the surfaces of the barrel and the screw,
- calculate the angle of the movement from the mass flow, taking the bulk density of the polymer into account,
- calculate the pressure directly under the hopper from equation (4.3),
- calculate the pressure increase from equations (4.6), or (4.28),
- calculate the temperature distribution,
- recalculate the density and the frictional coefficients,
- calculate the mass flow to the point of convergency.

The volume flow rate shows a near-linear relationship with the revolution number, r.p.m., this is demonstrated in Figure 4.10. taking soft PVC as an example. A similar

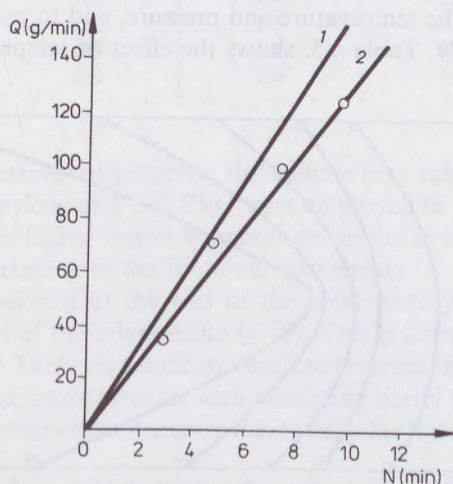


Fig. 4.11. The calculated and the experimentally determined values of the mass flow as a function of the revolution number
 $D=30$ mm, $E=30$ mm, $\Theta=17.75^\circ$, $H=1.5$ mm. Material: PE-1. Line 1. calculated values obtained by the direct isothermal method, and 2. the calculated values obtained by a non-isothermal method

Table 4.5. The effects of the temperatures of the materials on the volume flow.

$N=2.5/\text{min}$, 2 orifices

Material Temperature °C	Volume Flow cm ³ /s	Material
90	0.329	PP-1
120	0.413	PP-1
150	0.502	PP-1
170	0.711	PP-1
60	0.284	PVC-2
90	0.314	PVC-2
120	0.365	PVC-2
150	0.373	PVC-2

relationship exists for other like materials, which indicates that the dependency of the movement on the angle exerts only an insignificant influence on the volume flow rate. The back pressure decreases the volume flow rate as is to be expected from the relationships derived.

Table 4.4. shows the measured and calculated angles of motion, the values are in reasonable agreement. Figure 4.11. shows the measured and calculated mass flow values of the solid material as a function of the revolution number, r.p.m. Curve 1 is for an isothermal case, while curve 2 represents a non-isothermal case. In the latter case, the temperatures of the barrel and the screw surfaces, and the frictional coefficients were calculated in an iterative cycle. The greatest difficulty was to apply appropriate frictional coefficients. It is reasonable to determine the frictional coefficient as a function of the temperature and pressure, and to use regression functions obtained experimentally. Table 4.5. shows the effect of temperature on the volume

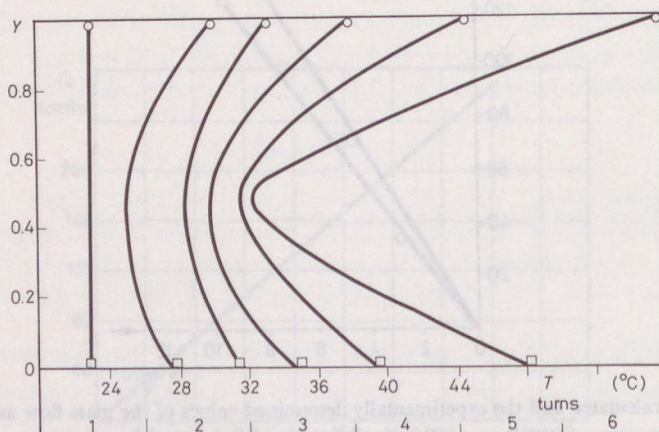


Fig. 4.12. The temperature distribution of the solid material $D=60$ mm, $H=7.5$ mm, $N=5 \text{ min}^{-1}$, $T_{be}=23^\circ\text{C}$. Material: PE-1.

Table 4.6. Calculated and measured pressure values for PVC-1 material

N min^{-1}	Q cm^3/s	P MPa	$P_{\text{calculated}}$ MPa	T_m $^{\circ}\text{C}$
2.5	0.72	0.5	0.4	60
5.0	2.15	0.6	0.6	
7.5	3.58	0.8	0.7	
9.8	4.90	1.1	1.0	
12.3	6.25	1.2	1.1	
15.0	7.40	1.4	1.3	
20.0	8.92	1.6	1.5	
25.0	10.75	1.8	1.7	
N min^{-1}	Q g/s	P MPa	$P_{\text{calculated}}$ MPa	T_m $^{\circ}\text{C}$
2.5	24	0.3	0.3	90
5.0	64	0.8	0.6	
7.3	100	0.8	0.8	
10	140	0.7	0.9	
12.5	160	0.9	0.9	
15	200	1.0	1.0	
20	281	1.1	1.1	
25	360	1.2	1.3	
2.5	36	0.1	0.1	120
5.0	80	0.2	0.2	
7.5	110	0.3	0.3	
10	170	0.3	0.4	
12.7	180	0.4	0.5	
15	210	0.5	0.6	
20	280	0.6	0.7	
25	350	1.0	1.0	

flow rate. With increasing temperature, the volume flow rate also increased in both cases, when polypropylene and soft PVC were employed in the experiments. This is due to the fact that a higher barrel temperature results in a smaller back pressure, owing to changes occurring in the frictional coefficients.

The pressures developed at the end of the solid conveying zone are simple to calculate with the aid of the relationship (4.28). This is illustrated in Table 4.6. The data presented in the Table also indicate that the pressure increases as a function of the revolution number, and decreases with increasing barrel temperature. The values of the pressure were observed to fluctuate due to periodic fluctuations occurring in the revolution numbers.

Figure 4.12. shows the temperature distribution of the solid material. The data used were calculated from equations (4.43–4.47). With increasing revolution number and increasing back pressure the temperature of the walls of the barrel and of the screw also increased. It was established that where only a small back pressure was applied, the

Table 4.7. The respective barrel and screw surface temperatures for various solid material pressures
Material: PP-1.

Revolution number: 5 rpm, nominal material temp. 150 °C								
Temperature, °C								
Pressure MPa	barrel surfaces				screw surfaces			
	12	11	10	9	16	15	14	13
0	118	150	150	151	100	131	135	138
0.8	110	150	154	152	111	147	151	152
1.4	111	148	153	153	115	148	152	154
2.0	116	151	155	156	121	149	153	156

temperature difference between the surfaces of the barrel and the screw was 10–20 °C, and it decreased with increasing back pressure. The temperature of the screw became equal to the temperature of the surface of the barrel, as shown by the data in Table 4.7.

4.2.1.3 The Melting Process

In the screw plasticating units, a melt is formed from the solid polymer in the melting zone which is transformed into a homogeneous mix in the homogenizing zone to suit the shaping processes that follow. From the point of view of the plasticating unit as a whole, it is of the utmost importance that the melting processes are to be restricted to a defined part of the screw assembly and that the processes occurring remain stable. Investigation and modelling of the melting process began during the middle 1960's, however, understanding of the complex processes and the evolution of suitable mathematical models are the achievements of recent times.

In order to investigate the melting processes experimentally, a small quantity of a dye was added to the polymer, a steady state plasticating process was established with chosen parameters of operation, and when a steady state was established the screw was abruptly stopped, and the barrel was rapidly cooled. The result was a fixed "frozen state". After slight warming of the screw, it was removed from the barrel, and the frozen material was sliced into sections for further investigation. From the cut sections the length of the molten mass was established together with the ratio of the melt pool to solid bed width [46 and 47].

Based on the experiment described above a model of the melting process was constructed, and this is illustrated in Figure 4.13.

The first such model was described by Tadmor and associates [48, 49]. The mechanism of melting was investigated and it was found that the melting process takes place at the interface of the barrel surfaces and the solid polymer. The solid polymer granules moving from the feed hopper to the die, are compacted into a solid plug upon

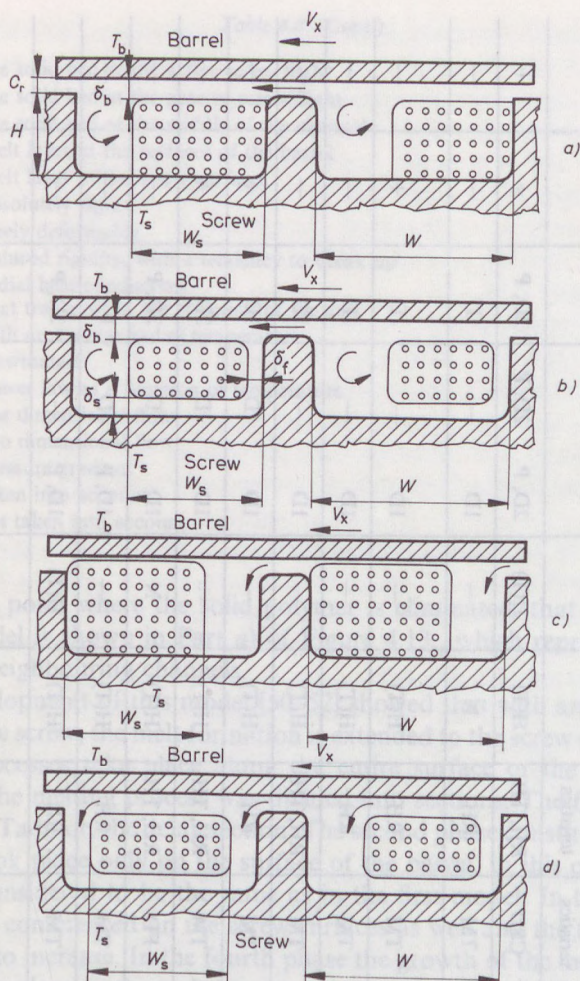


Fig. 4.13. Melting models

heating at the heated section of the barrel. Where the barrel surface temperature (T_b) exceeds the melting point of the polymer (T_m), melting takes place and a melt layer is formed on the surface of the barrel. The thickness of the melt on the surface of the barrel increases until a certain value and, upon continued melting of the polymer the melt pool is formed in the vicinity of the pushing flight of the screw. As the polymer proceeds along the channel, the width of the melt pool is broadened and a circulating flow is developed in the melt phase. Decrease in the channel depth results in a modification of the above picture, since it can result in widening of the solid polymer. The melting process is completed when the width of the solid polymer becomes zero. In this model, the melting process was divided into two sections, the so-called delay section that lasted until the thickness of the molten film becomes constant at the barrel, and the melting section, where the width of the solid polymer

Table 4.8. Melt models

Models	Melting mechanisms		Solid polymer		Characteristics of the melting zone					Delay section	Break-up criteria
	Location of solid bed	Location of melt film	Mechanical Characteristics	Thermo Dynamic Characteristics	Melt film	Melt zone	Upper melt	Lower melt			
Halász [11]	AM, K, PM	H, CS	CSD	RH, TH	H(T)	H(T)	2D, P	2D, P	2D, P	+	+
Tadmor [48]	AM	H	TM	RH	N	—	1D	—	1D	—	—
Tadmor, Duvdevani, Klein [49]	AM	H	TM	RH	H(T)	—	1D	—	1D	+	—
Chung [59]	AM	H	TM	RH	H(T)	—	1D	—	1D	—	—
Donovan [64]	AM	H	TM	RH, TH	H(T)	—	1D	—	1D	—	—
Mondvai, Halász [50]	AM	H, CS	TM	RH	H(T)	—	1D	1D	1D	+	—
Halász [51]	AM	H, CS	TM	RH, TH	H(T)	—	1D	1D	2D	+	—
Edmonson, Fenner [53]	AM	H, CS	FD	RH, TH	H(T)	N	1D	1D	2D, P	—	—
Lindt [60]	K	H, CS	TM	RH	H(T)	—	1D, P	1D	P	—	—
Basov, Kazankov [19]	AM	H	TM	RH	H(T)	H(T)	1D, P	—	2D, P	—	—
Shapiro, Halmos [55, 56]	AM	H, CS	FD	AH	H(T)	N	1D, P	1D, P	2D, P	—	—
Fukase, Kunio [66]	AM	H	TM	RH, TH	H(T)	H(T)	1D, P	—	1D, P	—	—
Ebirli, Lindt [68]	AM	H, CS	TM, FD	RH, TH	H(T)	H(T)	1D, P	1D, P	2D, P	—	—
Lindt, Ebirli [69]	AM	H, CS	TM, FD	RH, TH	H(T)	H(T)	1D, P	1D, P	2D, P	—	—

Table 4.8. (Cont.)

Legend: AM	the solid bed at the active screw flight
PM	the solid bed at the passive screw flight
K	the solid bed at the middle of the channel
H	melt layer at the surfaces of the barrel
CS	melt layer at the screw surfaces
TM	absolutely rigid
FD	freely deformable
CSM	reduced rigidity, with a tendency to break up
RH	radial heat conduction
TH	heat transport in the direction of the axis
AH	with an average radial temperature
N	Newtonian
H(T)	power law as a function of temperature
1D	one dimensional flow
2D	two dimensional flow
P	pressure gradient
+	taken into account
—	not taken into account

is reduced to the point where the solid polymer is eliminated, that is, it is entirely melted. This model is shown in Part *a*) of Figure 4.13., which represents the cross sections of two neighbouring channels.

A further development of this model [50–52] showed that with an increase in the temperature of the screw, the melt formation is extended to the screw surfaces as well, thus, melting processes take place along the entire surface of the solid polymer. Examination of the melting process was divided into sections. The first section was that described by Tadmor, the delay section. The second phase constituted the section where melting took place only on the surface of the barrel, in this case the melting processes were considered to be the same as in the first model. In the third phase, melting processes commenced on the screw surfaces as well and the thickness of the melt layer began to increase. In the fourth phase the growth of the melt layer ceases, a pressure flow develops in the melt layers at the screw surface and circulation flow begins around the solid polymer.

Other authors have described similar processes [53–56]. These authors established that a melt film is formed on the surface of the barrel and on the surface of the screw following the delay section. The thickness of the melt film at the surface of the barrel changes in the direction of the axis of the screw channel and in a direction perpendicular to this axis. The thickness of the melt film at the screw surface changes only in the direction parallel with the axis of the screw channel. During the melting process the width of the solid bed decreases, while the width of the melt pool increases. The melting processes are shown in Part *b*) of Figure 4.13.

Klenk [57], later on Gale [58] and Chung [59] described a different type of melting mechanism. Klenk and Gale, using rigid PVC powders, observed a melting mechanism during processing, in which melting processes took place in the section between the barrel and the flight of the screw, while the melt accumulates in the vicinity of the trailing flight of the screw. The melting rate was found to be slow, and the solid phase

survived to the tip of the screw. Klenk and Gale concluded that this type of melting process was due to the fact that rigid PVC did not adhere to the wall surfaces. Gale also proved that the melting processes of PVC powders were substantially influenced by the amounts of additives added to improve flow characteristics of the polymer. Chung, with the aid of a model, proved that the size of the clearance between the barrel and the flight of the screw also influenced the melting processes substantially. Where large clearances are employed, the melt tends to accumulate near the trailing screw flight. The melting processes observed by using rigid PVC material are shown in Part c) of Figure 4.13.

Lindt [60], using polypropylene and large extruder machinery described a melting process in which the melt formed a film around the solid polymer, and a melt pool did not form. The melt formed merely increased the film thickness on the polymer. In fact this seems to be the same melting process as was described earlier and labelled as phase two, here, melting takes place in such a way that the melt commences circulation around the solid polymer. This case is illustrated by Part d) of Figure 4.13. [51].

The stability of the melting process ceases as it gets towards its end and the solid bed begins to break up. This phenomenon, in turn, causes pressure fluctuations. Here, instead of the type of mechanisms dealt with earlier, the polymer particles floating in the melt are turned into a liquid almost individually. The characteristics of melt models are collected in Table 4.8.

In this Table the melting mechanism is described together with the assumptions regarding the solid polymer, its rigid nature and heating, and assumptions made with respect to the movement of the melt layers, finally, a description is provided dealing with the initial and the final phases of the melting zone.

4.2.1.3.1 Models Derived to Examine the Melting Process at the Surface of the Barrel

Tadmor and his school pioneered the derivation of the mathematics of the melting process. The first model originates from this source [48, 49]. In establishing a mathematical model the following assumptions were made:

- the screw channel may be described by a local Cartesian system,
- extrusion is a steady state process, thus, the velocity distribution and the temperature distribution at a given point are constant, as a function of time,
- the melting of the solid polymer takes place at the interface of the surfaces of the barrel and the melt layer,
- the solid bed is a homogeneous, isotropic continuum,
- the polymer has a sharp melting point,
- the melt formed is a viscous liquid,
- the solid polymer, due to its low thermal conductivity behaves as a homogeneous body of constant velocity and half infinity,
- the screw is stationary, the barrel is rotated,
- the physical properties of the polymer are true constants at any given point,
- the solid polymer moves with constant velocity.

When the model was established, Tadmor and his co-workers assumed a melt of Newtonian properties [48]. The solid polymer was substituted for by a half infinity space and only the y directional temperature changes were taken into consideration, in this way, the temperature profile of the solid bed was independent of the z coordinate. The melting rate (ω) is then given by:

$$\omega W_s = \frac{V_x \delta_b \varrho_m}{2} = \frac{d}{dz} (\varrho_s H V_s W_s) \quad (4.49)$$

where W_s is the width of the solid bed, V_x is the velocity at the surface of the barrel in the x direction, δ_b is the thickness of the melt layer at the surface of the barrel, ϱ_m and ϱ_s are the respective densities of the melt and of the solid polymer, finally, V_s is the velocity of the solid bed. The thickness of the melt layer and the width of the solid bed in the function of the axial z coordinate are determined from the mass and energy balances at the interface of the solid bed and the melt layer. Upon comparison of the experimental and calculated data obtained for the width of the solid bed as a function of the z coordinate, the model was altered to make a better fit. For the Newtonian equation the power law was substituted and first a linear, later on a parabolic temperature distribution was assumed in the melt film at the surface of the barrel [49]. Thus, the problem was solved by the method of iteration. The melting rate was provided by equation (4.49) above. With the introduction of these modifications the agreement between experimental and calculated values was substantially improved. It has to be mentioned, however, that in the experiments conducted by Tadmor and his associates, as a general rule, a large mass flow was employed, thus, the volume flow rate was greater than the volume flow rate calculated from the drag flow. This, however, represents a fairly narrow range in the normal operation mode of extruders.

The model developed by Tadmor was improved upon by several other workers. The most important of these are:

a) Chung [59] assumed that the solid bed was of finite thickness and the screw surface was regarded as thermally insulated. This modification meant an alteration of the temperature profile developed in the solid bed. However, although with this model the calculated results showed better agreement with values determined experimentally, the assumption introduced was not realistic since the screw does not behave as a neutral object in the melting zone.

b) Hinrichs and Lilleleht [61] and later on Tadmor and Klein [26] took into account the curvatures of the channel and the effect of the screw flight clearance. Thus, the relationship (4.49) of the melting rate took on the form:

$$\omega W_s = \frac{V_x \varrho_m}{2} (\delta - C_r) \quad (4.50)$$

c) Vermeulen et al. [62], Veresova and Kazankov [63] proved that the film thickness on the solid polymer is not constant, but varies as a function of x ; the melt layer thickness was calculated by them accordingly.

d) Donovan [64], basing his views on experimental observations, introduced the concept of variations occurring in the velocity of the solid bed and, thus, the velocity

of this bed was defined as:

$$V_s = a V_s^{(1)} + (1 - a) V_s^{(2)} \quad (4.51)$$

where a is a factor used to express the acceleration of the polymer, with values varying between 0 and 1, taken arbitrarily, $V_s^{(1)}$ is the movement velocity of the solid bed calculated from the volume flow rate, $V_s^{(2)}$ is the average velocity that coincides with the melt flow of the polymer. Donovan brought about improvements with respect to the temperature distribution of the solid bed by assuming that the polymer is bounded by the screw at temperature T_s . This approach resulted in a temperature distribution in the shape of a distorted parabola.

e) Mount, Watson and Chung [65], examining the Tadmor model with particular reference to an analysis of the processes in the melt layer, included the deformation of the solid polymer and derived analytical equations for some simplified cases.

f) Fukase, Kunio and their associates [66] proved that during melting it is possible for the melt located at the screw surface to be transferred upon application of pressure into the melt-layer zone. During the melting process the width and thickness of the polymer also change.

The velocity of the solid polymer undergoes characteristic changes in the solids conveying and melting zones,

- the velocity of the polymer in the vicinity of the hopper rapidly decreases, while its density increases,
- the velocity of the solid polymer is constant until the polymer reaches the heated zone,
- the velocity of the polymer upon reaching the heated zone decreases and reaches a minimum value, while its density reaches a maximum value,
- during the development of the melt zone in the presence of the melt layer on the screw surface, the velocity of the solid polymer remains constant, while the width and height of the polymer change approximately at the same rate,
- if the melt layer at the screw surface is passed across to the section filled with the melt, the velocity of the solid polymer increases.

g) Pervardchook and associates [67] showed that it is not possible to characterize the solid bed in terms of regular geometric shapes, and determined the velocity distribution of the melt flows along the solid polymer surfaces using numerical methods.

4.2.1.3.2 Models Applicable to Describe the Melting Processes of the Solid Polymer on all Boundary Surfaces

The first such model was derived by the author of this book and his associates [50–52].

The melting process was divided into three distinct parts. In the first section a melting process takes place as described by Tadmor, in the second section a melt layer is formed on the screw surface and on the surface of the trailing screw flight, the thickness of these melt films increase in the z direction. In the third section of the melting process a flow takes place in the x direction from the melt layer at the screw surface into the melt layer at the barrel surface and circulation takes place around the solid polymer. The calculation of the melt films was carried out by the method

introduced by Tadmor. The porosity of the surface of the polymer granules was also taken into account, together with the acceleration factor of the solid bed, introduced by Donovan.

The melting rate for the devised models was given by the following equation:

$$\int_{\delta_s}^{w_s + \delta_s} \omega_b dx - \omega_s W_s - \omega_f H = \frac{d}{dz} (Q_s V_s W_s H) \quad (4.52)$$

Based on this model, the pressure may be calculated from the flow of the melt pool and from the solids conveying model for the solid bed.

4.2.1.3.3 Models Devised to Bring the Melting Process and the Motion of the Solid Bed into Alignment

For the models considered thus far, the velocity of the solid bed in the screw channel has been some kind of constant. At a more advanced stage of the melting process, in most instances, this does not apply and, instead, a substantial acceleration of the solid bed is observed apart from the fact that the polymer also undergoes deformation. For these reasons the stresses that affect the solid bed must also be taken into account.

The first model in which these stresses were considered was devised by Shapiro, Halmos and Pearson [54–56]. The model described by Edmonson and Fenner [53] was similar to this, but in a simpler form.

The melting rate per unit surface area may be written in the form provided by the author of this book, equation (4.52), however, the melting velocity at the surface of the barrel is a function of the coordinate in the x direction. The mass balance of the surface melt layer consists of the melting rate and of the change of the mass flow of the circulating melt layer surrounding the solid polymer. The melting rate of the melt layers at the screw surface is given by:

$$\omega_s H = \frac{d}{dz} (Q_{s,z} W_s); \quad \omega_f H_s = \frac{d}{dz} (Q_{f,z} H_s) \quad (4.53)$$

where $Q_{s,z}$ and $Q_{f,z}$ are the mass flow of the melt layer near the screw surface and the screw flight, respectively, in the z direction. The mass flow of the melt in the melt pool depends on the width of the pool, the velocity of the barrel and on the pressure gradient. The mass flow of the plasticating unit combines the mass flows of the melt pool, the melt films and the solid bed.

In contrast to the models discussed so far, here, the force balance was also introduced into the calculations:

$$\frac{\partial P}{\partial z} H_s W_s = \int_{\delta_b}^{W_s + \delta_b} \tau_b dz - W_s \tau_s + H_s \tau_f \quad (4.54)$$

where τ_b , τ_s , τ_f are the relevant shearing stresses in the melt layers. In order to calculate the characteristic quantities which influence the melting processes, the mass flow and the heat flow quantities of the solid polymer and the melt zone and each of the melt films must be taken into account. For the solid bed, Edmonson and Fenner

utilized the equations devised by Tadmor et al. solved numerically for each of the down-channel sections. Shapiro, Halmos and Pearson regarded the solid bed temperature as a constant value equivalent to the initial temperature. As a result, this approach failed to calculate the changes occurring in the x direction, hence, the supposition $\delta_b = \delta_r$ was used. The melt pool was assumed to be isothermal and regarded as a channel filled with a melt of Newtonian behaviour, which, in general, is not really an appropriate approximation.

In the melt layers at the surface of the screw a flow parallel to the axis of the screw channel was assumed. Edmonson and Fenner regarded the melt flow at the surface of the screw as a drag flow and applied the analysis derived by Martin. Shapiro, Halmos and Pearson maintaining the combination of the pressure flow and drag flow, hence, their approach appears to be a more realistic description of the movement of the melt, which specifically holds true at the latter phases of the melting process when the thickness of the melt layers is already substantial. The thickness of the melt film at the surface of the barrel remains small at all times, hence, the assumption of the existence of a drag flow seems to be justifiable.

The melt layer at the barrel surfaces is a function of both the z and the x coordinates. Shapiro, Halmos and Pearson regarded the melt layers at the barrel surface as a function of the x coordinate only, while Edmonson and Fenner regarded the melt layer at the barrel surface as a function of the z coordinate only. Halmos, Pearson and Trottnow [56], based on the model outlined above, derived a numerical solution with the aid of a computer for the melt following a power law. Simulation calculations revealed that the melting rate is greater at the commencement of the melting process, the width of the solid bed decreases rapidly, while in the middle phase of the melting process the width changes and the pressure gradient changes are proportional, in a near-linear relationship, to the distance. Upon termination of the melting process the velocity of the solid bed increases substantially, the pressure gradient reaches a maximum and then begins to decrease.

The calculated data obtained by Edmonson and Fenner [53] were compared with data obtained experimentally using a laboratory extruder with a 38 mm diameter screw. Satisfactory agreement was found between the calculated and the measured values.

The most comprehensive model of the entire process was constructed by Lindt et al. [68, 69]. These workers showed that the model most closely approaches reality when a rigid solid bed is considered with a melt in circulating motion around the solid polymer. This model describes the initial and middle sections of the melting processes quite realistically.

A model has yet to be devised for the third type of melting processes.

4.2.1.3.4 Melting Process without a Decrease in the Width of the Solid Polymer

For the fourth type of melting process Lindt [60] devised a mathematical model. Using a simple Newtonian analysis, he examined the stresses acting on the solid polymer surrounded by the melt on all sides, as a function of the pressure gradients. The

approximation of forces in a cross-channel direction, is given by the relationship:

$$F_x \approx \left(\mu_b \frac{V_x}{\delta_b} - \frac{\delta_b}{2} \frac{\partial P_b}{\partial x} - \frac{\delta_s}{2} \cdot \frac{\partial P_s}{\partial x} - \frac{\partial P_b}{\partial x} H_s \right) W \quad (4.55)$$

where $\frac{\partial P_b}{\partial x}$ is the pressure gradient acting in the melt layer at the surface of the

barrel and $\frac{\partial P_s}{\partial x}$ is the pressure gradient acting in the melt layer at the screw sur-

face. The first two members on the right hand side of the above equation represent the shearing stresses on the upper surface of the solid bed, the third member represents the shearing stresses on the bottom surface of the solid bed, while the last term gives the difference of normal pressures acting on the solid bed in a sideways direction. Calculation of the normal forces showed that force acting in a crosswise direction decreases substantially where the pressure gradient increases in a down-channel direction, due to the fact that the pressure flow through the clearance is large, and this greatly influences the circulation of the melt in the melt pool. Where the pressure gradient is small, the normal stress is substantial, the solid bed is pressed to the trailing flight of the screw and hence, the same kind of melting process is formed as discussed earlier. In cases where the pressure gradient is very large the normal stress acts in the opposite direction, thus, the solid bed is pushed to the trailing flight of the screw and a melting process develops, observed and described by Klenk. Large normal forces produce substantial pressure gradients in a crosswise direction and hence, the effect of the pressure gradient in melt films becomes important.

The melting models reviewed so far describe the initial and the middle sections of the A, B and D type melting processes which were shown in Figure 4.13. The problems associated with models are as follows:

- models do not determine the break criteria of the solid polymer, essential from the point of view of operation;
- the pressure profile actually observed in the last phase of the melting process differs from that calculated and based on models;
- in the determination of the length of the melting section the calculation of the section following the break-up section presents certain problems;
- it would be highly expedient to include the various processes in a unified model containing the operating characteristics and the properties of the material used, which play important parts in the evolution of each process type.

The analyses presented thus far have covered standard screws only. The study of the melt processes has led to the design and construction of new screw types to increase the melting rate, with increased stability. The melting lengths for various screw constructions are collated in Table 4.9. [70]. The fundamental intention of such solutions is to modify the melting processes already in the stable section in such a way that built-in elements are provided to subdivide the solid polymer bed into small segments to ensure that the solid polymer is mixed with the melt. In the following text the model introduced [1] is described.

Consider the processes that take place in the melting zone: the formation of the melt layer on the surface of the barrel, followed by the formation of a melt layer on the

Table 4.9. Calculations of the length of the melting zone for various screw types

Screw types	The length of the melting zone
Traditional screws	
with constant thread depths	$Z_0 = 2 \frac{H_0}{\Phi}$
with reduced thread depths	$Z = 0.75 Z_0$
multi-channel screws	$Z = Z_0 / \sqrt{n}$
Maillefer's screw	$Z_M = 0.67 Z_0$
Barr's screw	$Z_B \cong 0.52 Z_0$
Dray-Lawrence's screw	$Z_{D,L} \cong 0.55 Z_0$
Kim's screw	$Z_K = 0.55 Z_0$

screw surface, and the development of one of the mechanisms of the melting processes. The melting process extends to all boundary surfaces of the solid polymer, then, as the melting processes proceed, the quantity of the solid polymer gradually decreases (indicated by the decrease of either the width or the thickness, or both, of the solid bed). A situation can evolve, where the solid polymer begins to break up and solid polymer particles enter the melt in the screw channel, and float in the melt; finally, these floating polymer particles also melt and the entirety of the channel is filled with the melt. This means that in the metering zone the whole screw channel is filled with melt and the homogenization of the melt is accomplished. Joint discussion of the processes of the two zones is justified, since the movement of the melt present in the two zones is similar, only the geometry of the space the melt occupies differs.

The various phases of melting are as follows:

- the development of the melt layer at the surface of the barrel,
- the main melting process,
- the breaking-up process, followed by a melting process.

The part processes involve:

- the formation of the melt layer at the surface of the barrel and the melt flow in the melt layer of the barrel surface,
- the movement of the solid bed until the appearance of the melt layer on the screw surface,
- the complete development of the melt layer at the screw surface, together with the appearance of melt flow in the screw surface layer, followed by circulation flow around the solid polymer,
- the movement of the solid bed surrounded by the melt,
- the melt flow in the clearance between the barrel and the screw flight (leakage flow),

- the melt flow along the solid polymer,
- the completion of melting of all floating solid particles,
- the flow of the melt filling the screw channel.

At the beginning of the melting process the melt formed on the surface of the barrel first fills the porous gaps present in the solid polymer, followed by the formation of the melt layer, finally, melting also takes place at the screw surface after the first few turns of the screw. The actual type of melting process occurring depends on the magnitude of the pressure gradient as illustrated by Figure 4.14. In the case where the pressure gradient in the channel in a crosswise direction is negative, Part a) of Figure 4.14., the width of the solid bed decreases and the melt formed is collected near the pushing screw flight. Where the pressure gradient is positive, Part c) of Figure 4.14., the melting process is essentially the same as described above, but the melt collects near the trailing screw flight, mainly between the screw flight and the barrel, obtained from the melt flow from the previous turn of the screw. If the pressure gradient is near zero, Part b) of Figure 4.14., melting takes place by increased thickness of the melt layer, primarily at the surface of the barrel and at the surface of the screw. The three possible mechanisms are distinguished on the basis of the crosswise pressure gradient.

The precise location of the point of break-up is of great importance.

The structure of the polymer has the form of compressed granules, the surfaces of the granules are covered with molten polymer particles; during the movement of the solid polymer bending moments and forces are acting on its surface. If the differences in the bending moments applied exceed the solid cohesive forces of the polymer, the polymer breaks up, resulting in floating polymer particles in the melt. The break-up process of the polymer continues as long as the bending moment exceed the mechanical strength of the polymer. The criterion parameter of break-up is represented by the

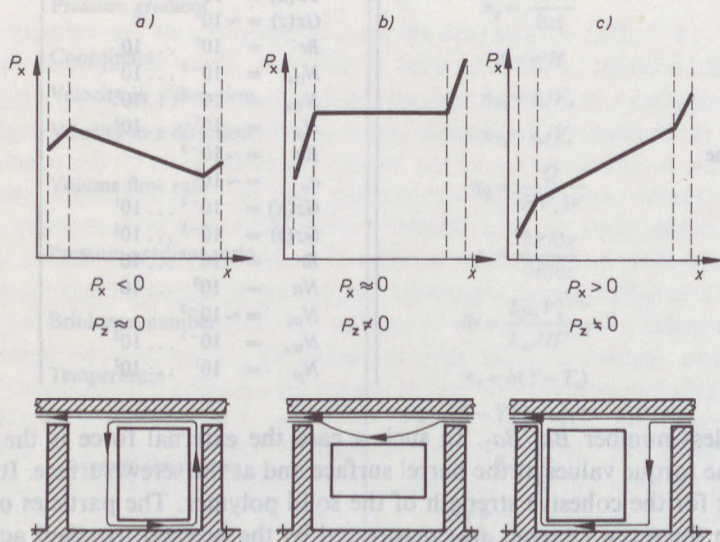


Fig. 4.14. Cross-channel pressure gradients of the various melting processes

Table 4.10. Dimensionless criteria parameters for the melting zone and for the metering zone

Process	Criteria parameter value ranges	Remarks
Melt layer at the surfaces of the barrel	$Re = \sim 10^{-5}$ $\sigma_p = 10^{-1} \dots 10^{-2}$ $Gz(x) = 10^{-3} \dots 10^{-2}$ $Gz(z) = 10^{-2} \dots 10^0$ $Br = 10^{-1} \dots 10^1$ $N_{De} = 10^{-2} \dots 10^{-1}$ $N_{we} = 10^{-1} \dots 10^0$ $N_{pl} = 10^1 \dots 10^3$	
Melt layer at the surfaces of the screw	$Re = 10^{-4}$ $\sigma_p = 10^{-1} \dots 10^0$ $Gz(x) = \sim 10^{-2}$ $Gz(z) = 10^{-3} \dots 10^{-1}$ $Br = 10^{-2} \dots 10^0$ $N_{De} = 10^{-3} \dots 10^{-2}$ $N_{we} = 10^{-2} \dots 10^{-1}$ $N_{pl} = 10^1 \dots 10^2$	
Melting zone	$Re = \sim 10^{-2}$ $\sigma_p = \sim 10^0$ $Gz(x) = 10^{-2} \dots 10^1$ $Gz(z) = 10^{-1} \dots 10^2$ $Br = 10^0 \dots 10^2$ $Na = 10^0 \dots 10^2$ $N_{De} = \sim 10^{-2}$ $N_{we} = 10^{-1} \dots 10^0$ $N_{pl} = 10^1 \dots 10^2$	
Clearance at the barrel surfaces	$Re = 10^{-5}$ $\sigma_p = 10^{-2}$ $Gz(x) = 10^{-2}$ $Gz(z) = \sim 10^0$ $Br = 10^0 \dots 10$ $N_{De} = 10^{-2} \dots 10^{-1}$ $N_{we} = 10^{-1} \dots 10^0$ $N_{pl} = 10^1 \dots 10^3$	
Metering zone	$Re = \sim 10^{-3}$ $\sigma_p = \sim 10^0$ $Gz(x) = 10^{-2} \dots 10^1$ $Gz(z) = 10^{-1} \dots 10^2$ $Br = 10^{-1} \dots 10^2$ $Na = 10^0 \dots 10$ $N_{De} = \sim 10^{-2}$ $N_{we} = 10^{-1} \dots 10^0$ $N_{pl} = 10^1 \dots 10^2$	

dimensionless number Ba_1/Ba_2 . In such a case the external force is the difference between the torque values at the barrel surface and at the screw surface. It is difficult to account for the cohesive strength of the solid polymer. The particles of the solid polymer in the screw channel are compressed by the pressure gradient acting in the direction of the axis; due to the melting process the surface particles are sintered. The

cohesive strength of the solid bed is best described by the pressure in the direction of the axis.

The various zones of the melting process with their characteristic criteria are summarized in Table 4.10., and the geometrical features are also listed. All the aspects mentioned above with respect to the movement of the solid material apply, provided that the process is one in which the entire surface area of the polymer is surrounded by a layer of melt, thus, the sliding forces are replaced by shearing stresses. The melting process influences the movement of the solid material in an indirect way, since the melting process is the determining factor in the formation of the thickness of the melt layer. The critical parameters relevant to the solid polymer are collated in Table 4.11.

Generally speaking, the thickness of the melt layer is in the range 10^0 to 10^1 Cr; apart from the short initial phase, it is characterized by an even thickness. The melt layer possesses velocity vectors in the x and z directions, the small Reynolds number is an indication that the inertia forces are negligible, and, the value of the parameter σ_p shows that the effect of the pressure flow is not negligible in many instances, hence, the momentum equation consists of the pressure gradients in the x and z directions, and of the shearing stresses.

Examination of the Graetz number shows that the heat transport in the z direction must be taken into account, furthermore, based on the Brinkmann number, the heat dissipation cannot be ignored. The Deborah number, the Weissenberg number and

Table 4.11. Dimensionless parameters for melt conveying

Parameters	Definitions
Pressure gradient	$\pi_p = \frac{\partial PH}{\partial z \bar{\tau}}$
Coordinate	$Y = y/H$
Velocity in x direction	$\pi_{v_x} = v_x/V_z$
Velocity in z direction	$\pi_{v_z} = v_z/V_z$
Volume flow rate	$\pi_Q = \frac{Q}{H V_z W}$
Pressure gradient ratio	$\alpha_1 = \frac{\partial P/\partial x}{\partial P/\partial z}$
Brinkman number	$Br = \frac{b \mu_0 V_z^{1+m}}{k_m J H^{n-1}}$
Temperature	$\pi_T = b(T - T_s)$
	$G_Y = (Y - Y_1)^2 + \alpha_1^2 (Y - Y_2)^2$
average shear rate	$\bar{\gamma} = \frac{V_z}{H}$
average shear stress	$\bar{\tau} = \mu_0 \left \frac{\bar{\gamma}}{\dot{\gamma}_0} \right ^{n-1} \exp [b(T_b - T_0)]$

the parametric linearity number indicate that the polymer in the melt layer is a viscous, non-Newtonian fluid. A study of the expansion number shows that its magnitude is of the order of 10^{-3} , which means that the physical state equation need not to be taken into account.

Upon examination of the boundary conditions, the Bikerman number is generally a large number, although in some equations it is close to unity, which means that for some materials the sliding of the polymer along the wall needs to be considered.

In the investigation of the flow at the clearance, the fact must be accounted for that the flow takes place between one moving and one stationary metal surface. The flow space is characterized by the ratio of $C_r/e \sim 0.005$. In the description of the flow by the momentum equation, apart from the shearing stresses in the z direction, all other members may be neglected, the flow is purely a drag flow. The role of the pressure gradient in the crosswise direction in the screw channel, due to the pressure distribution, must be considered. The heat transport may be ignored compared with the magnitude of heat conduction and heat dissipation. The effects of sliding at the surfaces of the barrel may be substantial.

The melt layer at the screw surface is generally thicker than the melt layer at the surface of the barrel, its thickness increases gradually in the z direction. The flow velocities at the screw surface are smaller than the flow velocities at the surface of the barrel, so that the role played by the pressure gradient is more important. The melt layer at the screw surface may be described by the system of equations relating to the surface of the barrel. The zone, filled with the melt, initially resembles a deep channel section ($\frac{H}{W} \sim 0.2$), the effect of the curvature is also substantial ($\frac{H}{D} \sim 0.2$), while the width of the melt zone upon progression of the melting process changes from O to W , which means that the ratio $\frac{H}{W_m}$ changes from infinity to a value in the range 10^{-1} – 10^{-2} . This means that all three components of the velocity field must be taken into account in the zone filled by the melt. In the momentum equation the force of inertia may be ignored and, where the screw depth does not decrease in an excessively rapid manner, the normal stress components may also be negligible (i.e. N_{we} is small). A consideration of the energy equation leads to the conclusion that the Graetz number cannot be ignored in either the z or in the x direction, which means that both constituents of heat transport must be taken into account. The large Brinkmann number indicates that the effect of dissipation is also substantial. The melt behaves as a non-Newtonian viscous liquid, it is an incompressible continuum, thus, the expansion due to heat may also be ignored. Of the boundary conditions, generally, the Bikerman number is large thus the effect of sliding may be ignored. Upon establishing the boundary conditions of the energy equation it is customary to assume that heat transfer does not take place at the screw. A feature of the metering zone is that the flow takes place in a shallow channel, with values of $H/W \sim 0.05$ and $H/D \sim 0.05$, hence in this case the effect of the curvature may be ignored. The criteria parameters characterizing the flow are contained in Table 4.10. The melting model is composed of the following major parts:

— a model describing the development of the melt layer at the surface of the barrel,

- a model describing the main process of melting, including the criteria equation as part of the choice of the model, together with the two melting process model, the break-up criterion equation, and the relationship describing the length of that part of the melt where the break-up process takes place, and
- the melt conveying models in the deep and shallow channels.

Based on an analysis of the criterion parameter, the melt flow in the metering zone may be described as a flow occurring in a shallow channel.

The Formation of the Melt Layer at the Surface of the Barrel

The melt layer at the barrel surface may be characterized by increasing thickness; the velocity vector is $\mathbf{v}=[v_z(y, z); 0, v_y(y, z)]$. The corresponding balance equations are:

$$\frac{\partial v_z}{\partial z} + \frac{\partial v_y}{\partial y} = 0 \quad (4.56)$$

$$\frac{\partial P}{\partial z} = \frac{\partial \tau_{yz}}{\partial y} \quad (4.57)$$

$$\rho C_P \left(v_z \frac{\partial T}{\partial z} + v_y \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} + \tau_{yz} \frac{\partial v_z}{\partial y} \quad (4.58)$$

The boundary conditions for solution of the equation are:

$$\begin{aligned} v_z &= V; & v_y &= 0; & T &= T_f & \text{if } y &= 0 \\ v_z &= 0; & & & T &= T_m & \text{if } y &= \delta \end{aligned} \quad (4.59)$$

The energy balance at the interface of the solid and the molten material is given by:

$$k_m \frac{\partial T}{\partial y} - k_s \frac{\partial T}{\partial y} = \rho_s \lambda^* (V_y - V \frac{d\delta}{dz}) \quad (4.60)$$

where $\lambda^* = \lambda + C_P (T_m - T_0)$ represents the apparent heat of conversion.

The mass balance, assuming constant melt densities, is given by:

$$\rho_m \frac{d}{dz} \int_0^\delta v_z dy = \rho_s (V_y - V \frac{d\delta}{dz}) \quad (4.61)$$

The power law may be used as the rheological state equation, thus:

$$\eta = \mu_1 e^{-b(T-T_0)} \left| \frac{\partial v_z}{\partial y} \right|^{n-1} \quad (4.62)$$

The physical state equation need not to be taken into account. Rewriting equations (4.56)–(4.62) in dimensionless forms yields the following relationships:

$$\frac{\partial \pi_{v_z}}{\partial Z} - \frac{1}{\Delta} \frac{d\Delta}{dZ} Y \frac{\partial \pi_{v_z}}{\partial Y} + \frac{1}{\Delta} \frac{\partial \pi_{v_y}}{\partial Y} = 0 \quad (4.63)$$

$$\frac{\partial}{\partial Y} \left[\varrho^{-B\pi_T} \left| \frac{\partial \pi_{Yz}}{\partial Y} \right|^{n-1} \frac{\partial \pi_{Yz}}{\partial Y} \right] = \Delta^{n+1} \frac{\partial \pi_p}{\partial Z} \quad (4.64)$$

and

$$\begin{aligned} Sf \left(\pi_{v_z} \frac{\partial \pi_r}{\partial Z} - \frac{1}{\Delta} \frac{d\Delta}{dZ} \pi_{v_z} Y \frac{\partial \pi}{\partial Y} + \frac{1}{\Delta} \pi_{v_y} \frac{\partial \pi_T}{\partial Y} \right) = \\ = \frac{1}{\Delta^2} \frac{\partial^2 \pi_T}{\partial Y^2} + \frac{Gn}{\Delta^{n+1}} \left| \frac{\partial \pi_y}{\partial Y} \right|^{n+1} e^{-B\pi_T} \end{aligned} \quad (4.65)$$

with limiting conditions

$$\begin{aligned} \pi_{v_z}(Z, 0) = 0; \quad \pi_{v_y}(Z, 0) = 0; \quad \pi_{v_z}(Z, 1) = 1 \\ \varrho_m \pi_{v_y}(Z, 1) = \varrho_s \pi_{v_y}(\varrho_s - \varrho_m) \frac{d\Delta}{dZ}; \quad \pi_T(Z, 0) = 1 \\ Z > 0 \quad \pi_T(Z, 1) = 0 \end{aligned} \quad (4.66)$$

$$\frac{\partial \pi_T}{\partial Y}(Z, 1) = \Delta \left(\pi_{v_y} - \frac{d\Delta}{dZ} \right) \quad (4.67)$$

$$\Delta = \frac{\delta}{\delta_0}; \quad Z = \frac{z}{l}; \quad Y = \frac{y}{\delta} \quad (4.68)$$

$$\pi_T = \frac{T - T_m}{T_f - T_m}; \quad \pi_{v_z} = \frac{v_z}{V}; \quad \pi_{v_y} = \frac{v_y l}{V \delta_0}$$

$$\begin{aligned} l = \varrho_s \lambda^* V \delta_0^2 / k_m (T_f - T_m) \\ \pi_p = \frac{P k_m (T_f - T)}{\mu_1 \varrho_s \lambda^* V^{n+1} \delta_0^{1-n}} \end{aligned} \quad (4.69)$$

$$Sf = \frac{\varrho_m C_m (T_f - T_m)}{\varrho_s \lambda^*} \quad (4.70)$$

$$Gn = \mu_1 V^{n+1} \delta_0^{1-n} / k_m (T_f - T_m) \quad (4.71)$$

The above equation may be solved numerically. In the case $n=1$ the melt shows Newtonian behaviour, and $Gn \ll 1$, which means that heat conduction dominates, the solution for equation (4.63) is given by:

$$\delta = \left(\frac{2Sf A k_m Z}{V} + \delta_0^2 \right)^{\frac{1}{2}} \quad (4.72)$$

where A is a constant with a value around unity. Determination of the initial value, δ_0 , presents problems in the above equation. In the initial phases of the melting process, when the temperature at the surface of the barrel reaches the melting point of the polymer (i.e. $Z=0$ and $\delta_b=0$), the melt formed first fills the gaps between the particles, then coats the particles, which means that at $z=z_1$ a melt layer $\delta=\delta_0$ is formed, and from this on, the melting process is the same as described above. The

values of z_1 and δ_0 , according to Kacir and Tadmor [132], are:

$$z_1 = 1,3 \frac{R}{K_0} \frac{\varrho_s V_s}{\varrho_m V} \frac{K_1 (1 - e^{-K_1})}{K_1 - (1 - e^{-K_1})} \quad (4.73)$$

and

$$\delta = 0.923 \sqrt{K_0 R} \quad (4.74)$$

where R represents the radii of the particles, while K_0 is given by:

$$K_0 = \frac{\pi}{2} \frac{\varrho_s k_m S f}{\varrho_m^2 C_m V} \frac{K_1 (1 - e^{-K_1})}{K_1 - (1 - e^{-K_1})} - \frac{\mu V}{2 \varrho_m \lambda^*} \frac{K_1}{1 - e^{-K_1}} \quad (4.75)$$

$$K_1 = \frac{b(T_w - T_m)}{n} \quad (4.76)$$

Once melting processes have commenced, the thickness of the melt layer increases rapidly, and it grows to a thickness equivalent to flight clearance. The thickness of the melt continues to grow at a rate dependent on the operating conditions and on the properties of the material under investigation, to a thickness described by the relationship:

$$\delta_b \int_0^1 (1 - \pi_{v_z}) dY = Cr \quad (4.77)$$

followed by a decrease of the width of the polymer. The width change upon melting is given by:

$$\omega W_s = \frac{d}{dz} (\varrho_s V_s W_s H) \quad (4.78)$$

This may also be expressed in terms of the cross flow, thus:

$$\omega W_s = \frac{1}{2} V_x \delta \varrho_m - \frac{1}{2} V_x Cr \varrho_m \quad (4.79)$$

The melt thickness can now be determined from equations (4.72), (4.78) and (4.79).

The Melting Process

All surfaces of the solid polymer are coated with a layer of the melt. The development of this phase commences when melting begins to take place at the screw surfaces.

Similar considerations apply to the melt pool. During the initial phase of the melting the characteristic feature is that flow in the deep channel takes place. Ignoring the corrections due to the specific geometry of the channel introduces only a small error, as was shown earlier, thus the movement of the melt may be represented by a model as follows [4]:

$$\pi_{Q_z} = \pi_p | \pi_p |^{\frac{1}{n}-1} \exp \frac{b \Delta T}{n} \int_0^1 (1 - Y) (Y - Y_1) \exp \frac{\pi_T}{n} | G_Y |^{\frac{1-n}{2n}} dY \quad (4.80)$$

$$\pi_{Q_x} = 0 \quad (4.81)$$

Table 4.12. Models employed to describe the movement (flow) of the melt

Characterisation of the model	Literature	Assumptions made										Method of calc.	Remarks
		1.1.	1.2.	1.8.	1.9.	1.10.	2.2.	2.3.	4.1.	5.3.	5.4.		
Isothermal flow, Newton's Law, Cartesian coordinate system	[77]	+	+	+	X	X	+	+	+	+	+	analytical	
Isothermal flow, Newton's Law, polar coordinate system	[78]	+	+	+	X	—	+	+	+	+	+	analytical	
Isothermal flow, power law, one dimensional, Cartesian coordinate system	[78]	+	+	+	+	+	+	+	+	+	+	numeric	
Isothermal flow, power law, two dimensional, Cartesian coordinate system	[78]	+	—	+	+	—	+	+	+	+	+	numeric	
Non-isothermal, power law, one dimensional, Cartesian coordinate system	[78]	+	+	+	+	+	+	+	—	+	+	numeric	
Non-isothermal flow, power law, two dimensional, Cartesian coordinate system	[78]	+	—	+	+	—	+	+	—	+	+	numeric	
Non-isothermal flow with convection, power law, two dimensional, Cartesian coordinate system	[85] and [86]	+	—	+	+	—	+	+	—	+	X	numeric	
Deep channel, non-isothermal flow, power law, curved coordinate system	[80]	—	—	+	+	—	—	—	—	+	+	numeric	
Non-isothermal, power law, convection, two dimensional, Cartesian coordinate system		+	—	X	+	—	+	+	—	X	X	numeric	author's model

Legend: + yes,

— no,

X means that one version of the model contains the given assumption, another version of the model excludes the given assumption

Table 4.12. (Cont.)

Assumptions made in the models used for description of the motion of the melt

- 1.1. "Lubrication approximation" applicable in one direction only.
- 1.2. "Lubrication approximation" applicable in two directions.
- 1.3. The processes may be examined in a Cartesian coordinate system (the screw channel is removable).
- 1.4. The screw is stationary, the barrel rotates.
- 1.5. The helix angle is zero.
- 1.6. The effects of the assumption that the surfaces of the screw and the surface of the screw flight are round in shape are negligible.
- 1.7. The location of the screw flights are radial.
- 1.8. The channel depths of the screw are constant.
- 1.9. The existence of the gap between the screw flight and the barrel may be ignored.
- 1.10. Cross directional flows may be ignored.
- 1.11. The channel is completely filled with the melt.
- 1.12. The velocity profile and the temperature profile, developed under steady state conditions.
- 2.1. The flow resembles a steady state flow.
- 2.2. The forces that exist in the melt may be ignored.
- 2.3. The inertia and the centrifugal forces may be ignored.
- 2.4. The polymer melt is incompressible.
- 3.1. The polymer melt is a Newtonian fluid.
- 3.2. The polymer flow follows the power law.
- 3.3. The polymer flow follows the Prandtl-Eyring equation.
- 3.4. The polymer melt may be described by the general viscosity equation.
- 3.5. The polymer melt follows the Oldroyd equation.
- 4.1. The Newtonian viscosity is independent of the temperature.
- 4.2. The Newtonian viscosity is independent of the pressure.
- 4.3. Heat conduction of the polymer melt is constant (independent of pressure and temperature).
- 4.4. The specific heat of the polymer melt is independent of pressure and temperature.
- 5.1. Slipping does not occur at the interface of the melt.
- 5.2. The temperature of the barrel is a specific, given function of the Cartesian coordinates in the direction of the axis.
- 5.3. Heat exchange between the screw and the polymer melt at the screw surfaces do not take place.
- 5.4. The temperature distribution of the screw is uniform, the temperature of the screw is the same at any given point.
- 5.5. A good thermal contact exists between the polymer melt and the surfaces of the metal.

$$1 = \pi_p |\pi_p|^{\frac{1}{n}-1} \exp \frac{b\Delta T}{n} \int_0^1 (Y - Y_1) \exp \frac{\pi_T}{n} |G_Y|^{\frac{1-n}{2n}} dY \quad (4.82)$$

$$\operatorname{tg} \Theta = \alpha_1 \pi_p |\pi_p|^{\frac{1}{n}-1} \exp \frac{b\Delta T}{n} \int_0^1 (Y - Y_2) \exp \frac{\pi_T}{n} |G_Y|^{\frac{1-n}{2n}} dY \quad (4.83)$$

$$Gz \pi_{v_z} \frac{\partial \pi_T}{\partial Z} = \frac{\partial^2 \pi_T}{\partial Y^2} + Br \exp \frac{b\Delta T}{n} \exp \frac{\pi_T}{n} |\pi_p|^{\frac{1+n}{n}} |G_Y|^{\frac{1+n}{2n}} \quad (4.84)$$

where the dimensionless quantities are those collated in Table 4.12.

In order to make clear distinctions, the boundary conditions of the equations are written in their original forms as follows:

— in the melt layer at the barrel surface:

$$\begin{aligned} y=0, \quad v_z = V_s, \quad V_x = 0, \quad T = T_m \\ y = \delta_b, \quad v_z = V_z, \quad v_x = -V_x, \quad T = T_h \\ z = z_1, \quad T = T_{\text{entry}} \end{aligned} \quad (4.85)$$

— in the melt layer at the screw surface:

$$\begin{aligned} y=0, \quad v_z = 0, \quad v_x = 0, \quad T = T_m \\ y = \delta_s, \quad v_z = V_s, \quad v_x = 0, \quad T = T_m \\ z = z_2, \quad T = T_{\text{entry}} \end{aligned} \quad (4.86)$$

— in the zone filled with the melt:

$$\begin{aligned} x=0, \quad v_z = 0, \quad T = T_m \\ x = W - W_s, \quad v_z = V_s, \quad T = T_m \\ y=0, \quad v_x = 0, \quad V_z = 0, \quad T = T_s \\ y = H, \quad v_x = V_x, \quad v_z = V_z, \quad T = T_b \\ z = z_1, \quad T = T_{\text{entry}} \end{aligned} \quad (4.87)$$

For the solid polymer the characteristic items are the heat transport in the y and z directions, together with heat conduction in the y direction, hence:

$$\rho_s C_p \left(V_{sy} \frac{\partial T}{\partial y} + V_s \frac{\partial T}{\partial z} \right) = k_s \frac{\partial^2 T}{\partial y^2} \quad (4.88)$$

with boundary values of:

$$\begin{aligned} z=0, \quad T = T_0(y) \\ y=0, \quad T = T_0, \quad V_{sy} = -V_{sy1} \\ y = H_s, \quad T = T_0, \quad V_{sy} = -V_{sy2} \end{aligned} \quad (4.89)$$

The velocity of the solid bed, assuming a rigid polymer, is derived from the relationship:

$$V_s = \frac{Q}{\rho_s} H_0 W \quad (4.90)$$

by taking into account the actual density of the polymer.

The mass balance characteristic of the melting process for the length Δz is given by the following three equations:

$$Q_{|z+\Delta z} = Q_{|z} - Q_{y|z} + Q_{bx|z} + \omega_m \quad (4.91)$$

$$Q_{bz+\Delta z} = Q_{b|z} - Q_{bx|z} + Q_{sx|z} + \omega_b \quad (4.92)$$

$$Q_{sz+\Delta z} = Q_{s|z} - Q_{sx|z} + Q_{y|z} + \omega_s \quad (4.93)$$

For the solid bed the relationship is:

$$Q_{sz+\Delta z} = Q_{s|z} - (\omega_m + \omega_b + \omega_s) \quad (4.94)$$

The heat flows for the boundary surfaces are as follows:

— for the barrel surface:

$$k \left. \frac{\partial T}{\partial y} \right|_{b; \text{melt}} - k_s \left. \frac{\partial T}{\partial y} \right|_{h; \text{solid}} = \rho_s A V_{sy1} \quad (4.95)$$

— for the screw surface:

$$k_s \left. \frac{\partial T}{\partial y} \right|_{s; \text{solid}} - k \left. \frac{\partial T}{\partial y} \right|_{s; \text{melt}} = \rho_s A V_{sy2} \quad (4.96)$$

— while the melting rates give the reduction of the width of the solid bed

$$\omega = \rho_s W_s V_{sy} \Delta z \quad (4.97)$$

The energy balance is,
in the x direction:

$$\left(\frac{\partial P}{\partial x} \right)^b + \left(\frac{\partial P}{\partial x} \right)^s = \frac{(\tau_{yx} + \tau_{yx|b})}{H} \quad (4.98)$$

in the z direction:

$$\left(\frac{\partial P}{\partial z} \right)^b = \left(\frac{\partial P}{\partial z} \right)^s = \frac{\partial P}{\partial z} \quad (4.99)$$

The force acting on the surface of the solid polymer is given by:

$$\left(\frac{\partial P}{\partial x} \right)^b W_s = \left(\frac{\partial P}{\partial x} \right)^s (W_s + H_s) \quad (4.100)$$

The break-up criterion is given by:

$$\sigma_t \leq \frac{\Delta M}{K_n W_s H_s^2} = \frac{2m-1}{m} \frac{DK_b \cos \Phi \Delta z - (D-2H)K_s \cos \Theta \Delta z}{H_s^2} \quad (4.101)$$

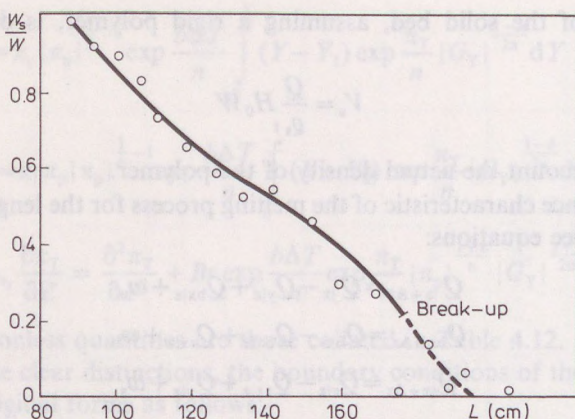


Fig. 4.15. Relative solid bed width profile for polyethylene
 $D=60$ mm, $Q=17$ cm³/sec, $T=190^{\circ}\text{C}$, $N=40$ min⁻¹

where K_b and K_s represent the shearing stresses in the z direction in the case of the melt layer, while K_s in the case of the cooled screw designates the product of the pressure and the frictional constants at the screw surface. H_s represents the height of the solid bed, assumed to be homogeneous. In the case where the solid polymer cannot be regarded as homogeneous, the right hand side of equation (4.101) should contain two members, representing the melt layer thickness at the surface of the barrel and the thickness of the melt layer at the screw surface, respectively. These thicknesses may be determined from the temperature distribution in the solid polymer. The values of m , representing the properties of the material lie between 1 and 1.3. The term σ_t is the break strength; in the case of compressed granules its value equals that of the pressure, in the case of the molten layer it corresponds to the expression $a_1 E (1 - T/T_m)$ related to the modulus, where $a_1 \approx 0.1$.

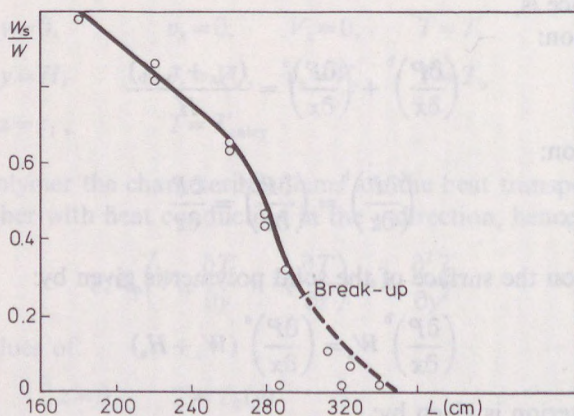


Fig. 4.16. Relative solid bed width profile for polypropylene
 $D=60$ mm, $Q=2$ cm³/s, $T=200^{\circ}\text{C}$, $N=10$ min⁻¹ Solid line: calculated values, — ○ —: experimental data,

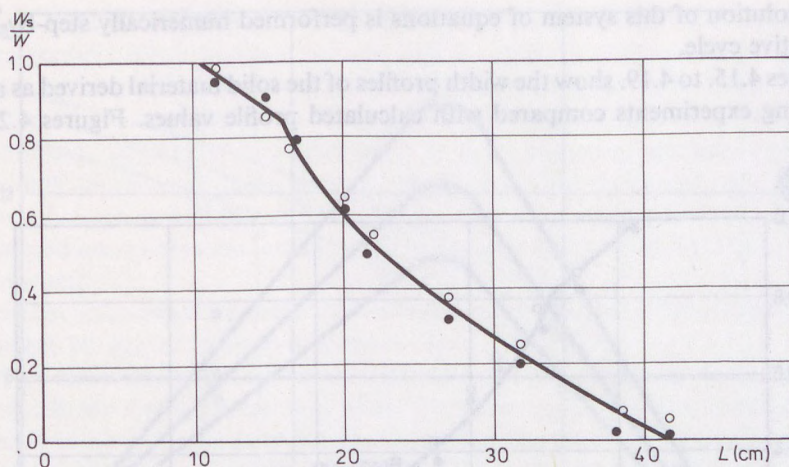


Fig. 4.17. Relative solid bed width profile for polyethylene
 $N=4.2$ revs/min, $Q=7.83$ g/mm², $T_b=155, 170$ and 190°C

It still needs to be determined whether a melt pool filled with the melt is formed, or whether during the melting process merely the thickness of the solid bed is decreased. For this purpose it is necessary to include the force acting on the solid polymer in a crosswise direction as in equation (4.55):

$$F_x \approx \left(\mu_b \frac{V_x}{\delta_b} - \frac{\delta_b}{2} \frac{\partial P_b}{\partial x} - \frac{\delta_s}{2} \frac{\partial P_s}{\partial x} - \frac{\partial P_b}{\partial x} H_s \right) W \quad (4.55)$$

Where this force is small, a zone, filled by the melt, does not form. In such instances the functions related to the melt zone must be excluded from the system of equations, thus, the melting process is characterized by a decrease of the solid bed height.

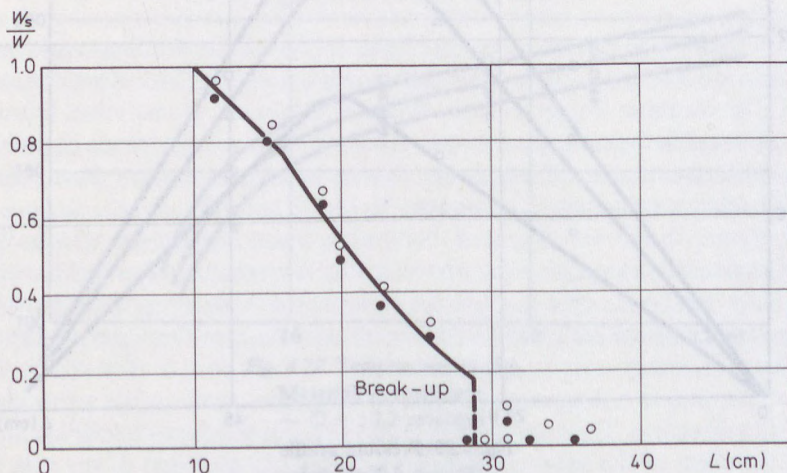


Fig. 4.18. Relative solid bed profile for polyethylene
 $Q=26.5$ g/min, $T_b=155, 170$ and 190°C , $N=22.3$ revs/min

The solution of this system of equations is performed numerically step-by-step in an iterative cycle.

Figures 4.15. to 4.19. show the width profiles of the solid material derived as a result of cooling experiments compared with calculated profile values. Figures 4.20. and

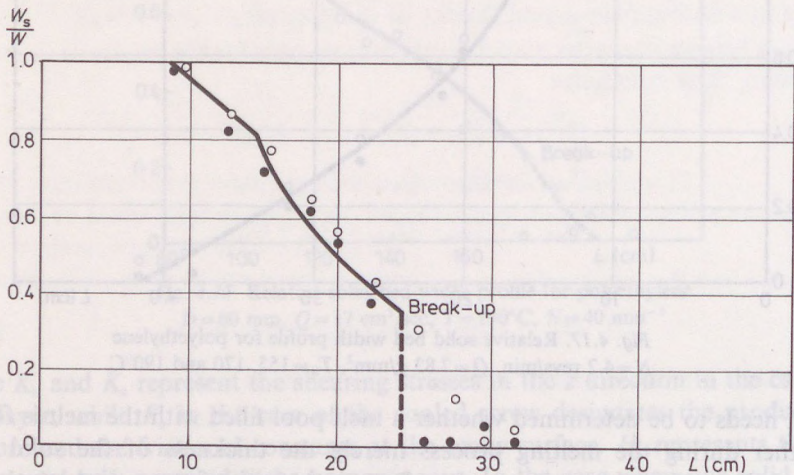


Fig. 4.19. Relative solid bed profile for polyethylene
 $Q = 71.2 \text{ g/min}$, $T_b = 155, 170 \text{ and } 190^\circ\text{C}$, $N = 46.4 \text{ revs/min}$,

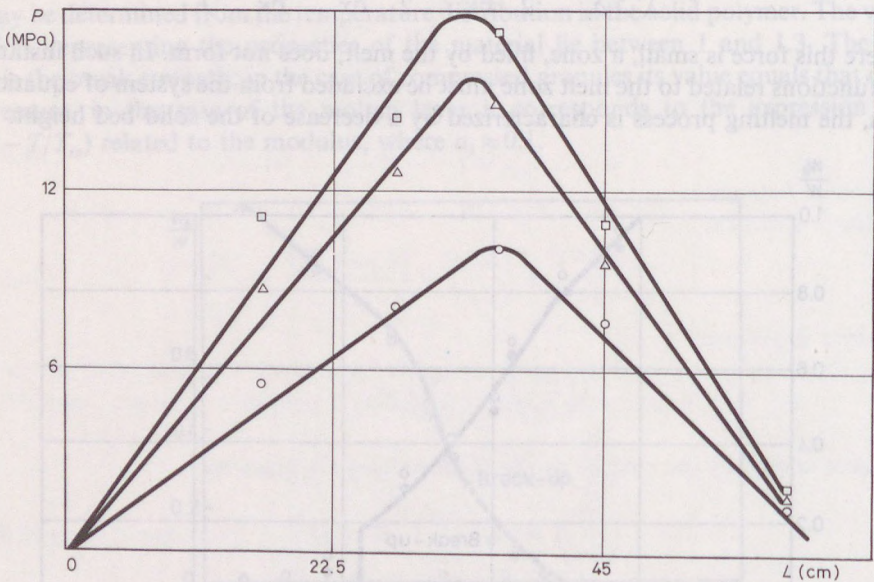


Fig. 4.20. Pressure profile
 — ○ —: 1.2 revs/min
 — △ —: 3.7 revs/min
 — □ —: 10.5 revs/min

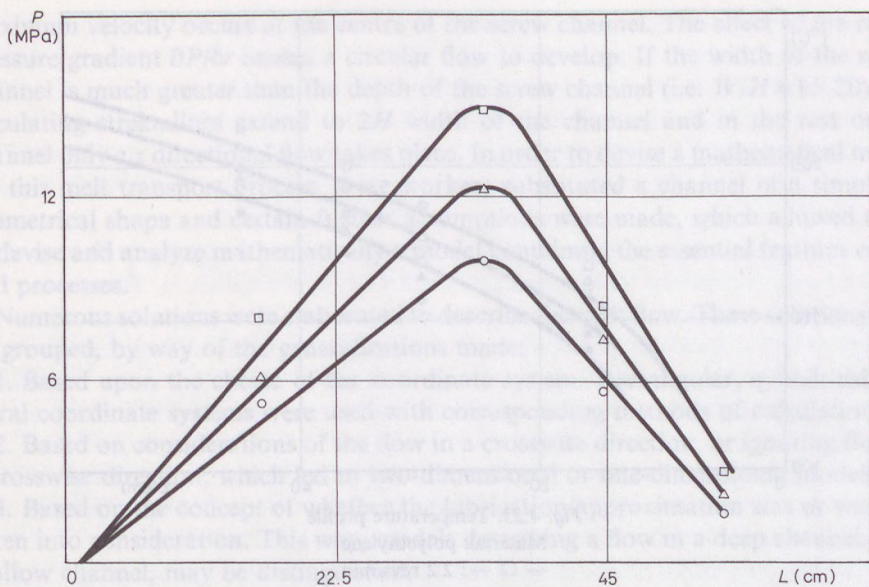


Fig. 4.21. Pressure profile

- ○ —: 2.2 revs/min
- △ —: 6.0 revs/min
- □ —: 15.0 revs/min

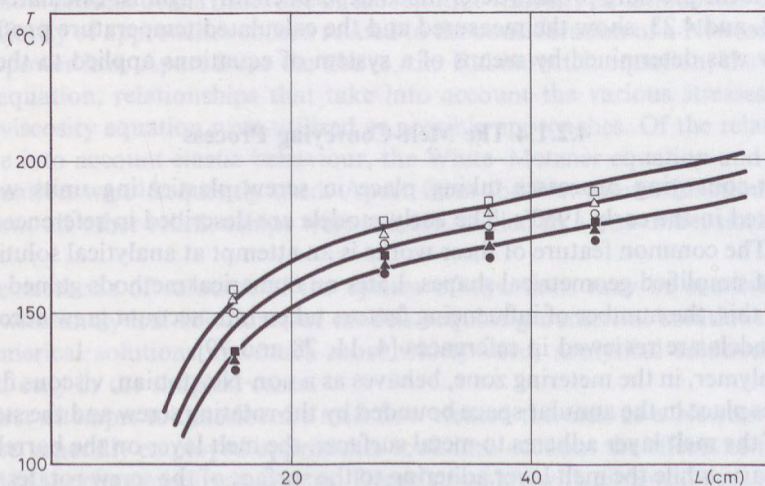


Fig. 4.22. Temperature profile

Material: polyethylene

- ○ —: 1.2 revs/min
- △ —: 3.7 revs/min
- □ —: 10.5 revs/min

Unfilled symbols: Temperatures at the barrel surfaces

Filled symbols: Temperatures at the screw surfaces

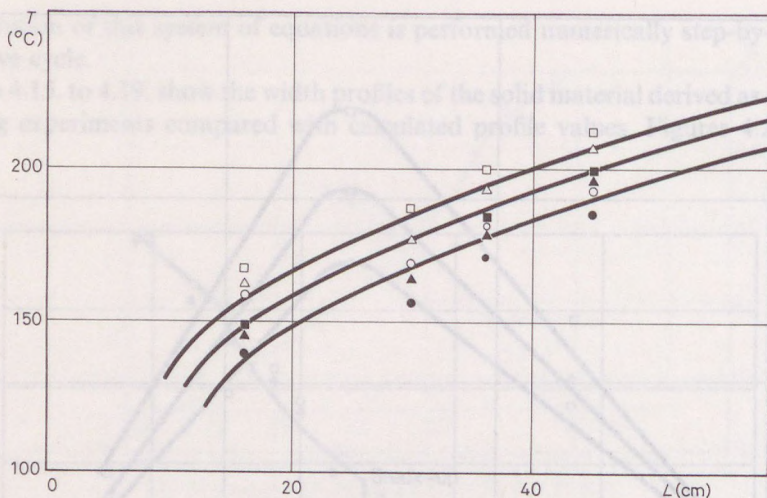


Fig. 4.23. Temperature profile

Material: polyethylene

— ○ —: 2.2 revs/min

— △ —: 6.0 revs/min

— □ —: 15.0 revs/min

Unfilled symbols: Temperatures at the barrel surfaces

Filled symbols: Temperatures at the screw surfaces

4.21. show the pressure profiles determined experimentally, against calculated values, Figs 4.22. and 4.23. show the measured and the calculated temperature profiles. The melt flow was determined by means of a system of equations applied to the model.

4.2.1.4 The Melt-Conveying Process

The melt-conveying processes taking place in screw plasticating units were first investigated in the early 1950's. The early models are described in references [23, 26 and 77]. The common feature of these works is an attempt at analytical solutions and a study of simplified geometrical shapes. Later on numerical methods gained grounds and with this, the number of influencing factors taken into account grew accordingly. These models are reviewed in references [4, 11, 78 and 79].

The polymer, in the metering zone, behaves as a non-Newtonian, viscous fluid, and flow takes place in the annular space bounded by the rotating screw and the stationary barrel. If the melt layer adheres to metal surfaces, the melt layer on the barrel surface is stationary, while the melt layer adhering to the surface of the screw rotates with the screw. The stationary melt layer on the surface of the barrel is removed by the flight of the screw, and in consequence, pressure differences occur in the screw channel in a crosswise direction. The components of the pressure gradients are $\partial P/\partial z$ and $\partial P/\partial r$. Due to the effect of the pressure gradient $\partial P/\partial z$ in the direction of the axis, the melt in the ring-shaped channel is displaced in the z direction, and the velocity of the melt, v_z , is considered zero at the surfaces of both the barrel and the screw, and the

maximum velocity occurs at the centre of the screw channel. The effect of the radial pressure gradient $\partial P/\partial r$ causes a circular flow to develop. If the width of the screw channel is much greater than the depth of the screw channel (i.e. $W/H \approx 15-20$), the circulating streamlines extend to $2H$ width of the channel and in the rest of the channel only a z directional flow takes place. In order to devise a mathematical model for this melt transport process, these workers substituted a channel of a simplified geometrical shape and certain further assumptions were made, which allowed them to devise and analyze mathematically a model containing the essential features of the real processes.

Numerous solutions were elaborated to describe the melt flow. These solutions may be grouped, by way of the generalizations made:

1. Based upon the choice of the coordinate system. Rectangular, cylindrical and spiral coordinate systems were used with corresponding methods of calculation.

2. Based on considerations of the flow in a crosswise direction, or ignoring flow in a crosswise direction, which led to two-dimensional or one-dimensional models.

3. Based on the concept of whether the lubrication approximation was or was not taken into consideration. This way, models describing a flow in a deep channel, or a shallow channel, may be distinguished.

4. Whether the effect of heat is or is not included in the model. Models that take heat conduction and heat dissipation into account are called non-isothermal models; in some instances, where the heat transport in the direction of the axis was also taken into consideration, the models are called convection models.

5. Based on the rheological state equation employed. Generally, in describing a viscous flow process of the melt, one of the relevant viscosity equations was used. The great majority of approaches chosen related to the consideration of a Newtonian fluid and the power law. Apart from the above, the Rabinowitch equation, the Prandtl-Eyring equation, relationships that take into account the various stresses and the general viscosity equation were utilized as possible approaches. Of the relationships that take into account elastic behaviour, the White-Metzner equation and the Oldroyd equation were frequently used. Apart from the Newtonian function and the power law, all other relationships were usually studied in a one-dimensional framework.

6. The methods of solution of the system of equations may be subdivided into models with analytical solutions, or models requiring numerical solutions. Models with numerical solutions are much more widely used; analytical solutions can be obtained only in the simplest cases.

The first attempts to describe the melt flow treated the melt as a Newtonian fluid. The more generally employed approaches took into account the effects of the cross-flow and of the channel curvature, too. The relationship with dimensionless quantities is:

$$\pi_Q = \frac{F_D F_{CD}}{2} - \frac{\pi_P F_P F_{CP}}{12} \quad (4.102)$$

where F_D and F_P are the shape factors of the drag flow and the pressure flow, respectively, while F_{CD} and F_{CP} are the curvature coefficients of the drag flow and

the pressure flow, being converging series of the characteristics of the channel H/W and of the curvature characteristics D_b/D_s . The applicability of this model for Newtonian fluids was proven experimentally. The advantages of this model are that it is easy to handle, and it can be used for approximative calculations. Its disadvantage lies in its substantial inaccuracy, since it does not take into account the effects of the shearing velocity and that of the temperature, on the viscosity of the fluid. In the case of screw plasticating units the assemblage of the barrel and the screw is, invariably, carried out within certain tolerance limits, to eliminate the effects of eccentricity of the screw and the barrel and to compensate for uneven heat expansion. This means that the clearance between the screw flight and the surface of the barrel influences the conditions of the flow and the thermodynamic conditions in the extruder, it affects the velocity profiles, the volume flow, the energy dissipation, the heat transfer coefficients between the barrel and the polymer, and also the melt velocity of the solid polymer [88–90].

The clearance, as a dead space, reduces the output efficiency of the extruder and, a portion of the polymer melt flowing forward may be reversed to flow back through the clearance, so that the effect of this clearance must be considered.

In the majority of solutions devised for non-Newtonian fluids, a simplified form of the rheological state equation of viscous fluids, the viscosity equation was generally employed. Detailed examination of the problem was carried out for the power law. Many studies included the application of other solutions based on the viscosity equation, such as the Ellis equation, the Prandtl–Eyring equation and the general viscosity equation in study of one-dimensional isothermal flow. The non-Newtonian solutions were either isothermal, or non-isothermal, subdivided into one- or two-dimensional attempts at solutions.

In most cases heat conduction and heat dissipation were taken into account. In these cases heat convection played an important part, and inclusion of these aspects improved the applicability of the model, particularly with respect to the description of temperature distribution and pressure distribution [91].

Many of the workers in this field were specifically concerned with the effects of the curvatures of the channel, and the question was raised as to how appropriate was the approximation considering a rectangular shape channel. Calculations revealed [76, 77] that using the curvature corrections derived by analytical approaches [80], the decrease of the volume flow due to the curvature was slightly over-estimated in cases of deep channels with large curvatures. In cases of shallow channels reasonable results were obtained by introduction of correction factors.

The rounding off of the channel results in an error only at small pressures [85], in the case of shallow channels this error is negligible.

Slipping along the walls influences the velocity distribution and the magnitude of the pressure gradient [86, 91 and 92].

The application of two-dimensional isothermal and non-isothermal flow was extended to various types of screw mixers, in which melt movement is similar to the melt flow in the screw plasticating units [93–95].

Numerical calculations revealed [4, 78, 80 and 83] that the time taken for calculation, by introduction of an additional value factor (such as velocity, pressure or

temperature), became substantial, unless the geometry and the balance equations are simplified. The model of flow movement, must be applied to the melting zone and the metering zone and must account for the fact that the calculated values may only apply in a localized fashion to a small proportion of the whole, which means, that in order to be able to describe the entirety of the melt transport processes, these calculations must be performed several times over, each describing a small portion of the whole process.

4.2.2 Plasticating Processes of Caoutchouc Mixes

In Section 4.1.2 the plasticating mechanisms of caoutchouc mixes have been already mentioned. The characteristic feature of these plasticating processes is that the caoutchouc mixtures undergo a melt-like movement, without a phase change. The screw channel is deeper than that employed for thermoplastic materials, the viscosity of the caoutchouc mix, at the lower process temperature, is substantially higher than that of thermoplastic materials. The criteria parameter analysis reveals that the Brinkmann number is substantial in magnitude, and the Gz number is not negligible. The process is the same as the non-isothermic flow in a deep channel, a phenomenon examined numerically for thermoplastic polymers by several workers [80 to 85].

A simplified method is now described. The volume flow of a Newtonian fluid in a deep channel is expressed as:

$$Q = i \frac{V_z H W}{2} F_d - \left(\frac{\partial P}{\partial z} \right) \frac{H^3 W}{12 \eta} F_p i \quad (4.102)$$

where F_d and F_p are the respective drag pressure and leakage flow shape factors, these are functions of the ratio H/W . The non-Newtonian behaviour of the flow can be taken into account by modification of equation (4.102) above [87] to give:

$$Q = i \frac{V_z H W (4+n)}{10} F_d - \frac{i H^3 W F_p}{4(1-2n)\mu_1} \left(\frac{\partial P}{\partial z} \right) \quad (4.103)$$

where n is the exponent of the power law and μ_1 is the viscosity corresponding to the shearing rate $\dot{\gamma} = 1 \text{ s}^{-1}$.

Considering a short section Δz , the average temperature for this section is:

$$\bar{T} = \frac{1}{\Delta z} \int_{z_1}^{z_2} T(z) dz \quad (4.104)$$

By ignoring the temperature changes in radial directions in the energy equation, and taking into account the average dissipation, the equation is written:

$$\rho C_v \bar{v}_z \frac{dT}{dz} = \mu_1 \left(\frac{V}{H} \right)^{n+1} \exp \frac{1}{b(\bar{T} - T_0)} + \frac{4k}{H^2} (T - T_b) \quad (4.105)$$

Integrating from the initial conditions $z = z_1$ and $T = T_1$, followed by substitution of the temperature obtained into equation (4.104) and integrating again, the average

temperature is:

$$\begin{aligned}\bar{T} = T_b + a_1 \exp \frac{1}{b(\bar{T} - T_0)} \left(1 + \frac{e^{-a_2 \Delta z} - 1}{a_2} \right) + \\ + (T_b - T_1) \frac{\exp(-a_2 \Delta z) - 1}{a_2}\end{aligned}\quad (4.106)$$

where

$$\begin{aligned}a_1 &= \frac{\mu_1 H^2}{4k} \left(\frac{V}{H} \right)^{n+1} \\ a_2 &= \frac{4k}{\rho C_v H^2 \bar{v}_z}\end{aligned}$$

Rearranging equation (4.106)

$$\frac{iWH^3 F_p}{4(1+2n) \left[\frac{iV_z H W F_d (4+n)}{10} - Q \right]} dP = \mu_1 dz \quad (4.107)$$

Introducing the temperature dependence of μ_1 and integrating between the z_1 and z_2 , that is, between P_1 and P_2 (note: $P_2 - P_1 = \Delta P$), the equation

$$\frac{iWH^3 F_p}{4(1+2n) \left[\frac{iV_z H W F_d (4+n)}{10} - Q \right]} \Delta P = \mu_0 \int_{z_1}^{z_2} \exp \frac{dz}{b(T - T_0)} \quad (4.108)$$

is obtained.

Approximating the integral

$$\int_{z_1}^{z_2} f(z) dz = \frac{\Delta z}{6} \left[f(z_1) + 4f\left(\frac{z_1 + z_2}{2}\right) + f(z_2) \right] = F_{\Delta z} \Delta z \quad (4.109)$$

where

$$\begin{aligned}f(z) = \exp \frac{1}{b(\bar{T}_z - T_0)} = \exp \left\{ \frac{1}{b} \left[T_b + a_1 \exp \frac{1}{b(T - T_0)} - \right. \right. \\ \left. \left. - \left(a_1 \exp \frac{1}{b(\bar{T} - T_0)} - T_1 + T_b \right) \exp(-a_2 \Delta z) \right]^{-1} \right\}\end{aligned}\quad (4.110)$$

Rearranging equation (4.110)

$$Q = \frac{i(4+n)V_z H W F_d}{10} - \frac{iH^3 W F_p}{4(1+2n)\mu_0 F_{\Delta z}} \left(\frac{\Delta P}{\Delta z} \right) \quad (4.111)$$

The relationship (4.111) may be solved by a method of successive approximation.

4.2.3 Dynamic Behaviour of the Single-Screw Plasticating Unit

The steady state operation of the single screw plasticating unit in the intermittent and continuous mode of operation was outlined earlier. The characteristic sections of the dynamic operation are the start up and stoppage processes and the processes eliminating disturbances during steady state operation.

The Disturbances Occurring During Steady State Operation Mode

The disturbances that occur during a steady state operation may be divided into three categories as follows:

a) High-frequency disturbances. These occur at the same frequency as the screw rotations. The causes of such disturbances are the periodic nature of the solid material transport, which was examined in connection with the movement of the solid material. These disturbances occur only at small pressures in the die.

b) Medium frequency disturbances. In general, these result in a loss of quality of product(s). The problems are mainly due to the formation of an unstable melt, which, in turn, is brought about by break-up of the solid polymer bed.

c) Low-frequency disturbances. These are usually due to external causes resulting from the cyclic operational mode of the heaters due, in turn, to voltage fluctuations.

4.2.3.1 Classical Control Experiments

These experiments were directed towards the determination of the transfer functions. For this purpose, in general, disturbances of step-function type were utilized to generate disturbances and the resulting transfer function curve is studied.

One of the most detailed studies into the dynamics of screw plasticating units was undertaken by Meissner [89 to 92] who determined the transfer functions with the aid of step tests. In order to derive these functions, Meissner established a simple model to determine the melt temperature changes occurring.

White and Schott [93] studied experimentally the dynamic behaviour of the screw plasticating unit affected by changes in the screw speed. A substantial change in the screw speed resulted in an under-damped, secondary melt pressure response in accordance with the transfer function:

$$\frac{P(p)}{N(p)} = \frac{(1+ap)^4}{T^2 p^2 + 2T\xi p + 1} \quad (4.112)$$

The nominator of higher exponent means that the exit flow determines the input flow, which is a kind of physical nonsense.

Tadmor and associates [95, 96] developed a dynamic version of the steady state model devised for the melting process. The fundamental assumption of this model is that the melting of the polymer takes place on the barrel surface, and melting occurs with a drag-flow melt discharge. The width change of the solid polymer is given by:

$$\frac{DX}{Dt} = \frac{\partial X}{\partial t} + V_s \frac{\partial X}{\partial Z} = -\frac{\Phi}{\rho_s H} X^{\frac{1}{2}} + \beta \frac{V_s X}{H} \quad (4.113)$$

where D/Dt is the material derivative, X represents the relative width of the solid polymer, V_s is the velocity of the solid bed, regarded as constant, Φ is a constant, ρ_s is the density of the solid polymer, H is the depth of the screw channel, and β is the tapering of the screw channel. In order to solve equation (4.113), constant Φ and $\beta = 0$ are taken into account to obtain:

$$X(z, t) = X_0(z, t) \left[1 - \frac{(t - t_0) \Phi}{2 \rho_s H \sqrt{X_0(z, t)}} \right]^2 \quad (4.114)$$

where $X_0(z, t)$ is the initial width of the solid bed.

The dynamic temperature profile is:

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + \bar{V} \frac{\partial T}{\partial z} = \frac{\Phi X^{\frac{1}{2}} (T_f - T)}{\rho_m H (W - X)} + \frac{q_v + q_T}{Q_m C_{mv} H (W - X)} \quad (4.115)$$

where $V = Q_m / \rho_m H (W - X)$ is the average melt velocity, ρ_m is the density of the melt, T is the average temperature of the melt layer, W represents the width of the screw channel, q_v and q_T are the dissipated heat quantity, and the heat quantity transferred across the wall from the heaters, and C_{mv} represents the specific heat of the melt. The solution of equation (4.115) is performed numerically. The calculations are simplified by assuming that the mass flow is constant at any given time. The mass flow is:

$$\frac{\partial Q}{\partial z} = \frac{\partial Q_m}{\partial z} + V_s \rho_s \frac{\partial (HX)}{\partial z} = \frac{\partial (HX)}{\partial t} \quad (4.116)$$

thus, the entire mass-flow change becomes zero when the densities of the melt and the solid polymer are the same or in a steady state when $\partial(HX)/\partial t = 0$. In practice, the density of the solid polymer does not differ substantially from that of the melt, and in such instances:

$$Q_m = Q - V_s \rho_s H \quad (4.117)$$

The local momentary pressure gradient is dependent on the localized melt flow and on the width of the section filled with the melt, hence, from the above relationship the dynamic properties may be determined with reference to the steady state flow. Brauner, Lavie and Tadmor [96] examined the behaviour of the above model using polymers of different properties and quality. Two variables were examined, first, a small change was introduced in the viscosity of the input material, in the second instance a substantial change was made in the viscosity of the material used. A small change produced a pressure wave in the melting zone. The die remained insensitive to this pressure wave until the pressure wave reached the die, at this point, however, the existing pressure and the volume flow changed abruptly. A large viscosity change produced a similar phenomenon, of greater intensity.

Reber, Lynn and Freeh [97] established a dynamic model, where the screw plasticating unit was assembled from small dynamic basic elements. The plasticating unit was modelled as a series of plug-type flow and mixing type units. In the plug-flow section a laminar, even velocity flow takes place free of mixing. In the mixing section, perfect mixing takes place. The solid material movement is characterized by a plug-type flow,

the melting section is characterized by a combination of plug-type flow and mixing, while the metering zone is characterized by mixing. With the aid of the model, the melt temperature and melt pressure in the dynamic section can be well simulated.

4.2.3.2 Examination of Time Sequential and Stochastic Control Modes

In the examination of time sequences a series of small amplitude signals are used (often a pseudo-random binary signal series) as the disturbing function.

When examining the correlation of the input and output signals for example, for the output signal, the following relationship applies:

$$P(t) = \frac{\Omega(z^{-1})}{\delta(z^{-1})} z^{-f-1} N(t) + A(t) \quad (4.118)$$

where P is the pressure, N is the revolution number, $\delta(z^{-1})$ is a polynomial characteristic of the dynamics of the system, $\Omega(z^{-1})$ is a polynomial compensating for the previous inputs, f is the number of sampling periods of delay, z^{-1} is the phase-shift operator $[z^{-1}X(t) = X(t-1)]$, and $A(t)$ is the noise. The parameters of the model may be determined experimentally.

Using the above method, Parnaby, Kochlar and Woods [98, 99] studied the effects of the screw speed changes upon the temperature and pressure of the material with sampling time of 12.5 s. Patterson and Kerf [100] studied the plasticating dynamics of low density polyethylene utilizing time sequence models. The temperatures and pressures of the material in the die, together with the thickness changes of the extrudate were studied as a function of the screw speed changes. It was established that the temperature showed a change with 120 s time constant and 25 s lapse time. Pressure fluctuations brought about by a die constrictor valve were also studied. Following an adjustment to the position of the valve a change occurred immediately in the pressure of the material and in the thickness of the extrudate, although no change occurred in temperature.

Costin, Taylor and Wright [101, 102] carried out time sequence experiments with polyethylene and examined three types of disturbances:

- screw speed changes,
- pressure fluctuations with a frequency of 0.125 Hz,
- low-frequency cyclic disturbances induced by the die temperature controls.

Based on these dynamic experiments, the value parameters of equation (4.118) were determined. Using the results obtained a digital PI control was designed to control the screw speed.

The discussion of the dynamic behaviour pattern which follows is based on references [103 and 104]. It is a difficult task to devise an analytic dynamic model, due to the complexity of the processes, thus it is advantageous to use simplified models. In the examination, it is necessary to analyze the changes occurring in each of the part processes and their roles in causing changes in pressure and temperature. A simple model was given in Table 4.12. The most important changes occurring are as follows:

- changes in the r.p.m.,
- changes in the wall temperature,

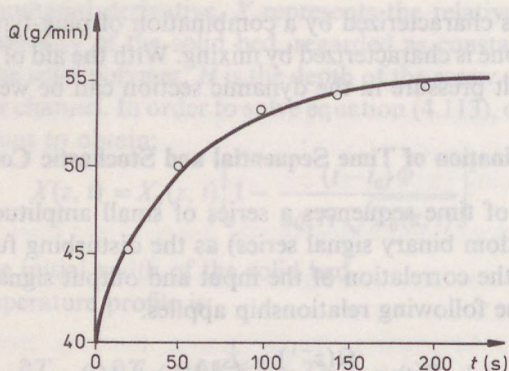


Fig. 4.24. Mass flow changes brought about by a change in screw speed, for polyethylene Tipolen FA material. The revolution number was increased from 14.4 min^{-1} to 18.6 min^{-1}

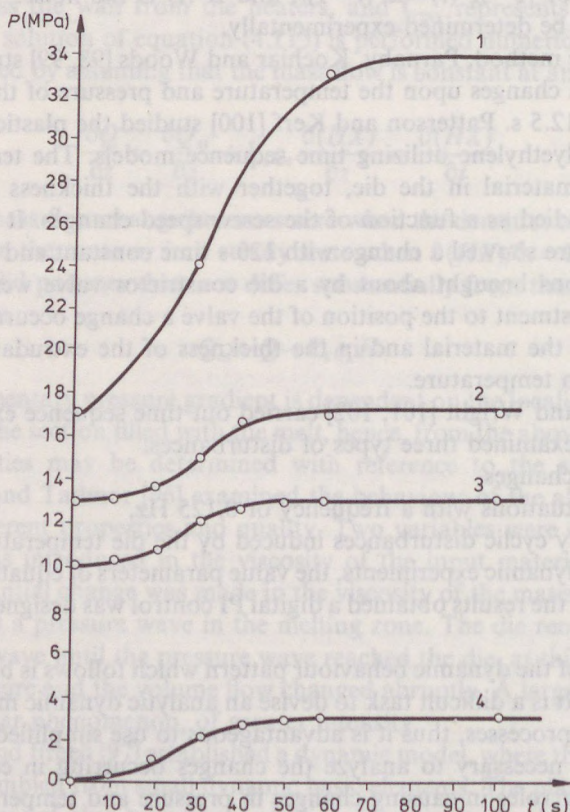


Fig. 4.25. Pressure changes brought about by changes in screw speed for Tipolen FA polyethylene. The revolution number was increased from 45 min^{-1} to 60 min^{-1}
 1. melting zone, 2. metering zone, 3. screw tip, 4. solid-conveying zone

— the changes in resistance at the die, and
 — changes in the quality of the materials.

The last of these can include changes in the frictional constant, the viscosity and specific heat.

Figure 4.24. shows the changes occurring in the mass flow due to changes in the revolution number of the screw. The curve characterizes all three part processes and it can be represented by a first order aperiodic transfer function, thus:

$$G(p) = \frac{K}{Tp + 1} \quad (4.119)$$

where T is a time constant and K is the gain. This type of behaviour is characteristic of ideal mixing, and the time constant, equivalent to the average residence time, is the ratio of the volume of the system to the volume flow passing through the system. Comparing the residence times with the measured time constants gave good agreement with each of the part processes.

Figure 4.25. shows the changes occurring in pressure at the end of the solids conveying, melting and metering zones brought about by a stepped change in r.p.m. The courses of the transfer curves are similar for all three part processes, they are second-order aperiodic functions. The pressure changes reflect the volume flow changes, and the temperature changes. The most prominent pressure changes were observed in the melting zone. The changes of the pressure profile with time are shown in Figure 4.26.

Figure 4.27. shows the effect of changes in the screw speed on the temperature. All curves show similarities to all three part-processes of the plasticating process as second-order aperiodic functions:

$$G(p) = \frac{K}{T_1 T_2 p^2 + (T_1 + T_2)p + 1} \quad (4.120)$$

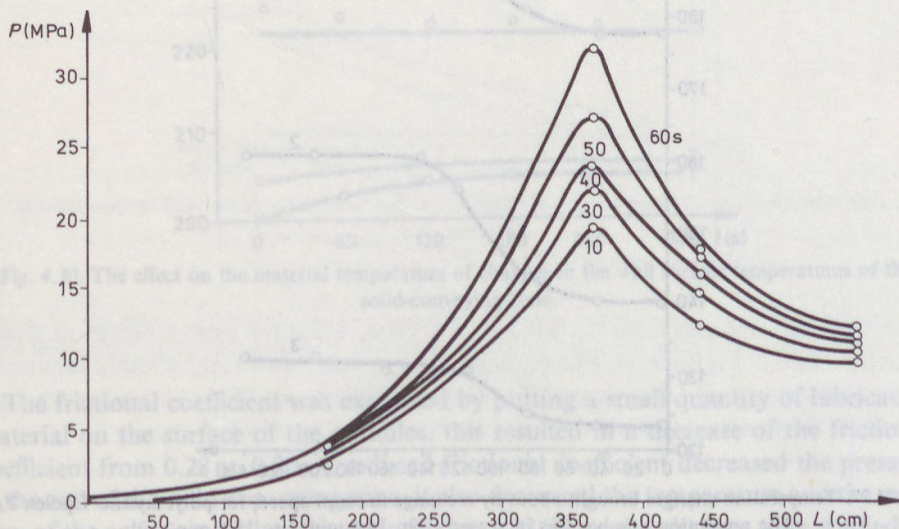


Fig. 4.26. Changes occurring in the pressure profile as a function of time, curves derived from Fig. 4.25.

The changes occurring in the solids conveying zone and in the melting section are more substantial than in the metering zone. The changes in dissipation energy exert the greatest influence on the processes in the melting zone.

Figures 4.28. and 4.29. illustrate the effect of screw speed change upon the temperatures of zones when the volume flow is maintained at a constant value. It shows the change of the behaviour of the melting zone. At low screw speeds the temperature at the beginning of the melting zone is a constant value, at the middle of the zone the temperature decreases and at the end of the zone it increases. At higher screw speed, as can be seen in Figure 4.29., the behaviour of the melting zone is the same as shown earlier in Fig. 4.27.

Figures 4.30., 4.31. and 4.32. illustrate the effects of changes in heat input. The greatest temperature changes happened where the modification heating efficiency took place, at some distance away from this point the temperature changes becoming progressively smaller. The curves could be described by first order aperiodic transfer functions. The changes in mass flow were small, the mass flow in the solid-conveying zone showed a slight decrease with increasing temperature of the barrel surface, while the mass flow in the melting zone increased. The pressure at the end of the solid-conveying zone increased slightly, while the pressure at the end of the melting zone increased due to the effect of temperature increases at the walls of the barrel.

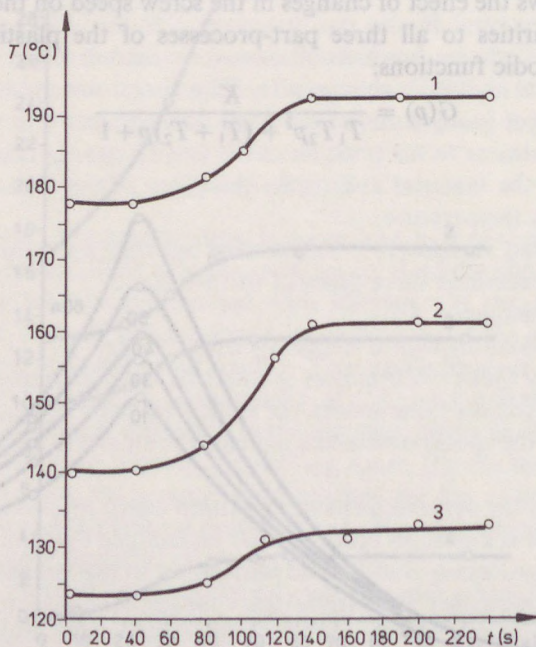


Fig. 4.27. Temperature changes brought about by a change in screw speed, for polyethylene Tipolen FA
The revolution number was increased from 14.4 min^{-1} to 18.6 min^{-1} in:
1. metering zone, 2. melting zone, 3. solid conveying zone

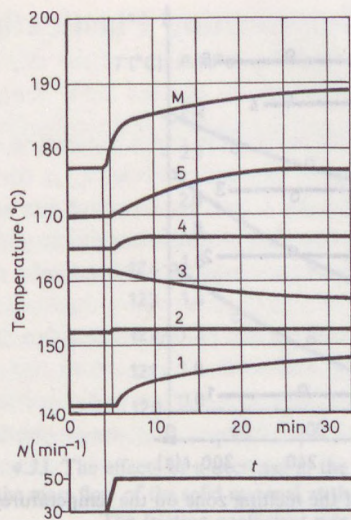


Fig. 4.28. Temperature changes brought about by an increase in screw speed for polyethylene n_s changed from 30 to 50 revs/min. $Q_i = \text{const.}$

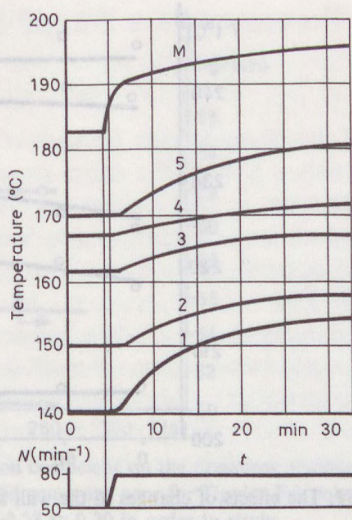


Fig. 4.29. Temperature changes brought about by an increase in screw speed for polyethylene n_s changed from 50 to 80 revs/min. $Q_i = \text{const.}$

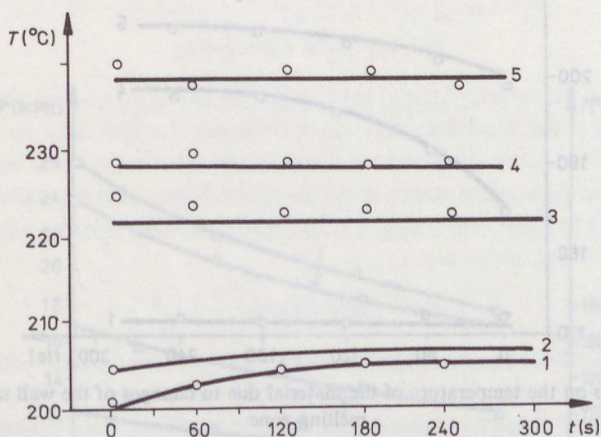


Fig. 4.30. The effect on the material temperature of changes in the wall surface temperatures of the solid-conveying zone

The frictional coefficient was examined by putting a small quantity of lubricating material on the surface of the granules, this resulted in a decrease of the frictional coefficient from 0.28 to 0.20. A reduced frictional coefficient decreased the pressure at the end of the solid-conveying zone, it also decreased the temperature and the mass flow of the solid material as shown in Figure 4.33. Viscosity changes were studied by introducing some of the same polymer but with a lower molecular mass, the viscosity

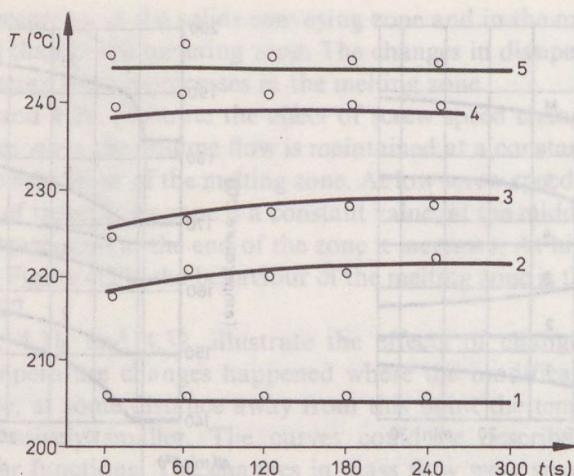


Fig. 4.31. The effects of changes in the wall temperatures of the melting zone on the temperatures of the material

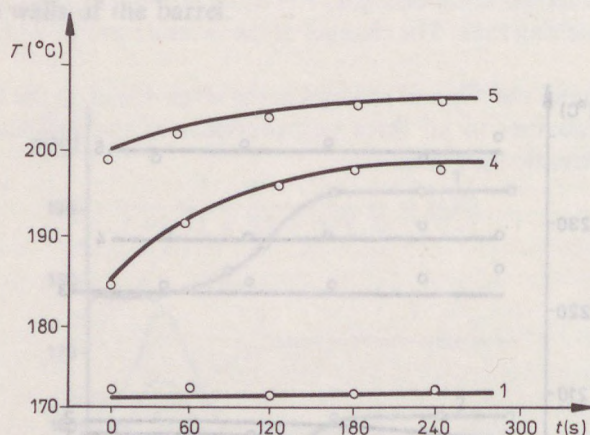


Fig. 4.32. The effects on the temperature of the material due to changes of the wall temperatures in the melting zone

value (μ_1) was reduced from 9.6 kPas to 1.1 kPas, while the exponent was changed from 0.34 to 0.6. Figure 4.34. shows that a drop in viscosity brings about a reduction in the temperature and pressure of the material. The shapes of the curves are characteristic of first order aperiodic transfer functions.

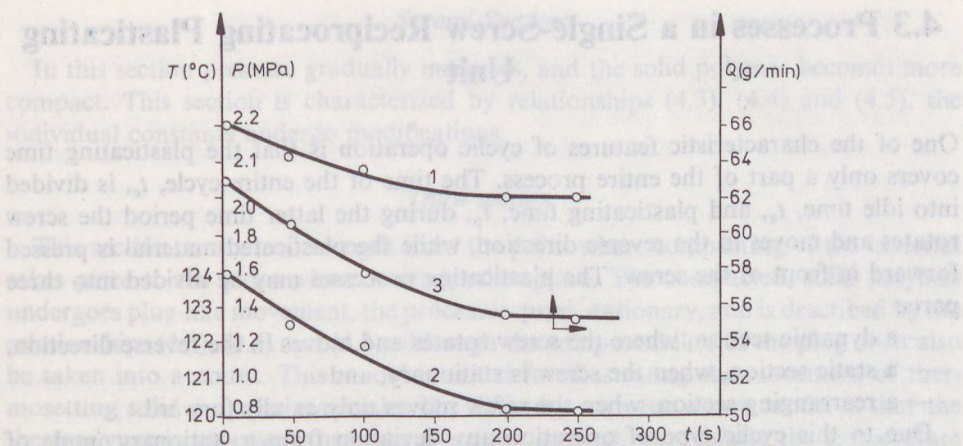


Fig. 4.33. The effects of a decrease in the polymer friction coefficient on the pressures, temperatures and the mass flow of the solid material at the end of the solid conveying zone for Tipolen FA polyethylene. The friction coefficient was reduced from 0.28 to 0.20 in order to study

1. the pressure changes, 2. the temperature changes, 3. the mass flow changes

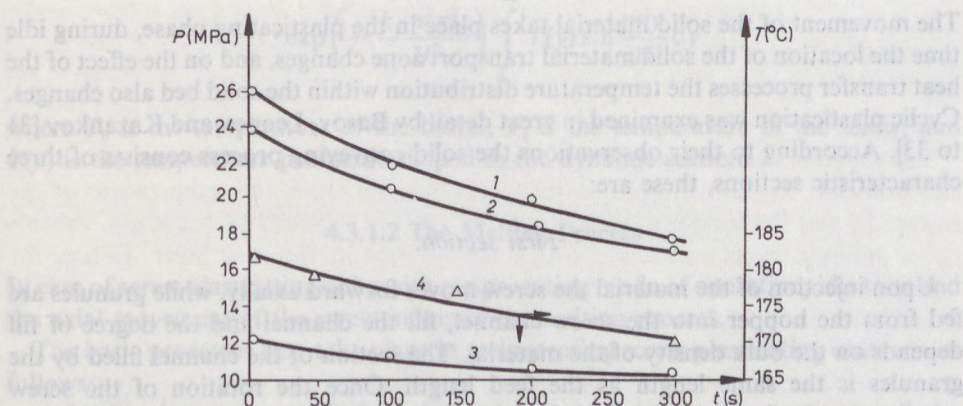


Fig. 4.34. The effects of mixing a smaller viscosity material into the bulk material, on the pressure and the temperature of the material, for Tipolen FA material to which one third of Tipolen AE polymer was mixed to study

1. the pressure at the end of the melting zone, 2. the pressure at the end of the metering zone, 3. the pressure at the tip of the screw, 4. the temperatures at the tip of the screw

4.3 Processes in a Single-Screw Reciprocating Plasticating Unit

One of the characteristic features of cyclic operation is that the plasticating time covers only a part of the entire process. The time of the entire cycle, t_c , is divided into idle time, t_a , and plasticating time, t_p , during the latter time period the screw rotates and moves in the reverse direction, while the plasticated material is pressed forward in front of the screw. The plasticating processes may be divided into three parts:

- a dynamic section, where the screw rotates and moves in the reverse direction,
- a static section, when the screw is stationary, and
- a rearranging section, when the screw moves only axially forward.

Due to this cyclic type of operation any deviation from a stationary mode of operation depends upon the ratio t_p/t_c .

4.3.1 Plasticating Processes Using Thermoplastic Materials

Here again the plasticating process is divided into three sections as was the case with the continuously operated plasticating units.

4.3.1.1 Solid Conveying

The movement of the solid material takes place in the plasticating phase, during idle time the location of the solid material transport zone changes, and on the effect of the heat transfer processes the temperature distribution within the solid bed also changes. Cyclic plastication was examined in great detail by Basov, Leonov and Kazankov [31 to 33]. According to their observations the solid conveying process consists of three characteristic sections, these are:

First section:

Upon injection of the material the screw moves forward axially, while granules are fed from the hopper into the screw channel, fill the channel and the degree of fill depends on the bulk density of the material. The section of the channel filled by the granules is the same length as the feed length. Once the rotation of the screw commences, further quantities of the granules are added to the channel, and the section which is only partially filled moves forward in such a manner that the material is compacted to some degree. In the first section the pressure does not increase, the velocity and the density remain constant along the channel. This section coincides with the cooled section of the barrel, thus, increase in the temperature of the polymer need not be taken into account at this stage. The angle of movement may be determined from equation (4.6) and $B_3 = 0$.

Second Section:

In this section pressure gradually increases, and the solid polymer becomes more compact. This section is characterized by relationships (4.3), (4.4) and (4.5), the individual constants undergo modifications.

Third section:

This section consists of a length from the point where compacting of the material takes place to the point where melting takes place. The compacted, solid polymer undergoes plug-like movement, the process is quasi-stationary, and is described by the relationships (4.3), (4.4) and (4.5), although the compressibility of the plug must also be taken into account. This model is suited for illustrating the movement of thermosetting solid polymer materials. The difficulty with the above model is that the thermodynamic processes that take place are ignored, particularly the temperature changes at the surfaces, caused by idle time. During idle time the solid polymer is heated, hence the temperature distribution changes. In a channel of finite length, where the parameter T_b is constant, the temperature changes are given by:

$$T = T_s + (T_b - T_s) \frac{y}{H} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{T_b \cos n\pi - T_b}{n} \cdot \sin \frac{n\pi y}{H} \exp\left(-\frac{k_m n^2 \pi^2 t}{H^2}\right) + \frac{2}{H} \sum_{n=1}^{\infty} \sin \frac{n\pi y}{H} \cdot \exp\left(-\frac{k_m n^2 \pi^2 t}{H^2}\right) \int_0^H T(y) \sin \frac{n\pi y}{H} dy \quad (4.121)$$

where T_b is the temperature of the barrel, T_s is the temperature of the screw, and $T(y)$ is the temperature profile developed in the dynamic section.

4.3.1.2 The Melting Process

In case of screw plasticating units with reciprocating mode of operation, idle time and the axial movement of the screw influence the melting process.

The basic processes that take place in reciprocating screw plasticating units are as follows:

- frictional movement of the solid polymer without back pressure (until the channel is completely filled);
- the processes in a) in the transition interval until a complete fill has taken place;
- the above process a) after this transition phase, until back pressure occurs at the metering entry zone;
- the transport of the melt layer in the melting zone;
- the movement of the solid polymer in the direction of the melt layer, in the melting zone;
- the movement of the polymer in the case of plug-like plasticating;

- g) lengthwise heat conduction along the barrel and the screw;
- h) radial heat conduction in the barrel and in the screw;
- i) heating of the solid polymer in the plasticating zone;
- j) heat transfer into the melt layer;
- k) heat transfer in the section filled by the melt in the melting and in the metering zone.

The deviations of these from steady state are caused by the periodic nature of the rotation of the screw and the movement of the screw in a direction of its axis. A deviation from the steady state is determined by the relationship between the time, characteristic of the process and the plasticating time, t_p .

Process *a*) lasts for an extremely short time $t(a) \approx 10^{-2}$, *b*) and *c*) last for a time $(0.1-0.2) t_p$. For process *d*), $t(d)$ is 0.5–1.0 s, while time *e*) is longer than the plasticating time. The changes occurring in the width and the height of the solid polymer, together with the thickness of the melt layer are characteristic of the entire plasticating process.

The duration of the heat conduction processes is given by:

$$t = \frac{L^2}{a}$$

where L is the length of the heat conduction in a relevant direction, and a is the thermal diffusivity. The data for process sections *g*) to *k*) are as follows:

	<i>g</i>)	<i>h</i>)	<i>i</i>)	<i>j</i>)	<i>k</i>)
L/R	30	1–0.5	0.005–0.1	$10^{-4} \dots 10^{-3}$	0.05...0.1
$a(m^2/s)$	$8 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	10^{-7}	10^{-7}	10^{-7}
$t(s)$	$10 \dots 10^2$	12–300	10–250	10^{-3}	10–250

It is apparent that process *g*) is of considerably longer duration than the plasticating and idle time, so that during the entire plasticating cycle, the temperature of the barrel, T_b and the temperature of the screw, T_s , are regarded as constants. Process *j*), in practice, leads immediately to a steady state in the melt layer. Hence, the velocity, v_y , may be derived from the data corresponding to a steady state. The processes *h*), *i*) and *k*) have approximately the same time durations as the plasticating time. According to estimates, the radial temperature changes in either the barrel or the screw do not exceed 2°C. This means that during the plasticating proper, temperature changes may be ignored all together. The process *i*) does not affect the temperatures of either the barrel or the screw. Process *k*), however, may exert a substantial influence upon the uniform temperature distribution, since $t(k) \approx t_p$ and heat convection and heat dissipation take place.

A movement of the screw in the direction of its axis results in changes in the useful length of the screw (L_s), and in the length of the channel ($L_s/\sin \Theta$). The change may reach a maximum of 3 D. The time for a total movement in the direction of the axis is t_p . This movement in the direction of the axis does not affect processes that take place in a time shorter than t_p .

The movement brings about a change in $T_b(z)$ and in $T_s(z)$, but, since the maximum movement does not exceed $3D$, for a coordinate system relative to the barrel, the change in T_b does not exceed 5°C and this does not lead to any substantial change in the melting processes.

The static sections exert the greatest effect upon the melting processes. On the effect of the increasing temperature of the solid substance, the start of the melting zone is shifted towards the feed hopper, and the thickness of the melt layers increases.

For the melting processes in the reciprocating plasticating units, models applicable are the melting processes at the barrel surfaces [33, 71 and 73] and the melting processes on the entire surface area [4, 74 and 75]. The melting processes should be studied by dividing these processes into two parts, firstly, the width and the thickness changes of the solid polymer in the dynamic section must be considered, secondly, the layer thickness changes, occurring in the steady-state section, must be calculated. The calculated and experimentally derived curves show reasonable agreement. Since the operation mode here is periodic, break-up of the polymer does not play any substantial role. In the static melt section the width of the solid bed changes.

The solid polymer-melt system is situated between the limiting value of $y=0$ and $y=\infty$, a semi-infinite space. The coordinates of the barrel surfaces and the screw surfaces correspond to $y=0$, the boundary values of the melt-solid interfaces are $y=y_0$. The movement velocity of the front of the melt is given by:

$$\frac{dy}{dt} = \frac{1}{\varrho_m A} \left(k_m \frac{\partial T_1}{\partial y} - k_s \frac{\partial T_2}{\partial y} \right) \quad (4.122)$$

where the first term in the brackets gives the quantity of heat entering at the interface of the melt and solid interfaces in unit time, the second term in the brackets represents the quantity of heat leaving the melt-solid interface. The heat conduction equation for the melt layer is:

$$\frac{\partial^2 T_1}{\partial y^2} = \frac{1}{\alpha_m} \frac{\partial T_1}{\partial t} \quad (4.123)$$

where $0 < y < y_0$. The boundary values of equation (4.123) are:

$$\begin{aligned} T_1 &= f_1(y), & \text{if } t=0 \\ T_1 &= T_b, & \text{if } y=0, \text{ and} \\ T_1 &= T_m, & \text{if } y=y_0 \end{aligned} \quad (4.124)$$

The heat conduction equation for the solid polymer is:

$$\frac{\partial^2 T_2}{\partial y^2} = \frac{1}{\alpha_s} \frac{\partial T_2}{\partial t} \quad (4.125)$$

where $y_0 < y < H$. The boundary values of the above equation are:

$$\begin{aligned} T_2 &= f_2(y), & \text{if } t=0 \\ T_2 &= T_m, & \text{if } y=y_0, \text{ and} \\ T_2 &= T_s, & \text{if } y=\infty \end{aligned} \quad (4.126)$$

The solution of this system of equations is:

$$y_0 = \beta \sqrt{t} \quad (4.127)$$

and

$$\frac{(T_1 - T_b)k \exp\left(-\frac{\beta^2}{4\alpha_m}\right)}{\sqrt{\alpha_m}\pi \left[1 - \operatorname{erf}\left(\frac{\beta}{2\alpha_m}\right)\right]} = \frac{(T_2 - T_m)k_s \exp\left(-\frac{\beta^2}{4\alpha_s}\right)}{\sqrt{\alpha_s}\pi \operatorname{erf}\left(\frac{\beta}{2\alpha_s}\right)} = \frac{\beta A Q_0}{2} \quad (4.128)$$

Equation (4.128) is solved by numerical iteration for the value of β , from this the movement of the melt front with time may be calculated from equation (4.127). At the beginning of the static melting process (i.e. when $t = t_0$), the initial melt layer thickness δ_0 is given by y_0 , which, in the case of a sufficiently long revolution time, is approximated by the melt layer thickness obtained in a steady state extrusion process. A static melt process extends to time $t_c - t_p = t_a$; the reference time t_0 is given by:

$$t_0 = \delta_0^2 \beta^2 \quad (4.129)$$

The thickness of the melt layer at the end of the static melt section is:

$$\delta(t_a) = \beta \left(t_a + \frac{\delta_0^2}{\beta^2} \right)^{\frac{1}{2}} \quad (4.130)$$

where t_a is the idle time of the screw. The width change caused by the static section is given by:

$$\frac{W_s}{W}(t_a) = \frac{W_s}{W}(t_p) \frac{H - \delta(t_0)}{H - \delta_0} \quad (4.131)$$

4.3.1.3 The Metering Zone in a Reciprocating Screw Plasticating Unit

Melt transport in the case of a reciprocating screw plasticating unit extends for the duration of the rotation of the screw and this differs from the melt flow of a plasticating unit of continuous mode of operation, since here the screw moves backward, the melt collects in front of the screw under pressure and the length of the metering zone gradually diminishes. At the end of the plasticating section the screw moves forward and the melt collected in front of the screw is pressed into the die, hence, at this point the metering zone is of minimum length. During idle time the polymer is heated by heat transfer from the surface of the barrel. This effect is largely compensated for by the changes in the temperature of the walls of the barrel, due to the movement of the screw in a reverse direction, provided that the plasticating time is sufficiently long. For purposes of approximation the models derived for a continuous mode of operation can be used [4].

The heating in the static phase may be calculated from the relationship:

$$T = T_b + \frac{2}{H} \sum_{n=0}^{\infty} \exp \left[-\frac{k_m (2n+1)^2 \pi^2 t}{4H^2} \right] \cos \frac{(2n+1)\pi y}{2H} \cdot \left[\frac{2H(-1)^{n+1} T_b}{(2n+1)\pi} + \int_0^H T(y) \cos \frac{(2n+1)\pi y}{2H} dy \right] \quad (4.132)$$

where $T(y)$ represents the temperature distribution at the end of the dynamic plasticating phase. The relationship (4.132) is applicable only for an elemental section, the magnitude of which may be determined, based on the initial conditions $T(z, y)$.

4.3.2 Plasticating of Thermosetting Polymers

Experimental studies show that thermosetting materials move in the channel of the plasticating unit in a plug-like fashion, in such a way that the movement is restrained by friction of the material against the walls, and in the bulk of the material shearing does not take place [31 to 33]. The phenomena that occur during extrusion of thermosetting plastics may be summarized as follows. The material, after entry into the screw channel via the feed hopper, proceeds via a plug-like movement. The heat entering from the surfaces of the barrel and the heat of friction at friction surfaces heat the polymer. As soon as the temperature of the polymer at the surface of the barrel exceeds the polymer melting point a melt layer is formed, followed by complete melting of the polymer material. The polymer, now in the fluid state, continues to move in a plug-like fashion. The screw section in which the polymer is in the molten state (L_p), is of variable length, depending on the pressure in front of the screw; with an increase in pressure the length of the plasticating section decreases. In the case of injection moulding the length of the plasticating phase changes from one cycle to the next, particularly where the back pressure is small. The average temperature of the polymer in the plasticating section fluctuates between wide limits, with increasing back pressures the average temperature increases and becomes stable at points of high pressure.

The first phase of the movement of thermosetting materials, the movement of the solid material, moving with some friction, is well described by the model of the solid material transport previously discussed. The plasticating phase is illustrated by the vector diagram shown in Fig. 4.9.

The friction of the melt layer against the walls is well characterized by the following relationship:

$$\tau_w = k V_w^m = k_0 e^{b/T} V_f^m \quad (4.133)$$

where τ_w is the shearing stress at the walls, V_w is the velocity of the melt at the walls, k , b and m are constants. This means that the shearing stresses in the plasticating zone do not depend upon the normal stresses, but are more dependent on the slip velocity along the walls. Since the melt layer near the walls is extremely thin, its average temperature is the same as that of the barrel.

In order to determine the relationship between the volume flow and the pressure gradient, it is best to commence from the momentum equation. The limiting values required for solving the system of equations are as follows:

$$\begin{aligned} x=0 \quad \sigma_{xz} &= k_1 V_1^m & x=W \quad \sigma_{xz} &= k_1 V_1^m \\ y=0 \quad \sigma_{yz} &= k_1 V_1^m & y=H \quad \sigma_{yz} &= \cos \Phi k_2 V_2^m \\ \sigma_{xy} &= 0 & \sigma_{yx} &= \sin \Phi k_2 V_2^m \end{aligned} \quad (4.134)$$

where $k_1 = k(T_b)$, $k_2 = k(T_s)$. It is assumed that the material entering the zone is sufficiently compacted for its density to be regarded as uniform, hence the angle of flow, Φ , may also be regarded as constant. This means that the volume flow rate is also constant at the z coordinates. The relationship between the volume flow and pressure gradient is:

$$\pi_p = J_2 (\cos \Phi - \pi_Q) (1 + \pi_Q^2 - 2\pi_Q \cos \Phi)^{\frac{m-1}{2}} - J_1 F_1 \pi_Q^m \quad (4.135)$$

where π_Q is the dimensionless volume flow rate, $\pi_p = \frac{\Delta PH}{V^m \mu_s \Delta z}$ is the dimensionless pressure gradient, and

$$F_1 = 2 \left(\frac{H}{W_s} \right) \left(1 - \frac{H}{D} \right) + \left(1 - \frac{2H}{D} \right).$$

The integrations J_1 and J_2 are the average temperatures corresponding to the channel section Δz

$$J_{1,2} = \frac{1}{\Delta z} \int_{z_1}^{z_2} \exp \frac{B}{T_{1,2}(z)} dz \quad (4.136)$$

where $T_1(z)$ and $T_2(z)$ are the respective melt layer temperatures at the screw and at the surface of the barrel. These two temperatures may be derived from the energy equation [33]:

$$T_{1z} = \frac{1}{2} \left\{ \frac{3B}{\ln \frac{4(T_{20} - T_0) \pi_Q 12 F_s^{-1} [1 - \exp(-12 F_s \pi_Q^{-1})] + F_4 + F_5}{F_3 \pi_Q^{m+1}}} - T_{10} \right\} \quad (4.137)$$

$$T_{2z} = \frac{1}{2} \left\{ \frac{3B}{\ln \frac{4(T_{20} - T_0) \pi_Q 12 F_s^{-1} [1 - \exp(-12 F_s \pi_Q^{-1})] + F_s - F_5}{F_3 (1 + \pi_Q^2 - 2\pi_Q \cos \Phi)^{\frac{m+1}{2}}}} - T_{20} \right\} \quad (4.138)$$

where

$$F_s = \frac{k \Delta z}{\rho C_v H^2 V}; \quad F_3 = \frac{V^{m+1}}{k} \mu_s H; \quad F_4 = 2F_1 (T_{1z} - T_{10});$$

$$F_5 = \frac{1}{3} (T_{10} - T_{20}) + 2(T_{1z} - T_{2z}); \quad F_6 = 2F_2 (T_{2z} - T_{20});$$

$$F_1 = \frac{k_m H(D-2H)}{4k\Delta z^2}; \quad F_2 = \frac{k_m H b_n^2}{kD\Delta z^2}$$

Equations (4.137) and (4.138) are solved by iteration, taking $F_4 = F_5 = F_6 = 0$ as the first approximation. By taking the value of Δz following the first approximation T_{1z} and T_{2z} take the places of T_{10} and T_{20} in the calculation and this process is continued until the end of the screw is reached.

Figure 4.35. shows the relationships between the pressure and the volume flow at various revolution numbers. The slope of the curves obtained is much less than that of the curves for the transport zone, the maximum ΔP , attainable at $\pi_Q = 0$, is smaller than the value attained at the end of the solid material transport zone. The transport capacity of the screw, π_Q at $\Delta P = 0$ rapidly decreases with an increase in the revolution number of the screw. The temperature of the melt leaving the screw channel is heavily dependent upon the revolution number and the mass flow.

Examination of the characteristic curves $Q-\Delta P$ showed that for a small pressure drop ΔP the volume flow rate increases proportionately with increasing revolution number, although in cases of large pressure drops the contrary was the case and initially the volume flow rate decreased with increasing revolution number. Figure 4.36. reveals that in the $Q-N$ curve the maximum is shifted towards the smaller revolution numbers with increasing ΔP . The explanation is that on the characteristic curve (Figure 4.35.) where the maxima of the $Q-P$ curves are depicted (dotted lines), these all fall into the region $\pi_Q < 0.15$, where the sliding velocity of the material on the surface of the barrel is some 5–6 times that of the sliding velocity of the material

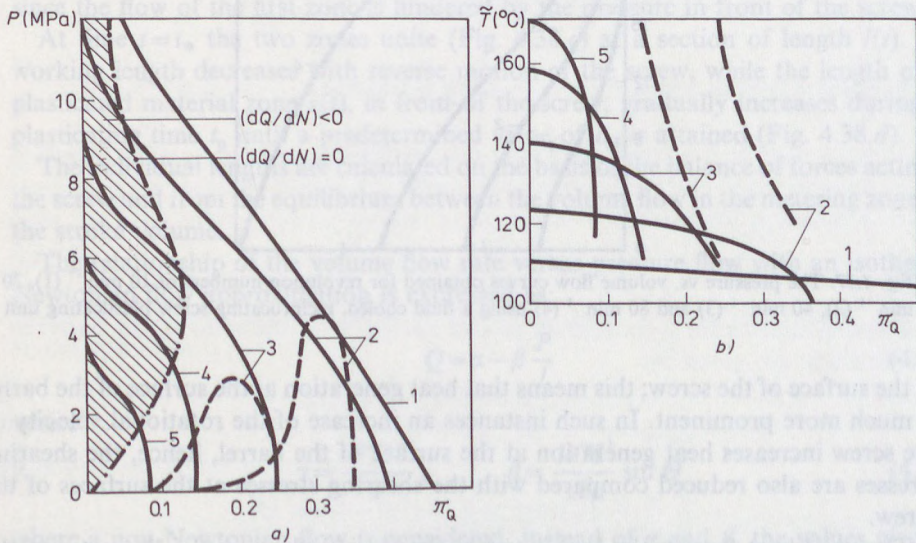


Fig. 4.35. Electrically heated, cyclic operation plasticating units; pressure vs. volume flow and temperature vs. volume flow curves obtained with thermosetting polymers as functions of the screw speed of 10 min^{-1} (1), 20 min^{-1} (2), 40 min^{-1} (3), 80 min^{-1} (4) and 120 min^{-1} (5). The dotted lines show the results of the isotherm calculations [63]

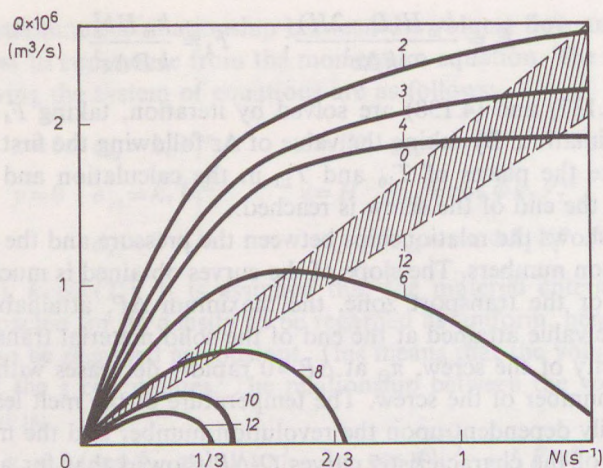


Fig. 4.36. The volume flow vs. revolution number curves obtained in an electrically heated, reciprocating screw plasticating unit at various back pressures

The numbers on the diagram represent the magnitude of back pressures, expressed in MPa. The shaded area represents the solid-conveying zone [63]

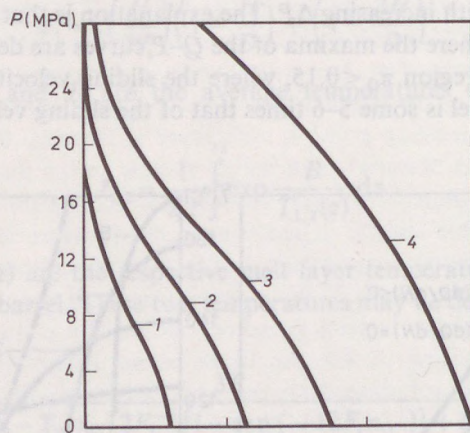


Fig. 4.37. The pressure vs. volume flow curves obtained for revolution numbers of 10 min^{-1} (1), 20 min^{-1} (2), 40 min^{-1} (3) and 80 min^{-1} (4) using a fluid cooled, reciprocating screw plasticating unit

at the surface of the screw; this means that heat generation at the surface of the barrel is much more prominent. In such instances an increase of the rotational velocity of the screw increases heat generation at the surface of the barrel, hence, the shearing stresses are also reduced compared with the shearing stresses at the surfaces of the screw.

The axial heat flow in the barrel and in the screw influences the character of the volume flow rate vs. pressure drop curves and the temperature of the melt leaving the screw channel. In Figure 4.35. the curves obtained without heat flow are depicted by the broken lines, clearly indicating the necessity to consider the effects of heat flow.

Figure 4.37. shows the relationship of pressure and volume flow, obtained with a fluid-heated plasticating unit heated with a fluid flow. In these units the maximum pressure ($Q=0$) does not decrease with increased revolution number(s) of the screw, on the contrary, the maximum pressure increases. Where such plasticating units are used, the temperature of the melt was observed to be dependent on the temperature of the screw to a lesser degree, compared with plasticating units heated electrically. The volume flow attainable with plasticating units heated by a fluid is considerably greater compared to plasticating units electrically heated. The reason for this is a more intense heat transfer across the surface of the barrel, and $T_b < T_s$ and change in this ratio due to changes in the revolution number is much less marked.

4.3.3 Plasticating of Caoutchouc Mixtures

A characteristic feature of plasticating caoutchouc mixtures is that the screw channel, during the entire process, is filled with a liquid-like, high-viscosity material, so that the aggregate state of the material in the entire process is practically uniform, thus the entire plasticating process may be characterized by a single model.

The flow of the caoutchouc mixture melts is shown in Figure 4.38. Following the start of the rotational movement (Fig. 4.38.a) the channel length filled with the caoutchouc mix will be $l_0 = L - L_d$, also considering the injected quantity in the preceding cycle, where L_d is the length of the stroke. During the rotational movement (Fig. 4.38.b) this section begins to shorten, and the added material forms a second section which moves forward at a faster rate than the material in the first zone, since the flow of the first zone is hindered by the pressure in front of the screw.

At time $t = t_*$ the two zones unite (Fig. 4.38.c) at a section of length $l(t)$. This working length decreases with reverse motion of the screw, while the length of the plasticated material zone $s(t)$, in front of the screw, gradually increases during the plasticating time t_p until a predetermined value of L_d is attained (Fig. 4.38.d).

The individual lengths are calculated on the basis of the balance of forces acting on the screw and from the equilibrium between the volume flow in the metering zone and the stroke volume.

The relationship of the volume flow rate versus pressure flow with an isothermal Newtonian flow approximation is expressed as:

$$Q = \alpha - \beta \frac{P}{l} \quad (4.139)$$

where

$$\alpha = \frac{WHV}{2}; \quad \beta = \frac{WH^3}{12\mu} \sin \Theta \quad (4.140)$$

where a non-Newtonian flow is considered, instead of α and β , the values given in equation (4.111) are used.

The apparent angular velocity of the barrel, based on Figure 4.37 is:

$$V_z = V \cos \Theta + V_l \sin \Theta; \quad V_x = V \sin \Theta - V_l \cos \Theta \quad (4.141)$$

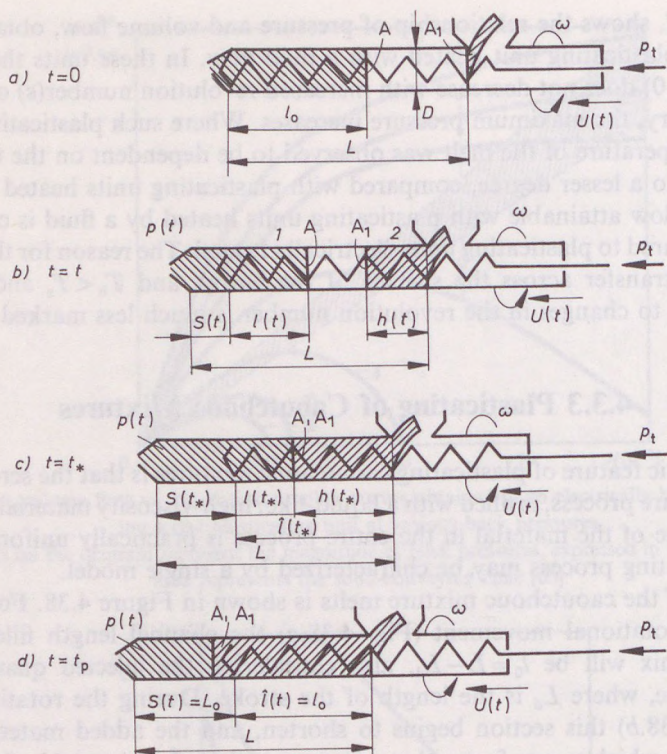


Fig. 4.38. Plasticating processes using caoutchouc mixtures

The shearing stresses along the walls of the barrel are:

$$\tau_{zy}|_{y=H} = \mu \left. \frac{\partial v_z}{\partial y} \right|_{y=H} = \mu \frac{V_z}{H} \frac{HP}{2l} \sin \Theta \quad (4.142)$$

and

$$\tau_{xy}|_{y=H} = \mu \left. \frac{\partial v_x}{\partial y} \right|_{y=H} = 4\mu \frac{V_x}{H} \quad (4.143)$$

The shearing stresses for a coordinate system parallel with the walls of the barrel in the λ direction are given by:

$$\begin{aligned} \tau_\lambda = \tau_{zy}|_{y=H} \sin \Theta - \tau_{xy}|_{y=H} \cos \Theta = \frac{P}{l} \cdot \frac{H}{2} \sin^2 \Theta - \\ - \frac{3}{2} \frac{\mu}{H} V \sin 2\Theta + \mu \frac{V_t}{H} (\sin^2 \Theta + 4 \cos^2 \Theta) \end{aligned} \quad (4.144)$$

The lengths of the channel sections are:

$$l(t) = l_0 - \sin \Theta \int_0^t v_z dt; \quad h(t) = \sin \Theta \int_0^t v_z dt + \int_0^t V_t dt \quad (4.145)$$

The mass balance between the space of the first zone and the tip of the screw is:

$$Q = \frac{\pi D^2}{4} V_t = v_z HW \quad (4.146)$$

from which

$$v_z \sin \Theta = -\frac{dl}{dt} = \frac{V(t)}{\Gamma_1}; \quad \Gamma_1 = \frac{4WH}{\pi D^2 \sin \Theta} \quad (4.147)$$

is derived.

The relationship of the force equilibria acting on the screw in the direction of its axis is given by:

$$\pi D [l(t) + \tau_\lambda h(t)] = \frac{\pi D^2}{4} [P(t) - P_t] \quad (4.148)$$

From the above system of equations the four unknown quantities, namely, $V_t(t)$, $P(t)$, $h(t)$ and $l(t)$ may be determined:

$$h(t) = \frac{V_t}{4} \sin \Theta + \left(1 - \frac{1}{2} \sin^2 \Theta\right) [l(t) - l_0] \Gamma_1 \quad (4.149)$$

$$l(t) = l_0 (1 - t/t_0)^{3/4}; \quad t_0 = \left[\frac{3}{2} (\sin^2 2\Theta \sin \Theta) \frac{\bar{V}\mu}{DHP_t} \right]^{-1} \quad (4.150)$$

$$\begin{aligned} P(t) \left(\frac{D}{4} - \frac{H}{2} \sin^2 \Theta \right) - \frac{D}{4} P_t = \\ = \left[\frac{\mu}{H} (\sin^2 \Theta + 4 \cos^2 \Theta) V_t(t) - \frac{3}{2} \frac{\mu}{H} V \sin 2\Theta \right] \times \\ \times \left\{ \left[1 + \Gamma_1 \left(1 - \frac{1}{2} \sin^2 \Theta \right) \right] l(t) + \left[l_0 \Gamma_1 \left(1 - \frac{1}{2} \sin^2 \Theta \right) + \frac{V_t}{4} \sin 2\Theta \right] \right\} \end{aligned} \quad (4.151)$$

The time $t = t_0$ designates the time when the length of the first zone is zero, thus, loading of the material does not take place via the feed hopper, hence the second zone does not exist either. The corresponding t_0 values are (from the equation 4.150):

$$10N^{-2} < t_0 < 10^3 N^{-2} \quad (4.152)$$

where N is the revolution number of the screw (in s^{-1}). The "clash time", t_* , may be derived from:

$$L = \int_0^{t_*} V_t(t) dt + h(t_*) + l(t_*) \quad (4.153)$$

based on the above relationship:

$$t_* \approx t_0 \frac{4(L/l_0 - 1)}{V(t_0/l_0) \sin 2\Theta} \quad (4.154)$$

the length of the channel filled with the material in this case is given by:

$$l_* = L - \Gamma_1 l_0 [1 - [1 - (t_*/t_0)]^{3/4}] \quad (4.155)$$

Continuing the plasticating process, the value of $l(t)$ decreases, while the value of $s(t)$ increases, hence:

$$V_t = dl/dt = l' \quad (4.156)$$

The relationship for the pressure in front of the screw is given by:

$$P = l \frac{12\mu}{H^2 \sin \Theta} \left(\frac{V \cos \Theta}{2} + l' \Gamma_1 \sin \Theta \right) \quad (4.157)$$

Taking the equilibria of the forces into account:

$$l_* - l + \bar{P}_t \ln \frac{l_* - \bar{P}_t}{l_* \bar{P}_t} = (t - t_*) \bar{V} \quad (4.158)$$

where

$$\bar{P}_t = P_t \frac{H^2}{\sigma \mu V} \operatorname{tg} \Theta; \quad \bar{V} = \frac{V}{2\Gamma_1} \operatorname{ctg} \Theta$$

The plasticating time $t_p = t$ (at $l = l_0$), thus, both the plasticating time and the pressure in front of the screw are determinable.

Figure 4.39. shows the calculated and measured positions of the screw, the pressure in front of the screw and the torque occurring due to the revolution of the screw. The agreement between these values, in spite of the assumed isothermal and Newtonian behaviour of the material, is quite satisfactory.

In precise examination of the temperature of the material it must also be taken into account that during injection moulding of caoutchouc mixes vulcanization also takes place in the die. Therefore the length of the idle time is longer than the time of plastication, so it can be assumed that the temperature of the material in the first zone is uniform and is approximately the same as the temperature of the walls of the barrel. Upon the start of rotation of the screw, the material in the first zone is deformed and moved forward simultaneously. The particles in the second zone join in this process upon entry into the screw channel.

The residence time in each of the zones is given by:

$$t_p = \begin{cases} t; & L - s(t) \geq z \geq z_1(t) & \text{1st zone} \\ \frac{z}{V_t}; & 0 \leq z \leq z_h(t) & \text{2nd zone} \end{cases} \quad (4.159)$$

where z_1 and z_h are the respective coordinates of cross-sections A and A_1 .

$$z_1 = \frac{L - [l(t) - s(t)]}{\sin \Theta}; \quad z_h|_{t < t_*} = \frac{h(t)}{\sin \Theta} \approx \frac{V_t t}{\sin \Theta} \quad (4.160)$$

$$z_h|_{t < t_*} = h_* + l_* - l(t)$$

In the examination of non-isothermal behaviour of the material, the term representing dissipation in the energy equation is taken into account as an average value, to obtain:

$$\rho C_p v_z \frac{\partial T}{\partial z} = k \frac{\partial^2 T}{\partial y^2} - \mu_1 \exp [-b(\tilde{T}(z)) - T_0] \left(\frac{V}{H} \right)^{n+1} \quad (4.161)$$

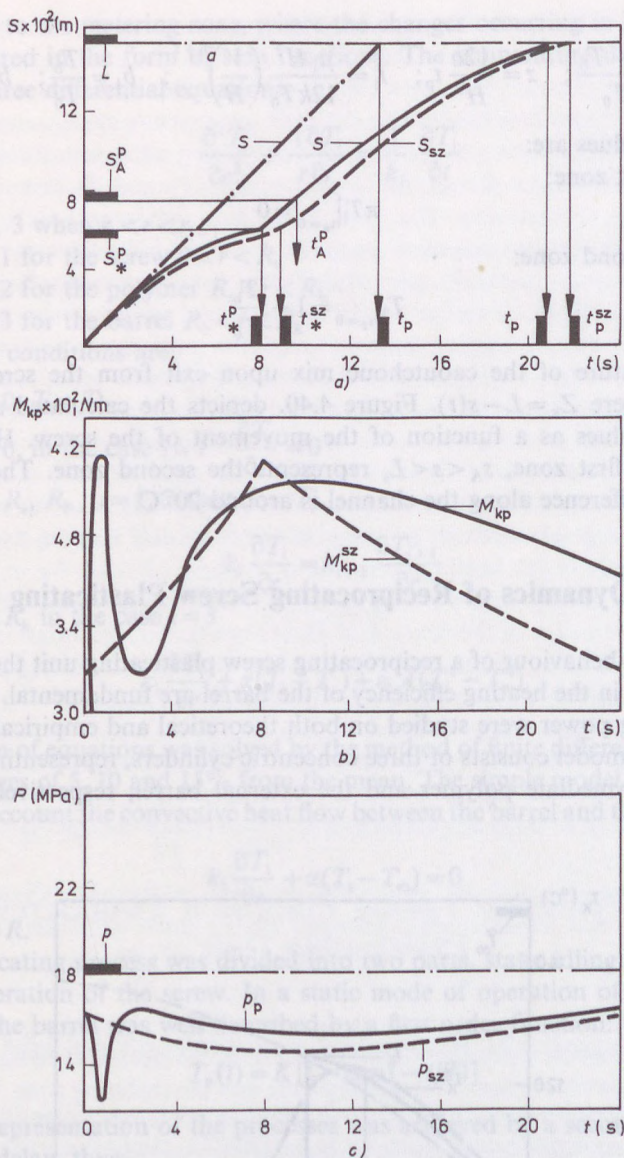


Fig. 4.39. Reciprocating screw plasticating units processing caoutchouc material [63]

a) Movement in direction of the axis as a function of time, b) The torque momentum of the screw as a function of time, c) The pressure changes in front of the screw as a function of time

rewriting this in a dimensionless form gives:

$$\frac{\partial \pi_T}{\partial z} = I_1 \exp[-b_0(\pi_T + b_1)] - \pi_T \quad (4.162)$$

where

$$\pi_T = \frac{T - T_b}{T_0}; \quad z = \frac{12a}{H^2} t_p; \quad I_1 = \frac{\mu_1 H^2}{12kT_0} \left(\frac{V}{H} \right)^{n+1}; \quad b_1 = \frac{T_b}{T_0}; \quad b_0 = \frac{b}{T_0}$$

The limiting values are:

— in the first zone:

$$\pi T_1|_{t_p=0} = 0$$

— in the second zone:

$$T_2|_{t_p=0} = 1 - \frac{T_b}{T_0} \quad (4.163)$$

The temperature of the caoutchouc mix upon exit from the screw channel is $T_k = T(Z_k)$, where $Z_k = L - s(t)$. Figure 4.40. depicts the calculated and measured temperature values as a function of the movement of the screw. Here, $0 < s < s_A$ represents the first zone, $s_A < s < L_s$ represents the second zone. The longitudinal temperature difference along the channel is around 20°C .

4.3.4 Dynamics of Reciprocating Screw Plasticating Units

In the dynamic behaviour of a reciprocating screw plasticating unit the disturbances due to changes in the heating efficiency of the barrel are fundamental. The effects of varying heating power were studied on both theoretical and empirical models [130, 131]. A simple model consists of three concentric cylinders, representing the internal screw, the intermediate polymer and the external barrel, respectively. Simulation

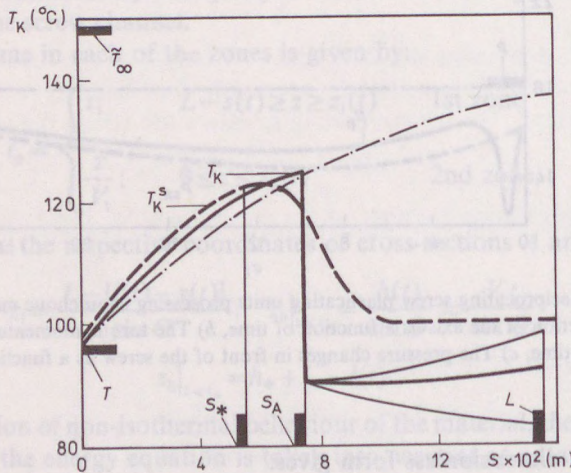


Fig. 4.40. Reciprocating screw plasticating units using caoutchouc material

The temperature of the material as a function of the length of the stroke. The dotted lines represent the calculated values [63]

extends only to the metering zone, where the changes occurring in heating capacity were considered in the form of step functions. The temperature distribution is described by three differential equations:

$$\frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r} \frac{\partial T_i}{\partial r} = \frac{1}{k_i} \frac{\partial T_i}{\partial t} \quad (4.164)$$

$t > 0$, $i = 1, 2, 3$ when $r_i < r < r_{i+1}$

— where $i = 1$ for the screw $0 < r < R_s$

$i = 2$ for the polymer $R_s < r < R_b$

$i = 3$ for the barrel $R_b < r < R_k$

— the initial conditions are:

$$t = 0, T_i = T_0,$$

$$r = 0, \text{ in the case } i = 1 \quad \frac{\partial T_i}{\partial r} = 0 \quad (4.165)$$

$$r = R_s, R_b \quad i = 1, 2 \text{ then } T_i = T_{i+1}$$

$$k_i \frac{\partial T_i}{\partial r} = k_{i+1} \frac{\partial T_{i+1}}{\partial r}$$

$$r = R_k \text{ in the case } i = 3$$

$$k_i \frac{\partial T_i}{\partial r} + \alpha(T_i - T_a) + \varepsilon_i A(T_i^4 - T_a^4)$$

The system of equations was solved by the method of finite differentials for heating output changes of 5, 10 and 15% from the mean. The simple model was modified by taking into account the convective heat flow between the barrel and the polymer, thus:

$$k_i \frac{\partial T_i}{\partial r} + \alpha(T_i - T_m) = 0 \quad (4.166)$$

provided $r = R$.

The plasticating process was divided into two parts, static idling of the screw and dynamic operation of the screw. In a static mode of operation of the temperature changes of the barrel was well described by a first order function:

$$T_b(t) = K[1 - \exp(-t/T)] \quad (4.167)$$

A better representation of the processes was achieved by a second order member with a time delay, thus:

$$T(t) = K \left[1 - \frac{T_1 T_2}{T_1 + T_2} \left[\frac{1}{T_2} e^{-\frac{(t-A)}{T_1}} - \frac{1}{T_1} e^{-\frac{(t-A)}{T_2}} \right] \right] \quad (4.168)$$

This behaviour is explained by considering that at the interface of the barrel with the heating elements in contact a considerable temperature gradient is developed, which influences the heat transfer to the barrel, and the heating and cooling of the barrel take place by different mechanisms; heating involves heat conduction, cooling includes heat transport and heat radiation.

The agreement between the theoretical and the experimental model is quite satisfactory.

In the dynamic operational mode, the changes in the temperature of the barrel could be described by a first order term, the melt temperature changes were described by a second order term with a time delay, as was the case when a static operation was considered. Here the gain K and the time constants T_1 and T_2 were smaller than in the static mode of operation. The rotation of the screw increases the rate of heat transfer, this decreases the response time, the portion of the material removed by injecting carries away a certain quantity of heat, hence, the steady-state gain is necessarily smaller. The theoretical model again agreed with experimental results.

The effects of stochastic heating output changes for both static and dynamic modes of operation were studied, the gain and the time constants obtained were compared and reasonable agreement was found between them.

The interactions of the various heating zones were also examined. It was found that changes in the heat output of the melting zone exerted a greater influence on the temperature of the melt than the changes in the heating output in the metering and the solids conveying zones. Thus, a change in the output of heating causes changes in temperature only in the heating zone.

Changes in the back pressure at the tip of the screw brings about changes in the axial velocity of rotation of the screw and causes changes in the rotation time of the screw. The result is that the screw influences the temperature of the melt. A temperature change quickly follows the change in pressure, even though the temperature change may be small (a maximum of 5°C).

The reason for this small change lies in the small influence of dissipation. The Brinkmann number is directly proportional to the square of the velocity, which means that in the operation of large machines greater temperature changes can be expected.

4.4 Processes Taking Place in a Twin-Screw Plasticating Unit

It was demonstrated earlier that the actual twin-screw plasticating units are the intermeshing twin screw extruders. The characteristic features of twin-screw units are again the solids conveying zone, the melting zone and the metering zone. The first two zones, but especially the melting zone of the twin-screw plasticating units are usually considerably shorter than in the single-screw plasticating units. The processes in the twin-screw plasticating units are governed primarily by the mode of operation, the volume of the chamber and the size of the gaps [105–115].

4.4.1 The Solid Conveying in a Twin-Screw Plasticating Unit

One of the characteristic features of a twin-screw plasticating unit is the forced transport. The two screws, rotating in opposite directions, transport the polymer granulation towards the centre of the gap between the screws, it is substantially

compacted and passed into the melting zone. The solid material transport here takes place in a closed, C-shaped chamber. The efficiency of the transport is greatly dependent upon the degree of fill of the chamber. Pressing and forcing the material through the calender gap is accompanied by considerable wear of the screws. In plasticating units where the screws are rotated in the same direction, the solid material, compacted by one of the two screws is transferred to the other screw before entry into the melting zone.

In the single-screw plasticating unit a continuous solid material bed is formed, while in the twin-screw plasticating units the solid material transport zone is repeatedly divided by the intermeshing of the other screw. Apart from the granules or the powder, a considerable quantity of air is also present in the hopper and the pressure difference between the chambers is small. The material changes in the separate chambers only slightly. Material transport is governed by the speed of rotation of the flight of the screw. In the solid material zone, the temperature of the screw must be maintained below the softening temperature of the polymer, otherwise the polymer adhering to the screw would rotate with the screw through the calender gap and side gaps of the calender and this would greatly reduce the material transport.

The mass flow of the solid material is given by:

$$Q_s = 2iNV\Phi \quad (4.169)$$

where i is the number of flights, N is the revolution number, V is the volume of the chamber and Φ is the degree of fill of the chamber.

The movement of the solid material is a forced flow with a flow angle of 90° , thus, a simplified form of the equation (4.7) holds true for the increase of pressure:

$$\frac{dP}{dz} = P \frac{f_s}{HW} [2H + W(1 + f_b)] \quad (4.170)$$

The solution of this equation, due to the difficulties in defining the initial conditions, presents a problem. The value of the pressure directly under the hopper may be employed here (equation 4.4).

4.4.2 Melting Processes in a Twin-Screw Plasticating Unit

As the material enters from the hopper in the form of a powder or granules, at a certain point it begins to heat up, melting of the material commences and, depending on the conditions, the melting process continues without the melt completely filling the available space in the chambers. The melt moves in the direction of the die, while the air moves in the reverse direction. The melt reaches a point where pressure develops and from this point onwards the chambers are completely filled with the melt. The melting processes take place similarly to the case in the single-screw plasticating units [105–110].

The individual stages of the melting processes are these:

- a film of melt is formed on the surface of the barrel then on the surfaces of the screws,

- a melt zone develops from the melt film in the chambers,
- the width of the solid polymer gradually decreases with increasing width of the melt pool.

Several variations of the melting processes may be observed in twin-screw plasticating units. The solid polymer is either pushed to the pushing flight of the screw or towards the trailing flight of screw, or else, the solid polymer may remain in the centre of the chamber. The melting processes are greatly influenced by the gaps of the twin-screw plasticating unit and by the construction and mode of operation of this unit. In cases of intermeshing, counter-rotating plasticating units, the movement of the screw, for example, may develop a vortex in the melt, which carries away solid material particles. The melt, passing through the calender gap is accumulated at the trailing flight of the screw, and the solid polymer is pushed towards the active flight of the screw.

In twin-screw plasticating units the length of the melting zone is generally very short, approximately equal to the diameter of the screw. The reduction in the width of the solid bed takes place in one of the chambers, however, the same phenomenon is observed in all the chambers of the melting zone. The length of the melting zone is independent of the screw speed, but it is highly dependent upon the pressure at the die, and the beginning of the melting zone greatly depends on the velocity of the screw. The pressure at the die also influences the mechanism of the melting processes. One of the principal differences between the melting processes of the single screw, versus the twin-screw plasticating units is that in the latter case fluctuations associated with break-up of the solid polymer do not take place, due to the absence of a continuous solid polymer bed. The whole melting process is influenced by the rapid compaction of the solid polymer and by its deformation in the calender and lateral gaps, since the liberated heat of dissipation helps the melting processes to begin, hence, the melting process takes place predominantly on the surfaces of the screws.

As the polymer proceeds in the plasticating unit, the polymer is compacted and becomes deformed in the calender gap. The processes are very similar to the processes in calendering.

The concept of mass balance is equally applicable to the twin-screw plasticating unit:

$$\varrho_m Q = \omega_b (2H_s + W_s) + \omega_s l = \omega \quad (4.171)$$

where ω is the overall melting rate, representing the combined melting rate at the surfaces of the barrel and that of the screws. The melting rate at the barrel surface ω_b may be calculated in a similar way as for single-screw plasticating units:

$$\omega_b \approx \varrho_m \left(\frac{\pi k_m W_s DN \sin \Theta}{S f_b} \right)^{\frac{1}{2}} \quad (4.172)$$

The melting rate at the surfaces of the screw is given by:

$$\omega_s = \varrho_m \left(\frac{\pi k_m DN l_s}{S f_s} \right)^{\frac{1}{2}} \quad (4.173)$$

Taking into account the fact that $Q = H_s W_s \, dl_s/dt$ holds true, where l_s is the length of melting along the surfaces of the screw, the length of the melting zone from equations (4.171–4.173) is derived as:

$$l_s = \left(\frac{2Sf H_s^2 N}{k_m} \right) W \ln 5 \quad (4.174)$$

4.4.3 Melt Transport in a Twin-Screw Plasticating Unit

The task assigned to the metering zone, as for the single-screw plasticating unit, is to homogenize the melt. The volume flow rate in the metering zone is governed by the screw speed, by the volume of the chamber and by the leakage flow at the gap. Figure 4.41 shows the various flow patterns for twin-screw plasticating units. The volume flow rate is given by:

$$Q = Q_{th} - \sum Q_r - Q_l \quad (4.175)$$

where Q_{th} is the maximum theoretical volume flow rate, calculated from the volume of the chamber and the screw speed. $\sum Q_r$ represents the sum of the leakage flow rates in the screw channel, while Q_l represents the leakage flow rate in the clearance between the surface of the barrel and the flight of the screw. Volume flow rate calculations are usually based on the assumption of Newtonian behaviour of the melt, since, due to the particular mode of operation of the twin-screw plasticating units, the shearing rates are low. The mode of operation affects the flow characteristics in the screw channel. The theoretical volume flow rate is given by:

$$Q_{th} = iN(2\pi - \Theta) (\pi D \operatorname{tg} \Theta - e) - 2\pi H(E - ie) \cdot \left[D \left(1 - \frac{\cos^2 \Theta}{2} F_d F_c \right) - H \right] N \quad (4.176)$$

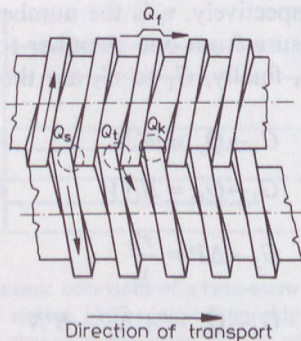


Fig. 4.41. The melt flow of a twin-screw plasticating unit

The flow rate in the gaps of the screw channel is:

$$\sum Q_r = 4Q_s + 2Q_k \quad (4.177)$$

where Q_s represents flow rate in the side gap, while Q_k is the flow rate at the calender gap. The various leakage flows in the gaps were given in Table 4.13.

The power law applicable to non-isothermal melt flow in a C-shaped channel, the increase of pressure as a function of the length of the channel, l_c , is expressed by the equation:

$$\Delta P = \frac{C_v Q \varrho (T - T_0)}{V_1 H W \varepsilon} \quad (4.178)$$

The temperature is:

$$T = \frac{1}{b} \ln \left\{ \frac{\mu_0 H W \varepsilon b \left(\frac{m}{A_k} \right)^n}{C_v Q \varrho} \left[(1-e) \left(\frac{V_1}{H} \right)^n \right] \right\} z + \exp(bT_0) \quad (4.179)$$

where

$$e = \frac{V_1}{V_2}; \quad \varepsilon = \frac{1 - (1-e) Y_0}{\cos \Theta}; \quad m = \frac{1+n}{n}$$

$$A_k = (1 - Y_0)^m - Y_0^m$$

The values of Y_0 may be calculated from the relationship:

$$\frac{1}{A_k} [(1 - Y_0)^{m+1} + Y_0^{m+1} - (m+1) Y_0^m] + \frac{1+2n}{n} \frac{e}{1-e} = 0 \quad (4.180)$$

4.4.4 The Dynamics of a Twin-Screw Plasticating Unit

The dynamic features of the twin-screw plasticating unit are summarized in Figure 4.42., based on [126]. The block diagram of the dynamic system is shown in part (a) of the Figure. The letter N represents the revolution number of the screw, Q_{th} , Q_s , Q_0 , Q_r represent the theoretical volume flow, that of the solid material transport, of the real and gap flows, respectively, v_f is the number of chambers filled with the melt, ΔP is the drop in pressure from one chamber to the neighbouring chamber, P_d is the pressure in the die, finally, G_1 to G_7 are the transfer functions, listed as follows:

$$G_1 \rightarrow Q_s = \Phi' N$$

$$G_2 \rightarrow Q_{th} = 2iNV$$

$$G_3 \rightarrow \Delta P = \frac{P_d}{v_f}$$

$$G_4 \rightarrow Q_r = A' \Delta P - B' N$$

$$G_5 \rightarrow Q_0 = Q_{th} - Q_r$$

$$G_6 \rightarrow P_s = \frac{Q_0}{C'} \quad (4.181)$$

$$G_7 \rightarrow \frac{dv_f}{dt} = \frac{(Q_s + Q_r - Q_{th})}{V - \Phi/2i} = \frac{Q_s + Q_0}{V - \Phi'/2i}$$

where A' and B' represent constants, Φ' the feeding coefficient of the solid material, and C' is the reciprocal value of the die resistance.

The changes occurring in the various parameters due to steady state disturbances are given below:

$$\Delta Q_s = \Phi'_s \Delta N + N_s \Delta \Phi'$$

$$\Delta Q_s = 2iV\Delta N$$

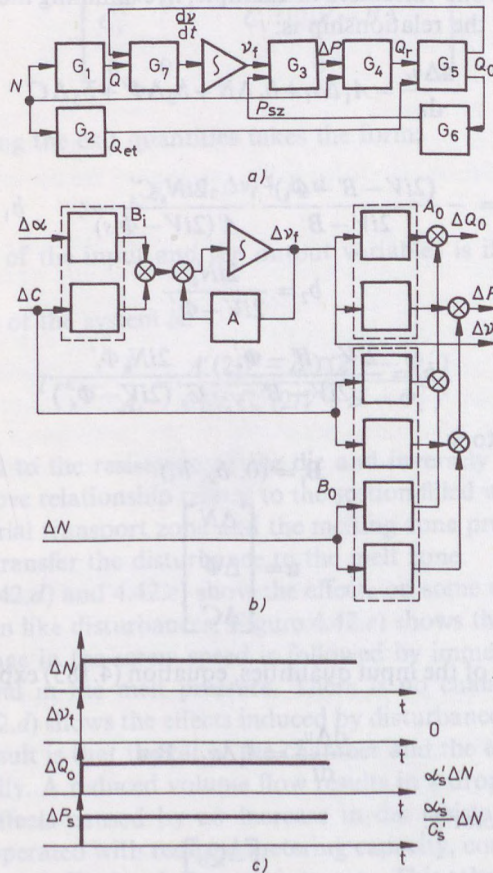


Fig. 4.42. The dynamic behaviour of a twin-screw plasticating unit [126]

a) Block diagram of the dynamic system, b) The interrelationship of the input and the output variables of the system, c) The effect of a change in revolution number on the volume flow, on the pressure at the die, and on the chambers filled with the melt

$$\Delta(\Delta P) = \frac{1}{v_{f,s}} \Delta P_s \frac{P_{d,s}}{v_{f,s}} \Delta v_f$$

$$\Delta Q_r = A' \Delta(\Delta P) + B' \Delta N \quad (4.182)$$

$$\Delta Q_0 = \Delta Q - \Delta Q_r$$

$$\Delta P_s = \frac{\Delta Q_0}{C'_s} - \frac{Q_{0,s}}{C'^2_s} \Delta C'$$

$$\frac{d\Delta v_f}{dt} = \frac{\Delta Q_s - \Delta Q_0}{V - \Phi' / 2i}$$

where subscript s refers to steady state conditions, while Δ represents the deviation from the steady state value. The equations are mutually interdependent, hence, it is possible to eliminate one variable. For example, in examining the number of chambers filled with the melt, the relationship is:

$$\frac{d\Delta v_f}{dt} = A_1 \Delta v_f + b_1 \Delta N + b_2 \Delta \Phi' + b_3 \Delta C' \quad (4.183)$$

where

$$A_1 = - \frac{(2iV - B' - \Phi_s)^2}{2iV - B} \cdot \frac{2iN_s C'_s}{A'(2iV - \Phi'_s)}; \quad b_1 = 0,$$

$$b_2 = \frac{2iN_s}{2iV - \Phi'_s} \quad (4.184)$$

$$b_3 = \frac{2iV - B' - \Phi'_s}{2iV - B'} \cdot \frac{2iN_s \Phi'_s}{C'_s(2iV - \Phi'_s)}$$

Introducing the vectors:

$$\mathbf{B}_i = (0, b_2, b_3)$$

$$\mathbf{u} = \begin{bmatrix} \Delta N \\ \Delta \Phi' \\ \Delta C' \end{bmatrix} \quad (4.185)$$

where $\mathbf{u}$ is the vector of the input quantities, equation (4.183) expressed in vector form gives:

$$\frac{d\Delta v_f}{dt} = A_i \Delta v_f + \mathbf{B}_i \mathbf{u} \quad (4.186)$$

Defining the exit vector $\mathbf{y}$:

$$\mathbf{y} = \begin{bmatrix} \Delta Q_0 \\ \Delta P_s \\ \Delta v_f \end{bmatrix} \quad (4.187)$$

and the following coefficient matrices:

$$A_0 = \begin{bmatrix} \frac{N_s C_s'}{A'} & \frac{(2iV - B' - \Phi_s')^2}{(2iV - B')} \\ \frac{N_s}{A'} & \frac{(2iV - B' - \Phi_s')^2}{(2iV - B')} \\ 0 & 1 \end{bmatrix} \quad (4.188)$$

and

$$B_0 = \begin{bmatrix} \Phi_s' & 0 & \frac{\Phi_s' N_s (2iV - B' - \Phi_s')}{C_s' (2iV - B)} \\ \frac{\Phi_s'}{C_s'} & 0 & \frac{\Phi_s^2 N_s^2}{C_s'^2 (2iV - B')} \\ 0 & 0 & 0 \end{bmatrix} \quad (4.189)$$

the function expressing the exit quantities takes the form:

$$y = A_0 \Delta v_f + B_0 u \quad (4.190)$$

The interconnection of the input and the output variables is illustrated by Figure 4.42.b).

The time constant of the system is:

$$T = -\frac{1}{A_1} = \frac{A' (2iV - B') (2iV - \Phi_s')}{2iN_s C_s' (2iV - B' - \Phi_s')^2} \quad (4.191)$$

directly proportional to the resistance of the die and inversely proportional to the screw speed. The above relationship relates to the section filled with the melt. At this point the solid material transport zone and the melting zone produce a certain time delay, necessary to transfer the disturbance to the melt zone.

Figures 4.42.c), 4.42.d) and 4.42.e) show the effects on some of the parameters by induced step function like disturbances. Figure 4.42.c) shows the effect of change in screw speed. A change in the screw speed is followed by immediate changes in the volume flow rate and in the melt pressure. There is no change in the fill of the chamber. Figure 4.42.d) shows the effects induced by disturbances in the feed of solid material. The net result is that the fill of the chamber and the exit volume flow rate decrease exponentially. A reduced volume flow results in a drop of pressure. Figure 4.42.e) shows the effects caused by an increase in die resistance. As long as the plasticating unit is operated with reduced metering capacity, compared with its total input capacity, the length filled with the melt increases. This takes place in such a way that the pressure drop between the chambers decreases further, the flow at the gap slowly decreases, while the volume flow tends towards a stable value.

4.5 Control Methods to Influence the Quality of the Melt

From the preceding it is clear that the aim of control application to a plasticating unit is to secure a melt of suitable quality. This is achievable by keeping the temperature, the pressure and the volume flow of the melt constant. By keeping the mass flow and the properties of the material constant and by application of a constant pressure and temperature it is possible to obtain a melt of the required quality. The methods employed to control the quality of the melt are:

- a) control of the temperature of the melt,
- b) control of the pressure of the melt,
- c) control of the viscosity of the melt.

Of these, the most widespread method for controlling the quality of the melt is that of temperature control. The other two methods are supplementary control methods. Control may entail individual adjustments or computer control (DDC). The latter is generally employed to control various production lines (such as sheet, tube extrusion and blow-moulding processes). The practicable control strategies [101] are:

a) Application of a small computer for purposes of process control; the data of previously-made products are stored in the memory of the computer on which control application is based.

b) Employment of a large computer to carry out all the tasks listed above together with functions to control velocities, zone temperatures and screw temperatures. This implies digital control based on a suitable algorithm.

c) Application of a large computer for all the above purposes together with cascade type of temperature control. In this case the computer is capable of adjusting near-optimum control values based on predetermined temperature profiles. Control of the plasticating units are subdivided according to the continuous or periodic mode of operation; it makes little difference whether single-screw or twin-screw processes are employed.

4.5.1 Quality Control of the Melt of Continuous Screw Plasticating Units

4.5.1.1 Methods of Temperature Control

Temperature control of a plasticating unit may be achieved by:

- simple wall temperature control,
- simple control of the temperature of the material used,
- cascade control (based on the temperature and the viscosity of the material),
- autogenous temperature control,
- direct digital computer control.

The above methods are summarized in Figure 4.43.

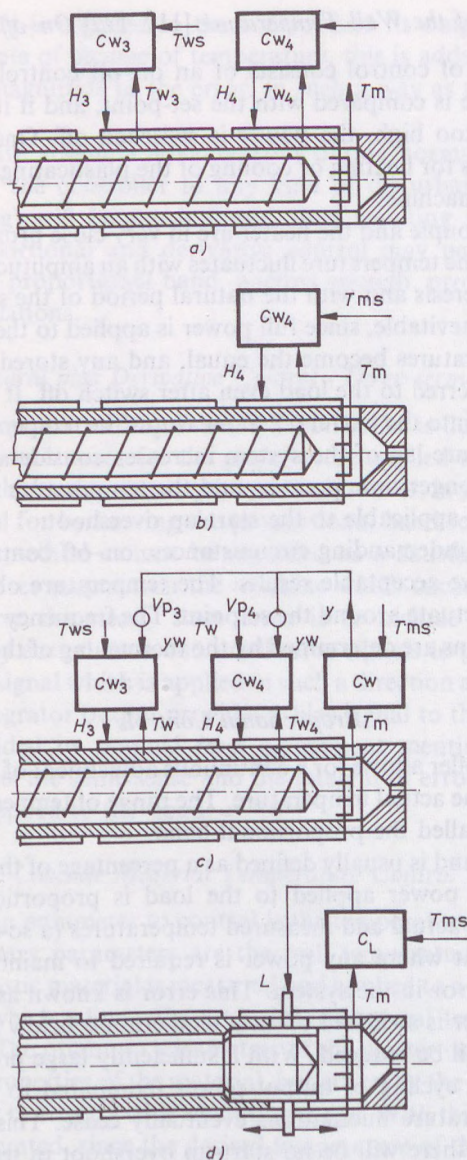


Fig. 4.43. Temperature control processes of plasticating units

a) Wall temperature controls of the barrel, b) Simple material temperature controls, c) Cascade material temperature controls, d) Autogenous material temperature controls, H_3 and H_4 represent the heating power of the barrel C_{w3} , C_{w4} , C_{w3} , C_{w4} , C_w and C_L , are controls, T_m is the temperature of the material, T_{w3} and T_{w4} are the temperatures of the walls of the barrel

The simplest form of control consists of an on-off control of load power. The measured temperature is compared with the set-point, and if it is too low, power is switched on, if it is too high, the power is switched off. One of the problems of applying such controls for heating or cooling of the plasticating unit is the significant thermal lag in these machines.

Where the thermocouple and the heater are in very close proximity, i.e. there is no appreciable time lag, the temperature fluctuates with an amplitude somewhat in excess of the controller hysteresis and with the natural period of the system. Overshoot on start-up seems to be inevitable, since full power is applied to the load until the preset and the actual temperatures become the equal, and any stored energy in the heater continues to be transferred to the load even after switch off. It is obvious that if the thermocouple is deep into the barrel (i.e. it measures the temperature of the melt very closely), the temperature lag of the system increases considerably, the temperature fluctuation cycles in longer time periods, and the temperature variations are larger. Similar comments are applicable to the start-up overshoot.

Thus, in relatively undemanding circumstances, on-off controller with a shallow thermocouple may give acceptable results. The temperature obtained by an on-off controller tends to fluctuate around the setpoint. The frequency and the amplitude of temperature fluctuations are determined by the thermal lag of the particular machine.

Proportional Controls

Proportional controller allows for a continuous adjustment of the level of the power input, depending on the actual temperature. The range of temperature over which the power is adjusted is called the proportional band.

The proportional band is usually defined as a percentage of the controller set-point scale span. Since the power applied to the load is proportional to the error or difference between the actual and measured temperatures (a so-called error-actuated system), it follows that where any power is required to maintain the temperature, there must be some error in the system. This error is known as offset or droop. On start-up the load power is switched off at a temperature below the set-point and the resultant overshoot will be reduced. With a sufficiently large proportional band and with sufficiently rapid cycling of output power (compared to the system's natural frequency), the temperature fluctuations eventually cease. This, however, does not necessarily mean that there will be no start-up overshoot in temperature, it merely means that subsequent oscillation will decay to zero amplitude.

Proportional and Derivative Control (PD)

One way to overcome the initial overshoot in a proportional-only control system would appear to be to widen the proportional band sufficiently, but the control would then be too "sloppy". A significant reduction in overshoot can be achieved (while still maintaining a sufficiently narrow proportional band to provide stable control) by adding a so-called "derivative" term (D) to the controller.

A differential circuit is coupled to the control and its output with a magnitude proportional to the rate of change of temperature, this is added to the signal, being proportional to the magnitude of the error, in such a way as to try to minimise the rate of change.

Obviously, derivative action is advantageous during normal machine operation, since the reaction of the controller to any kind of disturbance (such as machine starting and stopping) will be much faster, thus resulting in tighter control. A combination of proportional and derivative control may permit the use of deep thermocouples and a proportional band, narrow enough, provide tolerable control for undemanding situations.

Proportional plus Integral plus Derivative Control (Three-term or PID Controls)

The limited accuracy provided by P and PD controller is due to the fact that it is necessary to have a certain error for the power to be applied to the load. This error varies, depending on the load power requirements, however, in steady state conditions it can be compensated for by moving the proportional band relative to the set-point (manual reset). This method cannot be regarded as a satisfactory approach since many external influences may act on the machine which cause the error to change.

One way to remove the steady state error is to include an integrator in the controller. This slowly accumulates the small error signals to give out, eventually, a larger power-control signal which is applied in such a direction as to reduce the errors. The action of the integrator output provides a bias signal to the power output stage similar to that provided by manual reset adjustment mentioned previously. The proportional error acts the same sense and the integral of errors simply adds to the output power thus applied to the load.

Cascade Material Temperature Control

In this case the main parameter to control is the temperature of the material itself, while the supplementary parameters are the wall temperatures of the barrel. The temperature of the plastic material is measured and applied to a continuous controller (master controller), which adjusts the set-points of several temperature controllers built into the barrel. The optimum parameters of the master controller vary with the throughput and the properties of the material, but generally the adjustment of a single parameter is sufficient to cover a wide operating range. With this control, the start-up of processing is accelerated, since the desired temperature of the material is attained within a shorter time and maintained close to the desired value. When heating up the machine, the master controller is disconnected and the controller must operate at fixed set-points. This mode of operation may be simplified by an arrangement where the set-points are adjusted separately, using temperature controllers built into the barrel.

Figures 4.44. and 4.45. depict cascade control systems relevant to a single- and a twin-screw plasticating unit, respectively. The subsidiary controllers are PD controllers in the overall controller to ensure rapid operation. The main controller is a PI controller to provide total compensation. The control system utilizes the temperature

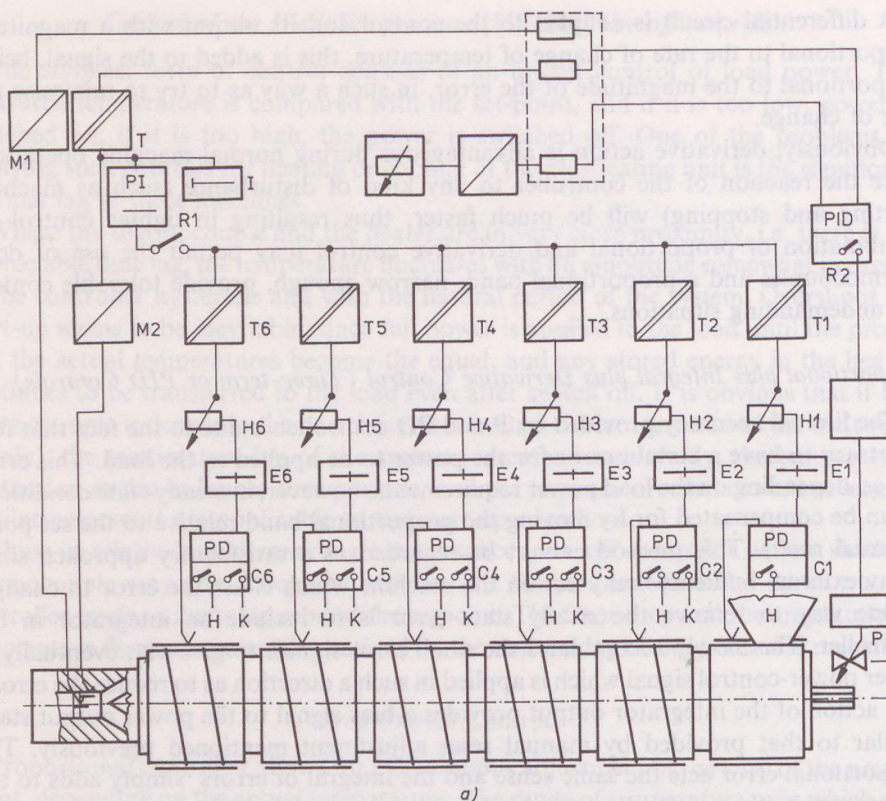


Fig. 4.44. Cascade temperature controls, single-screw plasticating unit

M_1 and M_2 are the material temperature gauges, C_1 to C_6 are controls assigned to control the temperatures of the barrel surfaces, H_1 to H_6 are manual control adjustment knobs, T_1 to T_6 are amplifiers, R_1 and R_2 are conduction controls, H =heating, K =air cooling, P =cooling of the screw

of the material as the basis for control and changes the temperature of the barrel by heating or cooling. In single-screw plasticating units the barrel can be cooled with air or water and the screw itself is cooled by air circulation. In twin-screw plasticating units both the barrel and the screw may be cooled by oil circulation [123].

Autogenous Control of the Temperature of the Material

The essence of autogenous temperature control is that the temperature of the material is maintained between the limiting values by varying the quantities of dissipated heat. Apart from the use of dissipation heat, the temperature of the barrel surfaces can also be adjusted, thus a cascade control system has been developed. Figure 4.46. illustrates some autogenous material temperature control methods [124]. Part a) shows a conical-shaped gap. This gap affects the temperature of the material considerably faster than the temperature of the barrel. The resistance and the influence of the gap on the temperature is proportional to the length of the gap. In this

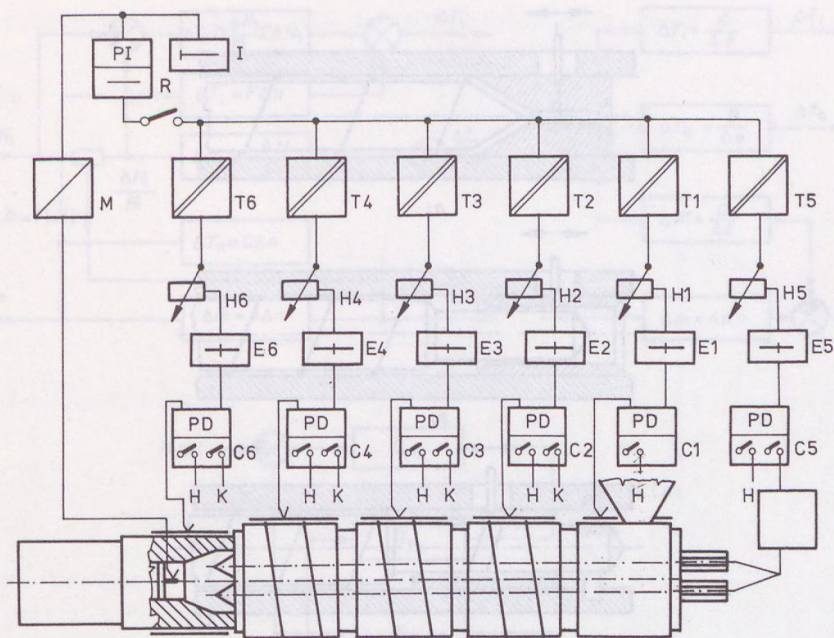


Fig. 4.45. Cascade temperature controls, twin-screw plasticating unit
The letters have the same meaning as in Fig. 4.44.

method problems arise because of the non-linearity of the characteristics. Part *b*) of the diagram shows a solution where the resistance of the shearing gap is adjusted by altering the length of the shearing gap. A linear relationship exists between the length of the shearing gap and the increase in the temperature of the material [125]. The length of the shearing gap is adjustable by means of a moving sleeve.

Figure 4.47. shows two different block diagrams of two autogenous temperature control systems, part *a*) of this Figure describes the system shown in Figure 4.46.*a*), and *b*) describes the system depicted by Figure 4.46.*b*).

Let us examine briefly the system shown by Figure 4.48. The output values of the controller are the values of the r.p.m. of the screw and the length of the shearing gap. The length of this gap influences the pressure and temperature in front of the die, and the screw speed also affects the pressure and the temperature. The values of the controller output represent the pressure and the temperature of the material, disturbing parameters are the temperature changes (which may be brought about by fluctuations in voltage and the temperature variations of the material fed into the system, etc.) and the changes in the properties and in the material used. Assuming that the controller is a linear transfer system, the relationship between the input and output values will be:

$$x(t) = \int_0^t g(t-\tau) y(\tau) d\tau \quad (4.192)$$

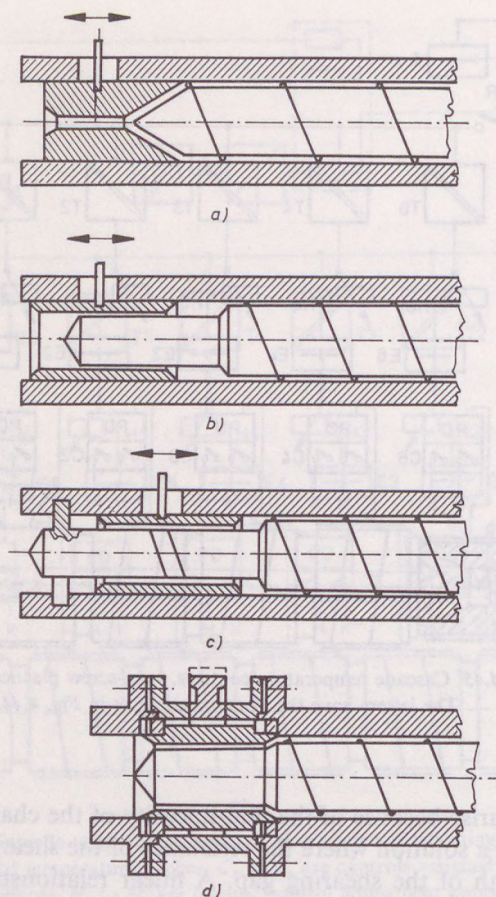


Fig. 4.46. Autogenous material temperature control methods [143]

- a) Conical shaped gap, b) Cylindrical shaped gap, c) Cylindrical shape gap with a rotating torpedo, d) Rotating screw tip

The transfer function is given by Laplace transformation of equation (4.192):

$$X(t) = G(p) Y(p) \quad (4.193)$$

where $X(t)$ and $Y(t)$ are the Laplace transforms of the input and output signals.

For the system depicted in Figure 4.46.b), equation (4.193) will yield by the relationships:

$$\begin{aligned} \mathcal{L}\{P_m(t)\} &= P_m(p) \\ \mathcal{L}\{T_m(t)\} &= T_m(p) \\ \mathcal{L}\{N(t)\} &= N(p) \\ \mathcal{L}\{I(t)\} &= L(p) \end{aligned} \quad (4.194)$$

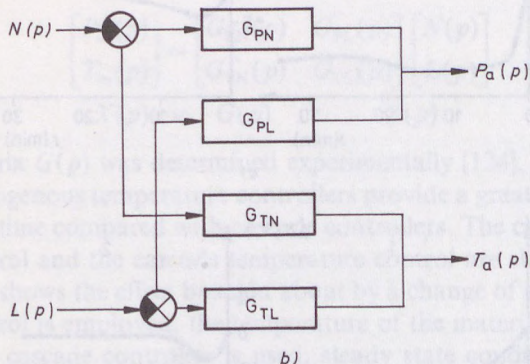
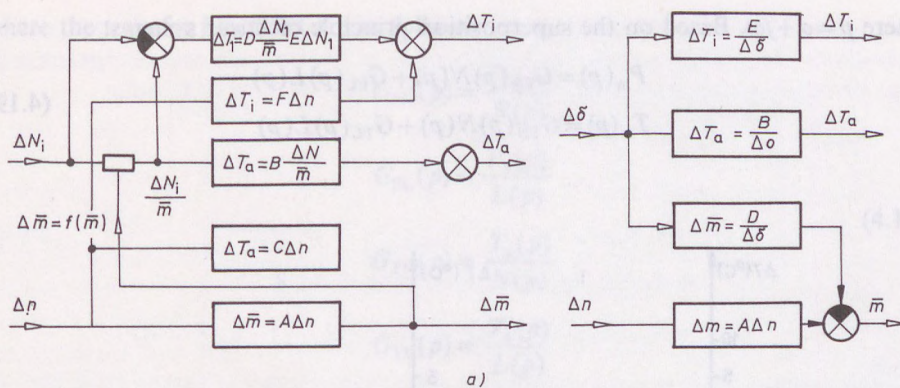


Fig. 4.47. Autogenous temperature control systems

a) Autogenous temperature controls with a shearing gap [102], b) Autogenous temperature controls with a cylindrical shaped gap [143]

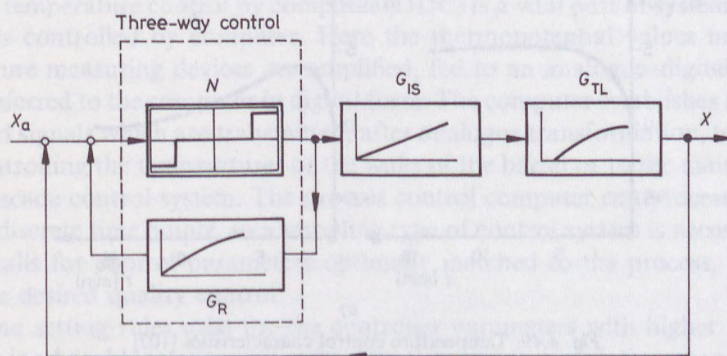


Fig. 4.48. Autogenous temperature controls with an adjustable length ring-shaped gap [143]

where $p = \sigma + j\omega$. Based on the superposition principle of linear systems:

$$\begin{aligned} P_m(p) &= G_{PN}(p)N(p) + G_{PL}(p)L(p) \\ T_m(p) &= G_{TN}(p)N(p) + G_{TL}(p)L(p) \end{aligned} \tag{4.195}$$

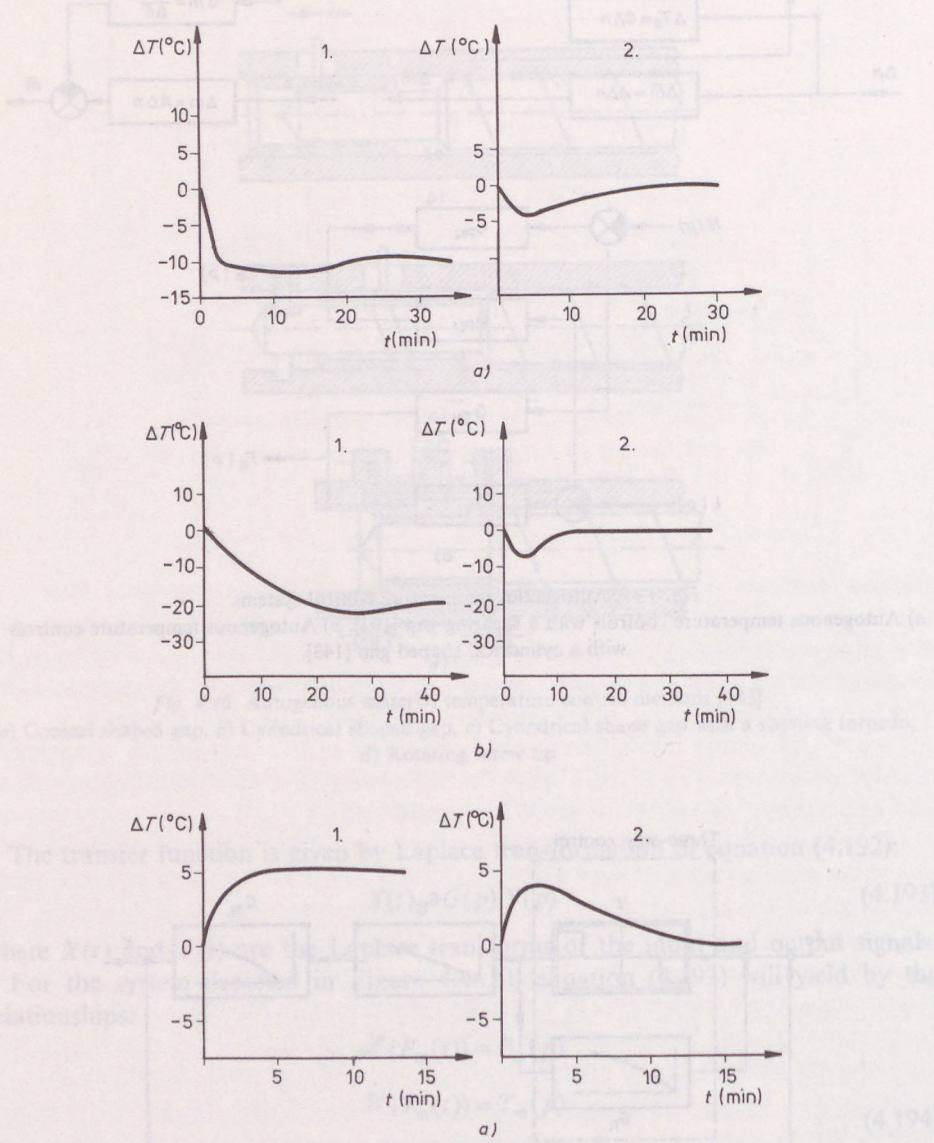


Fig. 4.49. Temperature control characteristics [102]

a) The effects of material change, b) The effects of switch-off of the last heating zone, c) The effects of a change in revolution numbers

where the transfer functions are as follows:

$$\begin{aligned} G_{PN}(p) &= \frac{P_a(p)}{N(p)} \\ G_{PL}(p) &= \frac{P_a(p)}{L(p)} \\ G_{TN}(p) &= \frac{T_a(p)}{N(p)} \\ G_{TL}(p) &= \frac{T_a(p)}{L(p)} \end{aligned} \quad (4.196)$$

Based on equation (4.195)

$$\begin{bmatrix} P_m(p) \\ T_m(p) \end{bmatrix} = \begin{bmatrix} G_{PN}(p) & G_{PL}(p) \\ G_{TN}(p) & G_{TL}(p) \end{bmatrix} \begin{bmatrix} N(p) \\ L(p) \end{bmatrix} \quad (4.197)$$

$$X(p) = G(p) Y(p)$$

The transfer matrix $G(p)$ was determined experimentally [124].

In general, autogenous temperature controllers provide a greater degree of reliability and less dead time compared with cascade controllers. The characteristics of wall temperature control and the cascade temperature control are shown in Figure 4.49. Section *a*) of this shows the effect brought about by a change of material. Where wall temperature control is employed, the temperature of the material drops by as much as 10 °C; when a cascade controller is used, steady state conditions are reached in about 20 min. Section *b*) of the diagram shows the effects of non-functioning of the last heating zone; the application of cascade controller, under certain conditions, ensures continued operation. Section *c*) shows the effects of changes in the revolution number. Where a wall temperature controller is employed a deviation occurs, while with cascade controller the required value is reached in about 10 min.

Direct Computerized Temperature Control

Direct temperature control by computer (DDC) is a vital part of systems where the process is controlled by computer. Here the thermopotential values measured by temperature measuring devices are amplified, fed to an analogue-digital converter, and transferred to the computer in digital form. The computer establishes the relevant command signals which are transmitted, after analogue transformation, to the equipment controlling the temperatures of the walls of the barrel or to the main controller of the cascade control system. The process control computer can process data measured at discrete time points, so a sampling type of control system is necessary. DDC control calls for control parameters optimally matched to the process, in order to attain the desired quality control.

Since no setting rules exist for the controller parameters with higher order algorithms, it is advisable to carry out optimization using a simulation programme that describes the closed control loop. The DPID (Differential, Proportional, Integral,

Differential closed loop control) algorithm will be described here for the purpose of illustration. The DPID system has been proven to provide the best compromise in terms of optimum command behaviour and fault rectification behaviour.

$$\begin{aligned}
 y(k) = & y(k-1) + K_Y (y(k-1) - y(k-2)) \\
 & + K_p (X_w(k) - x_w(k-1)) \\
 & + K_I x_w(k) \\
 & + K_{D1} (x_w(k) - 2x_w(k-1) + x_w(k-2)) \\
 & + K_{D2} (x_w(k) - 3x_w(k-1) + 3x_w(k-2) - x_w(k-3))
 \end{aligned} \tag{4.198}$$

where

$y(i)$ = correcting variable for the i th scan period,

$x_w(i)$ = controlled variable at scan time i ,

$$K_Y = \frac{T_v}{T_{AB} + T_v} \quad \text{digital filtering parameter,}$$

$$K_p = \frac{K_R}{\left(1 + \frac{T_v}{T_{AB}}\right)} \quad \text{proportional component parameter (and controller amplification),}$$

$$K_I = K_p \frac{T_{AB}}{T_n} \quad \text{integral component parameter,}$$

$$K_{D1} = K_p \frac{T_{v1}}{T_{AB}} \quad \text{parameter for the 1st differentiation of control difference,}$$

$$K_{D2} = K_p \frac{T_{v2}^2}{T_{AB}^2} \quad \text{parameter for the 2nd differentiation of control difference,}$$

T_{AB} is the scan time,

T_v , T_{v1} and T_{v2} are the delay times,

T_n is the reset time.

Figure 4.50. illustrates the control behaviour of the above algorithm in the heating zone of a barrel, with scanning intervals of 30 s. The relatively high inertia of the temperature control systems and the corresponding long scanning times allow a single computer system to process several temperature systems simultaneously in a multiplex mode.

The melt temperature control system, operated on the cascade control concept, is shown by the block diagram of Figure 4.51., depicting analogue controls with the melt temperature control operated as the command control and two zone controls operated as auxiliary, or supplementary controls. The command control derives a correction variable as its output, from the differences between the target melt temperature values and the actual melt temperature values, added to the zone temperature target values. These target value modifications lead to a change in the melt temperature zone, via the zone temperature controls.

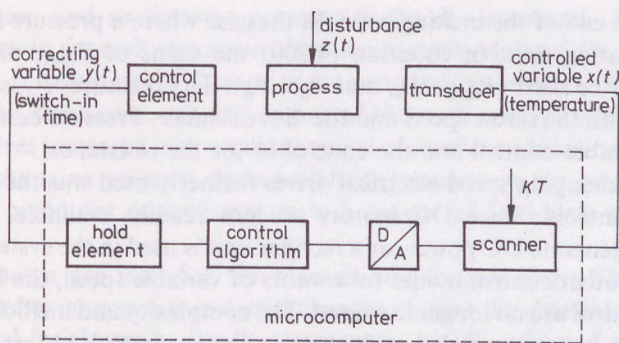


Fig. 4.50. Block diagram of a scanned-data system for temperature control. D/A: digital/analog converter, KT = scanning rate

An extension of the wall temperature zone control system opens up the possibility of using a microcomputer. This is followed by scanning of the melt temperature zone using the same scanning time to correspond with the scanning time of the wall temperature zone. The value of the melt temperature zone obtained by scanning now becomes the control variable, followed by scanning the walls of the barrel or housing at an appropriate distance, but, since the melt temperature profile is constant, it is also applicable to the temperature profile at the screw tip.

For control of the melt temperature zone a PID algorithm with self-optimizing parameters is used. The favourable control parameters are now calculated upon a request received from the step response, provided by the control system after adjustment of the parameters according to set rules, using the inflection tangent method.

4.5.1.2 Control of Melt Pressure

Another characteristic parameter of the plasticating process is the pressure at the entry of the melt into the die. The pressure is a function of the screw speed and the die resistance, so that a close relationship exists with the mass flow. The relationships of the above parameters with pressure in the case of a Newtonian melt's isothermal flow, may be expressed as:

$$P_d = \frac{Q}{K_Q} \bar{\eta}_d \quad (4.199)$$

and

$$P_d = \frac{\bar{\eta}_p (Q/Q - AN)}{B} + \begin{cases} P_{\max} \\ P_m \end{cases} \quad (4.200)$$

Equation (4.199) relates to the die, while equation (4.200) relates to the plasticating unit. A and B are the geometric constants of the metering zone, K is that of the die, $\bar{\eta}_d$ is the average viscosity of the melt in the die, and $\bar{\eta}_p$ is the average viscosity of the melt in the metering zone. P_d is the pressure at the point of entry of the melt into the die, $P_{\max}$ is the maximum pressure in the plasticating unit, and P_m is the

pressure at the end of the melting zone. In the case where a pressure maximum exists in the plasticating unit, in equation (4.200) the value of $P_{\max}$, or otherwise, the value P_m must be used ($P_{\max} > P_d$, and $P_d > P_m$). The pressure, P_d is in unambiguous relationship with the screw speed and the die resistance. Pressure control is related to revolution number control and the control of the die resistance.

One of the changing speed electrical drives formerly used was the DC motor with field speed controls. Since DC motors are not readily available, either a motor generator, to generate DC power, or a rectifier unit is used in the system instead. With the advent of other control modes for motors of variable speed, the DC motors with field speed control are no longer favoured. The complexity and inefficiency of generating DC power on site, coupled with the non-linear control patterns of the motors made this incompetent with SCR units and with the more recently developed variable-frequency AC motor drives.

In the majority of plasticating units manufactured at present, SCR drives are installed. They use the cycle clipping of the SCR units to supply DC energy at various levels as rectified spikes. The amount of power is controlled by the firing voltage of the SCR motors providing a low-level input signal voltage. This voltage is generated by a special circuit. The level can be set by means of a simple potentiometer control, remote from the motor, connected to the SCR control unit by simple wiring.

Another type of variable-speed motor drive is used in some of the more recently built machines. This is an electronic device to convert the line frequency of the AC motor to a variable frequency source to drive the AC motor. Two types of motors are in use. One is a conventional AC unit, fitted with a large squirrel cage, where regulation of speed is achieved by load changes of 2–3%. For closer control of speed to 1/4% or less, the drive motors are synchronous motors. Again, this superior speed control of the synchronous units is probably counter-productive in extruder operation. Load surges may be dampened in the output of the motor, provided that the motor slows down slightly when extra resistance is encountered in the machine.

Similarly to the SCR units, the control mode for the variable frequency AC drives are signal voltages, generated by potentiometer settings. In these drives control voltages change the frequency of the control oscillator, which produces the AC. In most of these systems the oscillators operate at many times the line frequency, counted down to the frequencies actually used. The generated frequencies are used as control signals for the large power transistors to generate the high currents required, and the power is generally passed through a transformer to generate the appropriate motor voltages and to isolate the transistor amplifier from the reactions of the motor. While tachometer feedback can be employed in the AC system, this is seldom used. Tight speed control is effected by the type of motor selected. Since the speed control is an open-ended system, it is less likely to react unfavourably to line transients, which can shut down an SCR drive.

Although they are not widely employed, valves can be used to control the pressure of the plasticating unit. In many instances the back pressure in the machine is controlled by the use of screen packs fitted to the back of a breaker plate. The type, size and number of screens are arrived at by a trial and error process to give the appropriate pressure drop, so that the machine assumes the back pressure required for

proper plastication and so that the pressure in the die is correct. As the screens accumulate debris in the melt stream and become partially clogged, the pressure drop increases and it is necessary to replace them periodically. In spite of the apparent limitations of this technique, still, this is one of the most widely used methods.

The use of valves increased in computer control of machine operation. Using valves is one way of changing pressure drop and back pressure in the machine while in operation. The computer control system is a means of feed-back control of the machine output.

The valves shown are intended for manual adjustments only. The designs for automatic control arrangements included changes so that the elements of the valves are now actuated by electro-hydraulic servo units, rapidly adjusted in response to electrical signals received from the control unit. The pressure in the plasticating unit at the head end is sensed by a bridge type instrument and matched to the desired head pressure setting. If the pressure is found to differ from the desired preset value, the valve opens to decrease the pressure and closes to increase the pressure by altering the size of the gap available for the polymer flow. As is the case with most adjustments on a single screw machine, other factors also influence the pressure that reacts to the valve adjustments. For example, a change in back pressure increases the magnitude of shearing stresses, and this reduces the viscosity of the melt to counteract the pressure drop caused by the increased restriction and vice versa. In addition to this, different magnitudes of shearing stresses are generated, depending on the size of the gap in the material flowing through the valve, which will also affect the pressure drop. A change in the valve setting to control the back pressure and the output of the machine is one of more effective ways to control machine performance. This is particularly true in comparison with the effects brought about by changing the rotational speed of the screw (another way of modifying the head pressure and the delivery rate of the plasticating unit).

There are various factors which make the melt pressure unstable and cause the pressure fluctuate considerably. It is therefore essential to use some type of electronic control to stabilize the pressure. The usual method of control is to leave the die resistance constant and to control automatically the screw speed of the plasticating unit. The control system can consist of a pressure gauge, controller, integrator and a motorised potentiometer. The helical potentiometer, driven by a stepping motor and connected to the screw-drive speed control unit is the final control element. Since the stepping motor drives the potentiometer via a friction clutch, the potentiometer can be set manually by the front panel knob during the start-up process of the machine, while the stepping motor is switched off.

One of the recommended methods for keeping the mass flow constant is the control of the pressure. It was demonstrated earlier, when the dynamics of the screw plasticating unit were examined, that the pressure in the die changes instantaneously, following changes in the revolution number of the screw. Usually a 1% change in the rotational speed of the screw brings about a pressure change of 10%, thus extremely fine setting is needed. Figure 4.52. shows a pressure control system. The signal from the pressure sensor is compared against the reference signal and, according to the magnitude of the deviation detected, the controller changes the setting of the poten-

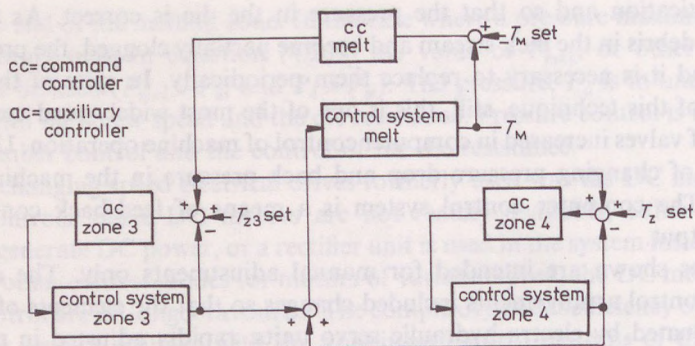


Fig. 4.51. Block diagram of a cascade control for melt temperature

tiometer of the motor drive via an integrator, with the aid of a stepping motor. The integrator is a current-frequency converter which gives impulses with frequencies proportional to the difference between the base signal and the measured signal [126, 127].

4.5.1.3 Viscosity Control Methods

The viscosity of the melt that enters the die may also be utilized for control purposes. According to equation (4.199) the viscosity is a function of the die pressure, the revolution number and the temperature. For this reason viscosity control is always applied in conjunction with temperature control and screw speed control.

The viscosity of the melt is measured by ultrasonics, or by the use of torsion instruments. Ultrasonic probes, typically resonating with a frequency of 850 kHz are used either singly, or in pairs with a specialized electronic unit to measure the time taken by a short ultrasonic pulse to traverse the melt flow. Figure 4.53. illustrates

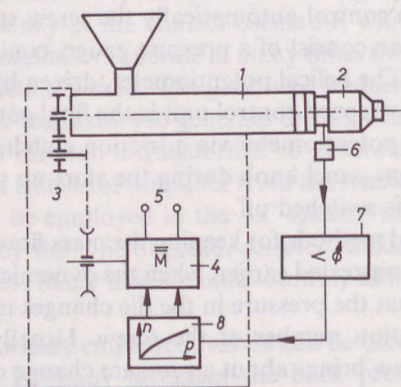
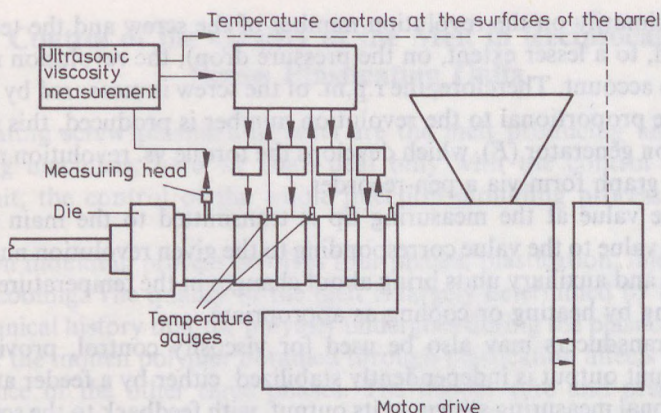


Fig. 4.52. Pressure control systems

1. plasticating unit, 2. die, 3. drive, 4. motor drive, 5. heating connection to the main circuit, 6. pressure gauge, 7. amplifier, 8. controls



viscosity control systems, using ultrasonic measurements. The main electronic unit compares the ultrasonic travel-time with a digitally set reference and produces an error signal, which is fed to the thermocouple unit to produce DC correction signals to each of the last three temperature control zones of the barrel.

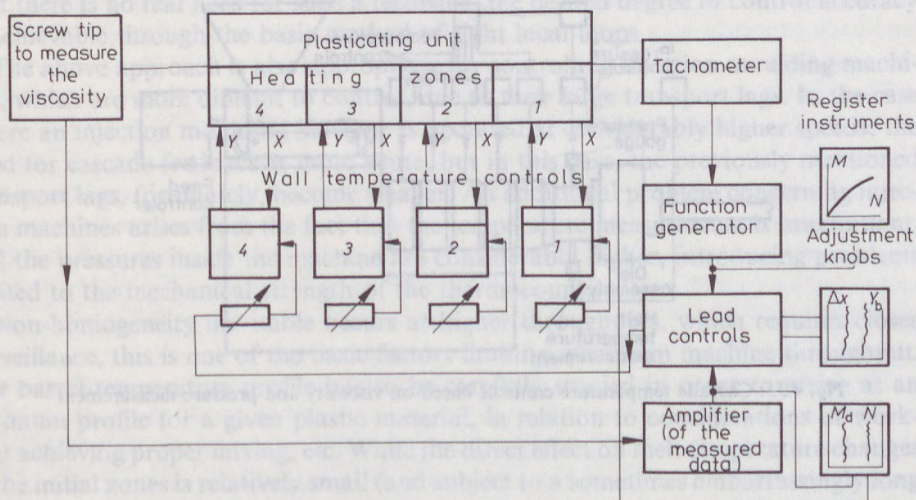


Fig. 4.54. Cascade temperature controls with the aid of viscosity measurements

dependent primarily on the revolution number of the screw and the temperature of the melt (and, to a lesser extent, on the pressure drop), the revolution number must be taken into account. Therefore, the r.p.m. of the screw is measured by a tachometer and a voltage proportional to the revolution number is produced, this is transferred to the function generator (F), which develops the torque vs. revolution number curve presented in graph form via a pen-recorder.

The torque value at the measuring tip is transmitted to the main controller to compare this value to the value corresponding to the given revolution number and the main control and auxiliary units bring about changes in the temperature of the barrel or the housing by heating or cooling as appropriate.

Pressure transducers may also be used for viscosity control, provided that the plasticating unit output is independently stabilized, either by a feeder at its input, or by a dimensional measuring system at its output, with feedback to the screw. In either case the pressure changes are proportional to viscosity and may be used with a viscosity control system.

Pressure-Temperature Feedback for Viscosity Control

Figure 4.55. illustrates a complete viscosity control system. The barrel is fitted with an efficient cooling system using circulating oil, controlled by solenoid valves, connected to accurate PID heating/cooling controls. The pressure control system used an integrator to provide compensation for the response lag in the feed-back loop and complete elimination of the pressure error. The output of the integrator feeds a motor potentiometer, adapted to give isolated correction signals in the thermocouple inputs of five barrel temperature controllers by a multi-zone thermocouple converter.

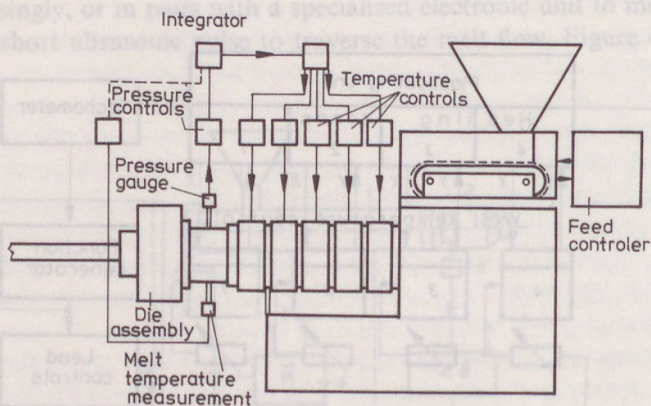


Fig. 4.55. Cascade temperature controls based on viscosity and pressure measurement

4.5.2 Control of the Quality of the Melt in Reciprocating Screw Plasticating Units

The reciprocating screw plasticating units are the melt producing units of injection moulding machines; here we shall deal only with the control of the melt producing unit, the control of the whole injection moulding process will be described later.

The injection moulding process involves four phases: plastication, injection, compression and cooling. The quality of the melt is largely determined by the complex thermo-mechanical history that the polymer undergoes during the plastication phase. The quality of the molten polymer obtained through plastication affects the processing performance of the other three phases. The temperature and pressure of the plasticated polymer that is injected into the mould are important variables in injection moulding.

In reciprocating screw plasticating units the most important controllable parameter is the temperature of the material used.

The injection moulding machine poses severe problems, compared with extruders. The screw speed is much higher in injection moulding machines and at higher throughputs some of the zones require cooling control, due to the greater excess heat-work energy produced by the screw. Homogeneity becomes more difficult to achieve, since the plastic residence time in the machine is shorter, hence the mixing is much less thorough.

In injection moulding machines, up to a medium throughput, it is often found that the melt temperature is within a few degrees of the final zone temperature, measured by the thermocouples inserted deep into the channel. Under these circumstances, although it is particularly difficult to implement an overall (cascade) feedback system (on account of the intermittent nature of the injection process), it is frequently found that there is no real need for such a feedback, the desired degree of control accuracy is achievable through the basic method of tight local loops.

The above approach is also appropriate for controlling injection moulding machines, which are more difficult to control, due to their large transport lags. In the case where an injection moulding machine is operated at considerably higher speeds, the need for cascade feedback is more acute, but in this case, the previously mentioned transport lags, fortunately, become smaller. An additional problem concerning injection machines arises from the fact that the temperature measurement is intermittent, and the pressures inside the machine are considerably higher, introducing problems related to the mechanical strength of the thermocouple.

Non-homogeneity inevitable occurs at higher throughputs, which requires closer surveillance, this is one of the basic factors limiting maximum machine throughput. The barrel temperature profile has to be carefully studied in order to arrive at an optimum profile for a given plastic material, in relation to considerations of work-heat achieving proper mixing, etc. While the direct effect on melt temperature changes in the initial zones is relatively small (and subject to a sometimes embarrassingly long transport lag delay), the zone temperatures of the early section may affect the quality of the output considerably. The effect of the final barrel-zone temperatures upon the

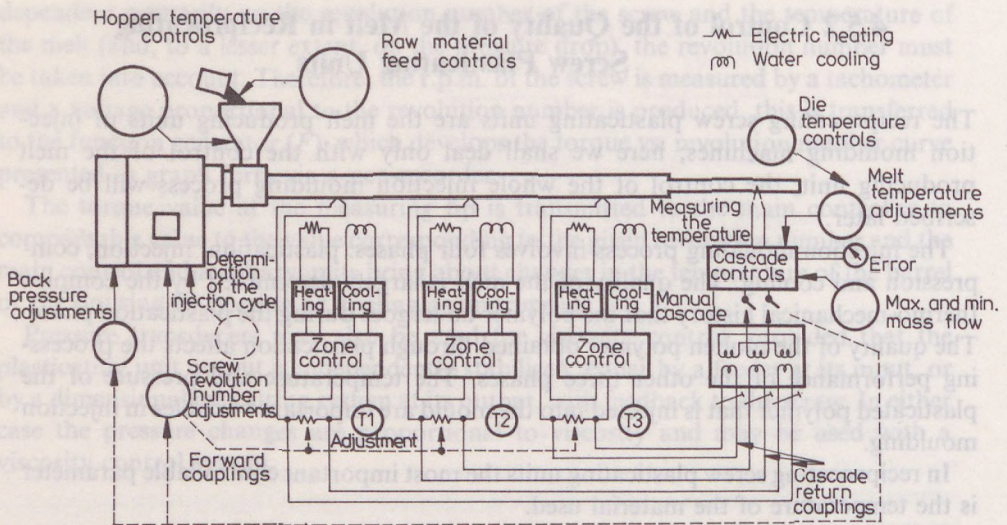


Fig. 4.56. Cascade temperature control system for continuous and reciprocating, single screw plasticating units

melt temperature is usually relatively large (depending on the specific design of this part of the machine); only a small transport lag occurs from this point on.

In injection moulding the most generally used method of control of the melt temperature is the cascade temperature control. A cascade control scheme for the melt temperature is shown in Figure 4.56. [130]. The master controller in the overall feed-back loop receives the current melt temperature signal from the thermocouples fitted in the nozzle. The error signal between the melt temperature and the required set temperature is proportioned to adjust the set-point of the zone controllers. The feed-back proportioning unit makes it possible to set up a temperature profile along the zone heaters.

The control strategy involves adjusting both back pressure and barrel temperature to achieve the desired melt temperature as measured by the screw tip thermocouple. Hydraulic back pressure and the melt temperature are measured from the process. The millivolt signals from the transducers pass through the signal conditioners to make them compatible with the higher voltage levels used at the computer interface. The measurements are read into the computer through an analogue-to-digital converter system (not shown in the above Figure), by multiplexing. The reference commands for the back pressure and the barrel temperature represent the outputs to the process after control calculations have been performed.

The barrel temperature controllers are proportional-reset type controllers, commonly used in industry. The difference lies in the fact that barrel temperature references can also be set from the computer or from the control station itself, depending on whether the control mode is in computer, or in manual. The advantages of this system are that the same hardware is shared in both modes of control and the stability of the controller itself, thus avoiding further complexity in the system.

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5 Sheet and Film Extrusion Processes and Process Control

5.1 The Structural Lay-out of Sheet and Film Manufacturing Extruder Lines

Sheet and film manufacturing is carried out by the plasticating units introduced in the previous chapter and with the aid of production lines consisting of shaping and other auxiliary units. The shaping of the product is achieved with the use of coat-hanger type dies.

The sheets and films made are distinguished by the flexibility of the material and by their thicknesses. Thus, for example, in the case of low density polyethylene, a sheet is considered to be thicker than 0.5 mm, while in the case of high density polyethylene, the sheet thickness is greater than 0.35 mm.

For sheet manufacturing, a coat-hanger type die is joined to the plasticating unit, here, the thickness of the film produced is governed by smoothing and cooling series of rolls. Figure 5.1. shows such a film manufacturing production line. On the diagram a plasticating unit (1), a die (2) and the smoothing-cooling rolls (3) can be identified. The rolls serve to adjust the thickness of the sheet and to cool the sheet in order to achieve the required surface quality. After leaving the rolls, the sheet is passed through a thickness gauge (4) and is transported to the storage equipment (12) by transport belts (6), (8) and (11). Part (5) applies supplementary cooling to the sheet. The knife (7) cuts the sheet's edges to even sizes, while the knife (10) cuts the sheet to equal size pieces. Sheets are products of large dimensions, for the production of which high performance extruders are necessary. For example, in order to manufacture sheets of 10 mm thickness and 1500 mm width, the necessary mass flow is of the order of 500 to 800 kg/h. Figure 5.2. shows a sheet extrusion line.

In sheet manufacturing it is necessary for the die to produce a uniform melt flow across the entire width of the die's orifice. The distribution channel of the most commonly used die construction is drop-shaped, and the flow is regulated by a

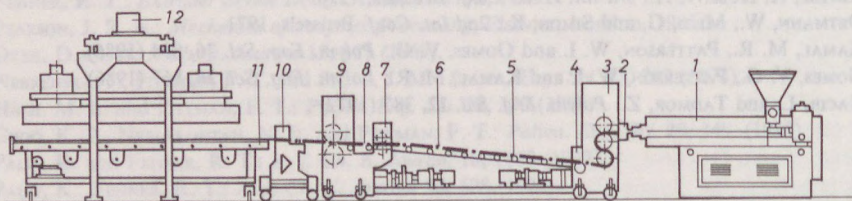


Fig. 5.1. Film processing production line

1. plasticating unit, 2. die, 3. smoothing and cooling series of rolls, 4. thickness gauge, 5. auxiliary cooling, 6, 8 and 11 transport belts, 7 and 9. stripping equipment, 10. slicing equipment, 12. storage

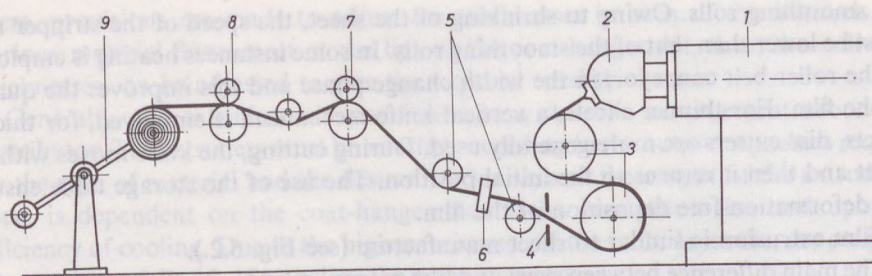


Fig. 5.2. Sheet manufacturing extruder line with progressively widening die

1. plasticating unit, 2. head, 3. cooling rolls, 4. edge trimmer, 5. leading rolls, 6. thickness gauge,
7. smoothing pair of rolls, 8. stripping rolls, 9. winding equipment

prism-shaped plug. Part of the die lip is mobile in the vertical plane, and in this way, the orifice size and, consequently, the thickness of the film produced is adjustable. The die is provided with heat insulation and with heating facilities. Generally, the pressure and the temperature of the polymer melt are measured. The nominal size of the orifice is adjusted by allowing for swelling. In practice the die-lip section is adjusted first to the dimensions of the finished product and the final dimensions are determined between the smoothing-cooling rolls. However, the size of the die-lip needs to be adjusted, in practice, to a smaller size than the dimensions of the finished product. Allowing for swelling is particularly important, since in sheet manufacturing the process temperature is lower than in film manufacturing, thus swelling is also greater. The die-lip equipment serves to fix the sheet thickness, to ensure the required surface qualities of the film and it pre-cools the product. Smoothing of the sheet on both sides is ensured by three rolls. The film emerging from the extruder in a horizontal position enters the middle roll. From here, forwarding of the sheet may be achieved in two different ways, it winds either onto the top roll or the bottom roll. The latter is more commonly used. The rolls must provide large cooling surfaces, thus, it is necessary to employ large diameter rolls; in the case of high temperature processing, rolls of 250 to 300 mm diameter are commonly employed. The surface of the rolls are chromium plated and highly polished, since the surface quality of the sheet depends greatly on the surface quality of the rolls. The forces pressing on the rolls lie in the range of 200 to 1000 N per cm length. The speed of rotation of the rolls is infinitely adjustable. Differences and fluctuations in the rotation velocities of the rolls influence the quality of the end product. It is of utmost importance to maintain constant temperature of the roll surfaces, since temperature differences produce stresses which cause uneven thicknesses of the sheets.

The pull off equipment is connected to the smoothing-cooling device and consists of a pair of puller rolls and a roller-belt conveyor. Depending on the output efficiency of the sheet production line, the roller-belt conveyor may be three metres in length or longer. In order to enhance cooling, the first few rollers are cooled inside, in some cases the film is also cooled with an air stream. The surface of the puller rolls is coated with a layer of rubber material. From the point of view of the quality of the sheet it is of utmost importance to synchronize the rotational speed of the puller rolls and of

the smoothing rolls. Owing to shrinking of the sheet, the speed of the stripper rolls must be lower than that of the smoothing rolls. In some instances heating is employed at the roller-belt conveyor, in the width change phase and this improves the quality of the film. For thinner sheets, a vertical knife mechanism is employed, for thicker sheets, disc cutters are more generally used. During cutting, the knife moves with the sheet and then it returns to the initial position. The use of the storage table ensures the deformation-free deposition of the film.

Film extrusion is similar to sheet manufacture (see Fig. 5.2.).

The main difference between sheet and film extrusion lies in the methods of winding employed. The method of winding is of utmost importance in production of high quality films. Winding is usually effected with constant stresses.

The major differences between film extrusion and film blowing are the following:

- film blowing is a more productive and a more controllable process,
- a coat-hanger die produces foils with better optical properties, and
- in film extrusion a coat-hanger die can make thicker foils.

Due to their relative advantages and disadvantages, both production methods are used. Axially or biaxially elongated foils may be produced by film extrusion although this is more common in manufacturing foils by blowing. The extruded films in general, are oriented to a lesser degree. The elongation of the polymer melt is carried out between the die and the cooling equipment, this results in some degree of orientation. The orientation process may be substantial in the initial stage of the foil cooling processes. Further elongation of the foil undergoing cooling may increase its orientation.

The manufacture of multi-layer foils and sheets is called sheet and foil coextrusion. In a more obsolete process, two extruders with a coat-hanger die are joined. One of them produces the base layer, while the other produces the cover layer on it. An example of this would be the extrusion of a transparent glass-like, so-called crystalline polystyrene onto a high-impact-strength polystyrene base. The disadvantage of this process is that the top layer does not adhere to the base perfectly, since, by the time the top layer is applied on the base, the latter has cooled off substantially. A further disadvantage is that the thickness tolerance of the two layers, naturally, is added together.

A more up-to-date method for producing double layer, or multi-layer foils is the so-called adapter method. This system includes as many extruders as the number of layers desired, and they pass the materials into an adapter. The adapter is positioned between the extruders and a traditional coat-hanger die. Subject to the arrangement of the layers the distributor inserts of the adapter are adjustable accordingly.

The great advantage of this technique is that corrosive materials may be fed into the adapter in such a way that it is covered on both sides with non-corrosive plastics. For example, a three-layer foil containing poly(vinylidene chloride) as the middle layer can be produced in such a way that this highly corrosive plastic material does not come into contact with metal, thus, it is not necessary for the coat-hanger die to be made of high-alloy steel.

Another fairly recent method is based on the application of multichannel coat-hanger dies. In this case the component materials are channelled separately to the die.

Here, provisions are made to adjust the thicknesses in each of the channels. The various material flows meet at the lips of the coat-hanger die, thus, the individual thicknesses can be adjusted to give the required total thickness.

Generally, the extruders are positioned in a star-like arrangement around the distributor. The extruders must be selected according to the output capacities required by the type of material and the desired thickness, and the output of the extruder, in turn, is dependent on the coat-hanger die of the production line and upon the efficiency of cooling. Due to the higher resistance of the multi-layer die, the output of the extruders falls 10–15% below the normal output.

In the case of sheet extruding equipment the rotating adapter follows the distributor, which supplies the coat-hanger die. The still-plastic material leaving the adapter passes between smoothing rolls, is then cooled, passes through the thickness gauge, it is sliced on a roller table and stacked. In this production line the extruder, the connecting mechanism, the rotatable adapter and the multi-channel die are the same as was in the case with the multi-layer sheet manufacturing line. Naturally, the cooling and the pull-off devices are again different. The melt is extruded to pass between a smoothing roll of 200 mm diameter and a 500 mm diameter cooling roll. These are followed by a second 500 mm diameter cooling roll, then the foil is passed through an isotopic thickness measuring device and where necessary, it is passed through a bath containing antistatic materials. Finally, the foil produced is pulled off by a rubber-coated pair of rolls, driven with speeds higher or lower than the speed of second pair cooler rolls 5% in order to minimize the shrinkage of the foil. For lengthwise cutting and trimming, disc cutters are employed. In general, rolls of 2000 mm diameter are produced. The output capacities of such equipment in the case of high impact strength polystyrene is 500 to 600 kg/h with a width between 800 and 1100 mm.

In the following, the processes involved in sheet and foil manufacturing will be examined, the cooling and smoothing processes will be considered, and finally the application control technology will be presented, based upon analyses of the processes.

5.2 Sheet and Film Extrusion Dies

The task of the extruder is to supply a melt of even flow rate at constant temperature into the shaping channel of the die. The dies are a series of heated channels, designed specifically to facilitate the flow of the melt and to accomplish other auxiliary functions, for example air inlet. Functionally these channels may be divided into two main parts, the connecting and shaping sections. The task of the former is to channel the melt produced by the screw plasticating unit to the shaping section, while the latter's task is to produce the required form. In the connecting channel(s) the flow velocity and the temperatures are evened out, while in the shaping part of the die certain size adjustments take place in a controlled mode.

We shall now examine the flow through the die, but design aspects will not be discussed; relevant references will be given [1–14].

Sheet and foil extruder dies are the so-called coat-hanger dies. From the point of view of construction, three types of dies are in use. These are:

- the T shaped dies,
- the fish tail, or triangular shaped dies, and
- arched triangular shaped dies.

The main aspects in design of a die are to ensure uniform velocity and temperature spaces and to avoid the formation of dead space. In order to ensure an even flow velocity field in the shaping section, the material particles must pass through a section of identical frictional resistance. To achieve this, the following methods are employed in practice:

- gaps of adjustable lengths,
- gaps of adjustable heights,
- triangular shapes,
- arched triangular shapes,
- development of the uniform temperature profile at the shaping part of the die,
- implementation of an adjustable frictional resistance section.

The construction of the die depends on the method used to change the size of the shaping gap. This, in turn, is greatly influenced by the intended thickness of the product. The characteristic feature of the dies intended for foil and/or sheet manufacturing (with thicknesses less than 0.2 cm) is the use of a long shaping section and a short connecting channel. In the case of dies to be used for the manufacture of sheets of medium thickness (0.2–0.7 cm), the die is equipped with a restrictor bar assembly, to control the relative flow to various portions of the die lips by adjustments of restrictor bar elements. The secondary manifold, used to permit redistribution pressure adjustment is substantially larger than that employed in thin sheet dies. In thick sheet dies the restrictor bar assembly functions more like a valve unit than in the medium sheet die, since this is the major controlling effect in obtaining a sheet of uniform thickness across its width.

Figure 5.3. shows some die constructions. Part *a*) of the diagram shows the melt leaving the plasticating unit (1) passing through channel (2) into the melt distribution channel (A), where the velocity field is homogenized initially. The final velocity adjustment is performed by valve (7), which is adjusted by the screw (4); the sheet or foil final forms are provided by the half-die or die-jaws (5) and (6).

The disadvantage of this construction is the evolution of dead space in the vicinity of the valve. Figure 5.3.*b*) shows a construction in which some mobile elements are positioned perpendicular to the melt flow. The design of these elements is such that dead space does not evolve. The elements are moved with the aid of screws (4), which are fastened with locking screws (11). Adjustment of the die gap is possible by moving the half die (8).

Figure 5.3.*c*) shows an arrangement where the melt passes through the transport channel (2) and connecting channel (3) into the distribution channel (6), where the initial pressure equalization takes place. The total velocity equalization takes place in the elastic deformation channel section (8). On the effect of pressure, the lower half of the die can twist through an angle of a few degrees, while the upper half of the die (7) remains parallel with the lower half of the die, and the size of the gap remains unchanged.

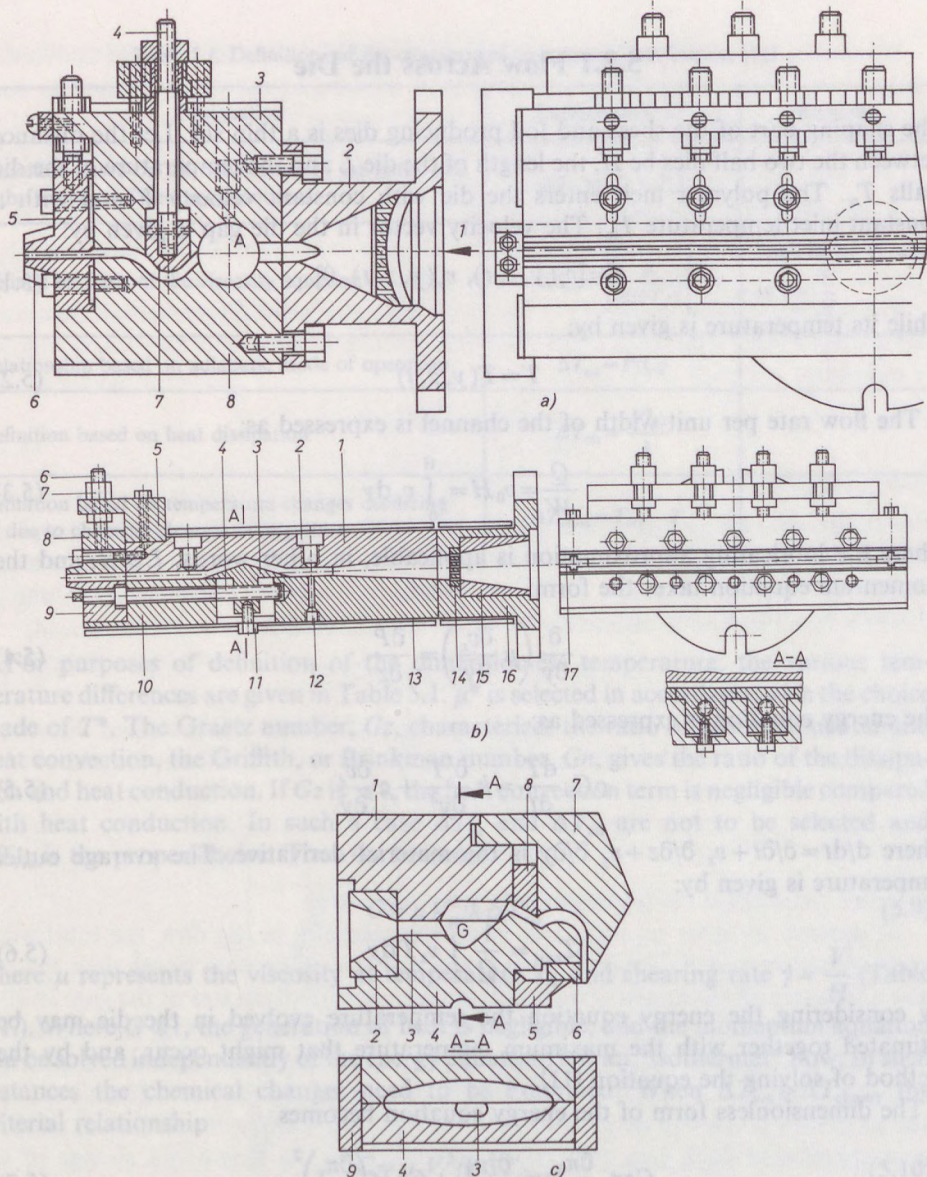


Fig. 5.3. Sheet producing extruder line with progressively widening die

a) Plane gap die

1. entry of the melt from the extruder, 2. transfer section, 3 and 8. die body, 4. adjustment screw, 5 and 6. the two halves of the shaping die, 7. elastically deformable pressure equalizing section, A. distribution channel

b) Fish-tale shape die

1 and 10. the two halves of the die, 2. pressure gauge, 3. sliding element, 4. control rod, 5. support, 6. adjusting screw, 7. nut, 8 and 9. shaping section, 11. locking screw, 12. thermo element, 13. electric heater, 14. screen, 15 and 16. transfer sections, 17. packing

c) Plane gap die with a deformable channel section

1 and 4. die walls, 2. transfer channel, 3. main channel, 5 and 6. die section providing for shaping of lower parts, 7. upper shaping die section, 8. mobile tap, 9. side wall

5.2.1 Flow Across the Die

The shaping part of the sheet and foil producing dies is a thin slit. Let the distance between the two half dies be H , the length of the die L and the temperature of the die walls T_w . The polymer melt enters the die with constant velocity V and with a constant inlet temperature T_{in} . The velocity vector in the die gap is given by:

$$\vec{v} = [v_z(y, z, t), v_y(y, z, t), 0] \quad (5.1)$$

while its temperature is given by:

$$T = T(y, z, t) \quad (5.2)$$

The flow rate per unit width of the channel is expressed as:

$$\frac{Q}{W} = v_0 H = \int_0^H v_z dy \quad (5.3)$$

where the lubricating approximation is applicable, in other words, $L \gg H$, and the momentum equation takes the form:

$$\frac{\partial}{\partial y} \left(\mu \frac{\partial v_z}{\partial y} \right) = \frac{\partial P}{\partial z} \quad (5.4)$$

The energy equation is expressed as:

$$\rho C_v \frac{dT}{dt} = k \frac{\partial^2 T}{\partial y^2} + \mu \frac{\partial v_z}{\partial y} \quad (5.5)$$

where $d/dt = \partial/\partial t + v_z \partial/\partial z + v_y \partial/\partial y$ is the material derivative. The average outlet temperature is given by:

$$T_{exit} = \frac{1}{Q} \int_0^H v_z T dy \quad (5.6)$$

By considering the energy equation the temperature evolved in the die may be estimated together with the maximum temperature that might occur, and by the method of solving the equation [11].

The dimensionless form of the energy equation becomes

$$Gz \pi_v \frac{\partial \pi_T}{\partial Z} = \frac{\partial^2 \pi_T}{\partial Y^2} + GnM \left(\frac{\partial \pi_v}{\partial Y} \right)^2 \quad (5.7)$$

where

$$Y = \frac{y}{H}, \quad Z = \frac{z}{L}, \quad \pi_v = \frac{v_z}{V}$$

$$\pi_T = \frac{T - T_0}{\Delta T^*}; \quad M = \mu/\mu^* \quad (5.8)$$

$$Gz = \frac{\rho C_v V H^2}{kL}; \quad Gn = \mu^* V^2 / k \Delta T^*$$

Table 5.1. Definitions of the characteristic temperature differences [11]

Designation	Definition of T^*	Remarks
Definition based on the relationship of the initial and the boundary (limiting) conditions	$\Delta T_{bc} = (T_w - T_0)$	
Defined on basis of the viscosity equation	$\Delta T_{vis} = \left \frac{\mu}{(\partial/\partial T)\dot{\gamma}} \right $	Defined at T_0 and at $\dot{\gamma} = \frac{V}{H}$
Relationship based on adiabatic mode of operation	$\Delta T_{ad} = P/Cq$	
Definition based on heat dissipation	$\Delta T_{dis} = \frac{V^2 \mu}{k}$	
Definition based on temperature changes occurring due to chemical changes taking place	$\Delta T_{chem} = T_{crit} - T_w$	

For purposes of definition of the dimensionless temperature, the various temperature differences are given in Table 5.1. μ^* is selected in accordance with the choice made of T^* . The Graetz number, Gz , characterizes the ratio of heat conduction and heat convection, the Griffith, or Brinkman number, Gn , gives the ratio of the dissipation and heat conduction. If $Gz \ll 1$, the heat convection term is negligible compared with heat conduction. In such a case ΔT_{bc} and ΔT_{ad} are not to be selected and ΔT_{vis} is the proper choice. Thus Gn becomes:

$$G = \mu V^2 / k \Delta T_{vis} \quad (5.9)$$

where μ represents the viscosity at temperature T_w and shearing rate $\dot{\gamma} = \frac{V}{H}$ (Table 5.1.). Where $G \ll 1$, the generation of heat is negligible, and the momentum equation can be solved independently of the energy equation, it is an "isothermal" flow. In such instances the chemical changes need to be examined. When $\Delta T_{vis} \gg \Delta T_{chem}$, the criterial relationship

$$C = \mu_1 V^2 / k \Delta T_{chem} \quad (5.10)$$

characterizes the occurrence of a chemical change (degradation) in the flow. If $C > 1$, the degradation may be substantial.

If $G \approx 0$, dissipation has to be taken into account, the flow is not isothermal and it is necessary to solve the momentum equation and the energy equation together. In the third possible case $G \gg 1$, heat dissipation predominates, thus, the flow becomes approximately adiabatic. In such instances, the base temperature will not be the wall temperature, the temperature advisable to use is:

$$T^* = T_w + \mu^* V^2 / k \quad (5.11)$$

Where the Graetz number is near zero, both heat conduction and heat convection play a part, thus, ΔT_{bc} , ΔT_{dis} and ΔT_{ad} may be used as reducible factors. In such instances Gn becomes the Brinkman number. Therefore numerical solutions are often necessary in solving the system of equations simultaneously. If Gz is > 1 , heat convection is dominant, and ΔT_{vis} may be used as a reducible factor. In case $Gn/Gz \ll 1$, heat generation is negligible and the dissipation term may be ignored in equation (5.7). If $Gn/Gz \approx 0$, dissipation must also be taken into account. In the third case when $G/Gz \gg 1$, heat generation is the dominant factor, the flow is heated up adiabatically.

The character of the processes in the die is indicated by the dimensionless quantities mentioned above. The die is subdivided into elemental units and the Graetz number is calculated for each unit. Thus:

$$Gz = \begin{cases} \rho C_v QH/kW \\ \rho PH^4/12 \mu kL \end{cases} \quad (5.12)$$

In this equation Q and P are known. From the equation it may be determined whether the flow is adiabatic, or totally developed. This is followed by the determination of the values of μ and $\partial\mu/\partial T$ at values of $\dot{\gamma} = Q/H^2$ (or $PH/12 \mu L$) and at $T = 1/2(T_w + T_0)$, and from the above values the parameter

$$B = |(T_w - T_0) \mu / (\partial\mu/\partial T)| \quad (5.13)$$

is derived in order to decide whether or not the momentum equation and the energy equation must be solved simultaneously. Finally, G is calculated from the relationship

$$G = \begin{cases} B\mu Q^2/kH^2(T_w - T_0) \\ BP^2 H^4/14 kL^2 \mu(T_w - T_0) \end{cases} \quad (5.14)$$

in order to estimate the importance of heat dissipation.

In general, in order to study the flow characteristics in the dies, the lubrication approximation may be applied, since the length is considerably larger than the gap size and, more often than not, the width is also larger than the size of the gap. In such instances the approach may be that the velocity profile obtained from the momentum equation is substituted into the energy equation, while the lengthwise temperature gradient is regarded as constant, followed by integration in transverse direction. From the so obtained velocity distribution the average temperature is calculated, which is now substituted back into the energy equation and the lengthwise change of the average temperature is calculated, thus:

$$\frac{\partial \pi_T}{\partial Z} - A_1 \pi_T - A_2 \exp \pi_T + A_3 = 0 \quad (5.15)$$

where

$$\pi_T = -b(T - T_{en}); \quad A_1 = \frac{12 aL}{vH^2}; \quad Z = \frac{z^*}{L}$$

$$A_2 = \frac{bL\mu_0}{\bar{v}\rho C_p} \left(\frac{v}{H} \right)^{n+1} \cdot \exp[-b(T_{en} - T_0)]; \quad A_3 = A_1(T_w - T_{en})$$

The boundary conditions of equation (5.15) are:

$$Z=0 \quad \pi_T=0 \quad (5.16)$$

A solution of the equation by approximation is given by:

$$\pi_T = \frac{A_4}{A_5} (1 - e^{-A_5 Z})$$

where

$$A_4 = A_3 - \frac{bL\mu_0}{\varrho C_p \bar{v}} \left(\frac{\bar{v}}{H} \right)^{n+1}; \quad A_5 = A_1 + A_2 \quad (5.17)$$

The average velocity:

$$\bar{v} = \frac{nH}{2(2n+1)} \left(\frac{H \partial P}{2\mu \partial z} \right)^{1/n} \quad (5.18)$$

which indicates that when the effects of dissipation are considerable, an approximately exponential temperature increase takes place in the flow. If the above approach does not yield a satisfactory solution, it becomes necessary to solve the energy equation numerically.

Discretization of the momentum and the energy equations yields the following system of equations:

$$v_z(y) = v(N) = - \frac{dP}{dz} \sum_{n=1}^N \frac{n-0.5}{\mu(n)} \Delta y^2 = S_1(n) \frac{dP}{dz} \quad (5.19)$$

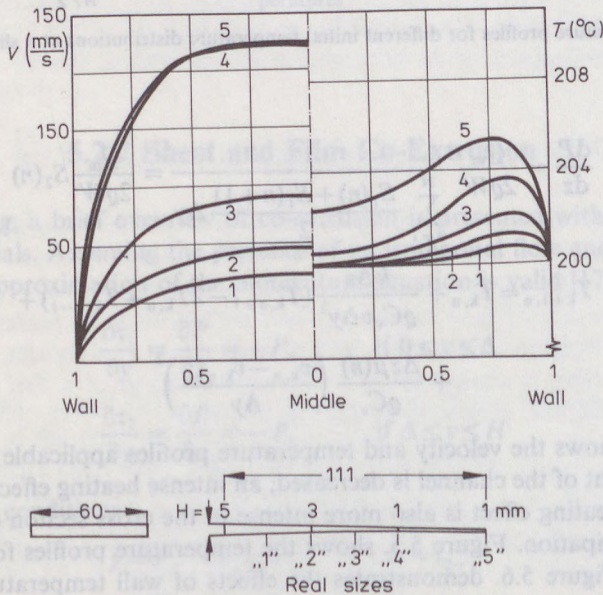


Fig. 5.4. Velocity and temperature distribution curves obtained at the exit of a rectangular slit, using High Density Polyethylene material (HDPE)

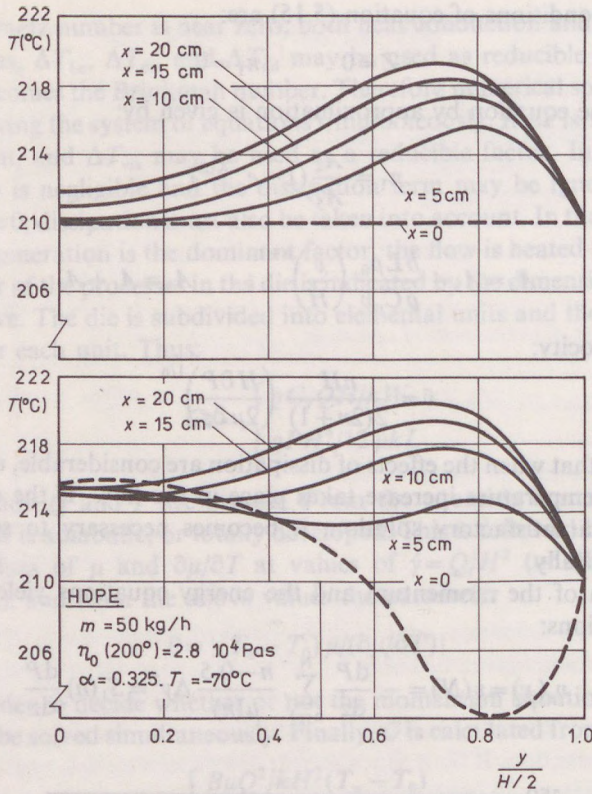


Fig. 5.5. Temperature profiles for different initial temperature distributions at a slit, $B/H = \frac{60 \text{ mm}}{3 \text{ mm}}$

$$\frac{dP}{dz} = \frac{Q_m}{2qW} \frac{1}{\sum_{n=1}^N \frac{S_1(n) + S_1(n+1)}{2} \Delta y} = \frac{Q_m}{2qW} S_2(n) \quad (5.20)$$

$$T_{k+1,n} = T_{k,n} + \frac{k \Delta z}{\rho C_v v \Delta y^2} (T_{k,n+1} - 2T_{k,n} + T_{k,n-1}) + \frac{\Delta z \mu(n)}{\rho C_v} \left(\frac{v_{k,n} - v_{k,n+1}}{\Delta y} \right)^2 \quad (5.21)$$

Figure 5.4. shows the velocity and temperature profiles applicable to a plane gap die. As the height of the channel is decreased, an intense heating effect takes place in the melt. The heating effect is also more intense in the cross section of the channel, due to heat dissipation. Figure 5.5. shows the temperature profiles for various inlet temperatures. Figure 5.6. demonstrates the effects of wall temperatures. The most even temperatures are obtained when the inlet temperature is the same as the wall temperature.

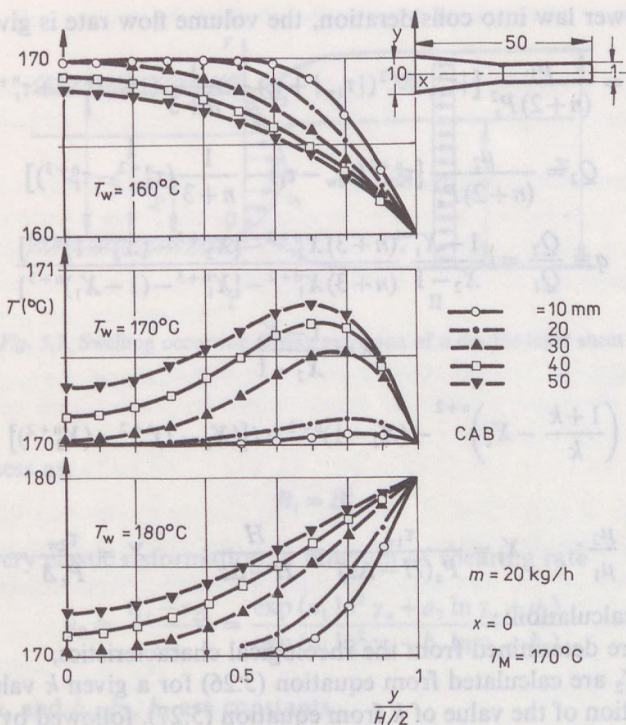


Fig. 5.6. Temperature profiles established for different wall temperatures with the same initial temperatures

5.2.2 Sheet and Film Co-Extrusion

In the following, a brief overview of co-extrusion is presented with respect to two different materials. Assuming the presence of an isothermal flow and assuming that a lubrication approximation of the momentum equation is valid [17, 18]

$$\begin{aligned} \frac{\partial \tau_1}{\partial y} &= \frac{\partial P}{\partial z} = -P_z & \text{if } 0 \leq y \leq \Delta \\ \frac{\partial \tau_2}{\partial y} &= \frac{\partial P}{\partial z} = -P_z & \text{if } \Delta \leq y \leq H \end{aligned} \quad (5.22)$$

with boundary conditions:

$$\begin{aligned} y=0 & \quad v_2=0 & \quad \tau_2=\tau_{2w} \\ y=H & \quad v_1=0 & \quad \tau_1=\tau_{1w} \\ y=\Delta & \quad v_1=v_2=v_r & \quad \tau_1=\tau_2=\tau_r \end{aligned} \quad (5.23)$$

Taking the power law into consideration, the volume flow rate is given by:

$$Q_1 = \frac{\mu_1}{(n+2)P_z^2} \left[|\tau_{1w}|^{n+2} (|\tau_{1w}| + \tau_r) - \frac{1}{n+3} (|\tau_{1w}|^{n+3} + \tau_r^{n+3}) \right] \quad (5.24a)$$

$$Q_2 = \frac{\mu_2}{(n+2)P_z^2} \left[\tau_{2w}^{n+2} (\tau_{2w} - \tau_r) - \frac{1}{n+3} (\tau_{2w}^{n+3} - \tau_r^{n+3}) \right] \quad (5.24b)$$

$$q \equiv \frac{Q_2}{Q_1} = i \frac{1-X_1}{X_2-1} \frac{(n+3)X_2^{n+2} - [X_2^{n+3} - (X_2-1)^{n+3}]}{(n+3)X_1^{n+2} - [X_1^{n+3} - (1-X_1)^{n+3}]} \quad (5.25)$$

$$k = \frac{1-X_1}{X_2-1} \quad (5.26)$$

$$\left(\frac{1+k}{k} - X_2 \right)^{n+2} - (X_2-1)^{n+2} = i [(X_2-1)^{n+2} - (X_2^{n+2})] \quad (5.27)$$

where

$$i = \frac{\mu_2}{\mu_1}; \quad X_1 = \frac{\tau_{1w}}{P_z(H-\Delta z)} = \frac{H}{H-\Delta z}; \quad X_2 = \frac{\tau_{2w}}{P_z\Delta} = \frac{H}{\Delta}$$

Method of calculation:

- i and n are determined from the rheological characteristics,
- X_1 and X_2 are calculated from equation (5.26) for a given k value,
- recalculation of the value of k from equation (5.27), followed by iteration until good agreement is reached,
- calculation of q from equation (5.25) together with calculation of Q_1 and Q_2 based on equations (5.24.a) and (5.24.b), respectively.

The layer thicknesses may be calculated from the volume flows.

5.2.3 Swelling and Relaxation at the Exit of the Die

The polymer melt undergoes swelling at the point of its exit from the die, due to its visco-elastic properties, and the swelling is expressed by the thickness swell $B_1 = h/h_0$ and the width swell $B_2 = W/W_0$, where h_0 and W_0 represent the dimensions of the die. Due to the effects of relaxation, the swell gradually decreases. The processes that induce swelling and relaxation lead to a dynamic equilibrium, thus, the time function of swelling is analogous with the time function of a first order reaction leading to equilibrium, expressed by the relationship:

$$B(t) = B_\infty - (B_\infty - B_0) \exp(-t/\lambda) \quad (5.28)$$

where B_∞ and B_0 are the swell values at times $t \rightarrow \infty$ and $t=0$, while λ is the characteristic relaxation time. Therefore, B_0 is the swell at the exit, expressed in relation to width as:

$$B_2 = \left\{ 0.5(1 + \gamma_R^2)^{0.5} + \frac{1}{2\gamma_R} \ln [\gamma_R + (1 + \gamma_R^2)^{0.5}] \right\}^{\frac{1}{3}} \quad (5.29)$$

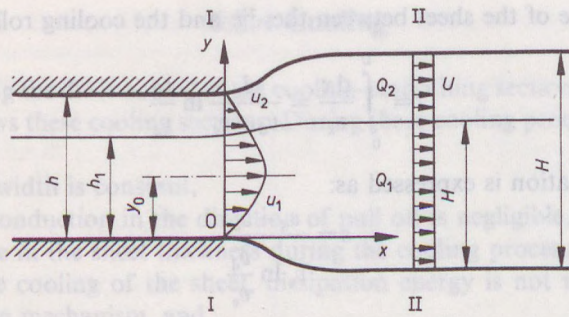


Fig. 5.7. Swelling occurring during extrusion of a double layer sheet

and for thickness as:

$$B_1 = B_2^2 \quad (5.30)$$

γ_R is the recovery elastic deformation, a function of shearing rate

$$\gamma_R = \frac{\tau_{11} - \tau_{22}}{\tau_{12}} = \frac{\exp(a_1 \ln^2 \gamma_w + a_2 \ln \gamma_w + a_3)}{\exp(b_1 \ln^2 \gamma_w + b_2 \ln \gamma_w + b_3)} \quad (5.31)$$

where a_1, a_2, a_3 and b_1, b_2, b_3 are constants.

The value of B_∞ can be determined experimentally from swell data measured at various times.

In the case of co-extrusion the evolution of swell is shown by Figure 5.7. The two layers leave the die with velocities v_1 and v_2 , after equalization the layers proceed further with velocity U .

$$\frac{Q_1}{Q_2} = \frac{H_1}{H - H_1}; \quad U = Q_1/H_1 = Q_2/(H - H_1) = Q/H \quad (5.32)$$

Swell is expressed as:

$$B_1 = \frac{1}{2(\Delta_1 + y_0)} \left[\Delta_1 (1 + f_1^2 \Delta_1^2)^{\frac{1}{2}} + \frac{1}{f_1} \ln \frac{|f_1 + (1 + f_1^2 \Delta_1^2)^{\frac{1}{2}}|}{|f_1 + (1 + f_1^2 y_0^2)^{\frac{1}{2}}|} + \dots \right] \quad (5.33)$$

Where $f_1 = P_z/2G_1$, $f_2 = P_z/2G_2$; $\Delta_{1,2}$ is the thickness of the individual layers, y_0 is the coordinate of the point of maximum velocity.

The hot polymer sheet strip upon exit from the die is subject to some degree of longitudinal pull due to the effects of the series of cooling rolls. The velocity of the sheet at the point of exit from the die is v_e , at the drawing rolls is v_d , hence its momentary velocity at a distance L between the die and the cooling rolls is given by:

$$v_x = v_e + \frac{v_d - v_e}{L} x \quad (5.34)$$

the residence time of the sheet between the die and the cooling rolls is given by:

$$t = \int_0^L \frac{dx}{v_x} = \frac{L}{v_d - v_e} \ln \frac{v_d}{v_e} \quad (5.35)$$

The total deformation is expressed as:

$$\varepsilon = \frac{v_d - v_e}{v_e \ln \frac{v_d}{v_e}} \quad (5.36)$$

Now, if some rheological state equation is assumed, the relationship between the pulling force and the pull-off velocity can be determined.

Choosing a rheological equation characterized by a relaxation constant [20] the tensile stress is expressed as:

$$\sigma_{xx} = \frac{4\eta_E \dot{\varepsilon}}{1 - 4\dot{\varepsilon}^2 \lambda^2} \quad (5.37)$$

Taking the momentum equation into account, the dimensionless pull-off velocity, π_{v_d} as a function of the dimensionless pulling force, π_F from equation (5.37) will be:

$$\pi_{v_d} = 2 \left[(1 + \pi_F^{-2})^{\frac{1}{2}} - (\pi_F^{-2} + Dr^{-2})^{\frac{1}{2}} + \frac{2}{\pi_F} \ln \frac{(\pi_F^{-2} + 1)^{\frac{1}{2}} - \pi_F^{-1}}{(\pi_F^{-2} + Dr^{-2})^{\frac{1}{2}} - \pi_F^{-1}} \right] \quad (5.38)$$

where $\pi_{v_d} = \frac{L}{\lambda v_d}$ is the dimensionless pull-off velocity, while $\pi_F = \frac{F \lambda v_d}{Q \eta_E}$ is the dimensionless force.

Taking the continuity equation into account, the relationship of the cross sections is given by:

$$W_0 H_0 v_e = B_1 H_0 B_2 W_0 v_x = B_1 H_0 B_2 W_0 \frac{v_e}{v_e + (v_d - v_e) \frac{X}{L}} \quad (5.39)$$

the sheet thickness $h = B_1 H_0$

$$h = H_0 \frac{1}{B_2 v_d} \quad (5.40)$$

Thus, the sheet thickness at the cooling roll is a function of the gap size of the die, the swell and the pull-off velocity. Equation (5.40) may be rearranged in a different form, since, according to the continuity equation the net mass flow of the sheet must be equal to the extruder's mass flow, hence the alternative form of equation (5.40) becomes:

$$h = Q \frac{1}{Dr B_2 W_0} \quad (5.41)$$

5.2.4 Cooling

The melt, leaving the die is cooled at the cooling-smoothing section of the equipment. Figure 5.8. shows these cooling sections. During these cooling processes it is assumed that:

- the sheet width is constant,
- the heat conduction in the direction of pull off is negligible,
- the change in the sheet thickness during the cooling process are negligible,
- during the cooling of the sheet, dissipation energy is not taken up from the forwarding mechanism, and
- shrinkage is restricted.

Applying these conditions, in a Cartesian coordinate system the equation becomes:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{1}{\rho C_p} \cdot \frac{\partial k}{\partial T} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 \right] \quad (5.42)$$

In a cylindrical coordinate system this equation is analogous to equation (5.42), however, the expression in brackets in the first term on the right hand side is modified by the addition of another term, namely:

$$\frac{1}{r_c + y} \frac{\partial T}{\partial y}$$

where r_c is the radius of the cylinder.

The boundary values of the equation change in the cooling phases, between convective heat transfer, heat transfer via heat conduction (on the cooling roll surfaces) and radiation heat transfer. The solution of equation (5.42) is performed by the method of finite differences. The finite difference equation is included in Table 5.2.

The temperature versus time curves are given in Figures 5.9. and 5.10.

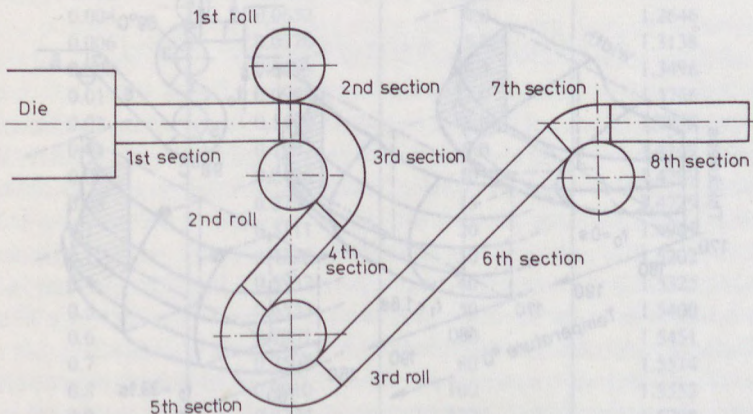


Fig. 5.8. The various sections of sheet and foil cooling processes

Table 5.2. The finite differential forms of the cooling equations [3]

Cartesian coordinate system	Cylindrical coordinate system
$T_{k,m,l+1} = T_{k,m,l} + \frac{a_{k,m,l} k_t \Delta t_0}{(k_x \Delta x_0)^2} (T_{k+1,m,l} - 2T_{k,m,l} +$ $+ T_{k-1,m,l}) + \frac{a_{k,m,l} k_t \Delta t_0}{(k_y \Delta y_0)^2} (T_{k,m,l+1} - 2T_{k,m,l} +$ $+ T_{k,m,l-1}) + d_{k,m,l} k_t \Delta t_0 \times$ $\times \left[\left(\frac{T_{k+1,m,l} - T_{k-1,m,l}}{2\Delta x_0 k_x} \right)^2 + \left(\frac{T_{k,m,l+1} - T_{k,m,l-1}}{2\Delta y_0 k_y} \right)^2 \right]$ $\text{ahol } k_x = 0.33 \sqrt[3]{\frac{Q_0}{Q_{k,m,l}}}$ $k_y = \frac{Q_0/Q_{k,m,l}}{0.33 \sqrt[3]{Q_0/Q_{k,m,l}}}$	$T_{k,m,l+1} = T_{k,m,l} + \frac{a_{k,m,l} k_t \Delta t_0}{(k_x \Delta x_0)^2} (T_{k+1,m,l} -$ $- 2T_{k,m,l} + T_{k-1,m,l}) + \frac{a_{k,m,l} k_t \Delta t_0}{(k_y \Delta y_0)^2} \times$ $\times (T_{k,m,l+1} - 2T_{k,m,l} + T_{k,m,l-1}) +$ $+ \frac{a_{k,m,l} k_t \Delta t_0}{2(r_i + m\Delta y_0) k_y \Delta y_0}$ $(T_{k,m,l+1} - T_{k,m,l-1}) + d_{k,m,l} k_t \Delta t_0$ $\left[\left(\frac{T_{k+1,m,l} - T_{k-1,m,l}}{2k_x \Delta x_0} \right)^2 + \left(\frac{T_{k,m,l+1} - T_{k,m,l-1}}{2k_y \Delta y_0} \right)^2 \right]$

In the calculation method described above the temperature dependence of the heat conduction constant was also taken into account. In many instances, however, this dependency is negligible, in such cases the second term on the right hand side of equation (5.42) becomes zero. For such cases exact solutions were derived [21–22], summarized in Table 5.3. Table 5.4. shows the solutions of the characteristic equation as a function of the Biot number.

In a frequently used method, to relieve the sheets from stress, the temperature of the section between the die and the cooling rolls and of the sheet on the cooling rolls is maintained at a constant value or cooled gradually in combination with heating [23]. In the latter instance it is necessary to expand equation (5.42) by an additional

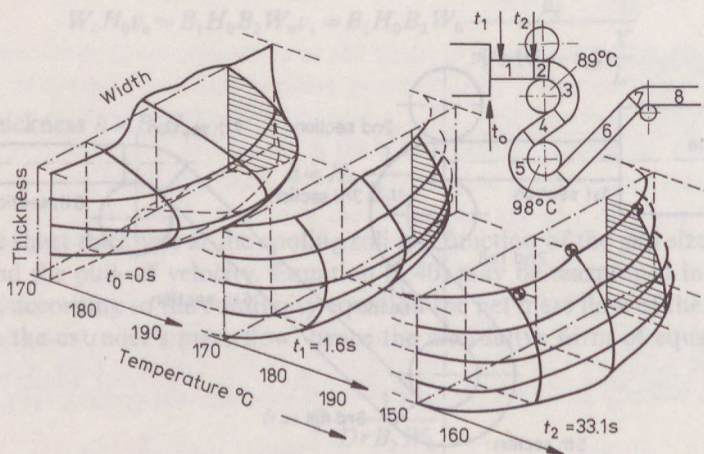


Fig. 5.9. Sheet cooling curves using polystyrene material [3]

Table 5.3. The exact solutions of the cooling equations [14]

For the temperature:

$$\Theta = A \cos \left(v \frac{Z}{h} \right) \exp \left(-v^2 \frac{at}{h_2} \right)$$

The characteristic equation is:

$$\operatorname{ctg} v = \frac{1}{Bi} v$$

term, a source member:

$$\frac{q(x)}{q C_v} = q_0 (1 - \kappa) \exp(-ax) \quad (5.43)$$

where q_0 is the radiation energy of the auxiliary heating bodies, κ is the reflection factor, while a is the heat absorption factor.

The stresses that evolve during cooling are firstly due to the temperature differences between the layers and secondly to the bending of the sheet on the cooling rolls. Expressed mathematically:

$$\Delta \varepsilon_{i,i-1} = \alpha (T_i - T_{i-1})_{T_i = T_s} + \varepsilon_{b,i} \quad (5.44)$$

where α is the heat expansion factor, T_s is the solidification temperature, $\varepsilon_{b,i} = L_i / R_{cr}$, where L_i is the distance of the i^{th} layer from the neutral thread, R_{cr} is

Table 5.4. The characteristic roots of the cooling equation

Bi	v	Bi	v
0	0.0000	1.5	0.9882
0.001	0.0316	2.0	1.0764
0.002	0.0447	3.0	1.1925
0.004	0.0632	4.0	1.2646
0.006	0.0774	5.0	1.3138
0.008	0.0893	6.0	1.3496
0.01	0.0998	7.0	1.3766
0.02	0.1410	8.0	1.3978
0.04	0.1987	9.0	1.4149
0.06	0.2425	10	1.4289
0.08	0.2791	15	1.4729
0.1	0.3111	20	1.4961
0.2	0.4328	30	1.5202
0.4	0.5932	40	1.5325
0.5	0.6533	50	1.5400
0.6	0.7051	60	1.5451
0.7	0.7506	80	1.5514
0.8	0.7910	100	1.5552
0.9	0.8274	120	1.5708
1.0	0.8603		

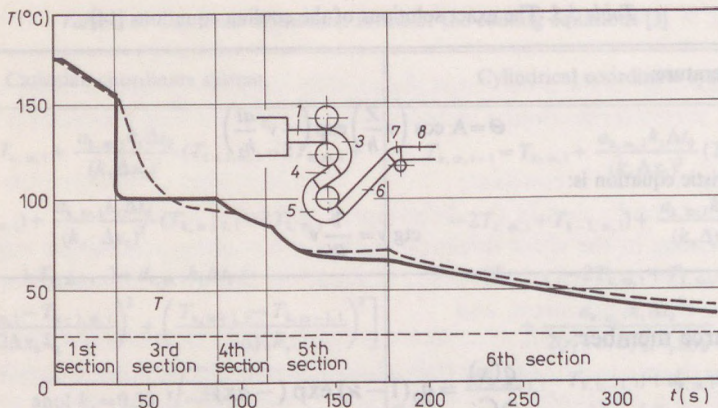


Fig. 5.10. Sheet cooling curves using polystyrene material [3]

Thickness: 1.6 mm, width: 800 mm, the temperatures of the cooling rolls 130°C and 100°C, respectively
 —: upper sheet layer, ---: bottom sheet layer

the radius of the cooling roll. The stress in a longitudinal direction is expressed as:

$$\sigma_{i,1} = \varepsilon_{i,1} E + \nu \sigma_{i,q} \quad (5.45)$$

and transverse:

$$\sigma_{i,q} = \varepsilon_{i,q} E + \nu \sigma_{i,1} \quad (5.46)$$

Including the deformation equation and then solving it:

$$\sigma_{i,1} = \frac{1}{1-\nu^2} [(1+\nu) \varepsilon_{\Delta T,1} + \varepsilon_{b,i}] E \quad (5.47)$$

$$\sigma_{i,q} = \frac{1}{1-\nu} \varepsilon_{\Delta T,1} E \quad (5.48)$$

5.3 Quality Aspects of the Sheet

The characteristic features of the sheet produced are the precision of dimensions, the surface quality, the degree of its tendency to shrink and its degree of orientation. The sheet thickness, based on the results of thickness measurements, is controlled by adjustments to the shaping part of the die. Even flow is ensured by means of a deformation element applied on the entire length of the die, while in the case of thin sheet production this is achieved by way of a movable half-die application. In order to secure a uniform sheet thickness, the temperatures of the extruder head can be varied. Where the temperature distribution in the head is not uniform, this will result in an increase of internal stresses in the sheet. For this reason, during operation it is imperative to maintain a constant temperature in the head. It is undesirable to adjust the sheet thickness by means of a smoothing pair of rolls, since this will result in a

calender effect and thus, orientation of the material increases. Apart from the above, in most instances, behind the gap after the rolls, the polymer melt acquires a cylindrical shape and "pine-tree" type of imperfections may occur on the surfaces of the film. The gap between the first pair of rolls should nearly be equal to the desired thickness of the sheet to minimize flow beyond the rolls, for the best result, no flow at all should occur beyond the rolls. One of the indications of a sheet of even thickness is the near-absence of flow.

In sheet manufacturing orientation is undesirable, since it may cause substantial anisotropy in the sheet's mechanical properties. Orientation may be reduced by an increase of the extrusion temperature, by the reduction of stresses between the groups of rolls (i.e. between the smoothing and pull-off mechanism) and by decreasing the pull-off velocity of the sheet. Orientation may also be decreased by reduction of the pressure applied by the upper roll and by an increase of the temperature of the middle roll. The thermal "memory" of the sheets stretched axially is important in the subsequent processing, since these sheets, upon the effect of heat treatment, acquire a non-oriented state and, in such instances, the orientation stresses cause deformation and shrinking. A sheet of single orientation is obtained when the sheet is passed through the gap between a roll pair with an orifice larger than the sheet thickness. This process takes place in a state of viscous flow; the lower the melt temperature, the smaller is the degree of viscous flow and the greater the orientation effect.

Internal stresses also evolve and influence the degree of orientation. The orientation effect occurs when the sheet is passed through the narrow gap between the smoothing rolls, that is, when a very thin layer of material is formed on a relatively cold and polished roll. The roll cools the polymer, hence, on the surface of the polymer large orientation stresses occur. In this way, the orientation effect is restricted to the surface layer of the sheet, so that the sheet can be regarded as a multi-layer product with a highly oriented external surface layer, while the internal layers are free of orientation. The average degree of the orientation stresses is dependent on the sheet thickness: the thicker is the sheet the less is the effect of orientation on the overall properties of the product. Shrinkage of the extruded sheets depends on the pull-off velocity between the die and the cooling rolls, and on the melt temperature.

Sheets produced by correctly applied technology, are free of orientation. The supermolecular structure is of spherulite type. In the case where polyolefin materials are utilized, the sheets usually have large spherulite structures, while foils consist of small-spherulite structures.

The effect of orientation in the case of foils is even more substantial. High extrusion temperatures are associated with minimal crystallisation in the foil. In such cases, an even distribution of the crystalline phase must be achieved, to produce a foil with excellent optical properties. In thin foils a rapid cooling results in a microcrystalline structure characterized by a low light scatter (4–6%). An increase in the temperature of the cooling equipment when the other parameters remain unchanged, results in a deterioration of the optical properties of the foil. An important processing parameter is the distance between the die and the surface of the cooling drum. This distance should be chosen so that the surface temperature of the cooling roll does not rise above 20 °C. In cases of thick foils, a temperature increase is highly probable. When

the cooling unit is at a distance of less than 40–50 mm from the shaping die, an increase in the temperature of the material and a decrease in the temperature of the drum can increase significantly the opacity of the foil. Auxiliary cooling provided for the melt increases the foil's transparency, and surface imperfections that may occur at high speed of production can be eliminated. It is important to choose carefully the amount of cooling air. In order to reduce the distance it is necessary to make the shaping part of the die as thin as possible and the die must bend to the roll at an angle. Approaching the cooling roll to the head improves the optical properties of the product, although, at the expense of strength factors. Where polyolefine materials are used the optimal distance of the cooling roll from the die is in the range 20–70 mm. The important factor is not so much the actual distance, but the time taken for the foil to cover this distance, thus, the optimal distance depends on the processing speed.

The velocity of extrusion also influences product quality to a substantial extent: the velocity may be controlled primarily by the speed of rotation of the screw and by the pull-off speed. A high screw revolution number can result in thermal decomposition, which deteriorates product quality, and may be accompanied by pulsation, furthermore, this may also cause lengthwise variation in thickness. The elasticity properties of the polymer melt also influence product quality. An increase in gap size, in such instances, reduces the linear velocity and the shearing stresses occurring. The optimal gap size is 0.25–0.70 mm. Cooling of the product on the roll is accompanied by the so-called roll effect. The foil structure of low density polyethylene attained by high temperature rolling was examined by means of low-angle and large-angle X-ray diffraction, infrared spectroscopy and low-angle light scatter. It was shown that axial high tensile strength was accompanied by *C*-oriented structure, evolved during elongation of the isotropic foil. The structure of the foils produced at various roll temperatures (ranging from 5–100 °C) showed that at temperatures between 5 and 60 °C the strength of the foil increases substantially (3 to 4-fold) in the direction of rolling; the highest linear strength was obtained at 60 °C. At 100 °C the *C*-type orientation was substantially smaller, at this temperature the material was virtually isotropic. In the case of polyethylene the crystallization temperature was about 0.8–0.85 T_m , that is, for high density polyethylene it was 80–85 °C. The structural rearrangement continues after the foil had passed through the cooling system, as the temperature of the roll approached that of maximum crystallization velocity of the material (60 °C), and *C*-type orientation was observed and a material with high mechanical strength was obtained.

In the case where $T_v > T_{max}$, structural changes were observed to continue after the foil had passed the gap between the rolls, disorientation took place and an anisotropic structure evolved.

5.4 Control of Sheet and Foil Production Lines

In Chapter 1 we discussed the controls for the machinery of the extruder production lines. To the plasticating units are connected shaping dies, calibrating equipment to control the shapes, cooling and pulling-off units, and finally cutting and wrapping

Table 5.5. Variables employed on an extrusion line

Variables	Load variables	Manipulated variables	Controlled variables
Resin properties	+		
Feed rates	+		+
Screw speed	+	+	
Barrel temperature	+		+
Barrel heater		+	
Power supply		+	
Melt temperature	+	+	+
Back pressure		+	
Die temperature		+	
Die pressure	+	+	+
Die size		+	
Output rates			+
Extrudate quality			+
Extrudate dimensions			+
Take-up speed		+	

equipment. Thus, the control of extruder lines is a complex process, where, apart from the control of each unit, control solutions must be provided for the overall system. Table 5.5. collates the characteristic parameters concerning an extruder production line. There are many variables in the extrusion process, some of which are used as manipulated variables, i.e. variables which are changed by external manipulation. Some others are controlled variables which are controlled through the manipulated variables. The rest of them are load variables, these being variables which are difficult or impossible to control.

Parameters influencing sheet and plane foil production are:

a) geometric characteristics;

- the height of the die gap,
- the width of the die, and
- the distance between the die and the cooling roll,

b) technological characteristics:

- the temperature of the material at the point of exit from the die,
- the temperature of the surrounding air, of the cooling rolls and of the thermostat system,
- the exit velocity from the die, and
- the pull-off speed,

c) material characteristics:

- rheological properties,
- density, and
- heat conduction factors.

For sheet and foil manufacturing the simplest mode of control is to change the dimensions of the die (for example, the height of the die). Several methods are available for changing the die size (24–32). Electrical signals originating from the

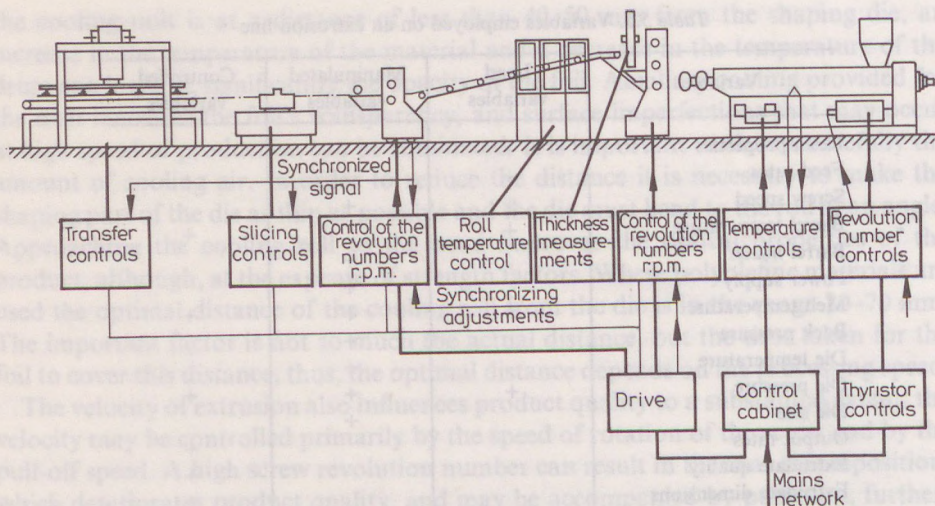


Fig. 5.11. Sketch of a sheet thickness control arrangement [23]

control equipment are used to change the size and the application of heating for this purpose.

To aid the control of plastic film thickness extruded from dies, generally, adjustable die bolts are employed, which control the height of the gap of the die. With the introduction of automatic gauging devices, it became advantageous to utilize the signals from the gauge to adjust the die orifice automatically to maintain uniform film thickness. A scanning thickness gauge measures the sheet thickness and provides a signal to a profile measuring device connected to a micro-computer. The computer uses this information to calculate the desired die bolt movements by solving a series of simultaneous equations to eliminate bolt interactions. The bolt temperatures are measured for each of the die bolts concerned. The temperature sensor in the die bolt provides a temperature signal to the micro-computer, where it is compared with the set-point temperature. Any deviation is corrected by increasing, or decreasing the power output current to the die bolt heater to bring the die bolt to the desired set-point temperature.

Control of the average dimensions of the extrudate on a continuous basis is quite straightforward. The profile of the extrudate is measured with an isotopic or other gauging device and an average dimension is determined. The average is then compared with the desired value and, if a deviation is detected, a correction is made in some of the process parameters to bring the average back within tolerance limits. In a typical arrangement an analogue loop measures the average thickness and controls the speed of the line. The analogue systems do not handle transport lags. However, a digital control system can adequately handle transport lag situations. A digital system is capable of utilizing a much more sophisticated control algorithm and it can make corrections by adjusting parameters other than the speed of the production line (see Fig. 5.11).

Different methods are available for controlling the thickness of the extrudate, these are:

a) Feedback control

The take-up speed is used here as the manipulated variable, the measured extrudate thickness is used as the controlled variable and the screw speed is chosen as the load variable. Two feedback control methods, a conventional PI controller and a Smith predictor dead time compensation are used [33]. These methods are satisfactory for the step changes of the set-point, but unsatisfactory for load changes.

b) Feed-forward control

The basic concept of this method is that under continuous measurement of the controlled variables, any disturbance which tends to deviate from the set values, may be forecast in advance. This is followed by a calculated adjustment, made on the manipulated variables to correct the potential departure from the set-point before it is likely to occur. The success of this method relies on a well-designed forecasting programme and a complete understanding of the dynamic behaviour of the process.

The extruder thickness detected is used as the controlled variable. The take-up speed is used as the manipulated variable in the control. The melt temperature and the die pressure are used as the load variables of the variables for feed-forward control, in which the melt flow rate was calculated by the use of a flow model and the thickness of the extrudate is estimated from the melt flow rate. The feed-forward control methods seem to work very well for various load disturbances, but they require a reliable process model and accurate on-line measurement of the manipulated variables and load variables.

c) Advanced automatic control

This control method is designed to keep the sheet thickness at a specified target. The algorithm maintains sheet thickness at the target by corrective actions based on average measurements obtained on-line, that is by full-sheet scanning of the thickness sensor. Where the scan average differs from the desired thickness, corrective actions are initiated. The frequency and the magnitude of the actions are determined by means of a reference model, a control technique allowing more frequent and accurate corrections. Direct digital control constantly monitors screw speed and take-up speed to prevent drifts or fluctuations in these elements.

d) Target optimization control

This control minimizes material consumption per unit area of the extrudate produced. Minimization is achieved by arranging that only a predetermined percentage of the sheet falls below a minimum thickness. Sheets of less than minimum thickness are considered defective and the set defective fraction is the basis of the algorithm. The sheet thickness is measured continuously, the defective fraction is calculated from the measurement data, the process variance is computed and the thickness target is shifted accordingly. Under target optimization control, upward target shifts are performed immediately to ensure constant lower limit protection.

e) Throughput optimization control

This method increases extruder production to a maximum obtainable level and maintains this level of output automatically. The throughput can be specified in terms of screw speed, take-up speed, or thermoformer shots per minute for primary

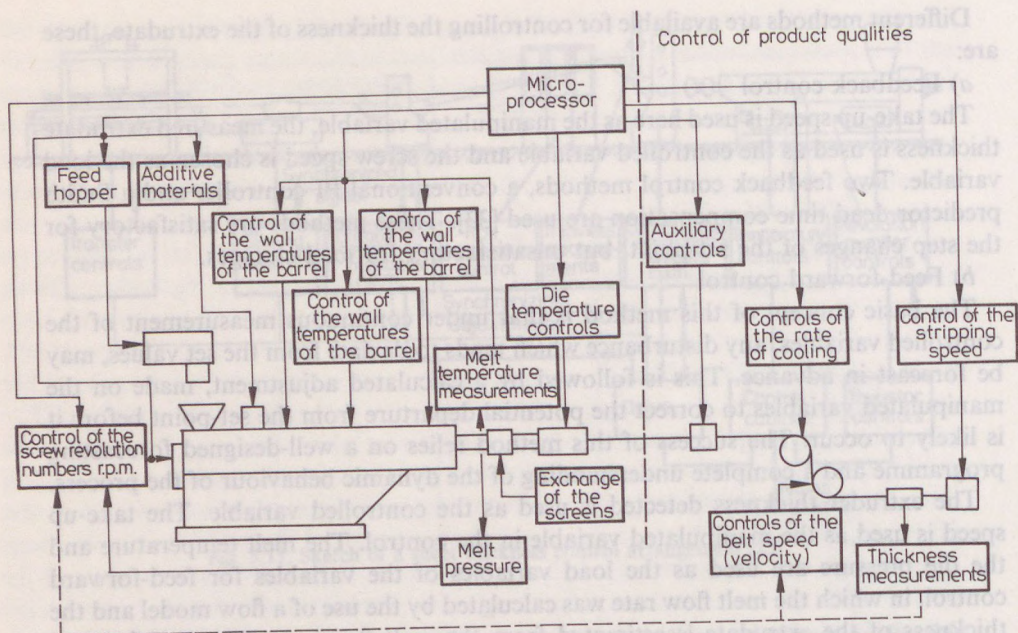


Fig. 5.12. Sheet manufacturing with control application to aid maximalization of output

thickness-adjustment control. If the throughput is defined in terms of screw speed, then maximization is achieved by screw speed adjustments. Since an adjustment in screw speed affects sheet thickness, a coordinated change in line speed is made to prevent step variations in product thickness. An example of the throughput optimization control is shown in Figure 5.12.

f) Hierarchical control system

This system is based on the concept of localized control, thus, the computers are located at the work site. The hardware can be divided into individual units. These may be:

- sensors to measure the thickness of the finished product,
- a frame to transverse the sensor across the sheet,
- process control station for the operator interface and to house the computer with the computer interface,
- printer/plotter for management printout and programme modifications.

The system utilizes a seven-colour interactive video monitor to provide a real-time display and the analysis of the extrusion process. Using the display, the operator monitors all process variables.

The system has the following control methods:

- Throughput control.

This control function is used to adjust production rate targets without alteration of product thicknesses. This is achieved by changing the line speed and the screw speed in a coordinated manner so that the resulting thickness variations are minimized.

- Throughput optimization control.
- Pull ratio control.

Here, the direct digital control function manipulates the pull-speed ratio signals to the drive control circuit in order to control the ratio of the pull-roll speed to the line speed.

— Target adaptive control.

The optimum control parameters can be stored in memory and transferred to the working store, when the operator loads the product specification into the system via an interactive video, these parameters may be recalled.

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6 Control of Tube and Profile Extrusion Processes

6.1 Equipments and Materials Employed in Tube Extrusion

The processes of tube and profile extrusions are similar, the only difference between them is the shapes of their cross sections. Thus, whatever is said about tube extrusion applies equally to profile extrusion.

The manufacturing process of tube extrusion is depicted in Figure 6.1. The homogeneous melt is prepared in the plasticating unit (1). Shaping of the melt occurs in the die (3), the calibration equipment (4) serves to make accurate adjustments of the dimensions of the tube, the cooling equipment (5) ensures the rapid cooling of the hot tube, the puller mechanism moves the tube (6), the rotary saw (7) slices the product into the required lengths, and finally, the tip-pan van (8) transports the tubes, cut to size, to storage. For tubes of a soft consistency, sections (7) and (8) are replaced by a winding mechanism.

The extrusion system's elements, for producing tubing, are:

1. Extruder,
2. Dies,
3. Sizing equipment,
4. Puller,
5. Cut-off unit,
6. Alternative winder.

A number of optional units are also used on tube production lines, such as:

7. Static die-head mixer,
8. Extruder valve,
9. Cooling tanks,
10. Vacuum sizing tanks,
11. Water-cooling troughs,
12. Dry vacuum sizers,

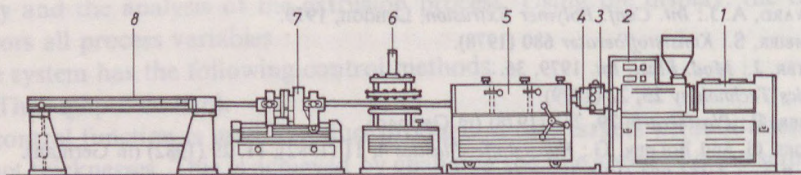


Fig. 6.1. Construction system of a pipe extrusion line [1]

1. plasticating unit, 2. control panel, 3. die, 4. sizing, 5. cooling unit, 6. puller equipment, 7. cut-off unit, 8. tiltable channel

13. In-line marking units,
14. Internal mandrel sizing units,
15. Diameter-gauging equipment,
16. Wall-thickness gauging equipment,
17. Dump tables and stackers,
18. Hopper drying equipment,
19. Acoustic flaw detectors,
20. Other specialized equipment.

It should be noted that this list is by no means exhaustive.

The dies are the major shaping elements of the pipe or tubing lines. Their design and construction have been covered in earlier descriptions. Again, the type of die selected for the particular system depends on the material being processed. Design and construction also depend on the dimensions of the product, the production rate and the lengths of runs intended to be made. If the materials are stable at the extrusion temperatures, the dies can be relatively simple in design, without undue attention paid to the material held back in the die in the stagnant-flow regions. On the other hand, if the material tends to decompose at the extrusion temperatures, it becomes important for long runs that the dies be completely streamlined, free of any stagnation zones in the tool that can lead to the production of streaked and burned products.

The selection of cooling and sizing equipment for the system is dictated by similar considerations as for the other line components—rate, material properties, dimensional control and product size—but here the parameters are different. The cooling system can be a simple water tank, a vacuum sizer, an internal cooling mandrel, an air-cooling system, or some of the above in combination. Since the tubing is sized as it is cooled, the sizing devices are intimately integrated into the cooling unit.

One of the simplest approaches is to pull the tubing directly into a water tank. Application of this method is frequently governed by the surface friction characteristics of the material in the hot state and by the stiffness of the softened plastic. As a consequence, the only practicable cooling method is to submerge these products directly in a water tank. The sizing is accomplished by controlling the pulling rate relative to the extruder delivery rate. There is usually little or no fixturing in the tank because of the friction problems. Occasionally, water-cooled rings are used to prevent flattening of the tube as it passes through the tank. Controlled sizing is not used in this arrangement.

One of the most widely employed schemes in tube and pipe manufacturing systems is the use of a vacuum sizing tank. The outside diameter of the tube is set by holding it against a set of sizing rings, immersed in water in the vacuum sizing tank. The water in the tank is held below atmospheric pressure to aid holding of the tube against the sizing rings while the outer layers of the tube are set by contact with the cooling water in the vacuum tank. This method is highly effective with medium to thick walled tubing in the range of 0.76–12.7 mm walls. Two problems arise in the use of the vacuum sizing method. Firstly, the amount of cooling the unit is capable of determining the length of the sizing unit. The second problem is concerned with the drag effects produced by intimate contact with the sizing rings. The contact pressure is determined by the level of vacuum in the tank and this, in turn, determines the amount of the drag

that can occur. The longer is the vacuum-cooling section, the larger is the surface area for cooling and the greater is the drag. Selection of the sizer is based on the best compromise between these factors, and the additional cooling necessary is realized in the atmospheric pressure units downstream from the vacuum sizing tank. It is clear that the drag effects are important with respect to the puller.

Other methods of sizing and cooling involve the use of an internally cooled mandrel (often used in the production of thin-wall tubing), the use of dry vacuum sizing units and the use of internally pressurized sizers. The internal mandrel system is employed to make polyethylene tubing with wall thicknesses of 0.15–0.51 mm and with diameters of 1.27–7.62 cm. Dry sizers are used with materials such as acrylic materials that cannot be rapidly cooled because of a tendency to internal void formation in thick-wall sections. The internal pressurization system is used for producing very heavy wall pipes with wall thicknesses in the range 0.64–5.08 cm. The vacuum system does not provide effective contact with the sizing rings when stiff materials are extruded, such as rigid PVC tubes with very heavy walls.

The pulling unit has an important function in the system, and is usually not investigated as carefully as it should be for performance characteristics. In the free-extrusion sizing system the controlling factor is the relationship of the puller's speed to the output of the extruder in determining the dimensions of the product. In a cooling arrangement related to vacuum sizing the outside diameter is controlled by the sizing sleeves, however, wall thickness control is dependent on the puller speed control. The factors determining the effectiveness of the operation of the puller include the power capability of the unit and the effect of "grabbing" by the puller belts or rollers. The puller employed to draw the pipe or tubing through a long vacuum sizer needs a drive of greater horsepower, than the type employed in free extrusion. Another system trade-off required is the comparative size of the puller and puller drive versus the length of the vacuum-cooling surface in the sizer.

The belt surfacing of the puller is an important factor in the control of both the size and the uniformity of the product. It is necessary to design the surfaces and to select the surface materials accordingly, in order to minimize the tendency of the tube to slip in the puller. Constant slippage tends to make the product larger in size than that calculated. Intermittent slippage or slip-and-stick phenomena cause variations in the dimensions of the product. The use of belt surfaces with high frictional coefficients against the plastic in the process of extrusion is important. In addition, the belt or puller rolls should be contoured to increase the available friction surface areas.

6.2 Dies Employed in Tube Extrusion

The shaping part of the tube-extrusion dies are ring shaped; the connecting channels vary according to the specific solution required. Figure 6.2. shows the most common die shapes. These may be:

- dies with a mandrel,
- dies with a screen casing,

- dies with melt distributors,
- spirally fluted dies,
- dies with rotating cores.

The die shown in Figure 6.2.a) is a straight flow die with a mandrel. This may be subdivided into two parts (3) and (6) with a mandrel-holding screen between them (11). The die (6) contains the ring-form shaping part (9), fastened by the rim (8). The melt, at the point of entry into the die passes through the sieve (1) and the screen (2), both of which serve to filter the melt. The mandrel holding screen (11) contains the mandrel parts (4) and (10). Pressure in the tube is generated via the air inlet channel (5). The melt from the plasticating unit reaches the mandrel containing the holding screen via the transfer channel between the half die (3) and the core (4), here the melt flow is divided into parallel flow streams. The mandrel holding screen is designed so that dead space cannot develop. Behind the mandrel casing another ring-shaped channel is constructed, which channels the melt to the shaping part of the die. The size of the shaping channel is adjustable by means of the screws (7). The characteristic l/h ratio of the shaping channel is of the order of 15–30. The length of the channel needs to be correct in order to minimize anisotropy in the channel. The length of the ring-shaped part of the die is given by:

$$L_a > 3\lambda \bar{v} \quad (6.1)$$

where v is the average velocity of the melt in the ring-shaped channel, while λ is the characteristic relaxation time. The average velocity is given by the relationship:

$$\bar{v} = \frac{Q}{\pi(R_{out}^2 - R_{in}^2)} \quad (6.2)$$

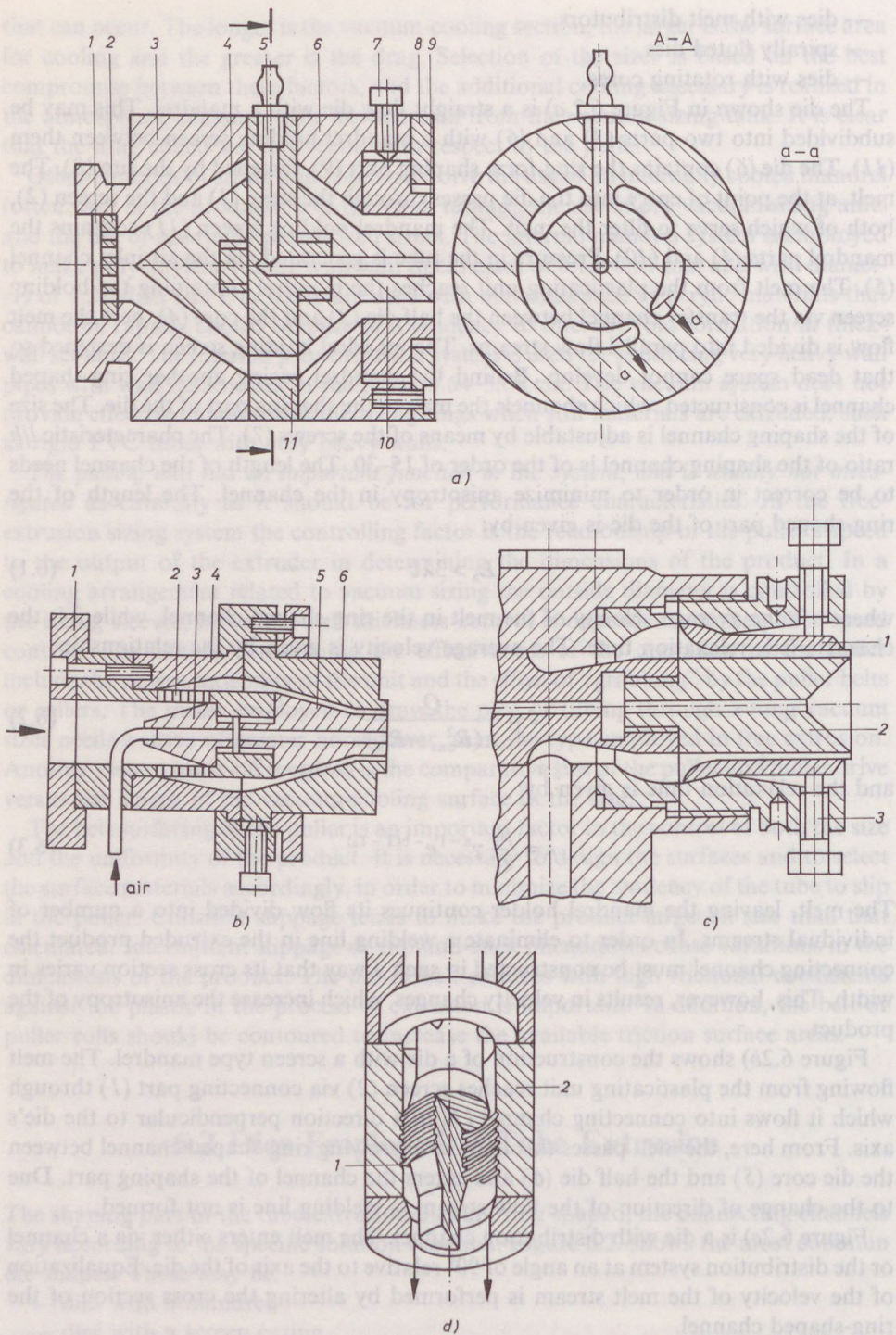
and the relaxation time is given by:

$$\lambda = \frac{\mu_0}{G} \gamma^{n-1} e^{-b(T-T_0)} \quad (6.3)$$

The melt, leaving the mandrel holder continues its flow divided into a number of individual streams. In order to eliminate a welding line in the extruded product the connecting channel must be constructed in such a way that its cross section varies in width. This, however, results in velocity changes, which increase the anisotropy of the product.

Figure 6.2b) shows the construction of a die with a screen type mandrel. The melt flowing from the plasticating unit reaches screen (2) via connecting part (1) through which it flows into connecting channel (3) in a direction perpendicular to the die's axis. From here, the melt passes through the narrowing ring-shaped channel between the die core (5) and the half die (6) and enters the channel of the shaping part. Due to the change of direction of the flow stream, a welding line is not formed.

Figure 6.2c) is a die with distribution channel. The melt enters either via a channel or the distribution system at an angle of 90° relative to the axis of the die. Equalization of the velocity of the melt stream is performed by altering the cross section of the ring-shaped channel.



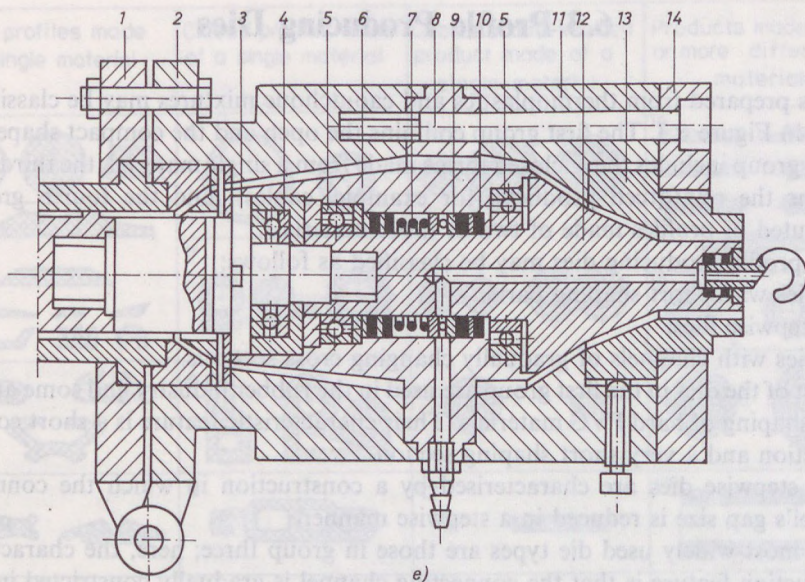


Fig. 6.2. Dies used in pipe manufacturing

a) Straight flow die with mandrel

1. sieves, 2. screens, 3 and 6. die body, 4 and 10. mandrel, 5. air inlet clamp screw, 7. setting screw, 8 and 9. shaping sections, 11. mandrel screen

b) Die with a screen type mandrel

1. edges, 2. mandrel with screen, 3 and 5. mandrel parts, 4. die body, 6. shaping ring

c) Die with distribution channels

1. shaping section, 2. mandrel, 3. screw adjustment

d) Die with a spirally tilted channel

1. channel on the core, 2. channel on the barrel

e) Die with a rotating core

1. edges, 2. die body, 3. joining element, 4 and 5. bearings, 6. core casings, 7. compression spring, 8. screw, 9. air distribution ring, 10. sealing, 11. middle section of the die, 12. core, 13. shaping ring, 14. edges

Figure 6.2d) shows the structure of a die with spirally fluted channel. Here again, the melt enters at a near vertical angle to the axis of the die. The equalization of the flow velocity is achieved by the grooves of the channel with gradually reduced depth.

Figure 6.2e) is a die with a rotating core. The die body (2) is joined to the plasticating unit by part (1). This die is similar in construction to dies with a mandrel. In core (6) the internal core (12) can rotate on ball bearings (4) and (5), which are fastened to the screw by the joining element (3). The air-inlet system is sealed off from the other parts of the die by the gasket (10). The shaping part of the die is the channel between the core (12) and the die head (13). The gap size is adjustable with the screw (8). The axial flow is hand-formed into a spiral flow on the effect of the rotation of the core, and this makes possible uniform temperature and velocity distribution.

6.3 Profile Producing Dies

Profiles prepared from thermoplastics and caoutchouc mixtures may be classified as shown in Figure 6.3. The first group contains the open and the compact shapes. The second group includes the enclosed forms made from a single material, the third group contains the reinforced products (for example, cables), and the fourth group is constituted of profiles made of two or more materials.

The profile producing dies may be classified as follows:

- dies with short shaping parts,
- stepwise dies,
- dies with channels of gradually changing cross sections.

Most of the dies in the first group are used in the rubber industry and some are used in the shaping of hard PVC materials. Their characteristic feature is a short connecting section and a very short shaping section.

The stepwise dies are characterised by a construction in which the connecting channel's gap size is reduced in a stepwise manner.

The most widely used die types are those in group three; here, the characteristic construction feature is that the connecting channel is gradually constricted in order to equalize the velocity of the flow.

6.4 Flow through the Dies

6.4.1 The Flow through Tube Dies

The characteristic process of the flow across a tube die is the flow in a ring-shaped gap or in a ring-shaped gap around the rotating core [9–13].

The flow processes are submitted to prior analysis by means of a criterion parametric method demonstrated earlier in the text. The momentum equation gives:

$$-\frac{1}{r} \frac{\partial P}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} (r \tau_{rz}) = 0 \quad (6.4)$$

$$-\frac{1}{r} \frac{\partial P}{\partial \varphi} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{r\varphi}) = 0 \quad (6.5)$$

while the energy equation is

$$\rho C_v v_z \frac{dT}{dz} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \tau_{r\varphi} r \frac{\partial}{\partial r} \frac{v_\varphi}{r} + \tau_{rz} \frac{\partial v_z}{\partial r} \quad (6.6)$$

The $\tau_{r\varphi}$ term of the energy equation (6.6), and equation (6.5), need to be considered only in the case of dies with rotating cores. The Deborah and the Weissenberg numbers are of such a magnitude that the melt flowing at the shaping part can be considered to be a viscous liquid and the power law can be employed.

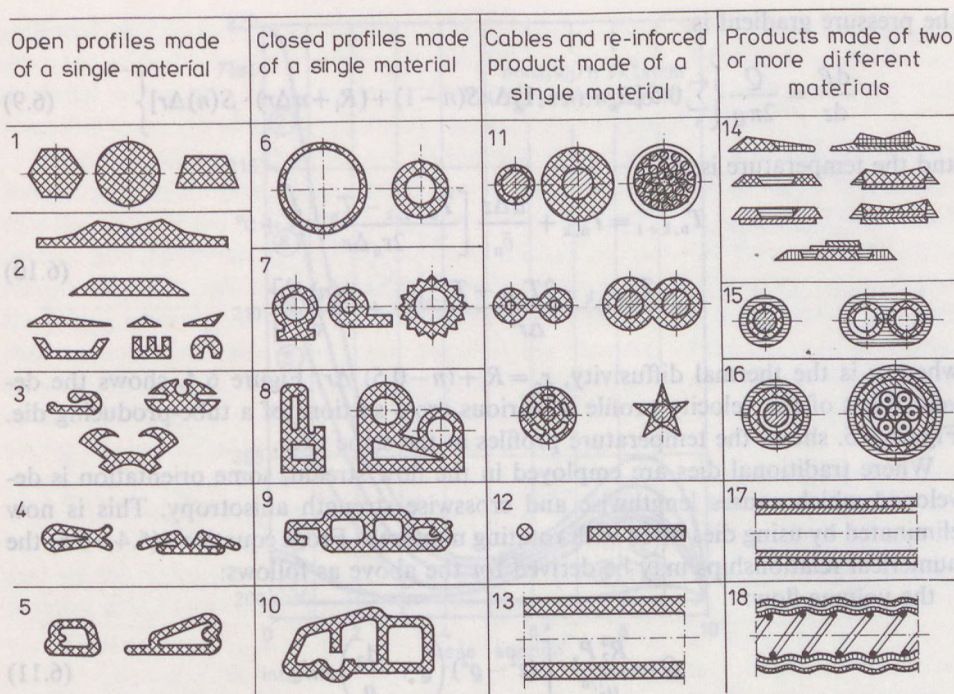


Fig. 6.3. Profile classification

1. compact products, 2. complicated, compact profiles without supports, 3. compact profiles without supports, 4. compact profiles with supports and with free flap sections, 5. closed, compact profiles, 6. ring-shaped products, 7. ring-shaped profiles containing supplementary elements, 8. profiles consisting of several closed rings, 9. compound profiles with several rings, 10. compact profiles with both closed and open elements, 11. cables, 12. coated wires, 13. re-inforced tubing, 14. profiles made of several materials, 15. and 16. two-layer and multi-layer cables, 17. metal reinforced multi-layer tube (or pipe), 18. multi-layer tube containing metal wires

Discretization of equations (6.4) and (6.6) applied to a die with a stationary core:

$$V_z(n) = \frac{dP}{dz} \sum_n \frac{1}{4\eta(n)} \{ [R_i + (n-1)\Delta r + R_i + n\Delta r] - r_0^2 [(R_i + (n-1)\Delta r)^{-1} + (R_i + n\Delta r)^{-1}] \} = S(n) \frac{dP}{dz} \quad (6.7)$$

where

$$r_0 = \left[\frac{\sum_n \frac{1}{\eta(n)} [R_i + (n-1)\Delta r + R_i + n\Delta r]}{\sum_n \frac{1}{\eta(n)} \left[\frac{1}{R_i + (n-1)\Delta r} + \frac{1}{R_i + n\Delta r} \right]} \right]^{1/2} \quad (6.8)$$

the pressure gradient is:

$$\frac{dP}{dz} = \frac{Q}{2\pi q} \left\{ \sum_n 0.5 [R_i + (n-1)\Delta r S(n-1) + (R_i + n\Delta r) \cdot S(n)\Delta r] \right\}^{-1} \quad (6.9)$$

and the temperature is:

$$T_{n,k+1} = T_{n,k} + \frac{a\Delta z}{\bar{v}_n} \left[\frac{T_{n+1,k} - T_{n-1,k}}{2r_n\Delta r} + \frac{T_{n+1,k} - 2T_{n,k} + T_{n-1,k}}{\Delta r^2} + \frac{\eta(n)\dot{\gamma}_n^2}{k} \right] \quad (6.10)$$

where a is the thermal diffusivity, $r_n = R_i + (n-0.5)\Delta r$. Figure 6.4. shows the development of the velocity profile at various cross sections of a tube-producing die. Figure 6.5. shows the temperature profiles at the same sites.

Where traditional dies are employed in the flow stream, some orientation is developed which causes lengthwise and crosswise strength anisotropy. This is now eliminated by using dies fitted with rotating mandrels. From equations (6.4—6.6) the numerical relationships may be derived for the above as follows:

the volume flow:

$$Q = \frac{R_2^4 P_z}{\mu_0^{1/n}} \int_1^{\epsilon} (\epsilon^2 - q^2) \left(q + \frac{A_2}{q} \right) F dq \quad (6.11)$$

the viscosity:

$$\eta = \frac{\mu_0^{1/n}}{R_2 F} \exp \left[\frac{-b(T - T_0)}{n} \right] \quad (6.12)$$

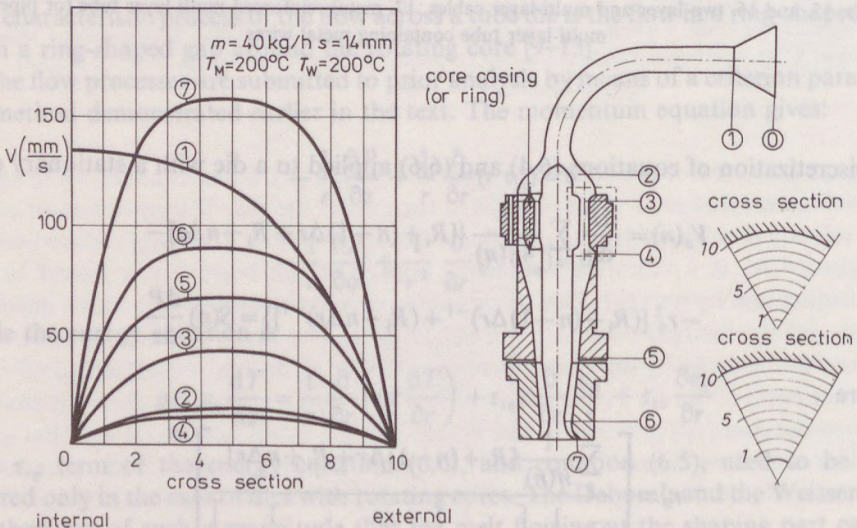


Fig. 6.4. Velocity profile representations in different parts of the channel of a tubing die

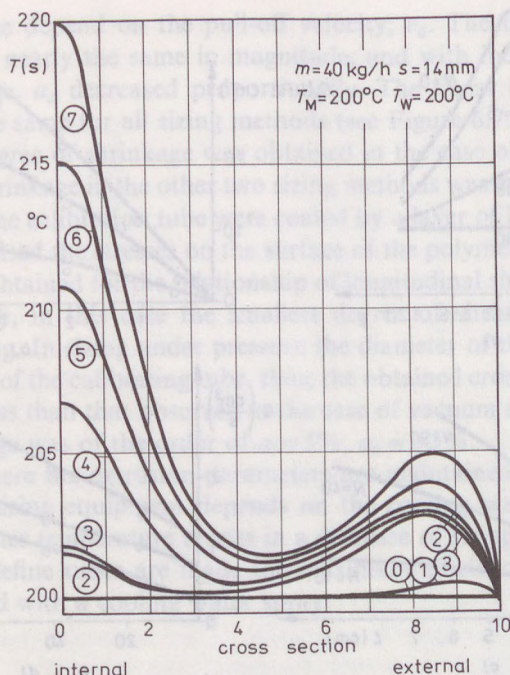


Fig. 6.5. Representation of temperature profiles in different parts of the flow channel of a tubing die

the energy equation:

$$\frac{Gz}{(\varepsilon-1)^2} \pi_v \frac{\partial \pi_T}{\partial Z} = \frac{1}{\varrho} \frac{\partial}{\partial \varrho} \left(\varrho \frac{\partial \pi_T}{\partial \varrho} \right) - \frac{Br}{(\varepsilon-1)^2} U^{n+\frac{1}{n}} \exp(-\pi_T) \cdot \exp \Delta T \quad (6.13)$$

where

$$\varrho = \frac{r}{R_2}; \quad A_1 = \frac{C_1}{R_2^2}; \quad A_2 = 2C_2/P_z R_2^2; \\ \varepsilon = \frac{R_1}{R_2}; \quad \pi_T = b(T - T_1); \quad Z = \frac{z}{L}; \quad U = \frac{(\tau_{\varrho\varphi}^2 + \tau_{\varphi z}^2) e^{-b(T-T_0)}}{\mu_0 \dot{\gamma}^n} \quad (6.14)$$

$$F = \left\{ \frac{A_1^2}{\varrho^4} + \frac{P_z^2 R_2^2}{4} \left(\varrho + \frac{A_2}{\varrho} \right)^2 \right\}^{\frac{1-n}{2n}}$$

In the rotating mandrel dies the viscosity profile is steady, as is demonstrated by Figure 6.6.a). Figure 6.6.b) shows the relationship between the pressure gradient and the volume flow rate comparing the calculated and measured data. Figure 6.6.c) shows the increase of melt temperature in the die at different revolution numbers of mandrel. Figure 6.6.d) shows the relationship between the volume flow rate and the pressure gradient at various rotation numbers of the mandrel. The advantages of a rotating mandrel die are quite obvious.

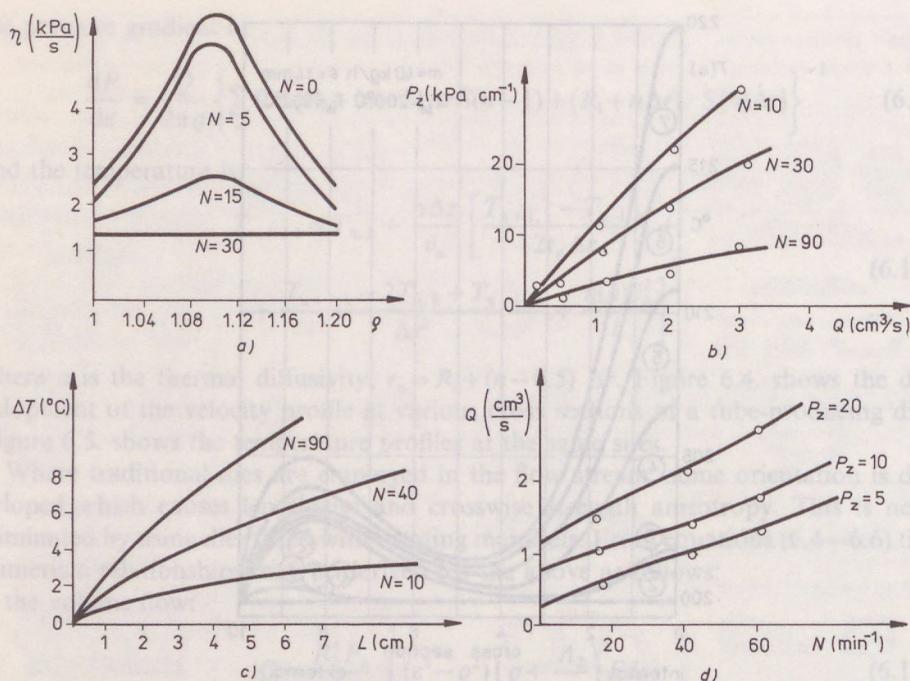


Fig. 6.6. Characteristic features of various flows that occur in dies with rotating core
a) Viscosity distribution in a rotating core die, b) The relationships between the pressure gradient versus volume flow in a rotating core die, c) The temperature increase in a rotating core die, d) The relationship between the volume flow versus revolution number in a rotating core die

6.4.2 The Flow Profiles inside the Dies

The approximating examination of flow profiles within a die is possible by dividing the die into simple constituent parts. Most of the profiles can be assembled from simple geometrical forms [15].

More accurate calculations may be performed by the use of the finite element method [14—16].

6.5 Processes Following Shaping

When leaving the ring-shaped channel of the shaping part of the extruder die, the polymer undergoes swelling, manifested by increased tube diameter and greater tube wall thickness. The degree of swelling depends on the type of polymer, the gap size of the shaping part and the conditions of the melt's deformation (velocity, temperature and pressure). During the cooling of the tube, shrinkage takes place, the degree of which depends on the type of polymer, the initial temperature and the rate of cooling. It was demonstrated for polyethylene [13] that the longitudinal and cross

sectional shrinkage depend on the pull-off velocity, v_d . The two shrinkage values were found to be nearly the same in magnitude, and with increasing v_d the cross-sectional shrinkage, a_d decreased proportionally. The linear character $a_d(v_0)$ was observed to be the same for all sizing methods (see Figure 6.7.) [14].

The greatest degree of shrinkage was obtained in the case of vacuum sizing. The lesser degree of shrinkage in the other two sizing methods was explainable by the fact that the walls of the calibration tube were coated by a layer of liquid, which reduced friction and decreased the stresses on the surface of the polymer tube. An analogous relationship was obtained for the relationship of longitudinal shrinkage versus velocity $a_l(v_0)$, however, in this case the smallest degree of shrinkage was associated with vacuum sizing. In sizing under pressure the diameter of the die core is smaller than the diameter of the calibrating tube, thus, the obtained cross-sectional shrinkage of the tube was less than that observed in the case of vacuum sizing. In general, the degree of shrinkage was of the order of $a_l=5\%$, $a_d=2.5\%$.

In instances where the extrusion parameters are maintained constant the output efficiency of the sizing equipment depends on the cooling water temperatures; an increase in the water temperature results in a decrease of sizing performance. In the case where polyolefine tubes are made the maximum efficiency was obtained with vacuum sizing and with a cooling water spray.

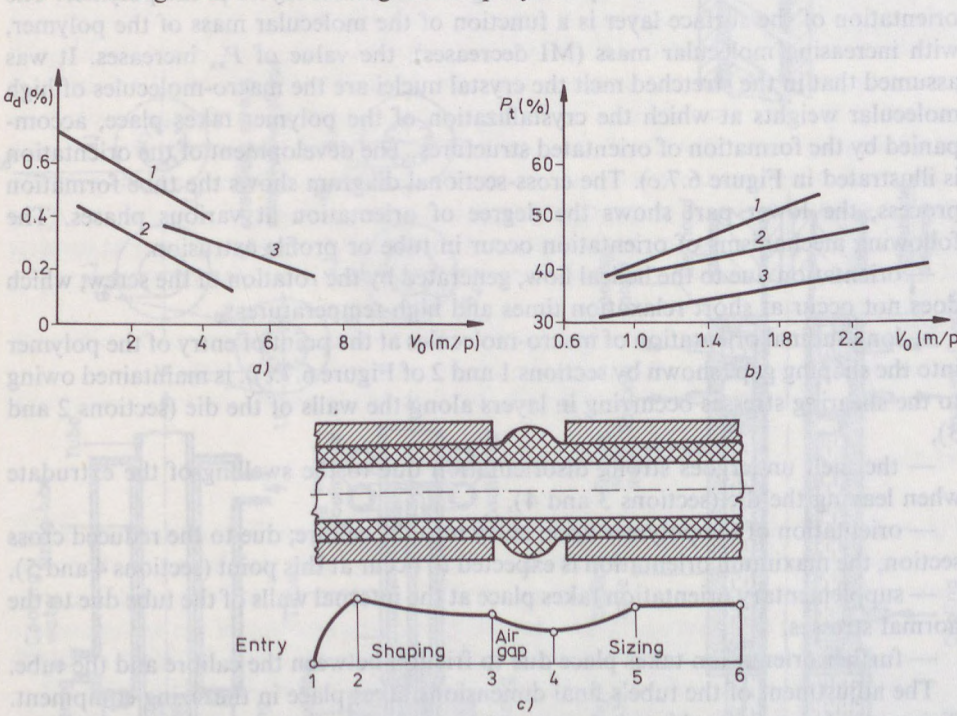


Fig. 6.7. The influence of the operating parameters upon the properties of the pipe [3]
a) The degree of shrinkage due to the speed of pull-off, b) Occurrence of orientation due to the stripping speed, 1. vacuum sizing, 2. vacuum sizing vs. water cooling, 3. vacuum sizing and water cooling by water spray, c) The evolution of orientation in pipe manufacturing

Upon exit of the melt from the tube shaping die, and independent of the extrusion velocity, swelling occurs and the starting relaxation processes prevent the detection of orientation at a certain distance away from the die. In reality there is no free exit from the die, since the sizing equipment is either attached directly to the die, or positioned at a short distance from it and hinders the swelling of the polymer and the polymer exhibits some degree of orientation. It is thus the calibration section itself that is responsible for the orientation. The orientation is a maximum on the external surface of the tube, especially in the direction of its axis. The degree of orientation rapidly decreases in the direction of the internal wall of the tube, and at a distance of 200–250 μm orientation practically disappears. A similar process occurs in the case of the sizing under pressure, here, orientation is substantial at the surfaces of the tube, while the internal material layers were found free of orientation. Maximum axial orientation is always expected on the cold external surface of the tube. The relationship of orientation versus pull-off velocity is shown in Figure 6.7.b).

With an increasing pull-off velocity the residence time of the tube also decreases from the die to the calibration system, thus, the time available for the intensive crystallization also decreases. The reason for the axial surface layer orientation is that the melt, on the surfaces of the tube, is subjected to stretching and the macro-molecule becomes immobile due to the rapid cooling of the surface layers of the polymer. The orientation of the surface layer is a function of the molecular mass of the polymer, with increasing molecular mass (M decreases), the value of P_{ax} increases. It was assumed that in the stretched melt the crystal nuclei are the macro-molecules of high molecular weights at which the crystallization of the polymer takes place, accompanied by the formation of orientated structures. The development of the orientation is illustrated in Figure 6.7.c). The cross-sectional diagram shows the tube formation process, the lower part shows the degree of orientation at various phases. The following mechanisms of orientation occur in tube or profile extrusion:

- orientation due to the helical flow, generated by the rotation of the screw, which does not occur at short relaxation times and high temperatures,

- longitudinal orientation of macro-molecules at the point of entry of the polymer into the shaping gap (shown by sections 1 and 2 of Figure 6.7.c)), is maintained owing to the shearing stresses occurring in layers along the walls of the die (sections 2 and 3),

- the melt undergoes strong disorientation due to the swelling of the extrudate when leaving the die (sections 3 and 4),

- orientation of the polymer upon entry into the calibre; due to the reduced cross section, the maximum orientation is expected to occur at this point (sections 4 and 5),

- supplementary orientation takes place at the internal walls of the tube due to the normal stresses,

- further orientation takes place due to friction between the calibre and the tube.

The adjustment of the tube's final dimensions takes place in the sizing equipment. Sizing may be performed in relation to either external or internal diameters. External sizing is a more common practice than internal sizing. Figure 6.8.a) shows the two types of sizing and the stresses appearing in the tube walls during calibration. In internal sizing smaller stresses appear, however, the equipment necessary for sizing is

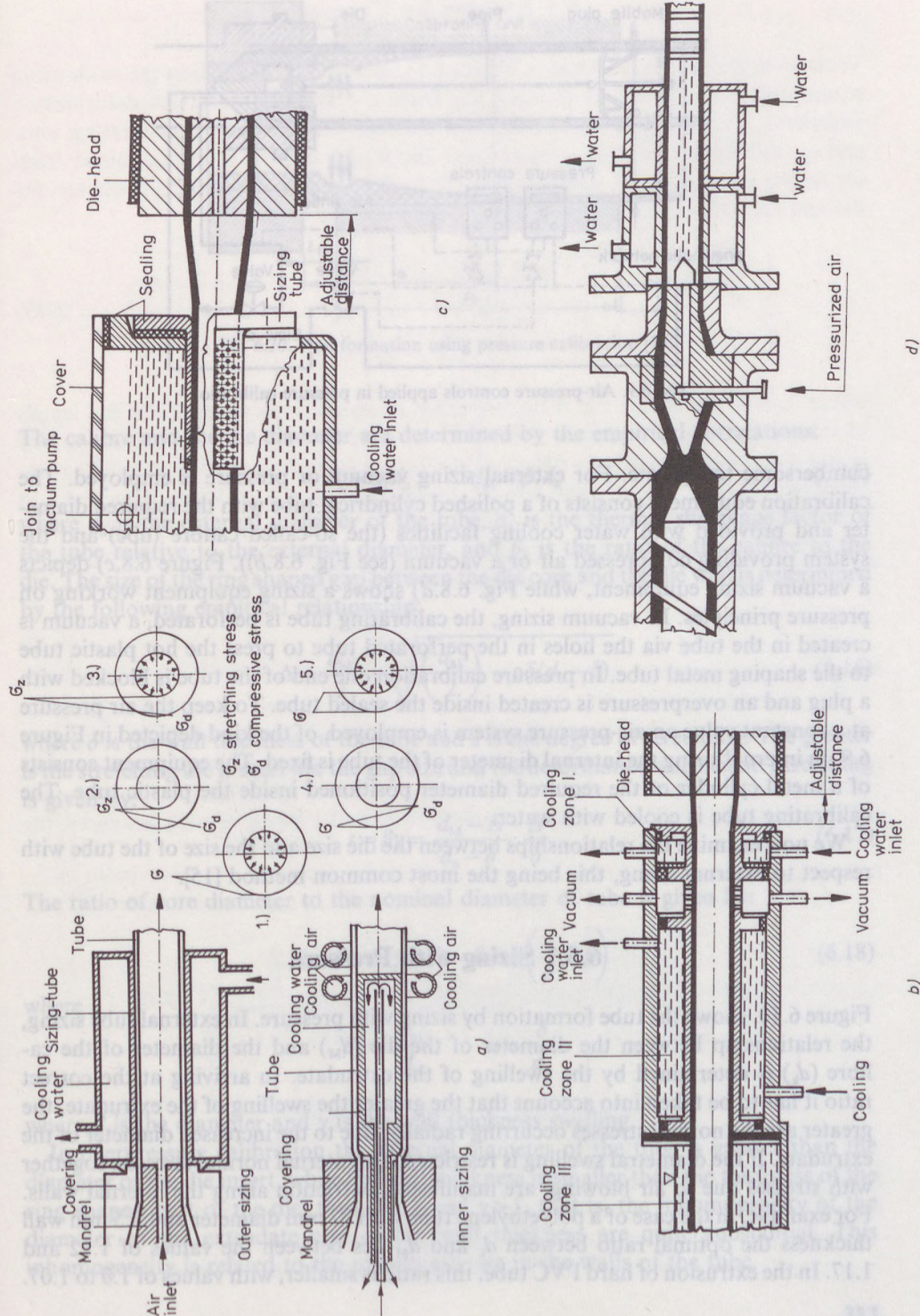


Fig. 6.8. Different sizing systems

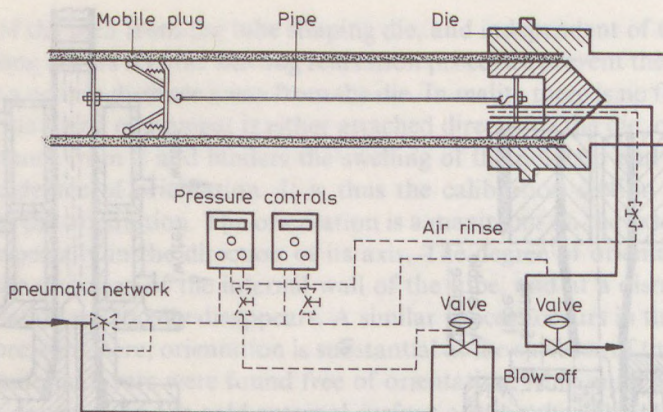


Fig. 6.9. Air-pressure controls applied in pressure calibration

cumbersome to operate. For external sizing vacuum or pressure is employed. The calibration equipment consists of a polished cylindrical tube with the required diameter and provided with water cooling facilities (the so-called calibre tube) and the system providing compressed air or a vacuum (see Fig. 6.8.b)). Figure 6.8.c) depicts a vacuum sizing equipment, while Fig. 6.8.d) shows a sizing equipment working on pressure principles. In vacuum sizing, the calibrating tube is perforated, a vacuum is created in the tube via the holes in the perforated tube to press the hot plastic tube to the shaping metal tube. In pressure calibration one end of the tube is blocked with a plug and an overpressure is created inside the sealed tube. To keep the air pressure at a constant value an air-pressure system is employed, of the kind depicted in Figure 6.9. In internal sizing the internal diameter of the tube is fixed. The equipment consists of a metal cylinder of the required diameter positioned inside the plastic tube. The calibrating tube is cooled with water.

We now examine the relationships between the die size and the size of the tube with respect to external sizing, this being the most common method [15].

6.5.1 Sizing with Pressure

Figure 6.10. shows the tube formation by sizing with pressure. In external tube sizing, the relationship between the diameter of the die (d_M) and the diameter of the calibre (d_k) is determined by the swelling of the extrudate. In arriving at the correct ratio it has to be taken into account that the greater the swelling of the extrudate, the greater are the normal stresses occurring radially, due to the increased diameter of the extrudate. If the diametral swelling is restricted, the internal normal stresses, together with stresses due to air blowing, are manifested as friction along the internal walls. For example, in the case of a polyethylene tube with 32 mm diameter and 2.5 mm wall thickness the optimal ratio between d_k and d_M lies between the values of 1.12 and 1.17. In the extrusion of hard PVC tube, this ratio is smaller, with values of 1.0 to 1.07.

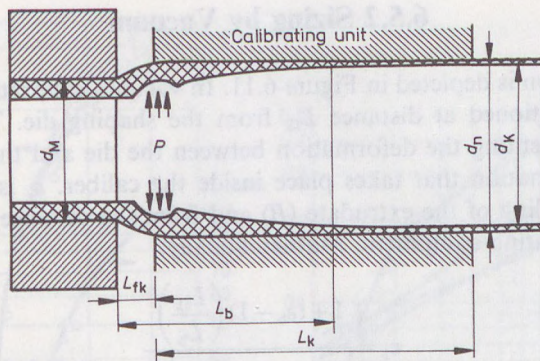


Fig. 6.10. Pipe formation using pressure calibration [14]

The calibre and the die diameter are determined by the empirical correlations:

$$d_k = \alpha_1 d_n; \quad d_M = \beta_1 d_k \quad (6.15)$$

where d_n is the external diameter of the tube, α_1 is the thermal shrinkage factor of the tube relative to the external diameter, and β_1 is the ratio of the calibre to the die. The size of the ring shaped gap between the die core and the die wall is determined by the following empirical relationship:

$$\Delta = \frac{d_M}{2} - \sqrt{\left(\frac{d_M}{2}\right)^2 - \varepsilon \delta (d_n - \delta)} \quad (6.16)$$

where δ is the wall thickness of the tube and ε is the degree of stretching. The greater is the stretching the greater are the gap size and the deformation coefficient. Stretching is given by:

$$\varepsilon = \beta \gamma = \frac{d_M - \Delta}{d_n - \delta} \cdot \frac{\Delta}{\delta} \quad (6.17)$$

The ratio of core diameter to the nominal diameter of tube is given by:

$$\beta'_n = \beta + a(\gamma - \beta) = \beta + a\left(\frac{\varepsilon}{\beta} - \beta\right) \quad (6.18)$$

where

$$\beta'_n = \frac{d_M}{d_n}; \quad a = \frac{\delta}{d_n}$$

where β is the diameter and γ is the wall thickness swelling.

In overpressure calibration the external diameter of the tube is greater than the diameter of the die insert, while the wall thickness is smaller than the thickness of the ring shaped part of the die, thus, $\beta < 1$ and $\gamma > 1$, that is, the inhomogeneity of the diameter of the extrudate and of the wall thickness are quite substantial. This inhomogeneity is related to the uneven stresses in the walls of the tube.

6.5.2 Sizing by Vacuum

Vacuum calibration is depicted in Figure 6.11. In vacuum calibration the calibrating equipment is positioned at distance L_{fk} from the shaping die. Tube deformation includes ε_1 , representing the deformation between the die and the calibrating unit, and ε_2 , the deformation that takes place inside the caliber. ε_1 is determined from the degree of swelling of the extrudate (B) and from the distance (L_{fk}) between the die and the calibrating equipment. Mathematically:

$$\varepsilon_1 = \frac{1 + (\varepsilon_b - 1) \left(\frac{L_{fk}}{L_b} \right)^n}{1 + (B - 1) \left(\frac{L_{fk}}{L_p} \right)^m} \quad (6.19)$$

where $\varepsilon_b = B\varepsilon$ represents the melt stretching in an isotropic state, L_b is the length of the melt at stretching, L_p is the elastic recoverable length of the extrudate, and m and n are power exponents defining the changes in dimensions due to swelling and stretching of the extrudate, respectively. Figure 6.12. shows the values of m and n as a function of L_p and L_b . Knowing the values of ε , B , L_p , L_b , m and n , the deformation ε_1 and ε_2 may be determined by the method of successive approximation in the ranges $L_{fk} < L_p$ and $L_{fk} > L_b$, using the relationship

$$L_{fk} = L_b \left(\frac{\varepsilon_1 B - 1}{B - 1} \right)^{1/n} \quad (6.20)$$

In a given method of calibration the deformation of the melt should be adjusted so that the degree of stretching and the value of ε_2 are nearly equal. The value of ε_2 is determined by the entry section of the calibration part and by the distance between the die and the calibration section. Experimental tests revealed that the diameter ratio of the die versus the calibre (β') lies between 1.03 and 1.2 and, in such instances, the

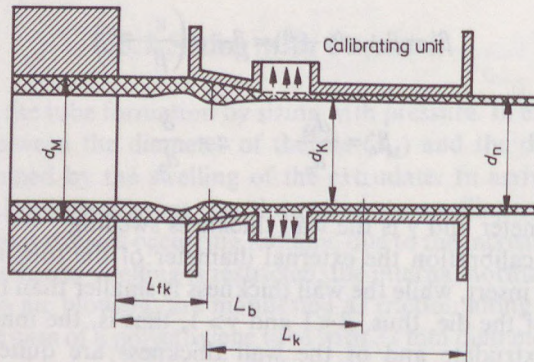


Fig. 6.11. Pipe formation using vacuum calibration [14]

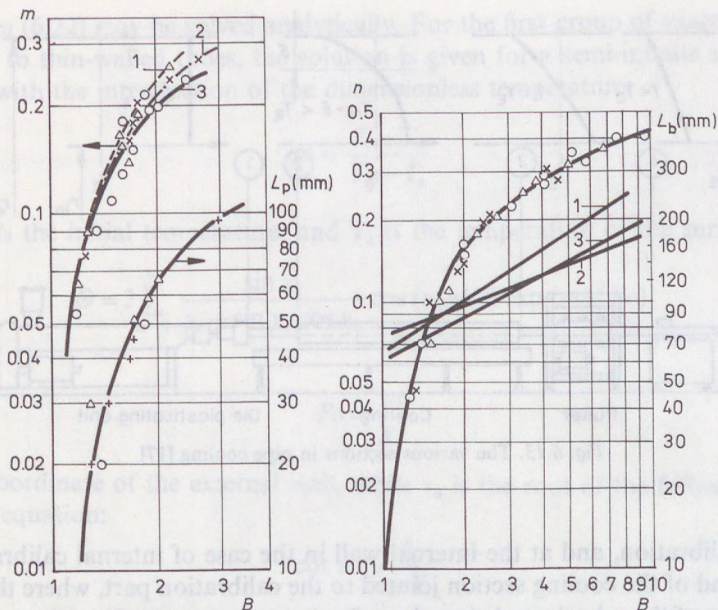


Fig. 6.12. The values of m and n for polypropylene (1) and for polyethylenes (2 and 3) as function of B and ε_n , respectively [14]

deformation of the external diameter and the deformation of the wall thickness are equivalent.

Calculation of the diameters d_M and d_k is made using the equations:

$$d_k = d_n \alpha \quad \text{and} \quad d_M = d_k \beta' \quad (6.21)$$

where $\beta' = d_M/d_n$. The size of the ring shaped gap is calculated from equation (6.16).

A more uniform tube is produced by vacuum calibration than by calibration performed under pressure.

6.6 The Cooling Section of the Plastic Tubes; the Development of Internal Stresses

6.6.1 Cooling of the Tube

The cooling processes in tube extrusion according to Kleindienst [21] are illustrated by Figure 6.13. At point (1) a melt of uniform temperature determined by the die and the plasticating unit leaves the die. Site (2) is the calibration section, where the temperature drops below the softening temperature at the external wall in the case of

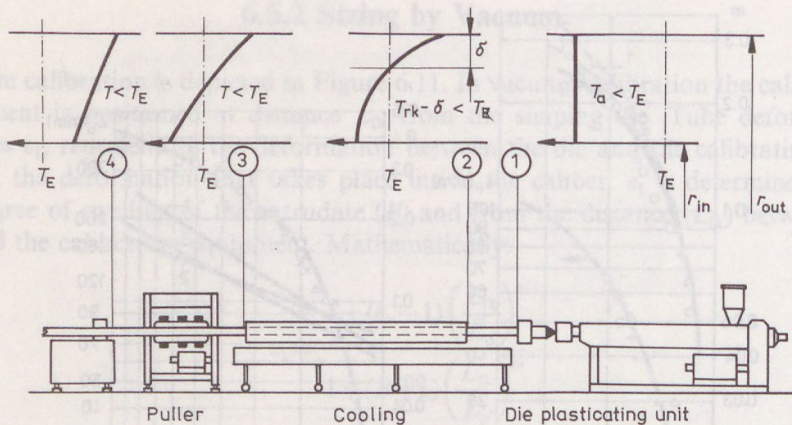


Fig. 6.13. The various sections in pipe cooling [17]

external calibration, and at the internal wall in the case of internal calibration. Site (3) is the end of the cooling section jointed to the calibration part, where the average temperature of the tube drops below the softening temperature. Site (4) represents the post-cooling section, here, the entire length of the tube is below the softening temperature.

The starting point for the temperature change calculations is the energy equation. Again, assuming a constant heat conductivity coefficient as was the case when sheet manufacturing was considered, the equation is:

$$\frac{\partial T}{\partial t} = a \Delta T \quad (6.22)$$

which can be solved analytically and where $a = k/\rho C_p$, while Δ is the Laplace operator. If the heat conductivity coefficient is temperature dependent then

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \left[k \Delta T + \frac{\partial k}{\partial T} (\Delta T)^2 \right] \quad (6.23)$$

holds true. The initial conditions in solving the equation is the knowledge of the exit temperature from the plasticating unit, which, in general, is considered to be constant.

The internal walls of the tube are regarded as thermally insulated, thus:

$$\left(\frac{\partial T}{\partial r} \right)_{in} = 0 \quad (6.24)$$

On the external walls of the tube, heat exchange takes place; the heat flow across the surfaces is proportional to the temperature difference between the tube surface and the environment, hence:

$$-k \left(\frac{\partial T}{\partial r} \right)_{out} = \alpha T_s \quad (6.25)$$

Equation (6.22) may be solved analytically. For the first group of exact solutions, applicable to thin-walled tubes, the solution is given for a semi-infinite sheet of $2x$ thickness with the introduction of the dimensionless temperature:

$$\Theta = \frac{T - T_s}{T_0 - T_s} \quad (6.26)$$

where T_0 is the initial temperature, and T_s is the temperature of the surroundings.

$$\Theta = 2 \sum_{n=1}^{\infty} \frac{\sin v_n}{v_n + \sin v_n \cos v_n} \cos(v_n x/X) \exp(-v_n^2 Fo) \quad (6.27)$$

where

$$Fo = \frac{at}{X^2}$$

X is the coordinate of the external wall, while v_n is the root of the following transcendental equation:

$$\cot v = v \frac{k}{\alpha X} \quad (6.28)$$

The temperature can be calculated on the basis of equation (6.27) with constant values of α and a and with temperature dependent values in such a way that the equation is rendered discrete. The general analytical solution is determined only at the first step. The initial conditions are taken from the previous step each time. X is divided into section of $X = M\Delta X$, thus the temperature in each of these sections is expressed as:

$$\begin{aligned} \Theta = & \frac{2}{3M} \sum_{n=1}^{\infty} \times \\ & \times \frac{v_n \left[\Theta_0 + \Theta_M \cos v_n + 4 \sum_{k=1}^{M/2} \Theta_{2k-1} \cos \left(v_n \frac{2k-1}{M} \right) + 2 \sum_{l=1}^{M/2-1} \Theta_{2l} \cos v_n \frac{2l}{M} \right]}{v_n + \sin v_n \cos v_n} \times \\ & \times \cos(xv_n/X) \exp(-v_n^2 Fo) \end{aligned} \quad (6.29)$$

The number Fo refers to the time step and to the given a values. $\Theta_0, \Theta_1, \dots, \Theta_M$ give the temperature profiles of the tube walls.

In the case of thick wall tubes and with α and a remaining constant:

$$\begin{aligned} \Theta = & \frac{2}{B} \sum_{n=1}^{\infty} \frac{1}{v_n} \frac{[J_1(v_n B) - M_1(v_n A) Y_1(v_n B)][J_0(v_n R) - M_1(v_n A) Y_0(v_n R)]}{[J_0(v_n B) - M_1(v_n A) Y_0(v_n B)]^2 [J_1(v_n B) - (A/B)]^2} \times \\ & \times \frac{\exp(-v_n^2 Fo)}{[J_0(v_n A) - M_1(v_n A) Y_0(v_n A)]^2} \end{aligned} \quad (6.30)$$

where $A = R_{in}/\delta$, $B = R_{out}/\delta$ are the dimensionless internal and external radii, respectively, δ is the wall thickness, J_0, J_1, Y_0 and Y_1 are Bessel functions, $M_1(v_n A) =$

$= J_1(v_n A)/(v_n A)$. v_n provides a solution to the following transcendental equation:

$$\frac{v}{Bi} \left[\frac{J_1(vB)}{J_1(vA)} - \frac{Y_1(vB)}{Y_1(vA)} \right] = \frac{J_0(vB)}{J_1(vA)} - \frac{Y_0(vB)}{Y_1(vA)} \quad (6.31)$$

In the case where the temperature field is calculated in a stepwise manner, the expression for the relevant temperatures is:

$$\begin{aligned} \Theta = & \frac{2}{3MB^2} \sum_{n=1}^{\infty} \frac{L_0(v_n B) \exp(-v_n^2 Fo)}{[L_0(v_n B)]^2 + [L_1(v_n B)]^2 - (A/B)^2 [L_0(v_n A)]^2} \times \\ & \times \left[\Theta_0 A L_0(v_n A) + \Theta_M B L_0(v_n B) + 4 \sum_{k=1}^{M/2} \Theta_{2k-1} \left(A + \frac{2k-1}{M} \right) L_0 \times \right. \\ & \left. \times \left(v_n \frac{AM+2k-1}{M} \right) + 2 \sum_{l=1}^{M/2-1} \Theta_{2l} \left(A + \frac{2l}{M} \right) L_0 \left(v_n \frac{AM+2l}{M} \right) \right] \end{aligned} \quad (6.32)$$

where

$$L_0 = J_0(x) - M_1(v_n A) Y_0(x)$$

$$L_1 = J_1(x) - M_1(v_n A) Y_1(x)$$

The solution of the equation containing the temperature dependent heat conductivity coefficient is performed by the finite differential methods. Equation (6.23) expressed in the form of finite differences is as follows:

$$\begin{aligned} \Theta_{m,j} = & \Theta_{m,j-1} + \frac{\vartheta}{h^2} \left[\Theta_{m+1,j-1} - 2\Theta_{m,j-1} + \right. \\ & + \Theta_{m-1,j-1} + \frac{1}{2(A/\vartheta + m)} (\Theta_{m+1,j-1} - \Theta_{m-1,j-1}) + \\ & \left. + \frac{1}{k} \frac{d\vartheta}{d\Theta} (\Theta_{m+1,j-1}^2 - 2\Theta_{m+1,j-1} \Theta_{m-1,j-1} + \Theta_{m-1,j-1}^2) \right] \end{aligned} \quad (6.33)$$

where m extends from $m=1$ to $m=M-1$, M represents the number of steps in the R direction, ϑ is the dimensionless length of the time step and h is the dimensionless step length in the R direction. The relationship between the two step lengths is:

$$\frac{\vartheta}{h^2} \leq \frac{1}{2} \quad (6.34)$$

The temperatures at the internal and the external walls are determined from the boundary values of equations (6.24) and (6.25):

$$R = A(m=0); \quad \frac{\partial \Theta}{\partial R} = 0; \quad \Theta_{0,j} = \Theta_{i,j}; \quad (6.35)$$

$$R = B(m=M); \quad \frac{\partial \Theta}{\partial R} = -\frac{\alpha \delta}{k} \Theta; \quad (\Theta_{M,j} - \Theta_{M-1,j})/h = -\frac{\alpha \delta}{k} \Theta_{M,j} \quad (6.36)$$

Table 6.1. Heat transfer factors established for various methods of cooling [17]

Cooling method employed	Data	Cooling media flow and cooling media temperature	Relationship	Usual value
Calibrating tube ring shaped cooling water space	$L=30$ cm $s=0.3$ cm $D^*/2=1$ cm	$G=300$ l/h $T=10$ °C	$Nu = Nu_{\infty} + (1 + 0.14 \sqrt{D_a/D}) \frac{0.19 (Pe D^*/L)^{0.8}}{1 + 0.117 (Pe D^*/L)^{0.467}}$ $Nu_{\infty} = 3.96 + \frac{0.9}{(D/D_a)^{0.95}}$ $D^* = D_a - D; \quad \alpha^* = \frac{1}{\alpha/2k \ln(D/d) + d/\alpha_a D}$	$\alpha_a = 338 \frac{W}{m^2 K}$ $\alpha^* = 354 \frac{W}{m^2 K}$
Calibrating tube spiral cooling channel	$L=30$ cm $s=0.3$ cm	$G=300$ l/h $T=10$ °C	$Nu = 3.65 + \frac{0.19 (Pe D^*/L we)^{0.8}}{1 + 0.117 (Pe D^*/L we)^{0.467}}$ $D^* = 4F/K$ $\alpha^* = \frac{1}{\alpha/2K \ln(D/d) + d/\alpha_a D}$	$\alpha_a = 861 \frac{W}{m^2 K}$ $\alpha^* = 883 \frac{W}{m^2 K}$
Water bath	$T_a - T = 30$ K	—	$\alpha = (18.61 + 20.76 \sqrt{(T_a - T)/2}) \sqrt[4]{(T_a - T)d}$	$\alpha = 412 \frac{W}{m^2 K}$
Water bath forced flow	$V_a = 2$ m/min $L = 2$ cm $L = 5$ cm	$T = 10$ °C	$\alpha = 0.664 K \sqrt[3]{Pr} \sqrt{V_a/2L}$	$\alpha = 916 \frac{W}{m^2 K}$ $\alpha = 579 \frac{W}{m^2 K}$
Counter flow	$D^*/2 = 0.3$ cm $L = 6$ cm $L = 1$ cm	$G = 1000$ l/h	$\alpha^* = \frac{1}{\alpha/2K \ln(D/d) + d/\alpha_a D}$	$\alpha = 578 \frac{W}{m^2 K}$ $\alpha = 821 \frac{W}{m^2 K}$
Spray cooling	$L = 6$ cm	$G = 1000$ l/h $G' = 83.3$ l/h · m	$\alpha = 430 (\sin \varphi)^{0.2} \sqrt[3]{G'}$	$\alpha_{45^\circ} = 1752 \frac{W}{m^2 K}$
Air cooling	$T_a - T = 20$ K	—	$\alpha = 9.54 + 0.0085 \sqrt[3]{T_a - T}^4$	$\alpha = 10 \frac{W}{m^2 K}$

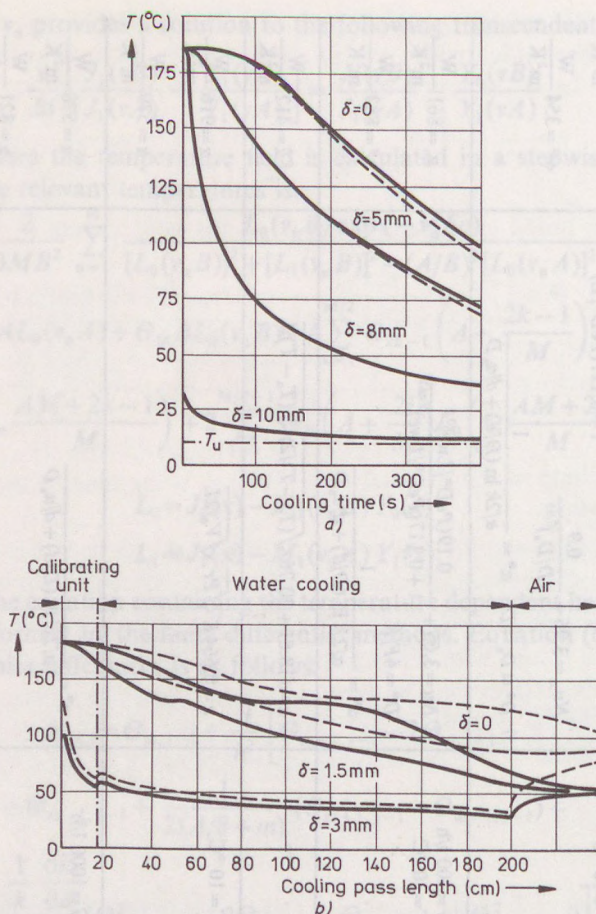


Fig. 6.14. Tube (pipe) cooling curves [17]

a) Cooling of the PVC tube as a function of time, 1. solid line: an exact solution, 2. a numerical solution. b) Cooling of a polyethylene tube along the cooling path, 1. $v_{1e}=2\text{ m/min}$, 2. $v_{1e}=3\text{ m/min}$.

From equations (6.33), (6.35) and (6.36) the temperature distribution may be determined, provided that the time value j and the point $j-1$ are known. The heat transfer constants necessary for the calculations are summarized in Table 6.1.

With respect to the method of calculation, it is pointed out that exact solutions are not possible for small Fourier numbers and for short periods of time. The discrete method has an accuracy similar to that of the method of finite differentials. The exact method of solution is, however, less accurate.

Figures 6.14.a) and b) show the cooling curves calculated for some of the locations. The deviation is greater at the internal wall and it increases with increasing wall thickness. This is due to the discretization of the boundary conditions.

6.6.2 The Internal Stresses Developed during Cooling

The temperature profile of the cooling tube wall has the shape of a half parabola, the melting temperature appears in the vicinity of the apex, while the wall temperature is identical with the die temperature. Shrinkage occurs related to the temperature differences of the various layers, which causes differences in deformation. These differences in deformation cause a difference in stress thus giving rise to internal stresses in the tube.

Divide the tube into N parts for purposes of stress calculations. The N^{th} layer in contact with the calibre tube cools at the highest rate and when it reaches the melting temperature, the shrinking commences as a function of the intensity of cooling and the heat expansion coefficient. Initially, this shrinkage is not hindered by the next layer, since the temperature in that layer is still above the material's melting range.

Forces evolve first, when the $(N-1)^{\text{th}}$ layer also freezes. When the temperature of the $(N-1)^{\text{th}}$ layer reaches the melting (or softening) temperature T_{me} , the temperature of the N^{th} layer is T_N . The temperature difference of the environment (in this case the die) measured for the N^{th} layer is $T_N - T_K$ and for the $(N-1)^{\text{th}}$ layer it is $T_{\text{me}} - T_K$. The shrinkages are:

$$\begin{aligned} \text{— for the } N^{\text{th}} \text{ layer:} \quad & \delta_N = \beta(T_N - T_K) \\ \text{— for the } (N-1)^{\text{st}} \text{ layer:} \quad & \delta_{N-1} = \beta(T_{\text{me}} - T_K) \end{aligned} \quad (6.37)$$

Due to differences in shrinkage elongation takes place in the $(N-1)^{\text{th}}$ layer and, simultaneously, compression occurs in the N^{th} layer shrinking in a lesser extent. The difference in shrinkage is equal to the difference of deformation, hence:

$$\Delta \varepsilon_{N, N-1} = \delta_N - \delta_{N-1}$$

or, more generally:

$$\begin{aligned} \Delta \varepsilon_{N, N-1} &= \beta(T_N - T_K) - \beta(T_{\text{me}} - T_K) \\ \Delta \varepsilon_{N, N-1} &= \beta(T_N - T_{\text{me}}) \end{aligned} \quad (6.38)$$

where T_N is the temperature of the N^{th} layer at the time when the temperature of the $N-1$ layer reaches the softening temperature T_{me} . This difference in deformation is the direct result of the different cooling rates in the individual layers and occur both in the direction of the circumference (φ direction) and in a lengthwise direction (z direction) in the tube.

The temperature difference $T_N - T_{\text{me}}$ of an infinitesimally thin wall thickness dr is the product of the gradient of the temperature curve $\partial T / \partial r$ and the layer thickness at site $r - dr$ ($\approx r$), at the time when the temperature of this site is equal to the softening temperature T_{me} (see Fig. 6.16.c):

$$\begin{aligned} T_N - T_{\text{me}} &\rightarrow (\partial T / \partial r)_{T=T_{\text{me}}} dr \\ d\varepsilon_\varphi = d\varepsilon_z &= \beta(\partial T / \partial r)_{T=T_{\text{me}}} dr \end{aligned} \quad (6.39)$$

This biaxial deformation gives rise to a biaxial state of stress, thus:

$$d\sigma_\varphi = d\sigma_z = \frac{E}{1-\nu} d\varepsilon \quad (6.40)$$

The tube, under the internal pressure, is affected by twice as high a stress along its circumference than along its longitudinal axis. Henceforth, in further derivations the longitudinal stresses will be ignored, thus σ is substituted for σ_φ . From equations (6.39) and (6.40):

$$d\sigma = \frac{E}{1-\nu} \beta \left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \quad (6.41)$$

Integrating between the limiting values r_i and r :

$$\sigma_r - \sigma_i = \frac{E}{1-\nu} \beta \int_{r_{in}}^r \left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \quad (6.42)$$

The power balance of an unloaded tube is given by:

$$\int_{r_{in}}^{r_{out}} \sigma_r 2\pi r dr = 0 \quad (6.43)$$

From equations (6.43) and (6.44) we have:

$$\begin{aligned} \int_{r_{in}}^{r_{out}} \left[\sigma_i + \frac{E\beta}{1-\nu} \int_{r_{in}}^{r_{out}} \left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \right] r dr = 0 \\ \sigma_i = - \frac{2E\beta \int_{r_{in}}^{r_{out}} \left[\left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \right] r dr}{(1-\nu)(r_{out}^2 - r_{in}^2)} \end{aligned} \quad (6.44)$$

Substituting equation (6.44) into (6.42), the tangential stress at site r is:

$$\sigma_r = \frac{E\beta}{1-\nu} \left[\int_{r_{in}}^r \left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \right] - \frac{2 \int_{r_{in}}^{r_{out}} \left[\left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} dr \right] r dr}{r_{in}^2 - r_{out}^2} \quad (6.45)$$

The term $(\partial T / \partial r)_{T=T_{me}}$ is not generally available in an analytical form, for calculation purposes the derivatives must be approximated by differences:

$$dr \rightarrow \Delta r$$

$$r \rightarrow r_i + m\Delta r; \quad m=0, 1, \dots, M;$$

$$r_k \rightarrow r_i + M\Delta r; \quad (6.46)$$

$$\left(\frac{\partial T}{\partial r} \right)_{T=T_{me}} \rightarrow \left(\frac{T_m - T_{m-1}}{\Delta r} \right)_{T_m=T_{me}}$$

From here on the index $T_m = T_{me}$ will be ignored, thus

$$(T_m - T_{m-1}) = (T_m - T_{m-1})_{T_m=T_{me}}$$

Solving the integral (6.45) by the trapezoid formula:

$$\int_{r_{in}}^r \left(\frac{\partial T}{\partial r} \right)_{T=T_E} dr \cong \frac{1}{2} (T_{me} - T_{-1}) + \frac{1}{2} (T_m - T_{m-1}) + \sum_{s=1}^{m-1} (T_s - T_{s-1})$$

$$r_{out}^2 - r_{in}^2 \cong M \Delta r (2r_{in} + M \Delta r)$$
(6.47)

The tangential stress at the point $r_i + m \Delta r$, based on equations (6.47) and (6.46), is:

$$\sigma_m = \frac{2E\beta}{(1-\nu)(2r_{in} + M \Delta r)M} \left\{ \left[\frac{1}{4} (T_{-1} + T_{me}) + \frac{1}{4} (T_{m-1} - T_m) + \frac{1}{2} \sum_{p=1}^{M-1} (T_{p-1} - T_p) \right] (r_{in} + M \Delta r) + \sum_{k=1}^{M-1} \left(\left[\frac{1}{2} (T_{-1} + T_0) + \frac{1}{2} (T_{k-1} - T_k) + \sum_{l=1}^{k-1} (T_{l-1} - T_l) \right] (r_{in} + k \Delta r) \right) \right\} - \frac{E\beta}{1-\nu} \left[\frac{1}{2} (T_{-1} - T_0) + \frac{1}{2} (T_{m-1} - T_m) + \sum_{s=1}^{m-1} (T_{s-1} - T_s) \right]$$
(6.48)

Assuming that $(\partial T / \partial r)_{r=r_{in}} = 0$, all $(T_{-1} - T_0)$ members are eliminated and:

$$\sigma_m = \frac{2E\beta}{(1-\nu)(2r_{in} + M \Delta r)M} \left\{ \left[\frac{1}{4} (T_{m-1} - T_m) + \frac{1}{2} \sum_{p=1}^{M-1} (T_{p-1} - T_p) \right] (r_{in} + M \Delta r) + \sum_{k=1}^{M-1} \left(\left[\frac{1}{2} (T_{k-1} - T_k) + \sum_{l=1}^{k-1} (T_{l-1} - T_l) \right] (r_{in} + k \Delta r) \right) \right\} - \frac{E\beta}{1-\nu} \left[\frac{1}{2} (T_{m-1} - T_m) + \sum_{s=1}^{m-1} (T_{s-1} - T_s) \right]$$
(6.49)

In the case of the internal wall of the tube, $m=0$ and based on equation (6.49):

$$\sigma_0 = \frac{2E\beta}{(1-\nu)(2r_{in} + M \Delta r)M} \{ \dots \}$$
(6.50)

for the case $m=1$:

$$\sigma_1 = \frac{2E\beta}{(1-\nu)(2r_{in} + M \Delta r)M} \{ \dots \} - \frac{E\beta}{2(1-\nu)} (T_0 - T_1)$$
(6.51)

In order to solve equations (6.49) and (6.51) the temperature field must be known. The stresses thus obtained are greater than in reality, since in the calculations the effects

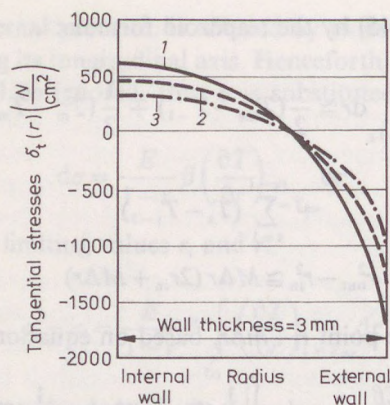


Fig. 6.15. Distribution of stresses in the walls of the tube [17]

1. water temperature 10°C, 2. water temperature 20°C, 3. water temperature 30°C

of relaxation were not considered. Figure 6.15. shows the stress distribution in the walls of the tube.

The quality features of tube manufacturing are:

- dimension tolerance,
- surface quality,
- freedom from orientation and internal stresses.

The technological parameters that influence these qualities are: the temperature of the melt, the mass flow, the pull off velocity, the correct adjustment of the die core and the intensity of heating. In the text to follow, automatization of tube manufacturing is considered from the point of view of one of the most important quality aspects, the size tolerance.

6.7 Reduction of Tolerance in Tube Diameter and Tube Wall Thickness. Automatization of the Tube Manufacturing Production Line

One of the basic considerations in tube manufacturing is the need for consistent quality, in other words, assurance of constant dimensions and properties of the product.

The changes occurring in wall thicknesses were examined, using a sample size of 800 items, and the outcome of the analysis is presented in Table 6.2 [23], where $\Delta\delta_0$ represents the wall thickness deviation, S_δ depicts the quadratic deviation, while $6S_\delta$ represents the standard deviation of wall thickness. In the study of the time course of the deviation in the wall thickness of the tube, the deviations could be divided into long- and short-period types. The statistical analysis revealed that for the short-period deviations the relative variance range was 40–60%, while for the long-period ones this

Table 6.2. Pipe thickness, standard deviation data

Types of deviation	Pipe sizes diameter x wall thickness, in mm						
	32 × 2.0	32 × 2.9	50 × 2.9	63 × 3.6	63 × 5.8	110 × 6.3	160 × 9.1
Deviation, $\Delta\delta_0$	0.5	0.6	0.6	0.8	1.1	1.2	1.6
Average area deviation, S_δ	0.116	0.095	0.105	0.185	0.182	0.240	0.313
Standard deviation range, $6S$	0.68	0.57	0.63	1.11	1.09	1.44	1.88
$6S/\Delta S_0$	136	95	105	138	99	120	118

was 70–90%. It thus follows that, deviations over a long period of time are the determining factors regarding the stability of production, characterized by the standard deviation $6S_\delta$. Table 6.3. shows the technological characteristics and the standard deviation of thickness. The standard deviation is also informative with respect to the capabilities of the specific manufacturing technology employed. These data are summarized in Tables 6.4. and 6.5. During production the technologists must attempt to maintain the average wall thickness δ . The maximum wall thickness is given by:

$$\delta_{\max} = M(\delta) + ls \quad (6.52)$$

the maximum deviation is expressed as:

$$\gamma_{\max} = M(\delta) + ls - \delta_0 \quad (6.53)$$

where $M(\delta)$ is the expected wall thickness value, being the same as the average wall thickness:

$$\bar{\delta} = M(\delta) \quad (6.54)$$

The minimum wall thickness is:

$$\delta_{\min} = M(\delta) - ls \quad (6.55)$$

When elaborating the control system of tube extrusion, the aims to be achieved must be considered, such as the stability of dimensions and strength and the surface qualities. In order to realize these aims, all the equipment must function in a near optimal mode, thus, the die must transform the melt to the required shape ensuring uniform wall thickness, the cooling equipment must provide the desired intensity of cooling, the calibration unit must bring about the required deformation in order to maintain the diameter within tolerance limits and the pull-off equipment must ensure tube movements at the required speed. Figure 6.16.a) shows the accuracy achieved in the case of a pipe of 32 × 2.0 mm size, 6.16.b) does the same for a pipe of 63 × 3.6 mm dimensions, and 6.16.c) depicts the measurements on a 110 × 6.3 mm pipe. The data was collated by measuring the dimensions of more than eight thousand low-density polyethylene pipes [22]. In these Figures the continuous line indicates the mean diameter, the two dotted lines indicate the standard deviations obtained as the region between the dotted lines. These graphs show that the standard deviation of the data is quite random.

Table 6.3. Characteristic data in

Number	Revolution number of the screw, min^{-1}	Pull-off velocity, m/min	Air pressure, MPa	Zone temperature		
				1	2	3
1	29.0	2.04	0.09	145	145	150
2	10.0	1.51	0.07	170	160	160
3	18.5	3.00	0.08	160	175	175
4	26.0	1.50	0.07	175	170	150
5	22.0	0.80	0.10	170	150	150
6	34.0	1.67	0.125	125	150	150
7	34.0	1.64	0.10	130	150	160

Quality problems that can occur in tube production:

- eccentricity: due to non-optimal centering of the die, associated with uneven wall thicknesses of the pipe,
- the minimum wall thickness is too large; the minimum wall thickness exceeds the specified value,
- local disturbances in wall thickness: excessively thin at certain points,
- sharkskin: regularly recurring thinner and thicker wall sections of shorter or longer lengths,
- sudden changes in wall thickness.

In the case of tube extrusion line, corrective actions include the centering and calibration of the pull rate [23–29]. By determining the wall thickness profile, the centre of the circle fitted to the profile can be established. The vector between the centre of this circle characterizes eccentricity as shown by Fig. 6.17., and the ideal centre.

Table 6.4. Characterization of short duration and

Technology (sequential numbers)	Deviation of a short run (duration)					Deviation
	D_r , 10^{-4} mm^2	S_r , 10^{-2} mm	R_r , mm	N	σ_r , 10^{-4} mm	D_h , 10^2 mm^2
1	21.02	4.6	0.21	1530	0.31	47.61
2	7.84	2.8	0.11	786	0.19	33.06
3	28.0	5.3	0.26	486	0.36	28.09
4	25.0	5.02	0.28	1014	0.33	61.10
5	14.4	3.8	0.18	276	0.26	46.0
7	39.5	6.3	0.35	1260	0.42	49.0

Legend: D_r and D_h are the dispersions of the respective short and long runs,
 S_r and S_h are the mean deviations of the respective short and long runs,

values, °C				Tube sizes, in mm		
4	5	6	7	diameter	wall thickness	wall thickness deviation
140	110	120	120	40	2.3	0.6
150	120	130	—	32	2.0	0.5
150	120	120	—	40	2.3	0.6
140	150	160	165	50	3.6	0.8
160	130	100	130	50	3.6	0.8
145	185	140	135	40	2.3	0.6
160	140	150	150	140	2.3	0.6

A simple control system is shown in Figure 6.18. The thickness gauge (1), operating on ultrasonic principles, is positioned at the calibrating section to record the wall thickness. The converter (2) automatically records the wall thickness of the pipe and transfers the signal to the integral control (3), which, via auxiliary equipment (4) influences the pull equipment through the equipment (5).

Figure 6.19. is a graph from such a control system. Here, the increase in thickness was induced by a stepwise increase of screw velocity. The deviations in thicknesses were sensed with a time lag, or transport lag, determined by time required to cover the distance between the site at which the deviation in thickness occurred and the position of the thickness gauge. Automatic controls are applied in discrete time periods T_p , after a time lapse of 2 to 3 T_p the thickness is again between the specified limits.

The automatic wall thickness control was studied for stability during the production of pipes with dimensions of 40 × 2.3 mm, with screw velocities of 24–32 revs/min

long duration wall thickness standard deviation

of a long run (duration)				$\Delta\delta_0$, mm	$\frac{\sigma_r}{\Delta\delta_0} 100$, %	$\frac{\sigma_h}{\Delta\delta_0} 100$, %
S_h , mm	R_h , mm	N	σ_h , mm			
6.9	0.37	255	0.48	0.6	50.1	79.6
5.75	0.32	131	0.40	0.3	38.0	80.8
5.3	0.25	31	0.40	0.6	59.7	66.4
7.8	0.39	169	0.56	0.8	41.3	70.0
6.3	0.27	46	0.54	0.6	43.1	89.5
7.9	0.52	210	0.57	0.8	52.5	71.2

R_r and R_h are the average square deviations of the respective short and long runs, N is the number of the observations carried out.

Table 6.5. Pipe wall thickness standard deviation

Types of standard deviations	Technological systems					
	1	2	3	4	5	7
$\Delta\delta_0$, mm	0.6	0.5	0.6	0.8	0.6	0.8
$S \cdot 10^{-2}$, mm	8.3	7.2	7.5	9.3	7.8	8.4
σ , mm	0.58	0.45	0.57	0.68	0.59	0.68
$\frac{\sigma}{\Delta\delta_0} 100$, %	96.6	90.0	95.0	85.0	98.3	85.0
γ , mm	0.72	0.58	0.74	0.83	0.67	0.85
$\frac{\gamma}{\Delta\delta_0} 100$, %	116.5	116.0	123.8	104.0	111.5	106.0
$\frac{\Delta\gamma}{\Delta\delta_0} 100$, %	23.3	16.0	18.3	18.7	13.3	21.2

and with pull-off velocities of 1.59–2.40 m/min. The results obtained are shown in Table 6.6., and they demonstrate stabilizing effect of automation on wall thicknesses during manufacturing.

Maximum savings in pipe extrusion are only possible by combining a centering control with a take-off control. For the automatic centering a mandrel die, where the outer ring is shifted radially in relation to a fixed internal mandrel, is introduced into

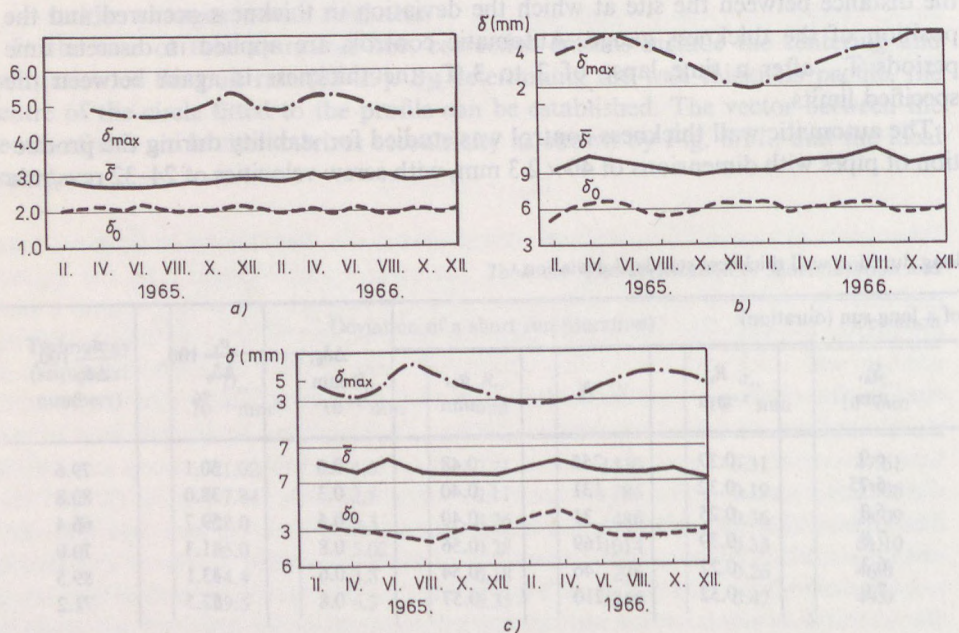
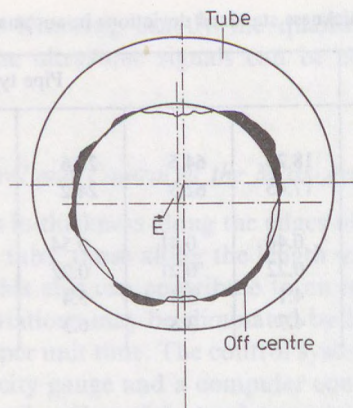


Fig. 6.16. Variations of the dimensions of the pipe as a function of time [24]
a) 32 × 2.00 mm pipes, b) 63 × 3.6 mm pipes and c) 110 × 6.3 mm pipes



$\vec{E}$: Eccentricity vector

Fig. 6.17. Eccentricity calculations

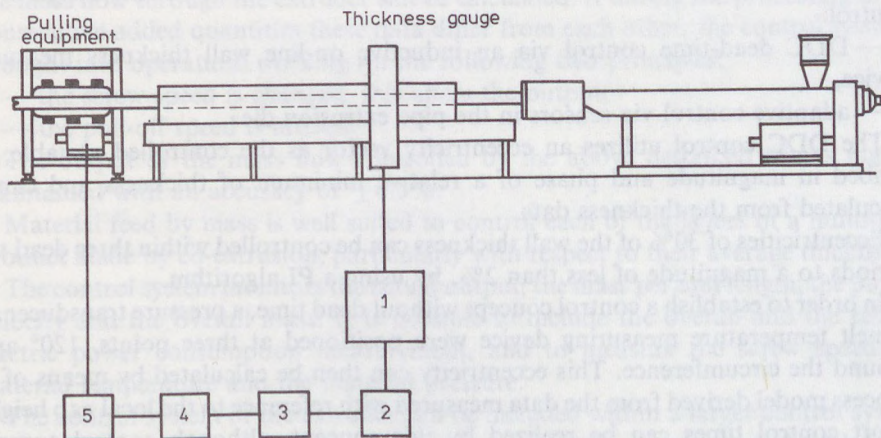


Fig. 6.18. Automated control system to control the wall thickness of the pipe [24]

1. wall thickness gauge, 2. registering and printing unit, 3. control mode, 4. amplifier, 5. mechanism to adjust the control of the speed of pipe pull of.

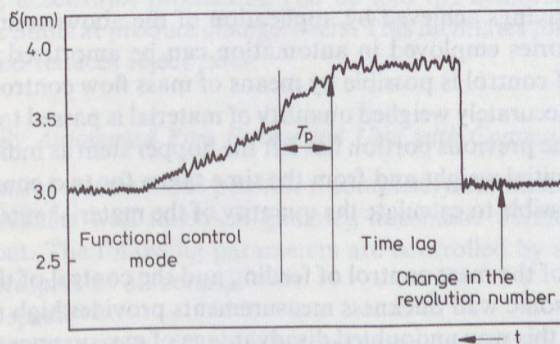


Fig. 6.19. Thickness register chart [24]

Table 6.6. Pipe wall thickness standard deviations in automated manufacturing [23]

Characterization	Pipe types					
Mass in kg						
normal (ordinary)	18.20	64.5	25.6	28.6	52.1	56.1
automatic	17.45	62.3	24.2	26.8	49.9	53.1
Standard deviation in mm						
normal (ordinary)	0.46	0.41	0.54	0.58	0.44	0.49
automatic	0.22	0.21	0.22	0.20	0.22	0.23
Relative mass, %	4.1	3.4	5.4	6.3	3.7	4.6
Relative standard deviation, %	4.7	3.8	6.3	7.5	4.3	5.3

the system. This shift is made by means of spindles adjusted by three motors controlled by a microprocessor. Two basic concepts were followed in the design of the control:

- DDC dead-time control via an inductive on-line wall thickness measuring device,

- adaptive control via sensors in the pipe extrusion die.

The DDC control utilizes an eccentricity vector as the controlled variable, described in magnitude and phase of a relative minimum of thickness and can be calculated from the thickness data.

Eccentricities of 30% of the wall thickness can be controlled within three dead time periods to a magnitude of less than 2%, by using a PI algorithm.

In order to establish a control concept without dead time, a pressure transducer and a melt temperature measuring device were positioned at three points, 120° apart around the circumference. This eccentricity can then be calculated by means of the process model derived from the data measured with reference to the local gap heights. Short control times can be realized by this concept, although control accuracy decreased by a factor of 2.5 in comparison with the DDC dead time control. This is due to variations in properties of the material and to the limited resolution of the sensors.

With material savings achieved by application of the above control concepts, the cost of the accessories employed in automation can be amortized within one year.

Improvement of control is possible by means of mass flow control in the plasticating unit [28]. The accurately weighed quantity of material is passed to the hopper from the feeder only if the previous portion has left the hopper stem as indicated by the level gauge. From the initial weight and from the time taken for two consecutive portions to dispatch it is possible to calculate the quantity of the material entering the extruder per unit time.

A combination of the mass control of feeding and the control of the gap size of the die based on ultrasonic wall thickness measurements provides high reliability in pipe manufacturing. In this way undoubted disadvantage of measurements taken solely by ultrasound is eliminated, namely, that it yields only relative values and thus careful

calibration is necessary. Knowing exactly the quantities of the material passed through the extruder, the ultrasonic signals can be converted into absolute wall thickness values.

Output Control and Control of the Mass-Area of Production

Apart from differences in thickness along the edges of the extruded sheet or along the circumference of the tube, those along the length of the pipe may also result in significant losses, since this also can contribute to an increase of the mass per unit length. The thickness variations may be eliminated by feeding the extruder with the correct mass of material per unit time. The control system consists of a weighing and feeding unit, a pipe velocity gauge and a computer control unit.

At the time when, upon the effect of the level gauge in the hopper, the next weighed quantity of material is passed into the feeder, the tube velocity gauge is also switched into action. From the velocity and from the mass fed into the extruder the output or the mass flow through the extruder can be calculated. If during the processing of two consecutive added quantities these data differ from each other, the control system is brought into operation, working on the following two principles:

- the screw speed is changed, this alters the output;
- the pull-off speed is altered.

The output or the mass flow controlled by the above described means may be maintained with an accuracy of $\pm 0.5\%$.

Material feed by mass is well suited to control each of the layers of a multi-layer product made by co-extrusion, particularly with respect to their average thicknesses.

The control system monitors the actual output, the mass per unit length, the pull-off velocity and the overall mass. It is possible to include the overall and the relative electric power consumption measurement, and to measure the screw speed, the material temperature and the material pressure.

The control system of the extruder can be included within a larger control system. The latter may operate the controls of the extruder directly from a centralized location together with collecting the relevant data.

The feeding of material by mass, together with control of the output and the mass per unit length, accelerates production run up and the achievement of dimensions within tolerance limits at product change-overs. This facilitates the control of material consumption and reduces reject rates.

A Fully Automated Pipe Production Unit with Computer Control

The CNC control system made possible a completely automated pipe manufacturing, based on reliable wall thickness gauging, automatic nozzle centralization and control of output. The following parameters are controlled by a computer:

- the temperatures of all zones,
- the screw speed,
- the vacuum in the extruder cylinder and in sizing unit, and
- the temperature of the cooling water.

In addition to this, the computer also controls the saw for automatic sampling of the product.

The printer prints out the wall thicknesses along the circumference, or this information is displayed on a screen. In a similar way production report and reject rate may also be displayed or printed. By means of the keyboard and the display unit a simple two-directional contact is possible. The data on the screen may be displayed in various languages.

The production line may be operated either manually or automatically. The automatic mode of operation is controlled by the computer with respect to:

- the input of standard data,
- heating,
- start up,
- run-up of production,
- manufacturing,
- deceleration of production,
- production stop.

Such a control system is capable of flexible adaptation to specific local conditions. Connected through a central computer, several extruders can be controlled concurrently, or in combination with other equipment.

6.8 Control of Profile Producing Extruder Lines

The automation of profile producing extruder lines is based on similar principles as for pipe (or tube) manufacturing lines. Automation is used to maintain the proper dimensions and shapes of the profiles made.

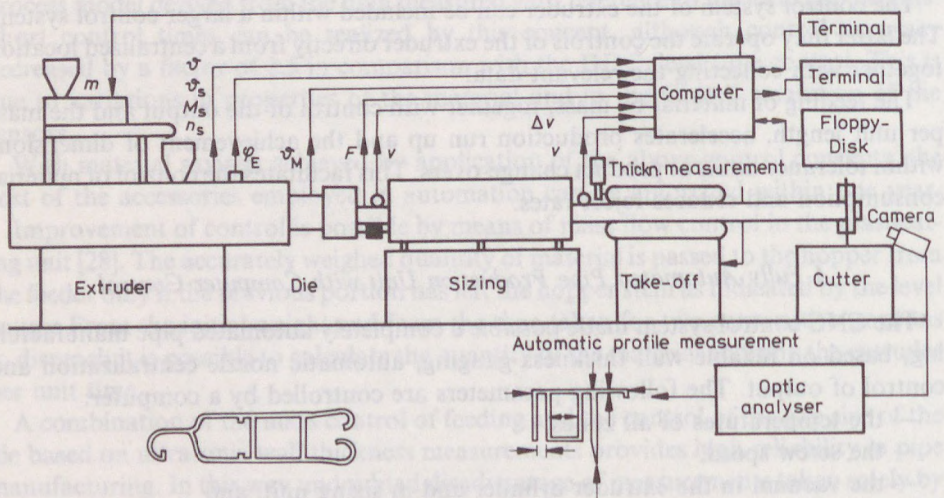


Fig. 6.20. Process control in a profile extrusion plant

In order to realize these aims it is necessary:

- to maintain the characteristic variables of the processes at constant values as much as is possible,
- to monitor the variables, and
- to employ process control.

In a simple control, the velocity of the screw, the stripping velocity and the rate of feed of the plasticating unit are controlled. The moisture content of the material fed must be maintained within set limits, this helps in the control of the above listed parameters, hence, makes for higher quality products.

One of the critical elements in control of profile manufacturing equipment is the constant surveillance of the dimensions of the products. Closed circuit television, or CCD battery sensors are employed. Control of dimensions are performed by means of a cascade control system. The main variable is the size of the cooled profile, the auxiliary variable is the width of the melt strip emerging from the die. Figure 6.20. is a sketch of the control equipment, in which the central unit is a microprocessor for process control.

A further means of control is the control of the elongation of the profile in the calibration unit, measured by establishing the velocity differences of the melt before the calibration unit and after the profiling. This elongation correlates well with the "shrinkage" of the profile that occurs as a result of stretching and cooling that take place simultaneously.

Beside a list of the usual measuring techniques a critical assessment of the often-used ultrasonic thickness measurement is also provided.

The possibility of recording all dimensions of the cross section with a semi-conductor line-scan-camera is treated in detail. In this case we use a configuration which measures the cut-off-end of the profile behind the saw, so that a comparison can be made with the target value.

Another configuration consists of a movable CCD line-scan-camera to measure a large number of different profiles off-line in order to compare them against the target and to generate a protocol for each. The camera contains a chip which can handle 2048 pixels, permitting a resolution of 0.05% of the greatest width.

A comprehensive process control is an aid in reducing the reject rates. Since frequent and accurate interference with the process cannot be effected, other possibilities are analyzed to introduce the automatic dimension control in profile extrusion.

In order to combine the closed-loop control of dimensions with rapid response to changes in the process, for example, to reduce batch-to-batch variations, a cascade control system was implemented. In this case the width of the melt-strand between the profile extrusion die and the calibration unit is measured by a non-contact method using a semi-conductor line-scan-camera, and the data obtained are used as the auxiliary controlled variable. The characteristic width of the cooled-off product is the main controlled variable. For the master controller, which works essentially on a system characterized by transport lag, a parameter-optimized control algorithm is applied. A disturbance variable with a response time of less than 8 s is controlled without overshoot and the main dimensions of the hollow profile are kept within

tolerance limits of 0.025 mm. With the savings achieved by reduced consumption of material and the reduction of reject rates, the use of a weight feeder became superfluous.

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7 Film Blowing Processes and Controls

7.1 Equipment Used in Film Blowing

Film blowing combines the processes of blowing and film extrusion. The advantages of blowing include a high output and film manufacturing with biaxial orientation. In the film blowing process the melt, produced by the plasticating unit, enters the die. From the die a tube-like intermediary product emerges, which is transformed into a bubble by blowing, pulled off by a mechanism, and forwarded to the winding equipment. The basic processes of film blowing consist of plasticating, production of the parison, blowing and cooling. During blowing, the blown film bubble may be pulled upwards, downwards, or in a horizontal direction, as is shown in Figure 7.1. The film bubble is blown with air under 1 to 10 kPa pressure through the die core, while the thickness of the film is adjusted by controlling the air blow and with the aid of a pair of traction rolls with adjustable velocity.

The components of a blown film production line are the following:

- Venturi ring support,
- bubble cooling units,
- cooling and blow-up tower,
- pinch draw rollers,
- bubble collapsing slats,
- winder units.

The Venturi cooling rings stabilize the blown bubble of the material by Venturi action of air, passed outside the expanding plastic tube. This creates a negative pressure on the material and helps to expand the bubble. Another function of the rings is to cool the bubble on the outside by a flow of cool air.

The bubble cooling units provide internal cooling of the bubbles in addition to external cooling.

The tower consists of a vertical unit to carry the blown film bubble up to the pinch-draw rollers. The slat unit collapses the blown film bubble so that it can be brought to the pinch-draw rollers. The slat surfaces are covered with silicone rubber material to minimize the risk of leaving indentations on the film surfaces. The slat units can be adjusted to control the collapsing effects with minimal interference to the bubbles formed.

The draw unit consists of a polished steel roller and a rubber-surfaced roller driven by a speed controlled drive to match production rate requirements. The rollers can be opened and closed by an air-cylinder drive. This is needed in the thread-up operation to pull the tubing through to start the run.

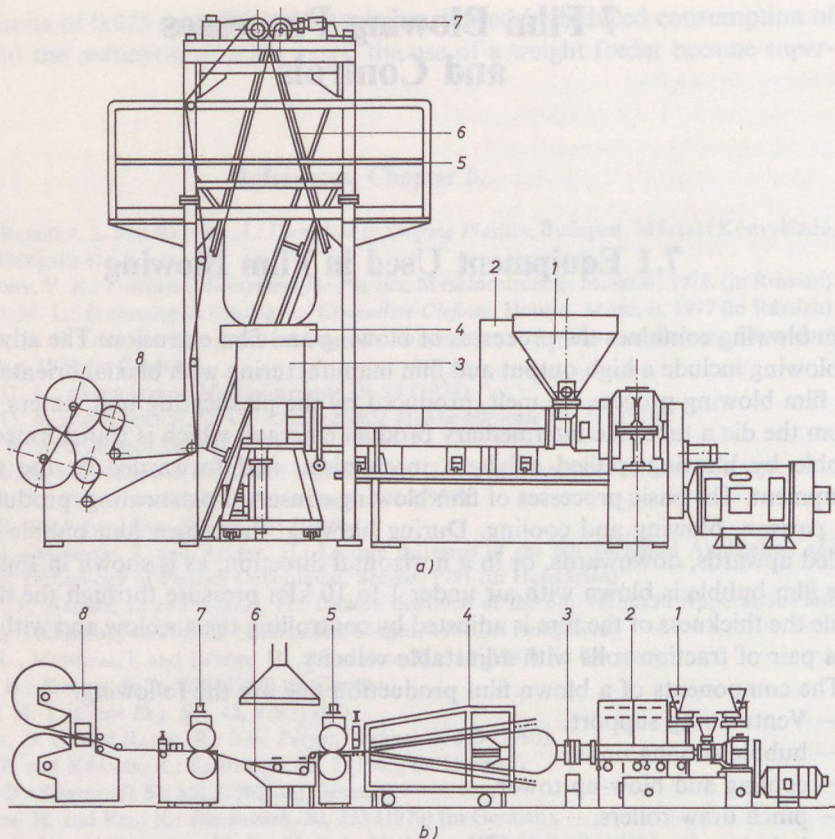


Fig. 7.1. Film blowing processes

- a) Vertically positioned film bubble 1. plasticating unit, 2. control panel, 3. die, 4. air cooling ring, 5. machine support, 6. film bubble tracking plates, 7. traction mechanism, 8. winding equipment.
 b) Horizontally arranged film bubble line 1. hopper, 2. plasticating unit, 3. die, 4. frame, 5. traction rolls, 6. anti-static unit, 7. pinch-squeeze rolls, 8. winding mechanism

The product, upon exit from the blown-film equipment, is wound onto rolls. The winding unit winds the tube onto a cardboard core as shown in Figure 7.1.

Three methods can be utilized for cooling of the film, these involve a combination of air and water or the application of water or air only. Some cooling methods are shown in Figure 7.2. Section a) of the diagram depicts an air-cooling ring, section b) is a cooling process using an air-cooling ring and a water cooling jacket combination, section c) shows an air-cooling ring and an upper water-cooling jacket, section d) shows an external air- and water-cooling combination together with internal water cooling, while section e) illustrates the functioning of a unit with internal air and water cooling. The most widespread method is cooling with air in a ring form. The cooled foil is pulled off the machine by a pinch-draw pair of rolls which forward the film to the stretching rolls. The positioning of the stretching rolls is designed to prevent lateral slip of the film. The first group of rolls rotate at a lower velocity and is fitted

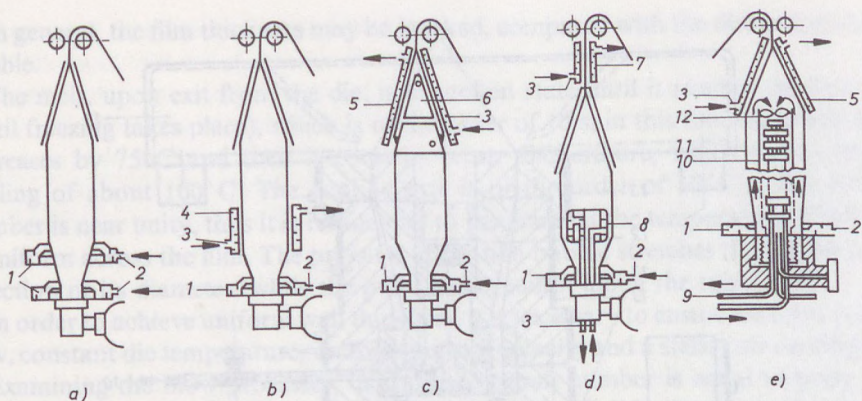


Fig. 7.2. Film bubble cooling methods [1]

- a) With an air cooling ring, 1. and 2. are cooling rings. b) Air cooling ring and water cooling jackets. 1. and 2. air cooling rings, 3. and 4. water cooling jackets. c) Air cooled rings and upper water cooling jackets. 1. and 2. air cooling rings, 3. and 5. upper coolers, 6. insert. d) External air and internal water cooling. 1. and 2. air cooling rings, 3. and 7. upper water cooling jackets, 8. internal water cooling. e) Combined cooling. 1. and 2. air cool rings, 3. and 5. upper water coolers, 9. water inlet, 11. film tube, 10. and 12. water cooled heat exchangers

with heating facilities, accurately adjustable to heat the film to its orientation temperature. The second group of rolls is provided with water cooling and is rotated at a speed 4 to 12 times higher than the first group of rolls. The cooling of the material occurs on the surfaces of these rolls. After this the stretched film is forwarded to the winding mechanism [1 and 2].

The initial part of the film blowing process is the passing of the foil through the annular die. This process is not considered here, since it was discussed in the previous chapter.

Film Blowing Dies

The film blowing dies may be grouped into types of core-holding dies or into distributing channel or spiral channel categories. About 20% of the dies used in film blowing fall into the category of dies with distribution channels, or troughs, 70% in the coreholding category and 10% in the spiral type.

Film thickness deviations and variations may be substantially reduced by using a rotating die type. In practice both the die and the cooling ring attached to the die can be rotated in both directions (shown in Figure 7.3.). Between the stationary part (3) and the mobile part (8) the packing element (4), with sliding bearings, is positioned. The electrical energy necessary for heating the rotating die is provided by overhead cables, or else, the wires are joined via the slip rings (8).

The electrical energy supply, apart from rotating the die, is often utilized to provide energy to the pull rollers and for the entire winding mechanism.

In order to reduce problems associated with transportation of the film or forwarding the film, the rotating velocities of the elements are maintained at a minimum. The time taken for a complete rotation, in general, is 2–3 min.

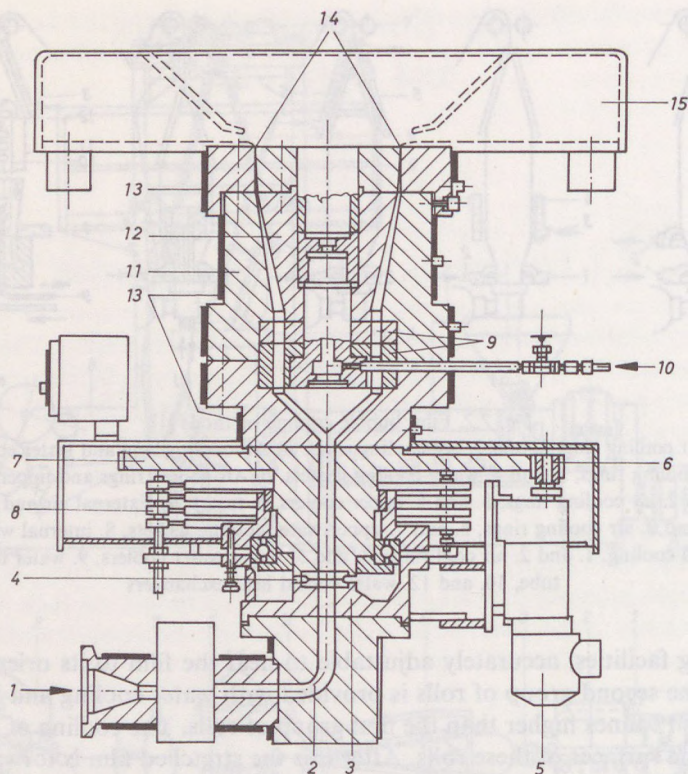


Fig. 7.3. Rotating die and cooling ring

1. polymer melt, 2. channel with a bend, 3. joints, 4. packing ring, 5. electric motor drive, 6. cog-wheel transfer, 7. upper joints, tooth-wheel rim, 8. slip rings, 9. arbour support, 10. air, 11. die body, 12. arbour, 13. heating, 14. nozzle gap, 15. cooling ring

7.2 The Film Blowing Processes

The characteristic features of film blowing (3) are the gap size of the die ($H = 1$ to 2 mm), the diameter of the die ($D = 50$ – 100 mm), the average extrusion velocity ($v_e = 10$ – 50 mm/s), the draw ratios ($Dr = v_d/v_e = 5$ – 15), the blow ratios ($Bu = D_f/D = 1.5$ – 3) and the distance of the crystallization line ($L_f = 0.25$ – 5 m).

The main features of the blowing process itself are:

- the film thickness,
- the film width,
- the quality of the film (strength and optical properties),
- the mass flow (production output).

The film thickness can be estimated from the blow ratio and the pull-off velocity:

$$h_f = \frac{H}{BuDr} \quad (6.1)$$

bubble.

direction of its diameter, while the pull rolls stretch it along the tube's axis.

flow, constant die temperature, uniform pull-off velocity and a steady air cooling rate.

term to be taken into consideration.

7.2.1 Characterization of the Blowing Processes [3–30]

die, h and H represent the wall thicknesses close to the die and at a point where

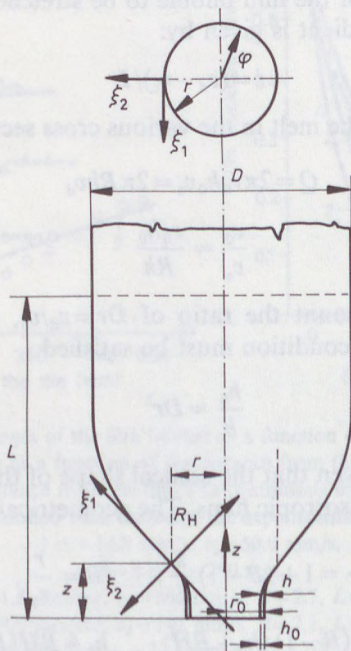


Fig. 7.4. The main parameters in blow process

crystallization has already taken place, d_0 , d and D are the diameters measured at points where the wall thicknesses are h_0 , h and H , ξ_1 and ξ_2 are the tangential and vertical coordinate directions at the point p , being at a distance of z from the die, ξ_3 is a third direction, and Θ is the angle between directions z and ξ_1 . It can be assumed that the film thickness h is much smaller than the radius of the film (i.e. $h \ll r$). The deformation of the film depends on the production method employed to make the intermediary product, for example, without the application of internal blow pressures (i.e. $\Delta P = 0$), purely unidirectional stretching is exerted on the film. In practice, the film is subjected to a biaxial stretch. In determining the direction of the resultant vector, the most important roles are played by the extrusion and pull velocities and the pressure inside the film bubble. The relationship determines the actual shape of the film bubble. The ratio of the linear pull velocity, v_d , and the average extrusion velocity, v_e , affects the wall thickness of the film, its molecular orientation and mechanical properties. Amongst the mechanical properties of the film produced, important criteria are the lengthwise and the cross-sectional strength. Where other factors can be ignored, the blow factor $Bu = d/d_0$ and the ratio of the pull velocity to the flow velocity v_d/v_e will determine the axial orientation. The degree of orientation of the film affects its mechanical properties. Films or foils of different properties are required for different applications. For example, for packaging purposes isotropic foil is the most suitable. This requires the same orientation in both directions, thus, in this case the stretching in each direction must be equal.

In the description of the manufacturing process of isotropic film it is assumed that along the blowing section of length L the longitudinal velocity is constant (i.e. $v_d = \text{const.}$), and the shape of the film bubble to be stretched is conical. Under these conditions, the velocity gradient is given by:

$$\dot{\epsilon} = (v_d - v_e)/L \quad (7.1)$$

The volume flow rate of the melt in the various cross sections of the film bubble is given by:

$$Q = 2\pi r_0 h_0 v_e = 2\pi R h v_d \quad (7.2)$$

from which:

$$\frac{v_d}{v_e} = \frac{r_0 h_0}{R h} \quad (7.3)$$

is derived. Taking into account the ratio of $Dr = v_d/v_e$, in the production of an isotropic film the following condition must be satisfied:

$$\frac{h_0}{h} = Dr^2 \quad (7.4)$$

It was experimentally proven that the conical shape of the film bubble is sufficient to ensure the production of isotropic films. The geometrical shape of the conical film bubble is given by:

$$\begin{aligned} \frac{r}{r_0} &= 1 + (B-1) \frac{z}{L}; & B &= \frac{r}{r_0}, \\ \frac{h}{h_0} &= Dr \frac{(B-1)(h_0 + BH)}{BHL^2} + z \frac{h_0 + BH(B-2)}{BHL} \end{aligned} \quad (7.5)$$

Assuming that $\dot{\epsilon} = \text{constant}$, the relationship between z and t for stretching is given by:

$$z = z_0(e^{\dot{\epsilon}t} - 1) = \frac{v_0}{\dot{\epsilon}}(e^{\dot{\epsilon}t} - 1) \quad (7.6)$$

In this expression z_0 corresponds to the cross section where stretching starts. From equations (7.5) and (7.6) the film thickness as a function of time is expressed as:

$$\begin{aligned} \frac{h}{h_0} = & \frac{(B-1)(h_0 - BH)}{v_e^2(v_d - v_e)^2 BH} \exp\left(2t \frac{v_d - v_e - 2}{L}\right) + \\ & + \frac{v_e}{v_d - v_e} \cdot \frac{h_0 - BH(B-2)}{BH} \exp\left(t \frac{v_d - v_e}{L} - 1\right) + 1 \end{aligned} \quad (7.7)$$

The evolution of the radius and the wall thickness of the bubble as a function of the distance measured from the die is shown in Figure 7.5.

In the preceding text a simple elongational flow was examined.

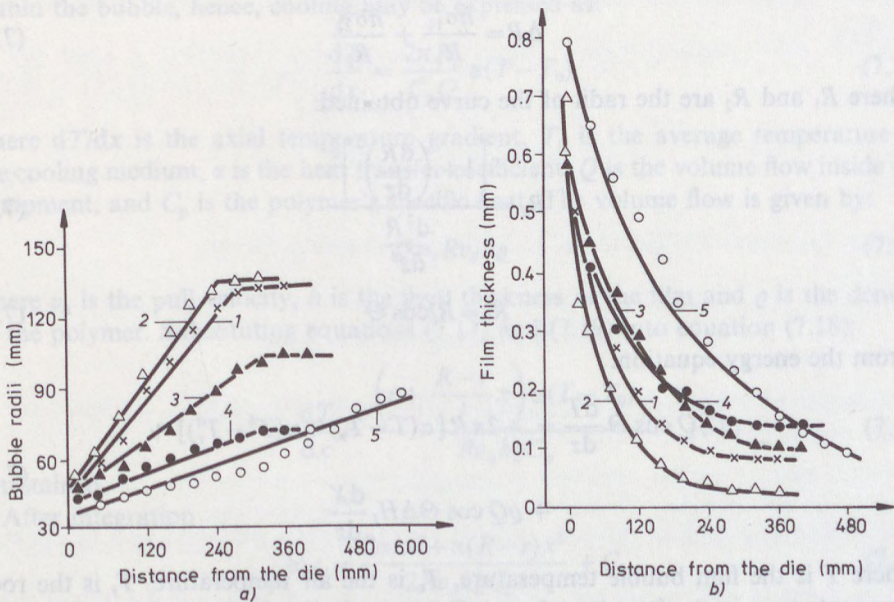


Fig. 7.5. Characteristic changes of the film bubble as a function of the distance from the die [2]
a) Radii changes of the bubble as a function of the distance from the die. b) Thickness changes of the film bubble as a function of distance from the die. The continuous lines represent the calculated values, the dotted lines represent the experimental data.

$$1 \quad v_0 = 14.8 \text{ mm/s}, v_d = 50.0 \text{ mm/s},$$

$$B = 2.8, L = 280 \text{ mm},$$

$$2 \quad v_0 = 41.8 \text{ mm/sec}, v_d = 500 \text{ mm/s}, B = 2.7, L = 260 \text{ mm},$$

$$3 \quad v_0 = 34.0 \text{ mm/sec}, v_d = 142 \text{ mm/s}, B = 2.1, L = 360 \text{ mm},$$

$$4 \quad v_0 = 16.0 \text{ mm/sec}, v_d = 71.8 \text{ mm/s}, B = 1.55, L = 320 \text{ mm},$$

$$5 \quad v_0 = 18.2 \text{ mm/sec}, v_d = 108 \text{ mm/s}, B = 2.3, L = 560 \text{ mm}$$

The continuity equation is:

$$Q = 2\pi Rhv \quad (7.8)$$

The blowing process of the film bubble as a biaxial stretch is expressed as:

$$\frac{\partial v_1}{\partial \xi_1} = \frac{Q \cos \Theta}{2\pi Rh} \left(\frac{1}{v} \frac{dv}{dz} \right) \quad (7.9)$$

$$\frac{\partial v_2}{\partial \xi_2} = \frac{Q \cos \Theta}{2\pi Rh} \left(\frac{1}{R} \frac{dR}{dz} \right) \quad (7.10)$$

$$\frac{\partial v_3}{\partial \xi_3} = \frac{Q \cos \Theta}{2\pi Rh} \left(\frac{1}{h} \frac{dh}{dz} \right) \quad (7.11)$$

The force balance from the momentum equation is:

$$F_L = 2\pi Rh \quad \sigma_{11} \cos \Theta + \pi \Delta P (R_L^2 - R^2) \quad (7.12)$$

The stresses, σ_{11} and σ_{22} are related to the applied pressure, thus:

$$\Delta P = \frac{h\sigma_{11}}{R_1} + \frac{h\sigma_{22}}{R_2} \quad (7.13)$$

where R_1 and R_2 are the radii of the curve obtained:

$$R_1 = \frac{\left[1 + \left(\frac{dR}{dz} \right)^2 \right]^{\frac{3}{2}}}{\frac{d^2 R}{dz^2}} \quad (7.14)$$

$$R_2 = R / \cos \Theta \quad (7.15)$$

From the energy equation:

$$\begin{aligned} \varrho C_v Q \cos \Theta \frac{dT}{dz} = & -2\pi R [\alpha(T - T_a) + \kappa(T^4 - T_r^4)] + \\ & + \varrho Q \cos \Theta \Delta H_f \frac{dX}{dz} \end{aligned} \quad (7.16)$$

where T is the film bubble temperature, T_a is the air temperature, T_r is the room temperature, α is the heat-transfer coefficient, κ is the Stefan-Boltzman constant, ΔH_f is the heat of fusion, and X is the degree of crystallization.

In order to solve the above equation, the existence of a rheological state equation must be assumed. Various models have been employed, such as the Newtonian flow equation, Hook's elastic material equation [4], the rubber like fluid equation [4 and 5], and the Maxwell material equation [28]. Application of numerical methods provides more accurate results; however, for technological calculations simple models are also suitable.

7.2.2 Cooling of the Film

In film blowing, the length of the cooling zone required is determined by the cooling system employed and the degree of efficiency of the system. The most frequently employed method of cooling is air cooling, where the air is channelled in a ring-shaped gap. With an increase of the amount of inlet air the crystallization zone is expanded. Cooling is achieved by heat conduction, heat radiation and by heat transport from the external surface [12].

The radius of the film bubble in the cooling zone can be expressed by the relationship:

$$R_x = \frac{R-r}{l}x + r \quad (7.17)$$

where R is the radius of the bubble above the crystallization line, r is the radius of the ring-shaped portion of the extruder head, l is the distance from the extruder head to the stable shape of the tube, and x is the distance from the extruder head to the point at which the cross section is examined. If it is assumed that the temperature of the bubble is 100–150 °C, heat radiation may be ignored together with the heat transfer within the bubble, hence, cooling may be expressed as:

$$\frac{dT}{dx} = \frac{2\pi R_x}{C_p Q} \alpha (T - T_0) \quad (7.18)$$

where dT/dx is the axial temperature gradient, T_0 is the average temperature of the cooling medium, α is the heat transfer coefficient, Q is the volume flow inside the equipment, and C_p is the polymer's specific heat. The volume flow is given by:

$$Q = Rv_d h \varrho \quad (7.19)$$

where v_d is the pull velocity, h is the final thickness of the film and ϱ is the density of the polymer. Substituting equations (7.17) and (7.19) into equation (7.18):

$$-\frac{dT}{dx} = \frac{\left(r + \frac{R-r}{l}x\right) \alpha (T - T_0)}{Rv_d h \varrho C_p} \quad (7.20)$$

is obtained.

After integration

$$\ln t_r = \frac{2\alpha r x l + \alpha (R-r)x^2}{2Rv_d h \varrho C_p l} + C \quad (7.21)$$

and

$$\ln t_r = \left[A r x + \frac{A(R-r)}{l} \cdot \frac{x^2}{2} \right] + C \quad (7.22)$$

are derived, where

$$A = \frac{\alpha}{Rv_d h \varrho C_p} \quad (7.23)$$

and

$$t_T = T - T_0 \quad (7.24)$$

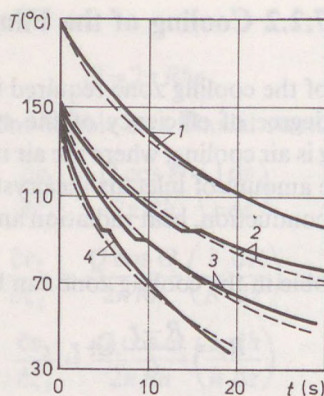


Fig. 7.6. The cooling rates of the film bubble [10]

The dotted line shows the calculated values, the continuous line shows the measured values.

1. PVC, 2. P 2020 T polyethylene, 3. P 2020 A polyethylene, 4. 10 812-02 polyethylene

and the integration constant can be determined from the following boundary conditions:

$$x=0, \quad T=T_p, \quad T-T_0=T_p-T_0 \quad (7.25)$$

$$T-T_0=(T_p-T_0)\exp(\xi) \quad (7.26)$$

$$\xi=\frac{\alpha x[r(2l-x)+Rx]}{2lRv_d hC_p} \quad (7.27)$$

Figure 7.6. shows the calculated and measured cooling curves.

7.2.3 Shrinkage of the Film

The degree of shrinkage may be calculated from the deformation, ε_1 , based on the stress versus deformation relationship [31]:

$$\sigma=G(\varepsilon_1^2-\varepsilon_1^{-1}) \quad (7.28)$$

The degree of shrinkage may be derived by using the right hand side of equation (7.28).

The stress $\varepsilon_1^2-\varepsilon_1^{-1}=\sigma/G$ can be derived with the aid of the elongational deformation:

$$\sigma=\bar{\eta}_E \dot{\varepsilon}=\dot{\varepsilon} \eta_E (2 \operatorname{cosec} 2\alpha_B)^{1+n} \quad (7.29)$$

where

$$\alpha_B=\frac{1}{2} \arctg \frac{\gamma_c}{2} \quad (7.30)$$

and

$$\gamma_B=2\dot{\varepsilon}\left[1+\left(\frac{\gamma_c}{2}\right)^2\right]^{0.5} \quad (7.31)$$

Table 7.1. Calculated and measured shrinkage values derived from polyethylene blowing processes [32]

Designation	Number of experiment					
	1	2	3	4	5	6
Diameter of the ringed part of the die, mm	50	150	50	50	50	50
Gap size, mm	0.5	0.8	0.5	0.5	0.5	0.5
Length of blowing zone, mm	40	520	310	260	100	540
Die temperatures, °C	197	165	173	173	160	168
Pull velocity, cm/s	8.2	10.0	12.6	3.3	3.3	7.7
Film bubble diameter, mm	64	286	52	51	69	74
Degree of shrinkage						
experimental	6.3	3.3	4.0	3.0	3.0	2.5
calculated	7.0	4.7	5.6	3.8	4.6	3.9
Pulling forces (N)						
experimental	2.4	—	2.2	1.5	1.6	1.1
calculated	3.1	3.8	1.7	0.9	2.0	0.9

The term γ_e represents recovery deformation. The shrinkage, from equations (7.28) to (7.31), may be written as:

$$\begin{aligned} \varepsilon_1^2 - \varepsilon_1^{-1} &= \frac{\eta_{\dot{\gamma}=\dot{\varepsilon}}}{\eta_{\dot{\gamma}=\dot{\gamma}_B}} \gamma_e \left[2 \operatorname{cosec} \arctg \left(\frac{1}{2} \gamma_e \right) \right]^{n+1} \\ &\cdot \frac{v_d - v_e}{l \dot{\gamma}_B} \frac{h}{H} \frac{R}{r} + \frac{1}{2} \frac{R^2 - r^2}{HR} \frac{\gamma_e}{\eta_{\dot{\gamma}=\dot{\gamma}_B}} \frac{P}{\dot{\gamma}_B} \end{aligned} \quad (7.32)$$

Table 7.1. compares the calculated and measured shrinkages.

7.2.4 Factors Affecting Film Thickness

We now examine the variations occurring in film thickness. Let the average thickness, in relation to the cross section, be h_{01} and the minimum thickness be h_{02} . Assuming identical stretching velocities, in simple stretching the stresses affecting the two layers may be expressed as:

$$h_{02}/h_{01} = \dot{\varepsilon}_1/\dot{\varepsilon}_2 \quad (7.33)$$

where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are the elongation rates. The width of the film elements examined is B , their lengths are l_1 and l_2 . The blowing zone may be regarded as nearly conical in shape, thus, the tangential deformation velocities are constant, so that the lengths of the individual elements are given by

$$l_1 = l_0 e^{(\dot{\varepsilon}_1 t)} \quad (7.34)$$

$$l_2 = l_0 e^{(\dot{\varepsilon}_2 t)} \quad (7.35)$$

where t designates the deformation time of the elements. During deformation the volume of the elements remains constant, thus the thicknesses at lengths l_1 and l_2 are given by:

$$h_1 = \frac{h_{01} l_0 B}{l_1 B} \quad (7.36)$$

and

$$h_2 = \frac{h_{02} l_0 B}{l_2 B} \quad (7.37)$$

the thickness ratios are:

$$\frac{h_2}{h_1} = \frac{h_{02}}{h_{01}} \exp \left[\varepsilon_1 t \left(1 - \frac{h_{02}}{h_{01}} \right) \right] \quad (7.38)$$

the deformation time is:

$$t = \frac{2L}{v_e(1 + Dr)} \quad (7.39)$$

where v_e is the extrusion velocity and Dr is the draw ratio. The maximum stretching velocity is given by:

$$\dot{\varepsilon}_1 = \frac{\pi v_e (Bu - 1)(1 + Dr)}{8L} \quad (7.40)$$

Taking equation (7.40) into account, from equation (7.38):

$$\frac{h_2}{h_1} = \frac{h_{02}}{h_{01}} \exp \left[-\frac{\pi}{4} (Bu - 1) \left(-\frac{h_{02}}{h_{01}} - 1 \right) \right] \quad (7.41)$$

is derived. By analyzing the equation it can be concluded that the initial variations in thickness increase with increasing blowing ratio.

7.3 The Dynamics of Film Blowing

The characteristics of the blown film in the complex process of film blowing are determined by several parameters. The analysis of the technological process reveals that these processes may best be illustrated by a multi-channel model, as shown in Figure 7.7. The output characteristics are the change in thickness Δh , and the change in width ΔB , while the controllable input characteristics are the pull-off velocity of the

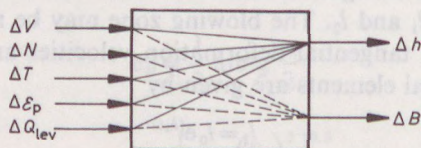


Fig. 7.7. Factors influencing thickness and width changes

film Δv , the change in screw velocity ΔN , the temperature variations of the melt ΔT_p , the variations experienced in the degree of blowing ΔBu , and the volume flow rate variations of the inlet cooling air ΔQ_{air} . In order to determine the relationships between all these quantities let us analyze the dynamics of the processes involved [32].

In the zone of film formation an elemental section with radius r , thickness dr and width dh is examined. The foil is of conical shape with a cone angle of Θ , the deformation of the film due to changes in pull-off velocity is unidirectional stretch. Let B_0 be the width of the foil, v_e be the velocity of the melt at the moment it emerges from the die head and let P_0 be the pressure of air inside the bubble, V_0 is the air volume at the soft part of the film bubble with an average radius of $\bar{r} = \frac{R+r}{2}$, and with average thickness $\bar{h} = \frac{h+H}{2}$. The stresses due to the air pressure may be approached by the Voigt-Kelvin model, thus:

$$\sigma(t) = E\varepsilon_H + \eta_E \frac{d\varepsilon_H}{dt} \quad (7.42)$$

where E is the elasticity modulus, η_E is the elongational viscosity, and ε_H is the relative deformation in the direction of the elongation. The solution of equation (7.42) provided that $\sigma(t) = \Delta\sigma$, $t=0$, $\Delta\sigma=0$ and $\varepsilon_{(0)}=0$ is:

$$\varepsilon_H = k_e \left(1 - e^{-\frac{t}{T}} \right) \quad (7.43)$$

where $k_e = \Delta\sigma/E$ and $T = \eta_E/E$. Based on the continuity equation the change in the deformation rate is given by:

$$\dot{\varepsilon}_H = \dot{\varepsilon}_h + \dot{\varepsilon}_r \quad (7.44)$$

where $\dot{\varepsilon}_H$ is the deformation rate in the direction of the elongation, $\dot{\varepsilon}_h$ is the change in the rate of deformation in the direction of the change in thickness while $\dot{\varepsilon}_r$ is a component of the deformation rate, perpendicular to the pull-off velocity, and tangential to the cross section of the film bubble.

The deformation, perpendicular to the pull-off velocity, is given by:

$$\varepsilon_h(t) = (1-\nu) \int_0^{\tau_0} \frac{d \left\{ \frac{\Delta\sigma(r, l, \tau)}{E(r, l, \tau)} \left(1 - e^{-\frac{t}{T(r, l, \tau)}} \right) \right\}}{dt} d\tau \quad (7.45)$$

where ν is the Poisson constant, τ_0 is the time lapse for the film from its exit from the die to the moment of its crystallization. The functions of E , T and $\Delta\sigma$ cannot be given, so that calculations must be based on certain boundary conditions. Such a boundary condition is, for example, the state of the film bubble just prior to crystallization, thus:

$$\Delta\sigma = - \frac{6\eta_E \Delta v \sin \Theta}{l} \quad (7.46)$$

The transfer function of the film thickness variation with respect to the pull-off velocity changes is expressed as:

$$G(h) = \frac{\Delta h/h}{\Delta v/v} = \frac{k_h}{1 + Tp} \quad (7.47)$$

where

$$k_h = - \frac{3\eta_E v \sin \Theta}{hE}$$

The rate of change with respect to time is:

$$\frac{\Delta h}{h}(t) = \frac{\Delta v}{v} k_h \left(1 - e^{-\frac{t}{T}}\right) \quad (7.48)$$

The effect of changes in the pull-off velocity upon the film width is shown by Figure 7.8.; $G_1(p)$ is the effect of the elongational deformation on the height of the freeze line, while $G_2(p)$ is the effect upon the width of the film:

$$G_1(p) = \frac{\Delta l(p)}{\Delta v/v(p)} = \frac{k_1}{Tp + 1} \quad (7.49)$$

$$G_2(p) = \frac{\Delta B/B(p)}{\Delta v/v(p)} = \frac{k_2}{Tp + 1} \quad (7.50)$$

where

$$k_1 = \frac{6\eta_E v \sin \Theta}{E}; \quad k_2 = - \frac{3\eta_E v \sin \Theta}{EB} \quad (7.51)$$

The transfer function $G_3(p)$ gives the change in the height of the freeze line due to the effect of thickness changes. The change in the freeze line originates from changes in cooling time:

$$\Delta l = \Delta t_c \cdot \bar{v} = \frac{\Delta F_0 h^2}{4a} \bar{v} \quad (7.52)$$

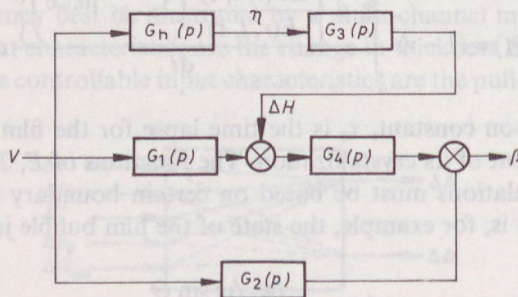


Fig. 7.8. The dynamics of the film width changes

where h is the average foil thickness, $\bar{v}$ is the average foil transport velocity, while a is the thermal diffusivity. The transfer function is written as:

$$G_3(p) = \frac{\Delta l(p)}{\Delta v/v(p)} = \frac{k_3}{T_3 p + 1} \quad (7.53)$$

The term $k_3 = f(Bi, Fo, \Delta h \text{ and } \bar{v})$ can be calculated from the relationships related to cooling. Changes in Δl are accompanied by changes in the width of the film, characterized by $G_4(p)$, also considering the pressure change in the film bubble due to the volume change.

The cross deformation of the film bubble takes place on the effect of the shearing stresses; for the shearing flow the Kelvin model gives the equation:

$$G\gamma + \mu \frac{d\gamma}{dt} = \tau(t) \quad (7.54)$$

The relationship between the shearing stress and the elongational viscosities is $\eta_E = 3\mu$. The stress change is given by:

$$\Delta\tau = \frac{\Delta V r}{V h} P_0 \quad (7.55)$$

where $\Delta V = \pi R^2 \Delta l$ gives the volume change. The transfer function is:

$$G_4(p) = \frac{\Delta B/B}{\Delta l(p)} = \frac{k_4}{T p + 1} \quad (7.56)$$

where

$$K_4 = \frac{3\pi B P_0 l (B/\pi + R + H)}{E V (h + H)}$$

The transfer function for the entire process is:

$$G_B(p) = [G_1(p) - G_h(p) G_3(p) G_4(p) - G_2(p)] \quad (7.57)$$

Substituting:

$$G_B(p) = \frac{k_B \left(\frac{k_1 k_4}{k_B} T_3 p + 1 \right)}{T^2 T_3 p^3 + (T^2 + 2 T T_3) p^2 + (2 T + T_3) p + 1} \quad (7.58)$$

where

$$k_B = \frac{3\eta_E v \sin \Theta [6\pi B^2 P_0 \bar{r} l - E V_0 \bar{h} (B k_3 + 1)]}{E^2 V B h} \quad (7.59)$$

and the velocity change of the film bubble with time is:

$$\begin{aligned} \frac{\Delta B}{B}(t) &= \frac{\Delta B/B}{\Delta v/v}(0) + \\ &+ \sum_{k=1}^n \frac{k_B \left(\frac{k_1 k_4}{k_3} T_3 p_k + 1 \right) e^{p_k t}}{p_k [3 T^2 T_3 p_k^2 + 2(T^2 + 2 T T_3) p_k + 2 T + T_3]} \end{aligned} \quad (7.60)$$

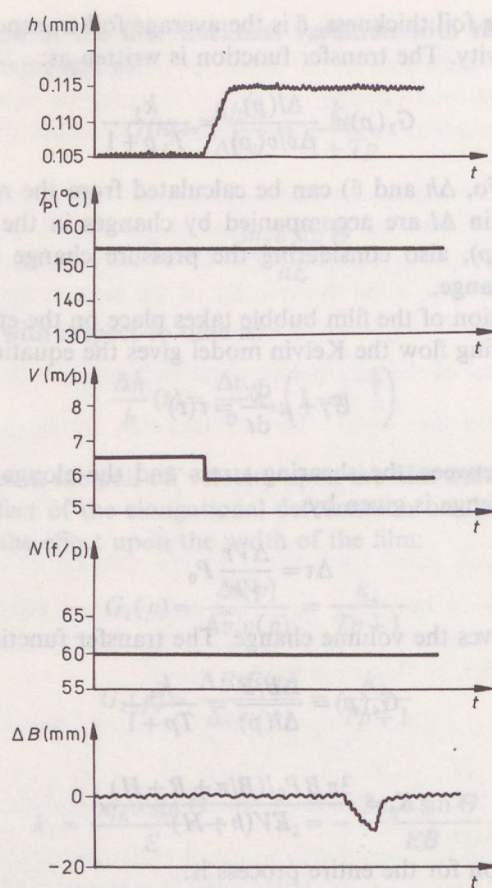


Fig. 7.9. Variations in the thickness and the width of polyethylene film affected by a sudden, step-like change of pull velocity [22]

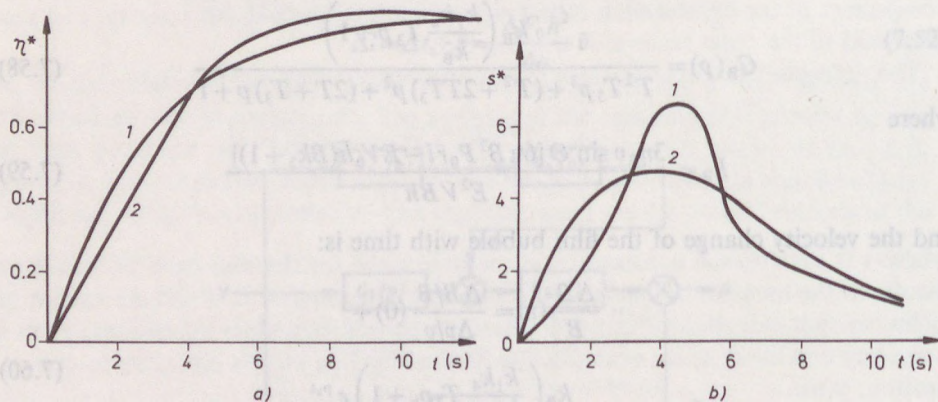


Fig. 7.10. Transfer function of polyethylene film thickness and width changes
1. calculated curve, 2. experimental curve, a) Thickness variation, b) Width variation

The practical applicability of the equations derived was studied using a PE 2020 T material. The dynamic characteristics were established by determining the functions $\Delta h(t)$ and $\Delta \beta(t)$, brought about by velocity step Δv . The increase in velocity did not exceed 10%. The time functions of the changes in film thickness, in the temperature of the material leaving the die, in pull velocity, in the screw speed and in film width are shown in Figure 7.9. The calculated and measured width and thickness curves derived by the method described above are shown in Figure 7.10. Correlations between the experimental and the calculated results were satisfactory.

7.4 Control Methods for Film Blowing Processes

In traditional film blow processes a static air cushion is employed for blowing of the tube. This cushion is bounded by the die and the film bubble in such a way that the escape of air is hindered by a squeezing pair of rolls. It is not possible, using a static air cushion, to compensate for the disturbing factors.

The major disturbing factors may be as follows:

- variations in the revolution number of the screw, resulting in variations in transport efficiency,
- variations in the revolution number of the pull-off mechanism, influencing the thickness of the film,
- changes in the viscosity and temperature of the melt,
- changes in the temperature of the surrounding atmosphere,
- the gradual temperature increase in the air blown into the bubble,
- changes in the temperature of the cooling air, and
- the imperfect closure of the pull-off pair of rolls, which results in a gradual escape of the air blown into the bubble.

Owing to such disturbing effects, the thickness tolerance of the bubble manufactured by a film blow unit where a static air cushion is employed is of the order of $\pm 6\%$, and this may give rise to problems at the end of the process.

The application of traditional cooling technology restricted the possibilities in bubble manufacturing, and, for this reason, internal air exchange cooling was developed. The major importance of this development was not only that the output efficiency of the film blow units increased substantially, but also that it made it possible to produce a film bubble with tighter tolerances.

Inside the bubble with a dynamical air cushion, air is continuously exchanged at a constant rate and this method, supplemented by suitable measuring and controlling devices led to the possibility of continuous calibration of the width of the bubble. The dynamic air cushion is operated by a blower and a sucking fan. The air from the blower is divided into two streams, one supplies the external cooling ring, the other enters the bubble through the die. A central air suction pipe is positioned coaxially with the die to remove the hot air from the upper part of the air in the bubble by the suction fan. The volumes of the inlet air and the outlet air must be the same. The volume of the outlet air is kept constant; this equilibrium in

air supply is achieved by a pneumatic throttle valve on the blower side. This throttle valve determines the distribution ratio of the external and internal cooling air of the bubble.

The equipment is also supplied with a calibrating ring constructed from segments equipped with teflon rings, its diameter and the height are continuously adjustable. A lower segment of the ring is a diameter sensor. The distance of the ring from the die is chosen so that the sensing part should reach the bubble somewhat below the freeze line. In practice, the height of the solidification line is dependent only on the surface, that is, the blow ratio. From this it follows that during size changes in production, the height of the new freeze line can easily be calculated in advance in order to assist in adjustment of the new ring height with reasonable approximation. This is one of the basic conditions for the development of an automated process control system.

The objectives of automation of film blowing processes are:

- to maintain the thickness and the width of the film without manual interference and to reduce material consumption,
- to reduce start-up and product change times,
- to optimize utilization of the equipment and to increase production output.

Quality control of the film includes measurement of the thickness and width of the film, measuring the diameter of the film bubble and monitoring its temperature.

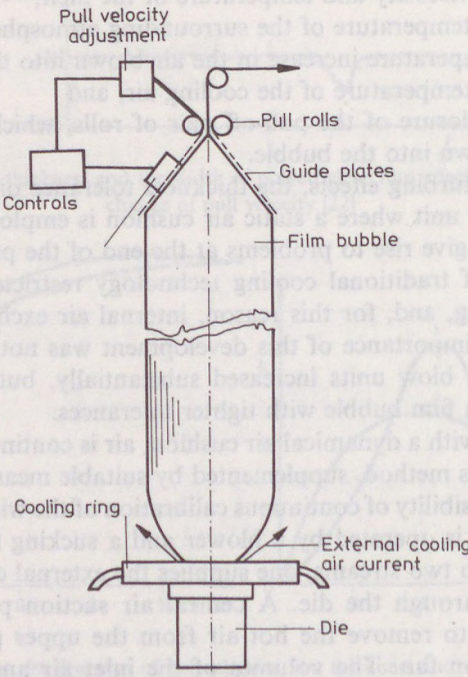


Fig. 7.11. Film-thickness controls

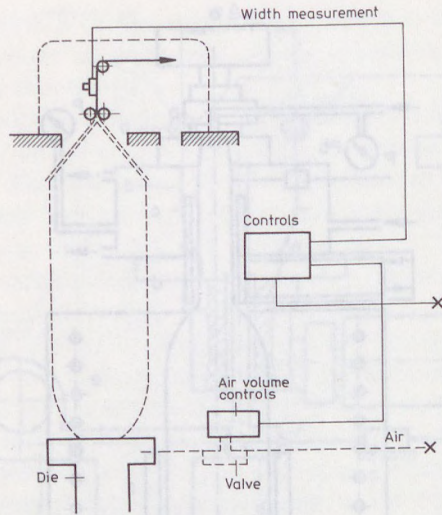


Fig. 7.12. Film-width controls

The control modes of the film blowing processes are [33–43]:

1. Thickness control

The thickness of the film is monitored continuously, either by measuring the film bubble produced, or after the pulling; for control purposes the pull-off velocity is altered. This equipment is shown in Figure 7.11.

2. Width control

An assembly at the extruder for control of the width of the film comprises monitors for detecting the velocity and the edge positions of the film during transport away from the extruder. A control circuit calculates the deviation of the actual film width from the predetermined target and emits a correction signal relayed via a stationary infrared radiation transmitter and a receiver is positioned on the extruder head which controls a valve in order to control the pressurization of the extruded bubble by the blower. The system is shown in Figure 7.12.

3. Control of the dimensions of the film bubble

The sizing basket control of a film bubble is shown in Figure 7.13. Upon exit of the film bubble from die b) it enters precalibrating sections c) and d) where constant air pressure is maintained. The diameter of the film bubble is controlled by the internal air pressure P_b and with calibration section f). The chamber e) is to maintain the temperature constant in order to eliminate the effects of variations in the temperature of the external atmosphere.

A bubble control system using an optical measuring device is shown in Figure 7.14. The photocell measures the changes in the diameter of the film bubble above the crystallization zone. A PID control adjusts the amount of air entering the film bubble

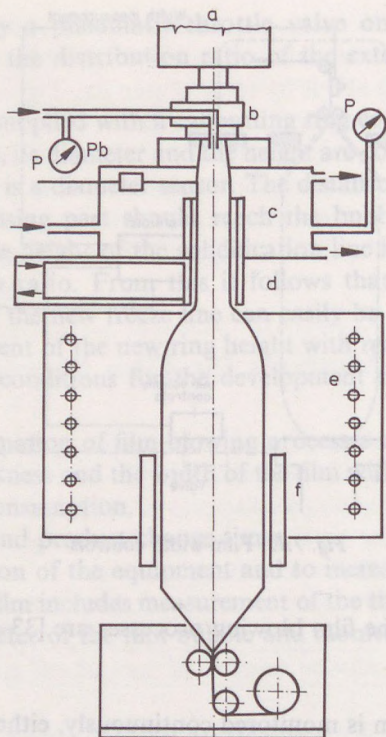


Fig. 7.13. Pressure controls applied to the film bubble

a. plasticating unit, b. die, c. precalibrating chamber, d. temperature chamber, e. cooling system, f. calibration section

according to the changes occurring. The control, connected to a printer records the fluctuations in the dimensions of the product.

Figure 7.15. shows a bubble diameter control system, fitted with a mechanical sensor.

In bubble calibration the time constants are relatively small, so that proportional (P-) control is necessary. P-control is based on the position of the sensor with linear conversion into pressure signals. This pressure signal influences the pneumatically operated throttle valve in the inlet air channel, to control the inlet volume of air. In other words, each position of the sensor corresponds to a certain position of the throttle valve, and thus, to a certain volume of inlet air. In the starting position of the sensor which corresponds to a given diameter of the calibrating ring, the volumes of the inlet and the outlet air are the same, thus, the system is in equilibrium. If, for any reason, the diameter of the bubble decreases or increases, the sensor is moved from its starting position, and the throttle valve increases or decreases the volume of the inlet air until the sensor returns to its starting position and the equilibrium of the system is restored. In practice, the same control process operates when the width of the bubble is to be changed deliberately and the diameter of the calibrating ring

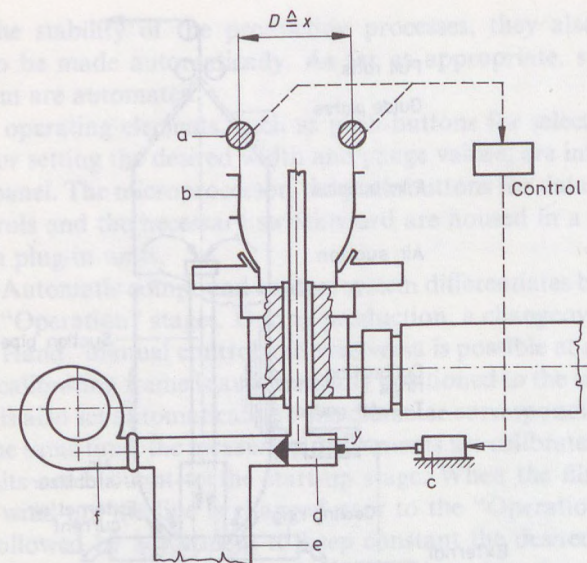


Fig. 7.14. Photocell sensor control of the diameter of the film bubble

a. photocell, b. calibrating section, c. motor to operate the valve, d. adjustment valve, e. buffer tank, f. air blower

adjusted, to accommodate a new value. However, the width of the finished product is always somewhat smaller, due to shrinkage, than the value obtained at the sensing point. For this reason, the diameter of the calibrating ring is adjusted so that the width of the finished product coincides with the desired value. Conditions of shrinkage, however, may be modified due to effects of the surrounding environment leading to changes in film thickness and also due to temperature changes during production.

4. Complex control methods

In film production, both the width and the gauge are of particular importance, apart from other properties. When considering the relations of these two parameters, the film gauge and the film width are found to exert some reciprocal influence.

For example, some films have an actual gauge that corresponds precisely to the specified value. However, the width of the film is somewhat smaller than the specified value. This parameter is now brought to the specified value by changing the diameter of the calibrating frame. However, this is accompanied by reduction of the film gauge. By changing the take-off speed, the actual gauge must be re-adjusted to the specified value. As the result of varying shrinkages, this cannot be achieved without exerting an influence on the film gauge, so that the latter need to be corrected again. Thus, verification of gauge and width, and the necessary corrections are required. Unless these are carried out continuously, appropriate allowances have to be set, which are checked and reset at specific intervals. During the period not monitored, these allowances keep the actual dimensions within the desired tolerances.

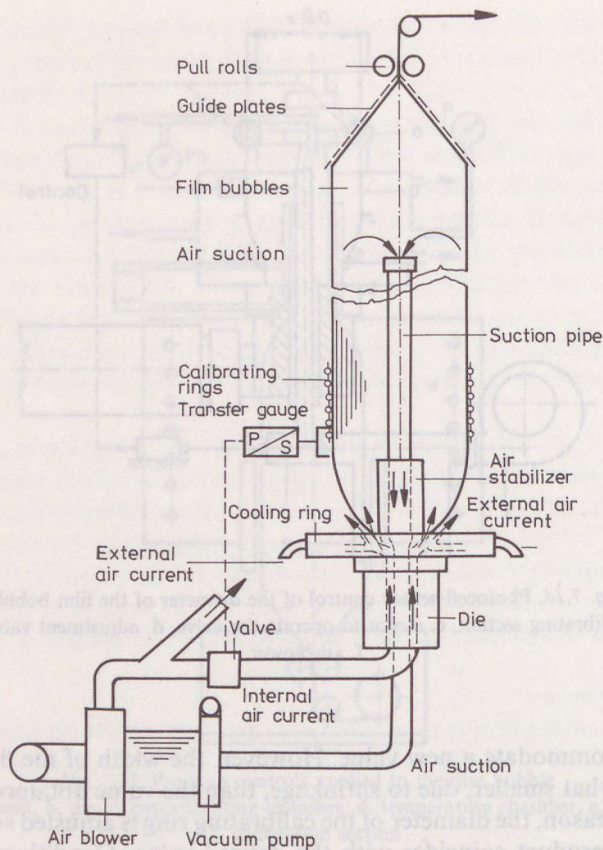


Fig. 7.15. Controls by mechanical sensors of the film bubble diameter

A thickness gauge with control system alone cannot ensure close adherence of the film to the desired gauge value at constant width. Keeping the film width and film gauge constant with the closest tolerances possible can only be achieved by a combination of the following control circuits:

- film width control circuit,
- film gauge control circuit,
- the degree of frame fill-out,
- frame height control circuit.

Owing to the interdependencies of the individual control circuits, such a compound control system is highly complex. For an optimum solution of the problem, and for a central process control of several lines, a microprocessor control system is used. The system is designed to lessen the burden on the operating personnel, so that the adherence to the correct film dimensions is no longer dependent on the qualification and skills of the operators.

In order to make optimum use of the advantages offered by such a compound control system, special thickness and width gauges have been developed. These do not

only increase the stability of the production processes, they also allow product modifications to be made automatically. As far as appropriate, specific processes within the system are automated.

The required operating elements, such as push-buttons for selecting the mode of operation and for setting the desired width and gauge values, are integrated into the central control panel. The microprocessor, the push-buttons for data input, the width and gauge controls and the necessary switchboard are housed in a cabinet together with the 19 inch plug-in units.

The Reicofol-Automatic compound control system differentiates between "Hand", "Start-up" and "Operation" stages. During production, a changeover from "Operation" mode to "Hand" manual control and vice-versa is possible at any time. During "Start-up", the calibrating frame is automatically positioned to the start-up level. The frame diameter is also set automatically to the diameter corresponding to the desired film width. At the same time, the measuring instruments are calibrated and the lay-flat and take-off units are brought to the start-up stage. When the film tube has been drawn into the wind-up, the line is changed over to the "Operation" stage. This is automatically followed by adjustment to keep constant the desired film gauge and width. At the same time, the level of the frame is adjusted to the particular level of the frost line. Optional product changes can be made simply by entering the particular width and gauge values into the computer.

The extension of the system consists of a central controlling and monitoring station requiring only a coaxial cable to connect it to various units. In addition to presetting the desired production data, this central station, even at this basic stage of extension, can monitor up to 36 production lines. Its operation does not require any knowledge of programming. In addition to the compound control data, the extended system permits the recording of up to eight further measuring data per line, such as the temperature data of the extruders. The mode of operation is selected on the machine, and the desired production data can be preset from the central station. Where the operation is integrated into the central station, only the desired set of data is accepted. The information shown on the monitor (arrangement and selection of the data) can be selected as required. A printer, of course, can also be added to the system to print out production data.

Figure 7.16. shows an automatic blown film line, the line's microprocessor control (Honeywell TDC 2000) operational mode is best illustrated by the description of the start-up procedure, which can be performed by a single operator. First, the operator sets up the machine using dial-in controls on the console, placed next to the die. After programming the controls for the desired film width and thickness, the operator initiates start-up by bringing the sizing basket to the proper starting height.

The sizing basket, with its own motorized controls, adjusts its diameter to the correct size for start-up. (Later, when the line is on stream, the basket will readjust itself to the proper diameter for the specified film layflat width, according to calculations made automatically by the microprocessor on the basis of film width and film thickness input requirements.) Once the sizing basket is in position, the take-off rolls and collapsing guides open automatically and the take-off speed is adjusted to a starting setpoint. Next, the film thickness monitor moves into position and automati-

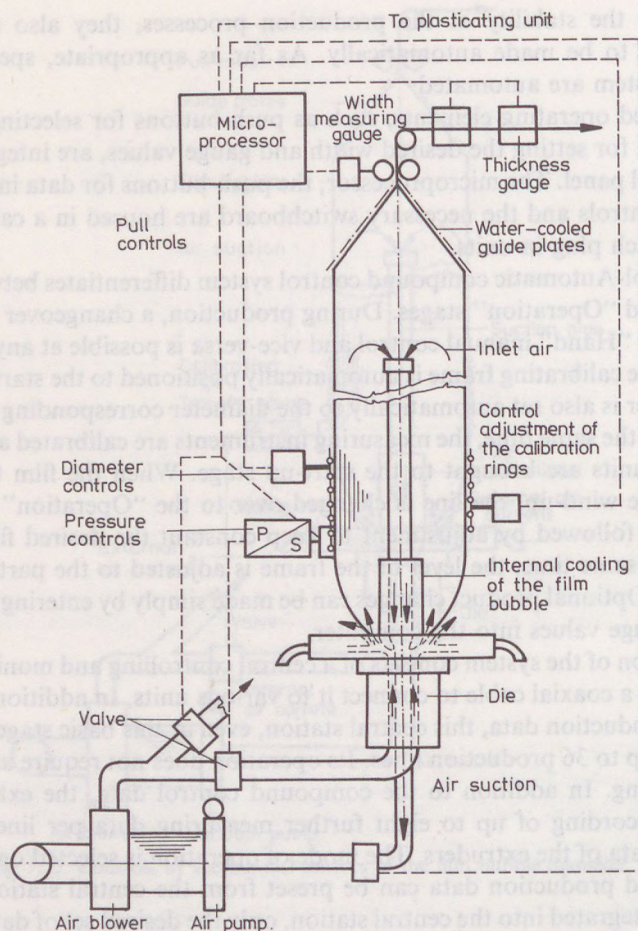


Fig. 7.16. Complex microprocessor control of film blowing [25]

cally recalibrates itself. The same routine is performed by the width measuring device, again automatically.

Following this whole sequence, which is claimed to take less than one minute, a light on the control console indicates to the operator that the line is ready to start. As soon as the melt emerges from the die, the usual rope or tape is applied to draw the film through the take-off rolls, at the preset speed. The objective of continuous monitoring and feedback adjustment of film thickness and layflat width is to produce films with the smallest possible deviation from specification and to economize on raw material usage. In order to take into account all possible sources of error, such as the die, sizing basket, conditions of the ambient air, bubble flattening and take-off units, the width and thickness measuring devices are located immediately after the take-off rolls, rather than on the bubble. In addition, the time required for measuring is said

to be minimized by sensing the film in a layflat configuration, instead of waiting for 20 min or so to measure a full rotation of the bubble.

The X-ray thickness gauge performs two types of measurement. First, the control system to check that the thickness across the full width of the layflat fall within manufacturing tolerances. Second, the microprocessor analyses the degree of variation in the complete transverse measurement and if the range of variation exceeds the preset limits, an alarm is sounded to call for recentering of the die.

The width measuring device uses two sensors to measure the position of each edge of the film layflat independently, relative to a fixed point representing the preset boundaries of the film path.

The vital benefit of having a microprocessor "intelligence" built into the line is that it can balance several mutually interactive control variables simultaneously. For instance, let us assume that a film is being produced with the proper thickness, but the width is found outside specifications. By altering the diameter of the sizing basket, and thus the blow-up ratio, the film width can be brought into line with specifications, but the thickness changes at the same time. Adjusting the take-off speed then corrects the film thickness, but shrinkage behaviour will be affected in consequence, which in turn, causes an error in thickness, requiring readjustment of the line speed, and so on. Such complexities of control are common to all blown film processing and where manual control is used, the consequence is almost continuous variation in product thickness, because of the relatively long time required for repeated corrections and adjustments. The microprocessor control system can make all the necessary adjustments almost simultaneously.

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8 Processes and Process Controls Applied in the Manufacture of Hollow Bodies

8.1 Blowing Processes

The application of blowing processes is widespread in the manufacture of two categories of plastic production, foils and hollow bodies. Hollow bodies, either open or closed, are produced by placing the injection moulded or extruded parison into a two-piece mould, then blowing it by air or inert gas to obtain the finished product. Blow moulding processes may be divided into two groups depending on the method of manufacturing the intermediates. These are:

1. Blowing with extrusion, the intermediates are extruded, and
2. Blowing with injection moulding, the intermediates are obtained by injection moulding.

The processes can be further classified according to other criteria such as the positioning of the mould, the type of extruder head employed, etc. [1-4]. From the point of view of a theoretical approach, however, the important distinction is between extrusion and injection moulding processes.

Figure 8.1. shows the principles of extrusion blowing, which consists of three distinct steps:

- the extrusion of parison being a standard tube extrusion process; the tube is cooled to a flexible state,
- the closing of the blowing mould sealing of the top and bottom sections of the intermediate,
- compressed air or inert gas is introduced through an orifice, to blow the

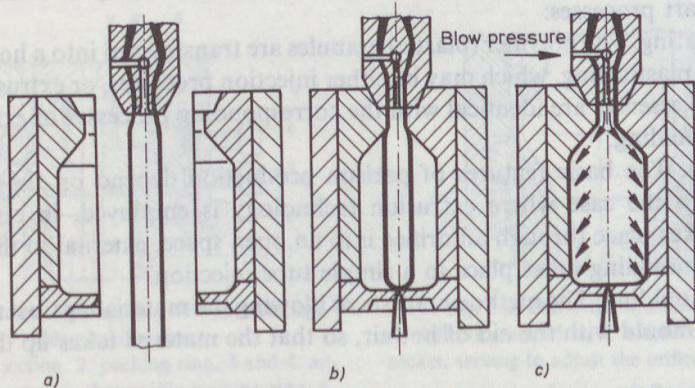


Fig. 8.1. Principles of extrusion blowing

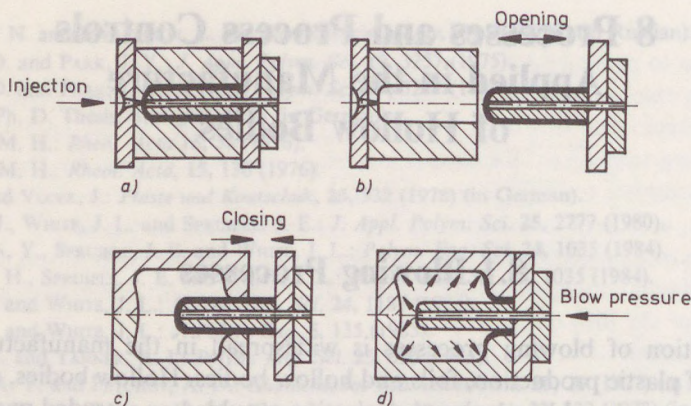


Fig. 8.2. Injection moulding by blowing

intermediate to fill the space in the mould to obtain the designed hollow formation. After cooling the product can be removed from the mould.

The process of blow following injection moulding is shown in Figure 8.2. Here, the intermediate is made by injection moulding with the following main steps:

- the injection moulding of the intermediate,
- the opening of the mould, where one part of the mould also serves for calibration purposes,
- the closing of the mould, where one part of the tool is fitted into the other part of the tool containing the intermediate,
- the blowing of the intermediary product.

The main equipment used in blow injection moulding is similar to that in simple injection moulding, the auxiliary equipment serves to open and close the mould, and to remove the product. Blow moulding was shown to be less efficient when compared with the extrusion process, and it is not suitable for making products of larger sizes. On the other hand, blow moulding is more suited for the production of items with smoother surfaces and superior dimensional precision.

The manufacture of products consisting of hollow bodies may be divided into the following part processes:

1. Plasticating. The polymer (plastic) granules are transformed into a homogeneous melt during plasticating, which may be either injection processes, or extrusion processes. Both, in essence, are identical with the corresponding processes of extrusion and injection moulding.

2. Parison. The basic features of parison production depend on the technology employed. In the case where extrusion technology is employed, in essence, tube extrusion takes place through an orifice into an open space, external to the machine, while blow moulding takes place in a simple tube injection.

3. Blow moulding. The method consists of blowing the material against the internal walls of the mould with the aid of hot air, so that the material takes up the shape of the mould.

4. Cooling of the product.

8.2 Dies Employed in Blow Moulding

The die used to produce hollow bodies, in the great majority of instances, is of circular cross section, it is thus a tube. The dies used in the production of hollow bodies are therefore similar to those employed in tube manufacturing.

8.2.1 Simple Dies

The diameter, the wall thickness and the surface qualities of the extruded preforms obtained are governed principally by the size of the die. In tube manufacturing several varieties of dies are employed. Figure 8.3. shows a typical die. By moving the conical shaped core (7) vertically during extrusion, the wall thickness of the preform can be altered in a lengthwise direction. With the aid of the interchangeable packing ring (5) the uniformity of the wall thickness may be adjusted around its circumference. In the use of all dies, the same general rule applies, as mentioned earlier, that no dead spaces should be formed anywhere in the flow path of the polymer melt, since these due to the prolonged residence time of the polymer, may cause it to overheat. The surfaces of the die in direct contact with the polymer, are usually polished. To ensure an improved flow of the material, it is advisable to employ the die shape shown in Figure 8.4. instead of the nozzle shown in the previous diagram. The size of orifice, here, is adjustable by means of screws positioned either horizontally or vertically.

Figure 8.5. shows sections of a die designed to control the wall thickness. The shaping element (1) of the die has a cone angle, α_1 of 15 to 20°, and the cone angle of the core surface, α_2 , is 10 to 15°. This type of die is often called a conical or tulip die. This shape is advantageous in small-diameter dies.

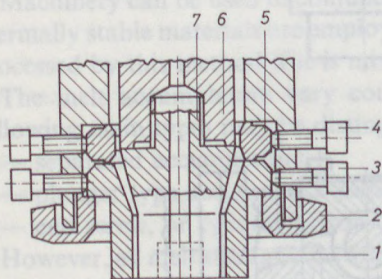


Fig. 8.3. Conical-shaped die with interchangeable packing insert

1. shaping section, 2. packing ring, 3 and 4. adjustment screws, 5. changeable packing ring, 6. deflection mandrel, 7. core

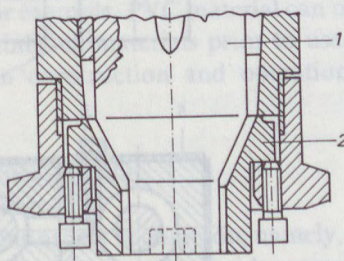


Fig. 8.4. Die with adjustable orifice

1. deflection mandrel, 2. a deformable external socket, serving to adjust the orifice of the nozzle.

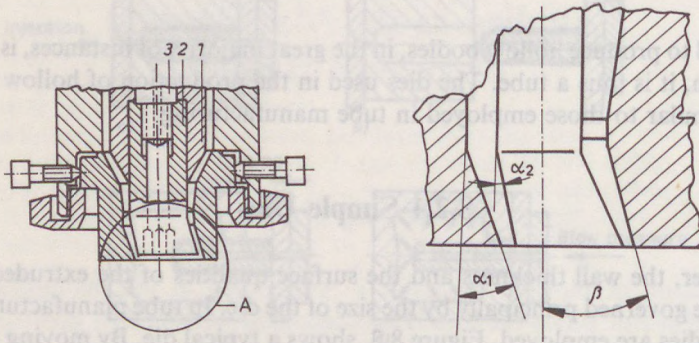


Fig. 8.5. A die designed to control the wall thickness in a lengthwise direction
1. deflection mandrel, 2. core, adjustable on a vertical plane, 3. adjustment rod

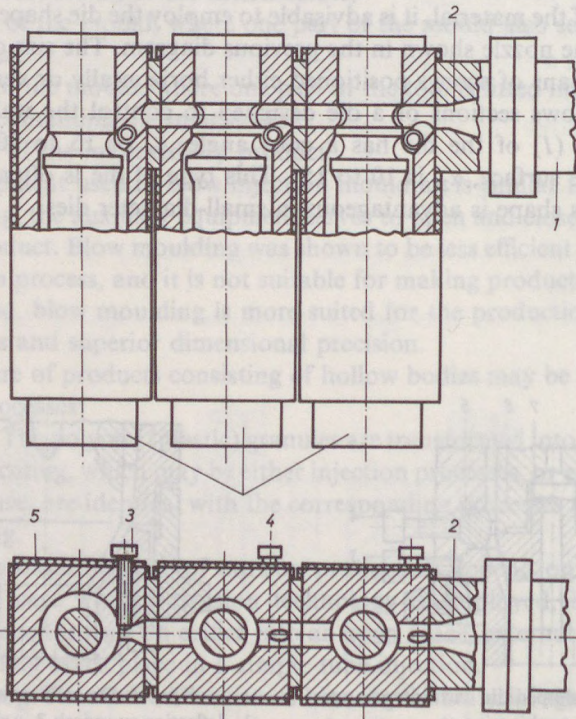


Fig. 8.6. A tube head with three orifices (arranged in series)

1. extruder, 2. material channel, 3. screws, serve to control the material flow, 4. parison emerging from the head, 5. heating

8.2.2 Dies with Multiple Orifices

The need to produce as many hollow body products per unit time as possible led to the design of multi-orifice dies. This means that several hollow bodies may be made simultaneously with the application of a single die. The extruder die is made in such a way that the material enters several nozzles of the same dimensions simultaneously. The nozzles themselves are thus called dual dies, or multi dies, accordingly. (Thus, the expression "multi-nozzle" implies that several orifices exist on the same nozzle so that several tubes can be made on the same machine simultaneously.)

Multi-orifice nozzles clearly have increased efficiency, since several preforms are produced simultaneously. A single closing unit and several dies are operated simultaneously.

The molten material produced in the extruder must be of uniform quality when supplied for the tools. Figure 8.6. shows two cross sections of a triple orifice tube die. The melt flows from the extruder to the three orifices. It is easily seen from this diagram that to ensure the supply of the predetermined quantity of material to the orifices simultaneously is a considerably more difficult task than for a die with a single orifice.

The cross sections of the die must therefore be chosen in such a way that to every orifice both the quantity and the quality of the material supplied remains the same. In most instances such dies are devised experimentally.

8.2.3 Accumulators and Dies with Accumulators

In order to prevent the stretching of the parison and for more efficient utilization of the extruder, storages, or accumulators were devised. As a result, the melt, leaving the extruder, does not flow directly to the orifice(s) of the die; instead, it enters a storage area, or accumulation area. From here the plasticated material is passed under pressure to the dies as required. In the storage area the material is maintained at the desired temperature and allows rapid discharging of a large quantity of the melt.

Machinery can be used in conjunction with accumulators in those instances where thermally stable materials are employed, thus, for example, PVC material can only be processed by this method if it is mixed with stabilizing materials prior to use.

The melt accumulators vary considerably in construction and operation. The following main types may be distinguished:

- separated accumulators,
- plunger type accumulator joined to a plasticating unit,
- end screw, or cylinder piston type accumulators.

However, all melt storage constructions have one aspect in common, namely, all are positioned between the plasticating unit and the die. Let us now consider some of the accumulators in use.

8.2.3.1 Separated Accumulators

The accumulator shown in Figure 8.7. is one of the simplest forms of construction. The melt is passed from the extruder, positioned near the accumulator, through the inlet. The flow resistance of the die is controlled by the ratio of the cross-sectional areas so that the material entering pushes the hydraulically operated piston (3) of the accumulator, then the piston presses material at a suitable rate through the die (5). The output of the extruder is designed so that the extruder overcomes the resulting resistance(s) and pressure changes. (These are called rigid extruders.) During the operation of the piston the material not only flows through the die, but some is returned to the extruder and alters the pressure developed.

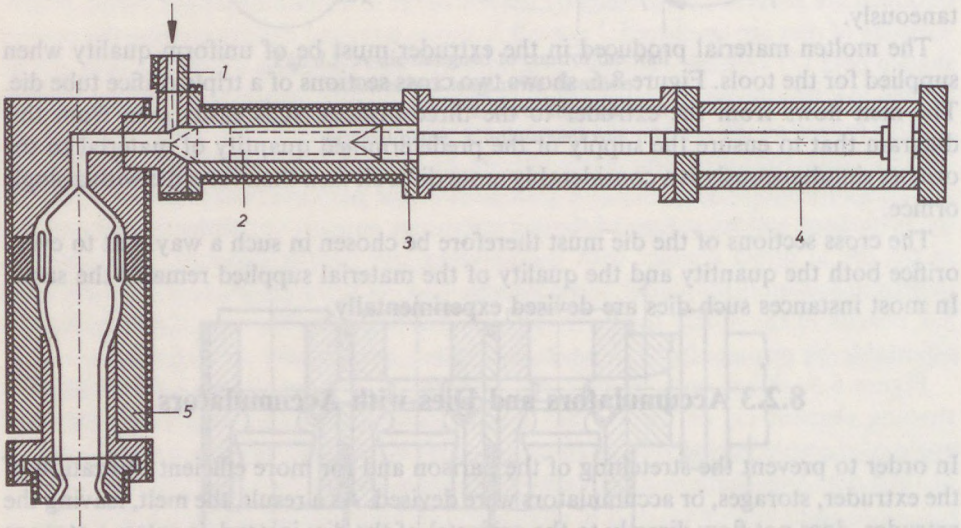


Fig. 8.7. Separated accumulator

1. material flow from the extruder, 2. storage space, 3. piston pump, 4. hydraulic roll, 5. die

The material in the piston cylinder is now mixed with fresh material from the extruder in the channel of the die. The temperature must be thoroughly checked.

In large machines, horizontal accumulators are constructed since vertical constructions would be too high. The accumulator can also be positioned along the axis of the extruder and fastened to it.

8.2.3.2 Accumulators Built into the Plasticating Unit

Accumulator with screw pumps

This arrangement is the same as the construction of the injection moulding equipment fitted with a screw pump. The screw plasticates the material which slowly flows in a reverse direction and fills the accumulator chamber. In this case the role of the pressure pump is taken over by the screw, which can also operate as an axially

movable pump. By ignoring the compressibility of the material, this may be expressed as:

$$V_i = VG_t,$$

where V_i is the adjusted volume of the accumulator in cm^3 , V is the specific volume of the melt, temperature dependent, cm^3/g , while G_t is the mass of the parison, in grammes.

The pump is generally operated hydraulically. The magnitude of pressure arising in the material depends on the pumping rate, on the resistance of the die and on the rheological behaviour of the melt. Where polyethylene is used the pressure may lie between 10 and 80 MPa, depending on the properties of the material (easily flowing or difficult to process).

An excessively rapid pumping rate may result in concentric "wrinkles" on the surface of the preform, which manifest themselves in different, subtle discolorations of plastic bottles produced; furthermore, the surface quality of the hollow product may also be adversely affected.

In machines fitted with an accumulator-head, the cross-sectional area of discharge and the surface area of the pressure pump are usually the same. Undesirable high temperatures originating from the heating of the accumulator can affect the hydraulic system, which, therefore, needs to be cooled; alternatively, long screws, capable of expansion, are fitted in the hydraulic system.

Accumulators fitted with a piston pump.

These usually have considerably larger storage capacities. Here, the melt is passed to the accumulator by means of a screw, axially mobile. Due to the large volume of the storage space, rapid discharge of the material with the required speed with the use of a screw of a relatively small cross section cannot be achieved. The cross-section of the pressure pump is increased in such a way that the plasticating screws are also built to move axially. This system has the advantage that the capacity of the accumulator is independent of the output of the extruder, it can be increased or reduced as needed.

Accumulator-heads

As the name suggests the accumulator-head is an accumulator unit built integrally with the die head, thus, it is combination of the accumulator and the blowing die.

Accumulator-heads with a pump

Figure 8.8. shows that the casing of the mandrel head is an elevated construction, compared with the previous accumulators. Such difference in heights is necessary to accommodate a larger storage vessel. The operation of this accumulator-head is the same in principle as of the separate storage chambers.

However, there is one considerable difference; the flow path of the melt is made shorter, hence, the flow resistance is reduced. Here, the construction of the piston face (3) makes complete and thorough rinsing possible, the opening from the extruder side is not closed even in the lowest position of the piston, thus the accumulator can be filled also in this situation. The material may still push the piston back; if this is not possible due to the large dimensions employed, the pump piston may still be moved

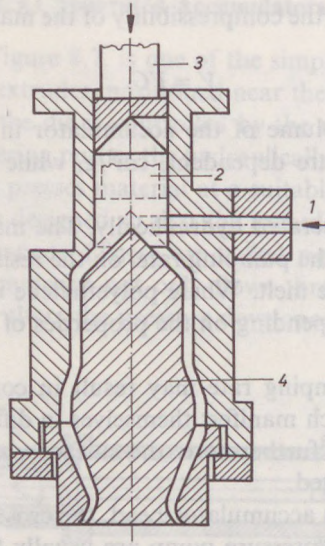


Fig. 8.8. Accumulator head with pump

1. material flow from the extruder, 2. storage space, 3. pump, 4. diverting mandrel

back by the application of a separate hydraulic system. This type of storage is employed mainly where large size blow products are manufactured.

Accumulator-heads with ring-shaped piston

Figure 8.9. depicts an accumulator-head fitted with a ring piston. The difference from previously described accumulators is, in essence, that the pump consists of a ring-shaped piston (3). For this reason the chamber of the accumulator (2) is also ring-shaped. Opposite to the inlet orifice a ring-shaped channel (6) is in the wall of the storage unit. The melt is passed through this channel from the extruder under the ring-shaped piston. This type of accumulator-head makes it possible to make another channel opposite to the inlet channel as shown on the sketch. Thus the head is supplied from two extruders simultaneously. Such a construction would be of particular advantage for making a particularly large size hollow vessel and only extruders with low output are available to the manufacturer. By coupling two small-capacity extruders via the head, the extruder capacity can be doubled.

Above the inlet ring-shaped channel a vertically moveable sleeve can be seen. If the sleeve is in its lowest position the cross section of the circular channel is reduced, while in the highest position it is increased. In this way it is possible to control the throttling of the system in accordance with the viscosity of the melt.

If there is sufficient room above the machine, it seems advantageous to position the hydraulic cylinder moving the ring piston above the machine. With such an arrangement substantial ground space may be saved. Naturally, in controlling the wall thickness of the parison another hydraulically operated unit is also necessary to move the thickness control core.

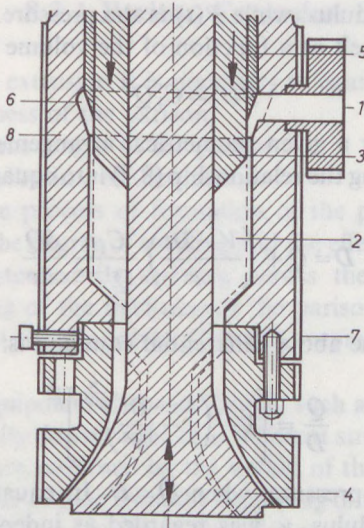


Fig. 8.9. Accumulated head with ring pump

1. material flow from the extruder, 2. ring-shaped storage space, 3. ring pump, 4. core to adjust wall thickness, 5. mobile socket, 6. ring channel, 7. heating, 8. housing

When changing the nozzle (6) and the mandrel (4) several parisons of varying sizes can be produced, thus, this kind of the head makes production quite versatile for considerable size variations.

8.3 Parison Formation

Parison manufacturing with the application of an extrusion blow may be continuous or intermittent depending on whether the machine is operated with or without an accumulator. For a machine without an accumulator, the flow through the die is substantially the same as was described in the case of tube manufacturing, while in the case of an accumulator the flow through the die is also influenced by the state of the melt (its temperature and viscosity) [5, 6, 7]. Accumulation allows the continuous operation of the extruder during intermittent bottle blowing. The mass flow pressed out from the accumulator is governed by the pump moving in the chamber. The mass flow may be regarded as constant, except for the reduction of flow at the end of pressure application. The volume flow (D) of the piston displacement may be divided into two components: the volume flow of the extruder, Q , and the volume flow originating from the compressibility of the polymer melt, Q_k . Let V be the initial volume of the material in the accumulator, and its volume at time t , $V - Dt$, the volume flow related to the compressibility of the material may be derived as:

$$Q_k = \frac{(V - Dt)}{\alpha} \frac{d}{dt} P(t) \quad (8.1)$$

where κ is the volume modulus, while $P(t)$ is the pressure. According to the power law, the pressure on the melt as a function of the volume flow rate is expressed as:

$$P(t) = C_1 Q^n \quad (8.2)$$

where C_1 is a constant for a given geometrical arrangement of the die used and n is the exponent. Substituting the relationship (8.2) into equation (8.1) and substituting $D = Q + Q_\kappa$

$$D = Q + \left(\frac{V - Dt}{\kappa} \right) \frac{C_1 n}{Q^{1-n}} \frac{dQ}{dt} \quad (8.3)$$

is obtained.

An approximation of the above differential equation is:

$$\frac{Q}{D} = \left[1 - \left(1 - \frac{Dt}{V} \right)^{\frac{\kappa}{nP}} \right]^{\frac{1}{n^2}} \quad (8.4)$$

where P is the extrusion pressure, when $Q = D$. In equation (8.4) two facts were ignored. The volume modulus, κ , was regarded as independent of both time and pressure, which is not entirely correct, since κ increases with increasing pressure and decreases with time. The above changes do not alter the value of κ by more than $\pm 10\%$, the two changes occur in opposite directions and compensate each other.

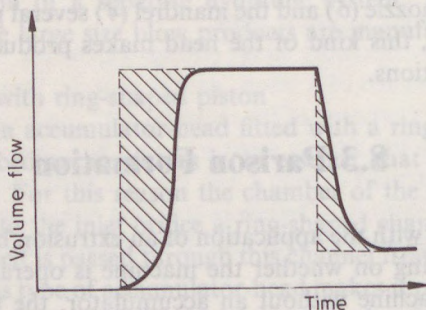


Fig. 8.10. Volume flow as a function of time

The dotted line depicts the speed of volume replacement, the continuous line represents the volume flow [11].

Figure 8.10. shows the function of volume flow versus time. The dotted line represents the volume flow rate of displacement, the continuous line represents the volume flow rate, while the shaded area represents the time delay due to the compressibility of the melt.

8.3.1 Parison Extrusion

In the analysis of parison extrusion it is necessary to examine

- the shape and thickness of the parison,
- time dependence of the length of the parison,
- the temperature distribution of the parison.

Let us examine first the process of formation of the parison. The shape of the parison is determined by the degree of swelling and the effect of gravity. The swelling of the parison is characterized by swelling across the diameter, expressed by $B_1 = D_p/D_0$ and by swelling of the thickness of the parison expressed by $B_2 = h_p/h_0$, where D_0 and h_0 represent the die, while D_p and h_p represent the characteristics of the extrudate.

Most blow moulding equipment is constructed in such a way that extrusion of the parison takes place vertically downwards, thus different stresses act on every point of the parison. The stresses are governed by the weight of the parison below the given section and thus by the lapse of time from the beginning of the extrusion. The initially extruded portion is exposed to a low stress, for a longer period, while the last section of the extruded product is under a higher stress for a short time. On every part of the product elastic and viscous deformation takes place. The evolved stress is the ratio of the force and the cross-sectional area. Assuming a constant volume the cross-section decreases with an increase in deformation. Thus, the stress increases with time in any given section of the parison.

Assume that extrusion starts at time $t=0$, and that a given section of the parison is characterized by time, t_1 , and finally let the moment of observation be t_2 . The initial cross-sectional area A_1 shows the effect of swelling at time t_1 , cross-section A_2 shows the effect of swelling at time t_2 , and the total deformation is given by:

$$\varepsilon = \ln \frac{A_1}{A_2} = \varepsilon_R + \varepsilon_V \quad (8.5)$$

where ε_R is the elastic deformation and ε_V is the viscous deformation. The elastic deformation is a function of the maximum stress, thus

$$\varepsilon_R = \frac{\sigma_{\max}}{E} = \frac{M_1 g / A_2}{E} \quad (8.6)$$

where M_1 is the mass of the polymer extruded prior to time t_1 , while E represents the modulus occurring during simple elongation under stress $\sigma_{\max}$. The viscous deformation is the sum of the individual viscous terms, thus:

$$\varepsilon_V = \sum_{t_1}^{t_2} \dot{\varepsilon} \delta t = \sum_{t_1}^{t_2} \frac{\sigma}{\eta_E} \delta t = \sum_{t_1}^{t_2} \frac{M_1 g \delta t}{A(t) \eta_E} \quad (8.7)$$

The cross-section $A(t)$ is a function of total deformation, which is a function of time. A given polymer is classified either as viscous or elastic by comparing the characteristic time function (λ) derived from the ratio of viscosity to the modulus against the deformation time $t_2 - t_1$. If the deformation time is less than the characteristic

time, the material will behave as a basically elastic body and $A(t)=A_2$. If the deformation time is longer than the relaxation time characteristic of the material then viscous deformation will predominate and hence,

$$A(t) = A_1 - \frac{A_1 - A_2}{t_2 - t_1} (t - t_1) \quad (8.8)$$

For small deformations the two equations may be added in the same expression format, that is, if $t_2 - t_1$ is greater than λ ,

$$\varepsilon = \frac{M_1 g}{A_1} \left[\frac{1}{E} + \frac{(t_2 - t_1)}{\eta_E} \frac{\ln(A_1/A_2)}{(A_1/A_2) - 1} \right] \frac{A_1}{A_2} \quad (8.9)$$

if, however $t_2 - t_1$ is less than or equal to λ ,

$$\varepsilon = \frac{M_1 g}{A_1} \left[\frac{1}{E} + \frac{(t_2 - t_1)}{\eta_E} \right] \frac{A_1}{A_2} \quad (8.10)$$

holds true, where E is the elongation modulus, η_E is the elongation viscosity due to the effect of the stress $M_1 g/A_2$. The change in the cross-section of the parison results in new dimensions, a new length, $\delta L'$, a new radius, R' , and a new wall thickness h' , for which the following relationships hold true:

$$\frac{\delta L'}{\delta L} = \frac{A_1}{A_2}, \quad (8.11)$$

$$\frac{R'}{R} = \left(\frac{A_2}{A_1} \right)^{1/3} \quad (8.12)$$

and

$$\frac{h'}{h} = \left(\frac{A_2}{A_1} \right)^{2/3} \quad (8.13)$$

By adding each of the $\delta L'$ values, the length L' at time t_2 is obtained. Thus, the dimensions of all elements of the parison can be calculated at any given time.

The medium range, the Deborah number refers to a viscoelastic behaviour, and the parison's change in length with time is examined for this case. The length of the parison [8 and 9] is given by:

$$\frac{dL}{dt} = v_x \quad (8.14)$$

The movement of the free surface of the parison can be examined on the basis of the continuity equation, thus:

$$\frac{\partial h}{\partial t} + \frac{\partial h}{\partial x} (hv_x) = 0 \quad (8.15)$$

The x -directional component of the motion equation (thus, along the longitudinal axis of the extruded product) is given by:

$$\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} = \frac{3\gamma}{2q} \frac{\tau_{xx}}{\partial x} + \frac{3\tau_{xx}}{2qh} \frac{\partial h}{\partial x} + g_x \quad (8.16)$$

In order to solve equations (8.14), (8.15) and (8.16) a rheological state equation must be chosen. Choosing the Maxwell equation and ignoring the convective term of the momentum equation (i.e. owing to the small extrusion velocity), the change in the parison length in the direction of the stress is given by the equation

$$\tau_{xx} = \frac{2}{3} q g_x (L - x) \quad (8.17)$$

the velocity is given by:

$$v_x = v_e \exp(-\lambda x) + \frac{L}{\lambda} [1 - \exp(-\lambda x)] - \frac{1}{\lambda^2 A} [L\lambda \exp(-\lambda x) - 1] \quad (8.18)$$

where $\lambda = \lambda g_x q / 3\eta$. The time function of the length of the parison is given by:

$$t = \int_0^L \frac{dL}{\frac{1 - \exp(\lambda x)}{\lambda^2 A} + \left[\left(v_e - \frac{L}{\lambda} \right) \exp(-\lambda L) \right]} \quad (8.19)$$

Equation (8.19) describes the changes in the length of the parison with time with sufficient accuracy to be used in practice.

When the melt is pumped out from the accumulator, the flow of the melt will initially be fast, then it slows down. This decrease in velocity causes a stress originating from inertia; at the end of the extrusion the stress due to inertia is given by the equation:

$$\sigma_{\text{inertia}} = \frac{M_1}{A_2} \frac{dv}{dt} \quad (8.20)$$

where v is the velocity of the parison. The elastic deformation corresponding to this stress is given by:

$$\varepsilon_k = \frac{\sigma_{\text{inertia}}}{E} \quad (8.21)$$

This deformation is superposed on all other deformations of the parison discussed so far. The stress due to inertia is the highest at the point of exit of die, it is zero at the end of the parison.

It changes approximately linearly between the above two values, along the length of the parison.

In calculations, therefore, it is customary to use half the volume of the maximum stress evolved. The extrusion velocity at the die is Q/A_2 , thus equation (8.20) becomes:

$$\sigma = \frac{1}{2} \cdot \frac{M_1}{A_2^2} \frac{dQ}{dt} \quad (8.22)$$

$$\ln \frac{L''}{L'} = (\varepsilon_k) \quad (8.23)$$

$$\ln \frac{L''}{L'} = (\varepsilon_k) \quad (8.23)$$

$$\ln \frac{L''}{L'} = \frac{1}{2E} \cdot \frac{M_1}{A_2^2} \cdot \frac{dQ}{dt} \quad (8.24)$$

where E is the modulus.

8.3.2 Calculation of the Temperature of the Parison

For the determination of temperature distribution, the model in Figure 8.11. may be used. In order to determine the temperature distribution, the energy equation is used. To solve the equation, simplifying conditions are assumed [13 to 16]:

- a constant external diameter exists, independent of time,
- tangential heat conduction is negligible,

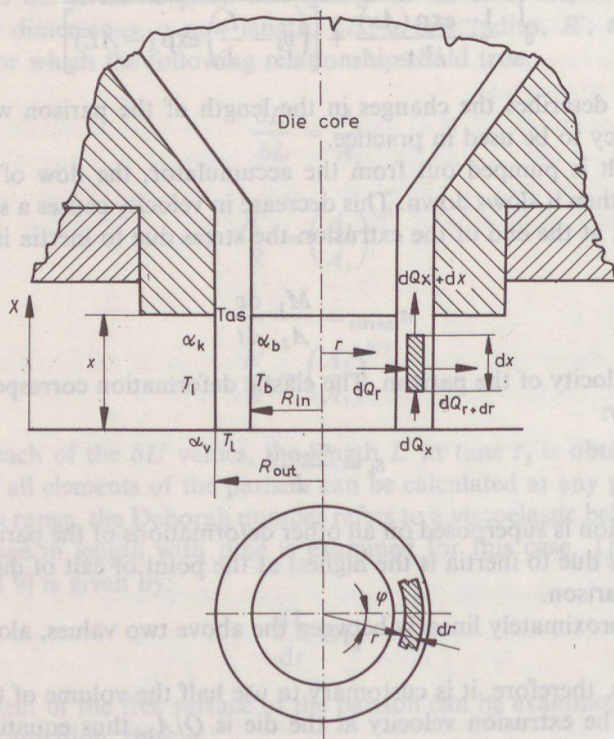


Fig. 8.11. A model used for the purposes of calculating the temperature distribution

T_{as} = the material temperature at the point of its emergence from the tool.

 T_1 = air temperature

- thermal diffusion and conductivity are constant,
- heat losses from the external surface take place by way of convection and radiation.

The energy equation becomes:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} + \frac{a}{r} \cdot \frac{\partial T}{\partial r} + a \frac{\partial^2 T}{\partial r^2} \quad (8.25)$$

boundary conditions for solving the equation are:

$$-k \left(\frac{\partial T}{\partial r} \right)_{x, r=R_{int}} = \alpha_K (T_a - T_{x, r=R_b, t}) \quad (8.26)$$

$$-k \left(\frac{\partial T}{\partial r} \right)_{x, r=R_{out}} = \alpha_a (T_l - T_{x, r=R_k, t}) \quad (8.27)$$

$$-k \left(\frac{\partial T}{\partial r} \right)_{x=0, r, t} = \alpha_v (T_v - T_{x=0, r, t}) \quad (8.28)$$

$$\begin{aligned} T_x &= x^*, r, t = T_{as}(r, t) \\ x^* &= ut \end{aligned} \quad (8.29)$$

Solution of the above system of equations can be achieved by the method of finite differences. The coordinate system is three-dimensional, it includes the lengthwise (x), the radius (r) and the time (t) coordinates.

Thus equation (8.25) with finite differences is expressed as:

$$T_{i, k, l+1} = k_1 T_{l+1, k, l} + k_2 T_{i-1, k, l} + k_3 T_{i, k+1, l} + k_4 T_{i, k-1, l} + k_5 T_{i, k, l} \quad (8.30)$$

where

$$k_1 = \frac{ah_3}{h_1^2};$$

$$k_2 = \frac{ah_3}{h_2^2};$$

$$k_3 = \frac{ah_3}{2R_k h_2} + \frac{ah_3}{h_2^2};$$

$$k_4 = \frac{ah_3}{h_2^2} - \frac{ah_3}{2R_k h_2};$$

$$k_5 = 1 - \frac{2ah_3}{h_1^2} - \frac{2ah_3}{h_2^2}$$

The criteria for choosing the individual step lengths are:

$$h_2 > \frac{4a}{v}$$

$$h_3 > \frac{2a}{v^2} \quad (8.31)$$

$$\frac{h_2^2}{4a} \left(1 - \sqrt{1 - \left(\frac{4a}{vh_2} \right)^2} \right) \leq h_3 \leq \frac{h_2^2}{4a} \left(1 + \sqrt{1 - \left(\frac{4a}{vh_2} \right)^2} \right)$$

A relevant example is shown in Figure 8.12. indicating the calculations made. Part *a*) shows the radial temperature distribution in six different cross-sections. The curves obtained are nearly of the same shape, a substantial change occurs only in the last section along the temperature axis. The position and shapes of the curves are strongly influenced by the speed of the extrusion, the temperature of the cooling air and the wall thickness of the parison. Part *b*) shows the axial temperature curve at various radial distances. Due to the higher heat losses of the external surface, hence, by approaching the external surface from the inside, the gradient of the curves decreases. With an increasing velocity of extrusion the axial temperature differences of the parison decrease. Part *c*) also takes into account the changes occurring in the diameter.

From the above diagram it becomes obvious that for practical calculations it is sufficient to know the average temperature of the parison. The overall heat balance is given by:

$$\rho C_p v \frac{d\bar{T}_a}{dt} = \alpha A (T_1 - \bar{T}_a) \quad (8.32)$$

where v is the volume and A is the surface area of the parison. Rearranging the equation

$$\frac{d\bar{T}_a}{dt} + k\bar{T}_a = kT_1 \quad (8.33)$$

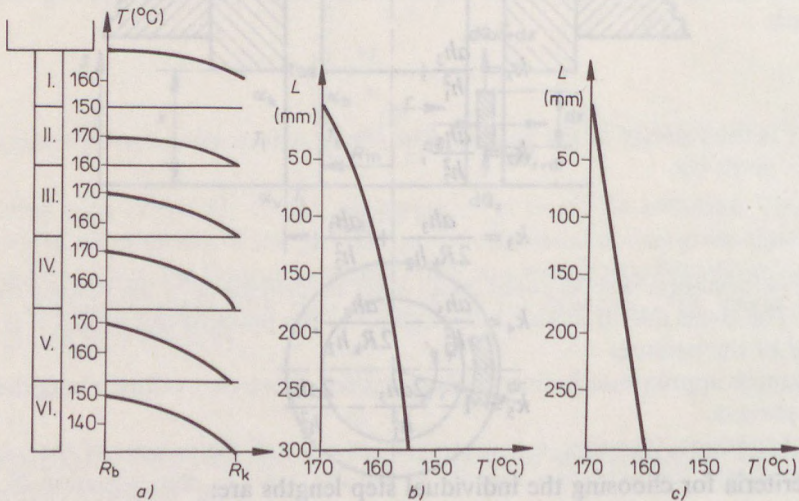


Fig. 8.12. Temperature distribution in the parison

a) Radial temperature distribution, *b*) Temperature distribution in the direction of the axis, *c*) Temperature distribution in the direction of the axis without taking the diameter changes into account

is obtained, where $k = \frac{\alpha A}{\rho C_p v}$ is a first order, linear, inhomogeneous differential equation. In a temperature range where parameters representing the properties of the material such as α , ρ and C_p are regarded as constant, the solution to equation (8.32) is given by:

$$\bar{T}_a = T_1 + (\bar{T}_{as} - T_1) \exp\left(-\frac{\alpha A}{\rho C_p v} t\right) \quad (8.34)$$

provided that the boundary conditions are:

$$\begin{aligned} \bar{T}_{t \rightarrow 0} &= \bar{T}_{as} \\ \bar{T}_{t \rightarrow \infty} &= T_1 \end{aligned} \quad (8.35)$$

By rewriting the ratios of the geometric quantities in a more simplified form, equation (8.34) becomes:

$$\bar{T}_a = T_1 + (\bar{T}_{as} - T_1) \exp\left(-\frac{2\alpha}{\rho C_p} \cdot \frac{x}{hv}\right) \quad (8.36)$$

since $x = tv$ and the wall thickness of the parison is h . Equation (8.36) above was used in the work [15] for the purpose of regression calculations supplemented by some additional regression constants.

8.4 The Parison Inflation

8.4.1 Parison Deformation

The moment the parison acquires the size necessary for blowing, the two half mould close and the inflation process commences with blowing of air.

In order to describe the parison inflation it is necessary to establish the relationships between deformation (shape), pressure and temperature [5-9, 15-18].

The parison inflation, in essence, means a steadily increased internal pressure, in a thin, cylindrically shaped tube. The simplified process can be regarded as isothermal, hence, the continuity and the motion equations become:

$$\frac{\partial}{\partial r}(rv_r) = 0 \quad (8.37)$$

and

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} \right) = -\frac{\partial P}{\partial r} + \frac{\partial \tau_{rr}}{\partial r} + \frac{\tau_{rr} - \tau_{\theta\theta}}{r}, \quad (8.38)$$

respectively.

Since $v_r(R) = dR/dt = \dot{R}$, the radial velocity is expressed as:

$$v_r = \frac{R\dot{R}}{r} \quad (8.39)$$

where R is the internal parison radius.

The limiting conditions are:

$$\begin{aligned} r=R \quad P-\tau_{rr}+\frac{\sigma}{R} &=P_i \\ r=S \quad P-\tau_{rr}-\frac{\sigma}{R} &=P_0 \end{aligned} \quad (8.40)$$

where P_i is the internal inflation pressure, P_0 is the external air pressure and σ is the corresponding surface tension. Integrating equation (8.38), assuming that the wall thickness is given by $h=S-R$,

$$\Delta P - \frac{\sigma}{R} \left(2 - \frac{h}{R} \right) - \rho \dot{R} h = - \int_R^S \frac{\tau_{rr} - \tau_{\theta\theta}}{r} dr \quad (8.41)$$

is obtained.

Equation (8.41) gives the growth of the parison due to the effect of the pressure ΔP . In order to solve the above equation it is best to utilize the parison's constitutive equations. The solutions of equation (8.41) were examined for Newtonian liquids, for elastic materials [10], and for materials characterized by the Zaremba-De Witt [8,9] and the White-Metzner [8,9] equations.

The second part of the inflation process commences when the blown parison reaches the walls of the die, since at this point the deformation becomes restricted in certain directions. In examining this part of the process it is assumed that the deformation process is isotropic, isothermal, the wall thickness of the parison is constant and that the polymer solidifies the moment it reaches the walls of the die, no further deformation then takes place.

Let us examine the development of a simple corner section [8]. At a given time, t , the wall thickness of the parison is h . At a later time $t+dt$ the wall thickness of the parison becomes $h-dh$. The elementary mass balance is given by:

$$\frac{\pi}{2} Rh = \frac{\pi}{2} (R-dR)(h-dh) + 2dR \left(h - \frac{dh}{2} \right) \quad (8.42)$$

Now, ignoring the higher order terms:

$$\frac{dh}{h} = \left(\frac{4-\pi}{\pi} \right) \frac{dR}{R} \quad (8.43)$$

Integrating the above:

$$\frac{h}{h_f} = \left(\frac{R}{R_f} \right)^{0.273} \quad (8.44)$$

where R_f and h_f are the parison radius and the wall thickness at the end of the first inflation period.

For the estimation of the inflation time the polymer may be regarded as a viscous liquid, thus, from the momentum equation

$$\Delta P = 4\mu_1 2^{n-1} \left(\frac{1}{h} \frac{dh}{dt} \right)^n \quad (8.45)$$

is derived [8], where μ_1 is the characteristic viscosity, and n is the exponent in the power law.

Rearranging and integrating the above equation from the end of free inflation i.e. $t = t_f$ the equation is transformed into:

$$t - t_f = A_g \left(\frac{2^{n+1} \mu_1}{\Delta P} \right) \ln \frac{R_f}{R} \quad (8.46)$$

where A_g is the geometric shape factor.

8.4.2 Cooling of the Blown Body

During the cooling phase the body may be cooled internally, or externally, or by a combination of the two. The die is usually kept at room temperature by means of cooling, thus external cooling is provided by the cool walls of the die. Internal cooling is provided by cool air, or by liquid carbon dioxide blown into the body formed.

During cooling, heat is transferred from the polymer to the walls of the die and to the internal air. Let the temperature of the die surface be T and let the air temperature be T_a , the energy equation is thus

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[k \frac{\partial T}{\partial x} \right] \quad (8.47)$$

with boundary values of:

$$\begin{aligned} x=0 \quad k \frac{\partial T}{\partial x} &= \alpha_a (T - T_a) \\ x=L \quad T &= T_d \end{aligned} \quad (8.48)$$

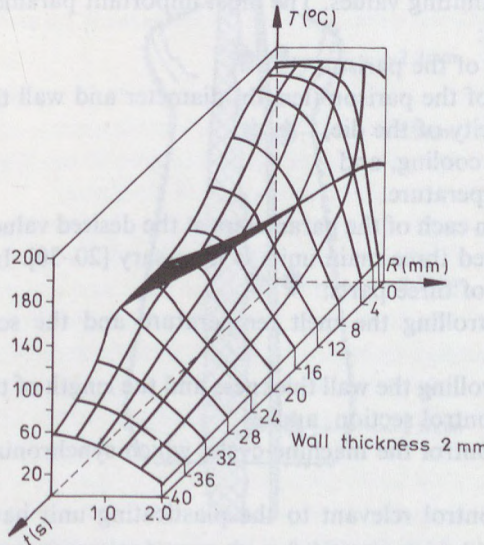


Fig. 8.13. Curves derived during bottle cooling [15]

where α_a is the internal heat transfer factor. The initial conditions are:

$$t=0, \quad 0 < x < L \quad \text{and} \quad T=T_0 \quad (8.49)$$

Equation (8.49) may be solved with finite differences [19]. A better approximation of the cooling process may be obtained if the sides of the parison, the mouth and the bottom are investigated separately. The cooling curves derived by using such a method are shown in Figure 8.13.

8.5 Control in Blow Moulding

Extrusion blowing is a complex manufacturing process which involves

- plastication,
- shaping and formation of the parison,
- parison inflation and cooling of the finished product.

The over-all process is a cyclic, intermittent process, where the cycle period is governed mainly by the time required to cool the finished product. The most essential quality requirements of the finished product are that it should have:

- the prerequisite shape and size,
- the required strength of the product, and
- acceptable appearance.

These properties in turn are governed by the quality standards of the material used, together with the accomplishment of three production phases and their interconnections. Quality criteria cannot be measured during the manufacturing, only on the finished product. Control of quality, thus, may only be achieved by carrying out the processes within the limiting values. The most important parameters from the point of view of quality are:

- the temperature of the parison,
- the dimensions of the parison (length, diameter and wall thickness),
- the closing velocity of the die,
- the efficiency of cooling, and
- the blowing temperature.

In order to maintain each of the parameters at the desired values concerted control of the above mentioned three main units is necessary [20–30]. In general, a control system is constituted of three parts:

- the section controlling the melt temperature and the screw speed (i.e. the plasticating unit),
- the section controlling the wall thickness and the length of the parison, together with a temperature control section, and
- the section to control the machine cycle, which synchronizes the applied controls.

The methods of control relevant to the plasticating unit have been outlined in Chapter 4.

8.5.1 Control of the Wall Thickness of the Parison

The wall thickness of the parison is controlled by movement of the mandrel. Adjustments of the mandrel can be achieved by means of mechanical, hydraulic or electronic control. The last of these is considered to be the most reliable, with the added advantage that it is the method best suited to interconnections with other units. The wall thickness of the parison must conform with requirements of the finished article as is shown in Figure 8.14. Thus, the wall thickness of the parison must be greater in those areas where the diameter of the blown bottle is bigger and consequently, the wall thickness must be less in those points where the diameter of the bottle is smaller. It is thus necessary to control these variations of the wall thickness of the parison in the blow mould.

In some machines a mechanical system is operated via a cam drive of a motor, which in turn moves the tooling according to the cam profile.

In a hydraulic flow control machine, the hydraulic cylinder adjusts the tooling orifice, governed by an oil flow, controlled by needle valves, solenoid valves and one or two mechanical timers triggered by the machine. Figure 8.15. shows a typical installation of an electronic parison programmer system. The tooling is adjusted by hydraulic means with the aid of a servo valve installed on the hydraulic cylinder which moves the mandrel or the die. A position feedback is obtained by means of a feedback transducer. The parison programmer is synchronized with the cut-off mechanism of the parison to begin the programme sequence when the extrusion process starts. The programme sequence is governed by an electronic timer that divides the

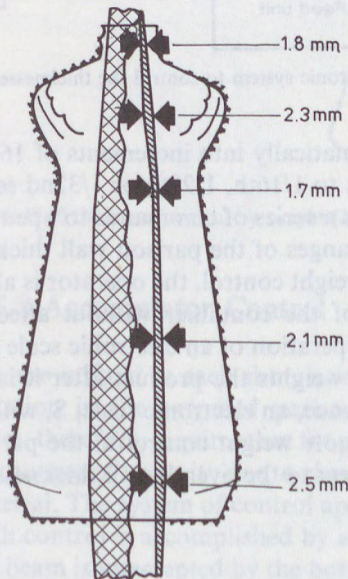


Fig. 8.14. Example of the relationship between the wall thickness of a bottle and the wall thickness of the parison [24]

Programme to make the
wall thickness adjustment

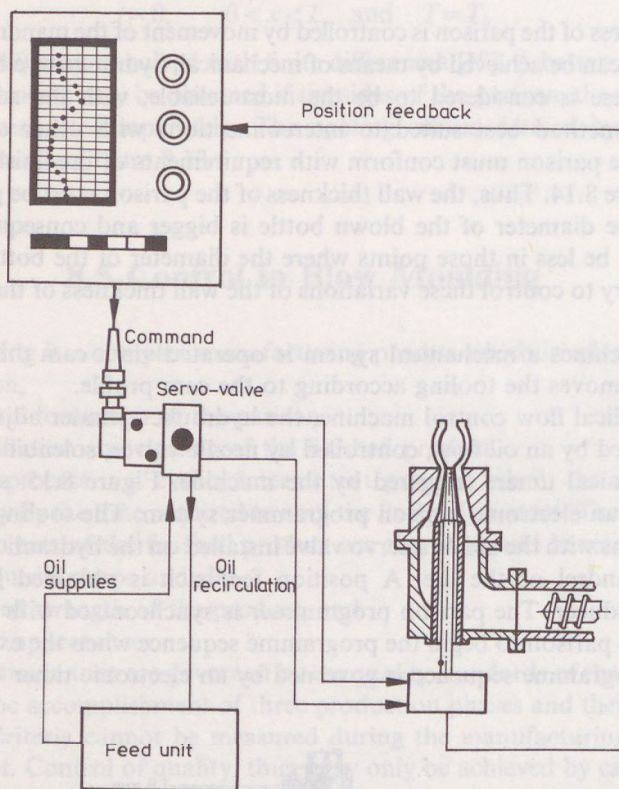


Fig. 8.15. Electronic system to control the thicknesses of the preform [24]

parison drop time automatically into increments of 16, 20, or 32 units by assigning given programme points to 1/16th, 1/20th or 1/32nd segments of the parison. Thus, the programmer supplies a series of commands to open or to close the tooling, which results in subsequent changes of the parison wall thickness.

By utilization of the weight control, the operator is able to increase or decrease the overall wall thickness of the container without affecting the programme profile. Figure 8.16. shows the operation of an electronic scale and weight control system. A weight cell receives and weights the product after it is ejected from the machine, a photocell tracks its presence, an electronic scale, S, with upper and lower limits, sets the tolerance, and a remote weight control in the parison programmer adjusts the weight control with respect to the overall wall thickness of the parison, thus forming a closed control loop.

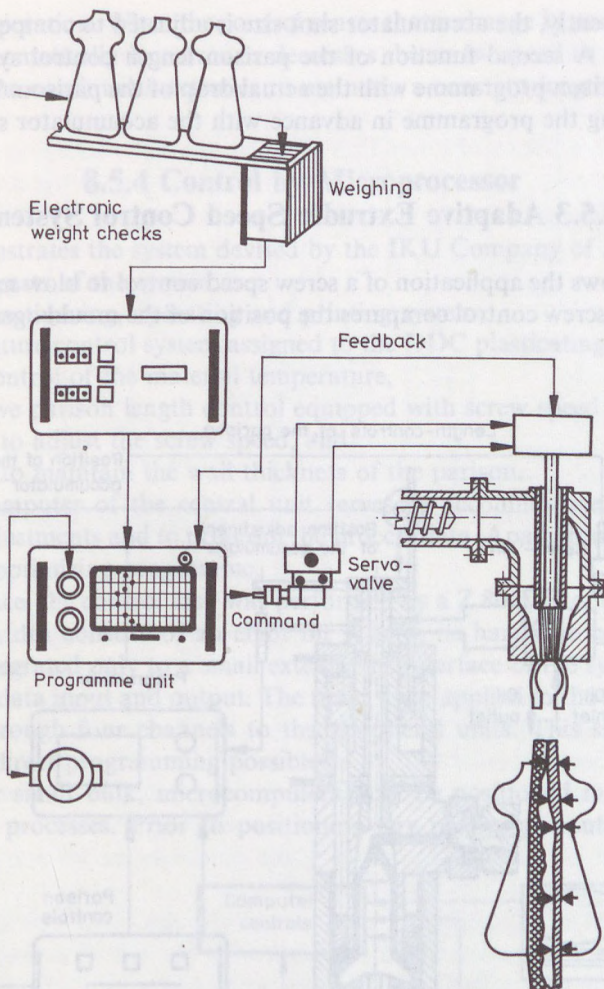


Fig. 8.16. Wall thickness control by weight [24]

8.5.2 Accumulator Control

Since large volumes of plastic are utilized in each shot, small variations in viscosity can cause a substantial variation in the extruded parison length in production. Programming of large machines, therefore, requires that the parison length is properly controlled, compensating for changes of viscosity due to changes of temperatures and in the composition of the material. The system of control application consists of two basic functions. Parison length control is accomplished by a photocell mounted in a position so that the photocell beam is intercepted by the bottom edge of the parison, just before the moulds are closed. The parison length control system will determine whether the parison is too short or too long on each drop before the moulds are

closed. Subsequently, the accumulator shot size is adjusted to compensate for variations in length. A second function of the parison length control system is to synchronize the parison programme with the actual drop of the parison. This is achieved by synchronizing the programme in advance with the accumulator stroke.

8.5.3 Adaptive Extruder Speed Control System

Figure 8.17. shows the application of a screw speed control to blow mould machines. In this case the screw control compares the position of the mould against the parison

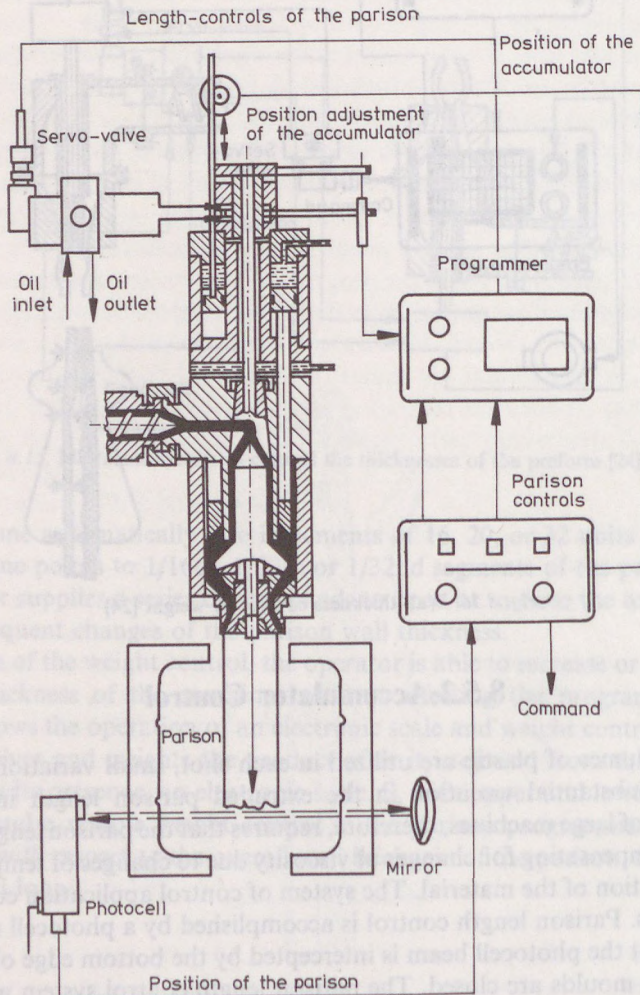


Fig. 8.17. The length and wall thickness control of the extruder speed

length during operation. When the control senses that a change in parison length had occurred, it automatically increases or decreases the screw speed to compensate for the output of the continuous extruder to maintain a constant length.

8.5.4 Control by Microprocessor

Figure 8.18. illustrates the system devised by the IKU Company of Aachen [13 and 25]. The main parts of the system are:

- a central optimizing, operating and printing system,
- a temperature control system assigned to the DDC plasticating unit, operating with cascade control of the material temperature,
- an adaptive parison length control equipped with screw speed control,
- a control to adjust the screw speed, and
- a control to maintain the wall thickness of the parison.

The microcomputer of the central unit serves to accommodate the input data required for adjustments and to print out the process data. Apart from this it contains the cycle time optimizing programme.

In this instance, the control task was performed by a Z 80 type of microprocessor. Its data base width consists of an eight bit system, its hardware consists of semi-conductors, integrated only to a small extent. The interface of the system allows for parallel digital data input and output. The timer to be applied to the system can send time signals through four channels to the peripheral units. This simple hardware system makes direct programming possible.

Due to their small bulk, microcomputers may be positioned in the immediate vicinity of the processes. Prior to positioning any particular control system it is

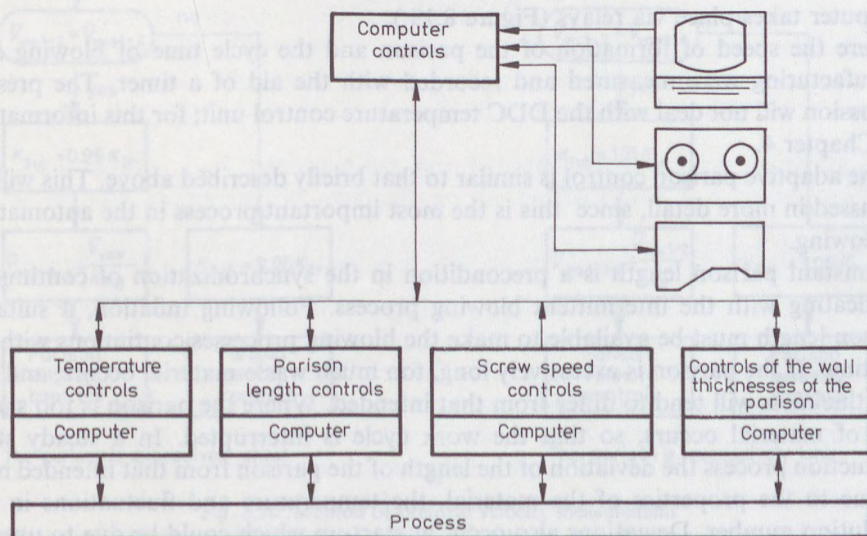


Fig. 8.18. A schematic diagram of process controls by microprocessor

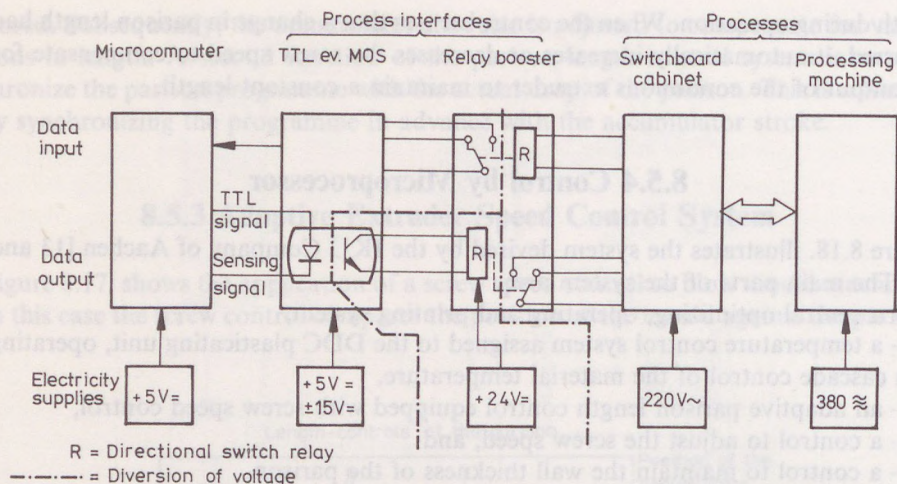


Fig. 8.19. A schematic diagram of current supplies to control processes performed by a microcomputer

advisable to give due consideration to any potential disturbing factors that might influence the proper functioning of the microprocessor. The elements of the control system and their modes of application must be considered to suit the processes to be controlled. Both the computer and the interface, due to their sensitivity to disturbing factors must be handled carefully. Voltage fluctuations and peaks may lead to errors in functioning of the computer. It is advisable to operate the computer on a voltage different from the voltage used for the peripherals (Figure 8.19).

The exchange of information between the processes to be controlled and the computer takes place via relays (Figure 8.19.).

Here the speed of formation of the parison and the cycle time of blowing and manufacturing were measured and recorded with the aid of a timer. The present discussion will not deal with the DDC temperature control unit; for this information see Chapter 4.

The adaptive parison control is similar to that briefly described above. This will be discussed in more detail, since this is the most important process in the automation of blowing.

Constant parison length is a precondition in the synchronization of continuous plasticating with the intermittent blowing process. Following inflation, a suitable parison length must be available to make the blowing processes continuous without idle time. If the parison is excessively long, too much waste material occurs, and the wall thickness will tend to differ from that intended. Where the parison is too short, lack of material occurs, so that the work cycle is interrupted. In a steady state production process the deviation of the length of the parison from that intended may be due to the properties of the material, the temperature and fluctuations in the revolution number. Deviations also occur at start-up which could be due to uneven temperature distribution in the material and to deviations from the steady state.

Control of the parison is based on the velocity of the parison, which is measured with a photocell system (Figure 8.20.). The time taken by the parison to pass between the photocells is measured. The start time is given by cut-off point of the equipment converted into the first time interval by the signal of the photocell LS1. Further start time signals are provided by photocells LS2, LS4 and LS6, and the end of these time intervals are detected by photocells LS3, LS5 and LS7. The actual velocity of the extrusion process is derived from the ratio of distances between the photocells and the

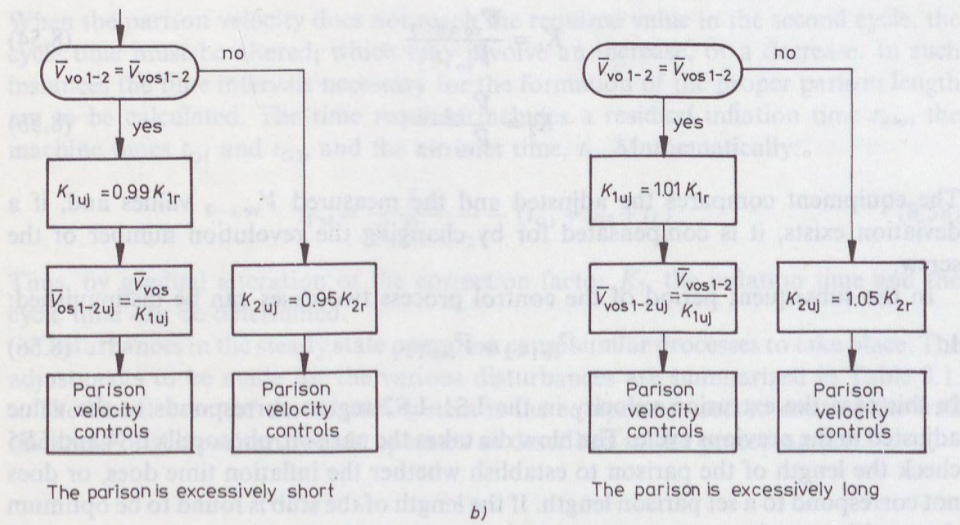
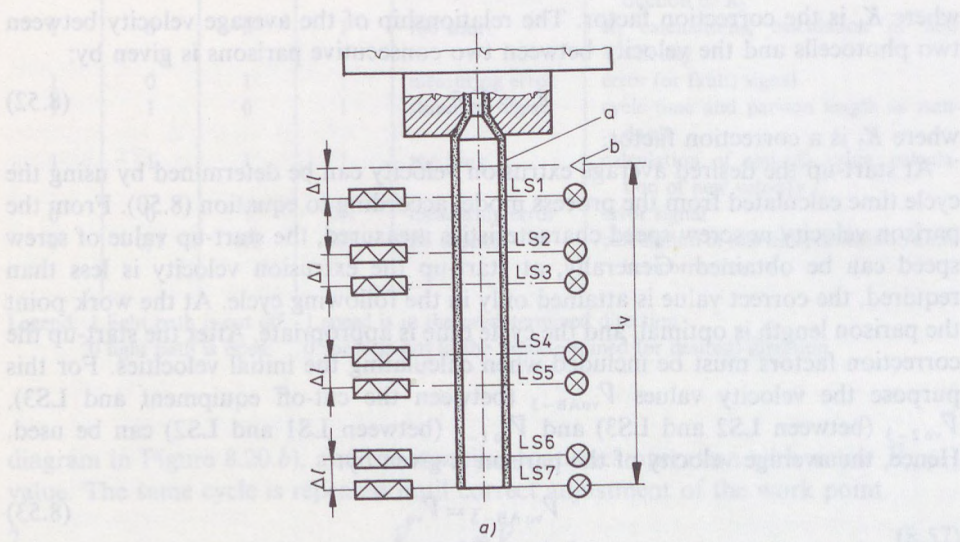


Fig. 8.20. Method of preform velocity measurement

a) Positioning of the photocells assigned to measure the velocity of parison formation, b) A flow chart for calculating the parison velocity

time intervals. The average extrusion velocity is thus:

$$v_{ex} = \frac{l_v}{t_c} \quad (8.50)$$

that is, the ratio of the length of the parison and the cycle time. The relationship of the average velocity between the photocells and the average extrusion velocity is given by the equation:

$$v_{ex} = K_1 \bar{v}_{ex1/2} \quad (8.51)$$

where K_1 is the correction factor. The relationship of the average velocity between two photocells and the velocity between two consecutive parisons is given by:

$$\bar{v}_{ex} = K_2 \bar{v}_{ex1/2} \quad (8.52)$$

where K_2 is a correction factor.

At start-up the desired average extrusion velocity can be determined by using the cycle time calculated from the process model according to equation (8.50). From the parison velocity *vs* screw speed characteristics measured, the start-up value of screw speed can be obtained. Generally, at start-up the extrusion velocity is less than required, the correct value is attained only in the following cycle. At the work point the parison length is optimal, and the cycle time is appropriate. After the start-up the correction factors must be included when calculating the initial velocities. For this purpose the velocity values $\bar{V}_{voAB-3}$ (between the cut-off equipment and LS3), $\bar{V}_{vo2-3}$ (between LS2 and LS3) and $\bar{V}_{vo1-2}$ (between LS1 and LS2) can be used. Hence, the average velocity of the parison is given by:

$$\bar{V}_{voAB-3} = \bar{V}_{vo} \quad (8.53)$$

The two correction factors are:

$$K_1 = \frac{\bar{V}_{voAB-3}}{\bar{V}_{vo1-2}} \quad (8.54)$$

$$K_2 = \frac{\bar{V}_{vo2-3}}{\bar{V}_{vo1-2}} \quad (8.55)$$

The equipment compares the adjusted and the measured V_{vo1-2} values and, if a deviation exists, it is compensated for by changing the revolution number of the screw.

In the subsequent period of the control process two cases can be distinguished:

$$1. \quad \bar{V}_{vo1-2} = \bar{V}_{vob1-2} \quad (8.56)$$

In this case the extrusion velocity in the LS1–LS2 region corresponds to the value adjusted in the previous cycle. The blow die takes the parison, photocells LS4 and LS5 check the length of the parison to establish whether the inflation time does, or does not correspond to a set parison length. If the length of the stub is found to be optimum the machine continues operating with the previous velocity of extrusion. If the stub length deviates from the desired value, the given cycle time is not suitable for the set parison velocity. In this case a new K_1 value is obtained as is shown by the block

Table 8.1. Programme alterations related to the various light phases [20]

L_3	L_4	L_5	$V_{vo\ 1-2}$	Preform length	Interference
1	0	0	0	too short	correction to the revolution number, reduction of K_2
1	0	1	0	measuring error	error signal
1	1	0	0	standard region	$V_{vo\ 1-2}$ calculation
1	1	1	0	too long	correction to the revolution number reduction of K_2
1	0	0	1	too short	K_1 calculations, calculation of new velocity
1	0	1	1	measuring error	error (or fault) signal
1	1	0	1	standard region	cycle time and parison length as standards
1	1	1	1	too long	calculation of new K_1 value, calculation of new velocity
0	0	1	0/1	measuring error	error signal
0	0/1	0/1	0/1	no checks	calculation of idle time, revolution number correction

Legend: 1 light path is cut off 1 speed is in the predetermined direction
 0 light path is open 0 speed is not in the predetermined (or desired) direction.

diagram in Figure 8.20.b), and the machine continues operation with a new $\bar{V}_{vo\ 1-2}$ value. The same cycle is repeated until correct adjustment of the work point.

$$2. \quad \bar{V}_{vo\ 1-2} \neq \bar{V}_{vos\ 1-2} \quad (8.57)$$

When the parison velocity does not reach the required value in the second cycle, the cycle time must be altered, which may involve an increase, or a decrease. In such instances the time intervals necessary for the formation of the proper parison length are to be calculated. The time required includes a residual inflation time t_{FM} , the machine times t_{G1} and t_{G2} , and the air inlet time, t_L . Mathematically:

$$t_{FM} = \frac{L_M}{K_2 \bar{V}_{vo\ 1-2}} - (t_{G1} + t_{G2} + t_L) \quad (8.58)$$

Thus, by gradual alteration of the correction factor K_2 , the inflation time and the cycle time can be determined.

Disturbances in the steady state operation cause similar processes to take place. The adjustments to be made for the various disturbances are summarized in Table 8.1.

The last element of the control system is the equipment used to control the wall thickness of the parison, which operates as described in the preceding text.

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9 Control in Injection Moulding

9.1 The Injection Moulding Process and Characterization of Injection Moulding Machinery

Injection moulding is one of the most widespread and most efficient plastic processing methods. Using injection moulding, thermoplastic, thermosetting and caoutchouc mixtures can be processed. The injection moulding process includes plasticating units to convert plastic materials into a melt or a melt-like substance, this material is then forced into a mould of the desired shape making sure that the material completely fills it. By application of cooling the material solidifies where thermoplastic materials are used, while in the case of thermosetting materials and caoutchouc mixtures solidification is achieved by maintaining the temperature at a high level, so that thermosetting or vulcanization takes place.

The main parts of an injection moulding machine are as follows:

- the plasticating unit,
- the mould clamping unit,
- the injection unit,
- the hydraulic unit, and
- the control unit.

It is possible to classify injection machines according to a number of possible criteria. If classified according to the material used, they may be divided into:

- injection moulding units used for thermoplastic materials,
- injection moulding units used for thermosetting materials, and
- injection moulding units used for caoutchouc material.

Classified by the working mechanisms of the plasticating unit and the injection unit, the following types may be distinguished:

- ram type,
- screw and ram combination, and
- screw type injection moulding machinery.

If classified according to the type of injection unit and the mould clamping mechanism, these may be:

- horizontal,
- vertical,
- combined, and
- machines positioned at an angle.

According to the drive employed distinctions may be made as to whether they are:

- mechanical,
- pneumatic,

- hydraulic, or
- combined machines.

Apart from the normal types of machines, other special purpose machinery is also used, such as rotating machines and foam injection machines.

The data which best characterize injection moulding machines are:

- the maximum possible injection weight,
- the output of the plasticating unit,
- maximum injection pressure,
- the maximum mould clamping force,
- barrel diameter,
- limits for the screw revolution number,
- maximum stroke number,
- the minimum and the maximum height of the mould that can be fitted,
- the dimensions of the mould receiver plates,
- the motor drive output,
- heating power,
- dimensions and weight of the machine.

The most widely used injection moulding machines are those with horizontal screws and injection volumes of 30 to 125 cm³.

9.2 Description of Injection Moulding Machines

In the following, the main parts of the injection moulding machinery and their functions are briefly summarized.

One of the most important sections of injection moulding machinery is the plasticating unit. Its task is to transform the powder, granule or the ribbon-shaped solid or a plastic material into thermally and rheologically homogeneous melt. A detailed description of the plasticating processes has already been given in Chapter 4. At the present day, screw plasticating units are much more commonly used, so these machines will be considered here [1 to 9].

Figure 9.1. shows a ram and a screw type injection machine. The cylinder (1) of the hydraulically operated mould clamping unit moves with piston (2), the mobile mould plate (3), which, with the aid of the stationary mould plate (5) closes the two mould halves (4). The barrel (6) of the plasticating unit, the torpedo of the ram type machinery (7), the material being processed (8), ram (9), the casing of the hydraulic system operating the piston, the piston of the hydraulic unit (10), (11), the piston controls of the hydraulic system (12) and (13), the screw (14) and the transmission of the screw drive (15) are the main parts shown in the Figure.

The melt produced by the plasticating unit is passed through the nozzle to the system of channels leading to the mould. The task of the nozzle is to produce a sealing in the inlet channel of the mould.

The screw tip. The tip of the screw operates as a flap valve, which allows the melt to flow into the reservoir during plasticating, but prevents backflow during injection

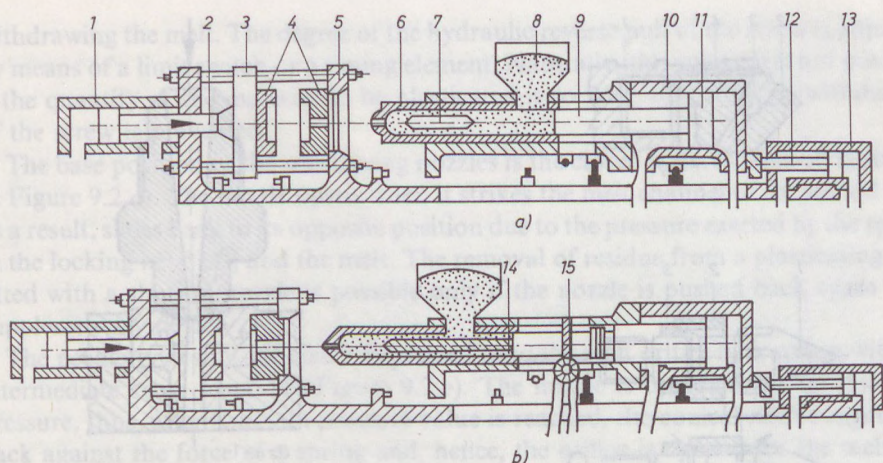


Fig. 9.1. Injection machines

a) Ram type,

b) Screw type

1. hydraulic cylinder, 2. the piston's axle, 3. and 5. mould support plates, 4. mould halves, 6. barrel, 7. torpedo, 8. material to be processed, 9. ram, 10. the hydraulic's barrel, 11. the hydraulic's piston, 12. and 13. control pistons, 14. screw, 15. screw drive transmission

(Figure 9.2.a). The external diameter of the screw tip is the same as the diameter of the screw flights, thus, due to the imperfection of matching the screw tip and the bore, a gap always remains and some reverse flow takes place. But if the screw tip were absent altogether, almost the whole of the melt would return in the troughs of the screw, especially in cases of low viscosity melts.

Several screw tip variations exist, one of which is the ring shut-off type, widely used, shown in Figure 9.2.b).

Some materials, sensitive to mechanical stresses, such as high viscosity hard PVC material, would suffer damage by being forced through the narrow orifice of the screw tip (hard PVC would decompose due to excessive local heat). In such instances the tip of the screw has a somewhat smaller diameter without a separate closing element.

The nozzle. The most important task of the nozzle is to maintain the connection between the injection unit and the die.

The nozzle is positioned at the inlet channel of the mould in such a way as to form a kind of sealing to ensure the flow of the melt into the bore of the melt channel. This requirement can be satisfied, when the bore of the nozzle (d) and the radius (r) of its contacting surface are somewhat smaller than the bore of the melt inlet channel (D) and the radius (R) of the pit hole. These are illustrated in Figure 9.2.c).

In general, the bore of the nozzle lies between 3 and 8 mm. The actual diameter of the bore is a function of the material processed and the size of the machine used.

Materials of small melt viscosity can be retained in the reservoir when using an open nozzle only if the applied reverse pressure is small and if upon termination of the plasticating step, the screw is moved in the reverse direction, i.e. backwards, thus

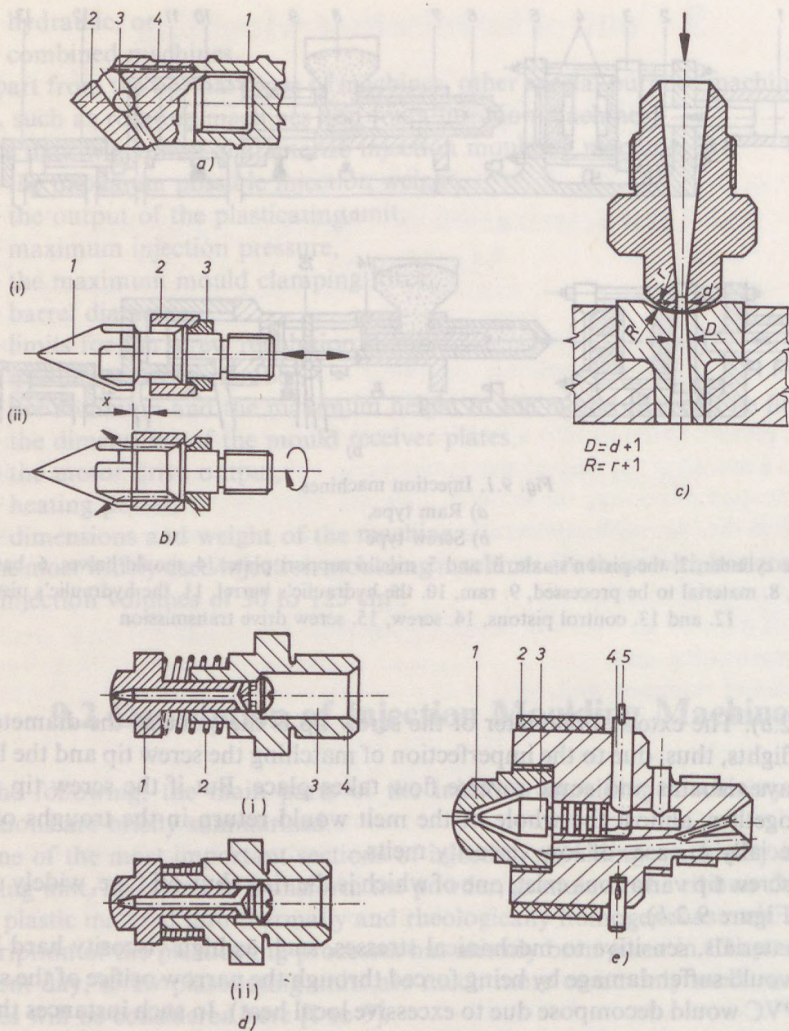


Fig. 9.2. Various screw tip and nozzle types

a) Ball point screw tip

1. screw, 2. screw tip, 3. ball, 4. split ball support pin to stop the ball falling out

b) Ring shut-off type of screw tip

(i) Injection position

(ii) plastication position

1. screw tip, 2. ring shut-off 3. support ring; x indicates the direction of motion of the closing ring

c) The connection of the nozzle to the inlet channel of the mould

d) Shut-off nozzle

(i) in closed position

(ii) in open position

1. shut-off nozzle with a mushroom-shaped locking head

2. spring 3. reservoir 4. division piece

e) Needle-type shut-off nozzle

1. nozzle, 2. the body of the nozzle, 3. needle, 4. cross plate, 5. spring

withdrawing the melt. The degree of the hydraulic reverse pull of the screw is adjusted by means of a limit switch or a timing element. Naturally, this solution is not possible if the quantity of the material to be plasticated is so large that effective withdrawal of the screw is prevented.

The base position of the self-closing nozzles is the closed state. A shut-off is shown in Figure 9.2.d). The nozzle opens when it strikes the melt channel of the mould and, as a result, slides back to its opposite position due to the pressure exerted by the spring in the locking head (1), and the melt. The removal of residue from a plasticating unit fitted with a shut-off nozzle is possible only if the nozzle is pushed back again by a supplementary device.

The needle-type shut-off nozzle is pressed onto the melt orifice by a spring with an intermediate cross plate, see Figure 9.2.e). The nozzle is operated by the injection pressure, thus, after a certain pressure value is reached, the conical needle is pressed back against the force of a spring and, hence, the orifice is opened for the melt.

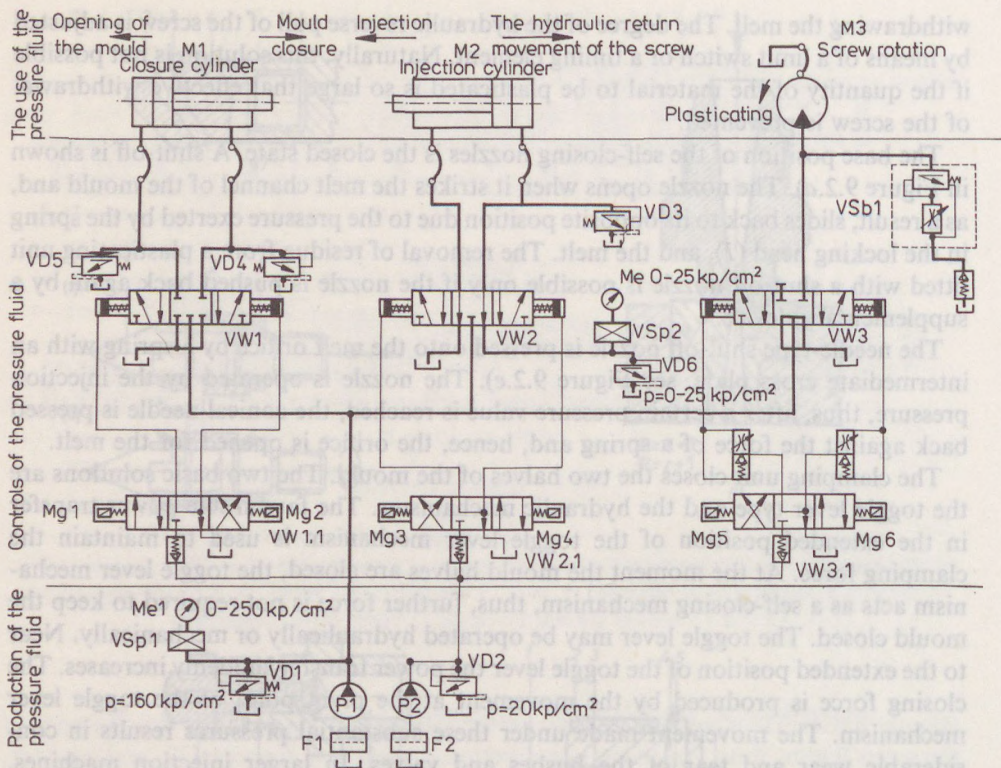
The clamping unit closes the two halves of the mould. The two basic solutions are the toggle lever type and the hydraulic mechanisms. The favourable power transfer in the extended position of the toggle lever mechanism is used to maintain the clamping force. At the moment the mould halves are closed, the toggle lever mechanism acts as a self-closing mechanism, thus, further force is not required to keep the mould closed. The toggle lever may be operated hydraulically or mechanically. Near to the extended position of the toggle lever the power transfer suddenly increases. The closing force is produced by the movement at the pivot point of the toggle lever mechanism. The movement made under these substantial pressures results in considerable wear and tear of the bushes and valves. In larger injection machines, hydraulic closing mechanisms are often used as clamping units; the mould halves are moved entirely by hydraulic means.

The following movements must be designed into the proper operation of injection moulding machines:

- the forward and backward movement of the injection ram,
- the rotation of the screw,
- the opening and closing of the two halves of the mould.

These movements may be brought about manually, mechanically, pneumatically, hydraulically or by their combination. Manual operation is almost unknown these days. In mechanically driven machines the movement is transferred from the drive unit by means of various lever and gear mechanisms. In these machines, stepless movements are produced and controlled with difficulty only, hence, their use is not very common. Mechanical drives are often employed to drive the screw.

Pneumatically operated injection machines did not gain substantial popularity either, since production of very large pressures using air as the medium proved difficult; this is only possible in machines of small size. The great majority of injection moulding machines are built to employ a hydraulic transfer of power. The operation of a machine based on oil hydraulics is illustrated by Figure 9.3., which shows an injection moulding machine, type KUASY 25 × 32 [4]. The pressure fluid is utilized by three units, the locking cylinder, the injection cylinder and the hydromotor, respectively. The pressure fluid needs of the energy consuming units are supplied by



Direction of motion	Work process	Pressure magnet		VW1.1		VW2.1		VW3.1	
		Mg1	Mg2	Mg3	Mg4	Mg5	Mg6		
—	Idling with safety screen in open position	o	o	o	o	o	o		
M1	Mould closure	L	o	o	o	o	L		
M2	Injection	o	o	L	o	o	L		
M3	Screw rotation	o	o	o	o	L	o		
M2	Hydraulically operated return movement of the screw	o	o	o	L	o	L		
M1	Mould opening	o	o	L	o	o	L		

Fig. 9.3. The operational mode of the oil hydraulics fitted to injection machines

the gear pump *P1*, obtaining the necessary oil by suction through filter *F1*, with a transport capacity of 40 l/min, the oil is transferred through the pressure line to the controlled reversible valves. The pressure of the hydraulic cycle is maintained at 160 MPa by a pressure limiting valve *VD1*. The pressure value may be checked by the manometer *Me1* after opening the manometer protecting valve *VSp1*. The gear pump *P2* of 4 l/min transport capacity, built into pump *P1*, is utilized to produce the pressure fluid for the cycle operating the precontrolled reversible valves. The pressure fluid output of pump *P1* in idling mode is passed back to the reservoir through the reversible valve *VW3*. For the control cycle a relatively small volume of oil is required, this, at times of idling, is transferred back to the reservoir through the pressure limiting valve *VD2*. The pressure fluid works in cylinders *M1* and *M2* only when the reversible valve *VW1* prevents the flow of oil back into the oil reservoir and the reversible valves *VW1* and *VW2* are switched on. The mould halves are closed when pressure magnets *Mg1* and *Mg6* are brought into operation. Magnet *Mg6* moves the piston of the precontroller valve *VW3.1* into position so that the oil necessary for control is allowed to flow, according to the control mode governed by *Mg6*, to the left-hand setting unit of precontrolled valve *VW3*. Now, reversible valve *VW3* is switched in the required direction of flow, to prevent the flow of the pressure fluid into the reservoir, so that the pressure increases in the cycle. Together with magnet *Mg6*, magnet *Mg1* comes into operation and the control fluid, the pressure fluid flows to the surface of the piston on the left hand side of the locking cylinder *M1*. The piston of the cylinder, *M1* now moves from left to right and the toggle lever fastened onto the piston rod pushes the mobile mould bolster in the direction of the stationary plate. The oil, pushed out from the right hand side cylinder space flows to the reservoir through the reversible valve. Similar processes take place upon opening the mould, but this time, in addition to magnet *Mg6*, magnet *Mg2* is also brought into operation. The pressure necessary to close the mould is adjustable by pressure limit valve *VD5*, while the pressure required to open the mould is provided by pressure limit valve *VD4*. The injection pressure is adjustable by means of valve *VD3*, while the dynamic pressure is adjustable by pressure limit valve *VD6*. The gear motor *M3* driving the screw comes into operation, when the pressure magnet *Mg5* switches the reversible valve *VW3.1*, and, in consequence, the reversible valve *VW3* allows the pressure fluid to flow in the direction of the gear motor. The required revolution number is adjustable by means of the flow control valve *VSb1*.

For processing thermosetting plastics, special plasticating units must be employed. All such plastics require a certain optimal plasticating time and temperature. It is necessary to maintain the barrel temperature of the plasticating unit with high accuracy, and the die must be heated.

The characteristic feature of injection moulding machines for caoutchouc materials is that the mould must also be heated, like in the case of thermosetting materials, and the material fed to the machine is only rarely in the form of granules, it is much more likely to be a strip. Multi-mould systems in injection moulding machine are generally used for elastomers.

The control of three kinds of injection moulding is now considered, highlighting the similarities and differences between them.

9.3 The Characteristic Features of Injection Moulding Processes

Injection moulding is a cyclic process. A complete cycle is shown in Figure 9.4. The ordinate represents the four phases of movements. The first phase represents the opening and closing of the mould, the second represents the nozzle movement, the third shows the axial movement of the screw, finally, phase four shows the rotation of the screw. The injection moulding cycle begins with closure of the mould (section 0-1), the nozzle is adjusted to the orifice of the die (section 1'-2), and injection then takes place (section 2'-3). After a certain time interval (section 3-4') the screw piston pushes another quantity of material into the mould. The pressure is maintained for a certain time then the nozzle is repositioned by moving backwards (section 4-5), followed by rotation of the screw (section 5''-6). During the plasticating process the material in the mould solidifies (section 4''-7''), then the mould opens (section 7-8). During injection moulding, the above cycle is repeated over and over again. Application of control ensures that the process parameters are maintained constant.

The characteristic steps of the injection process are:

- plasticating,
- material flow through the nozzle, the sprue and the runner,

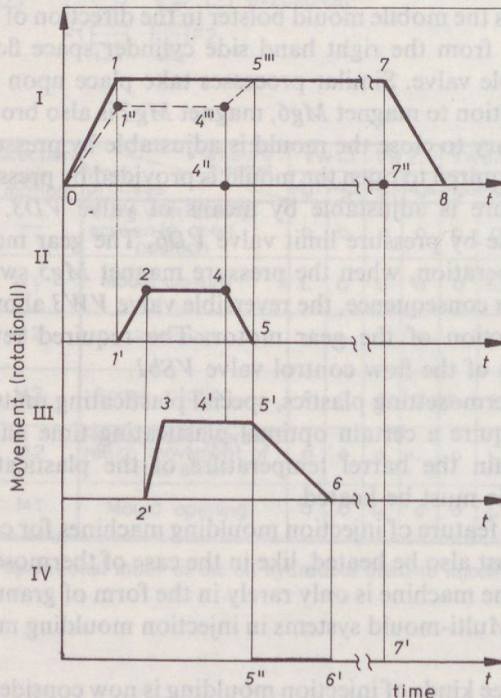


Fig. 9.4. The complete injection cycle

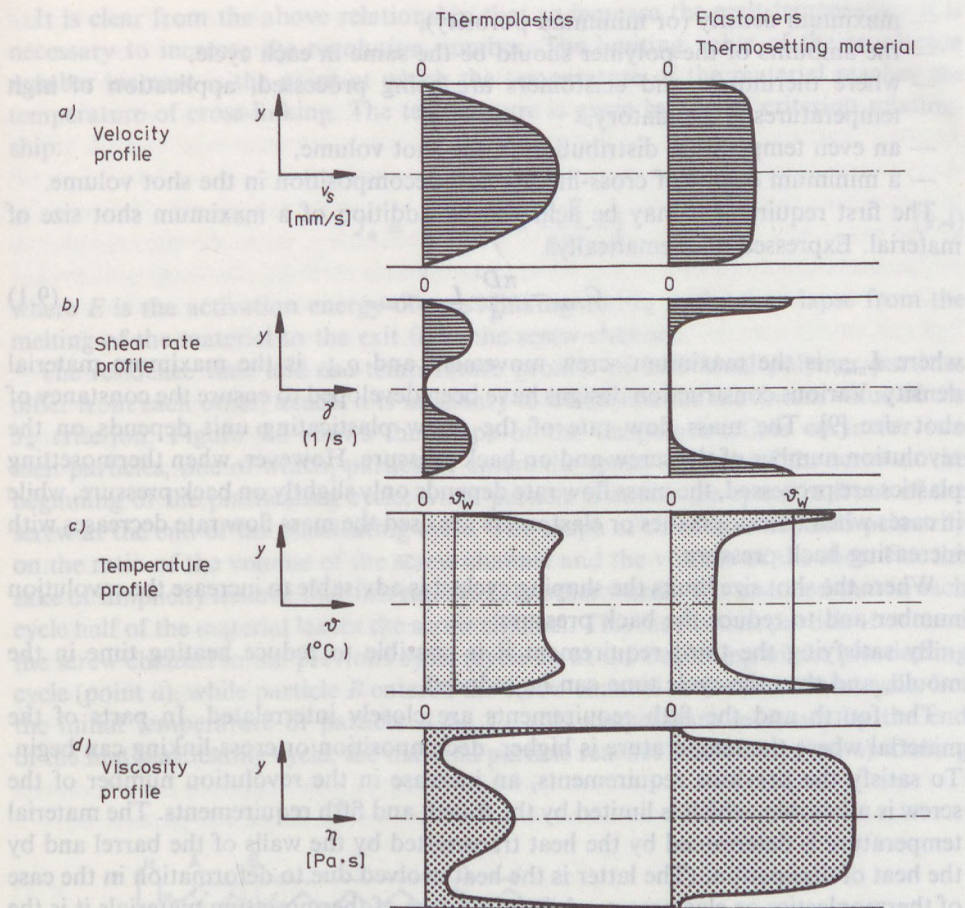


Fig. 9.5. Parameter profiles during injection

- filling of the mould,
- packing and holding of the pressure,
- cooling or curing.

Before we turn to description of process control it is necessary to indicate the characteristic features of these processes with the aid of models.

The part-processes are dependent on the type of material used, which may be thermoplastic, thermosetting or elastomer materials. Figure 9.5. shows these behaviour differences which are due to rheological characteristics; in the case of thermosetting materials and caoutchouc mixtures the cooling phase is, at the same time, the phase of curing, too, which takes place in the hot mould.

The plastication process was discussed in Chapter 4; here, only some factors influencing the quality of the melt will be mentioned.

The quality of the melt produced by a reciprocating screw plasticating unit of intermittent mode of operation depends on the following factors:

- maximum density (or minimum porosity),
- the amounts of the polymer should be the same in each cycle,
- where thermosets and elastomers are being processed, application of high temperatures is mandatory,
- an even temperature distribution in the shot volume,
- a minimum degree of cross-linking and decomposition in the shot volume.

The first requirement may be achieved by addition of a maximum shot size of material. Expressed mathematically:

$$G_{\max} = \frac{\pi D^2}{4} L_{\max} \varrho_{\max} \quad (9.1)$$

where $L_{\max}$ is the maximum screw movement and $\varrho_{\max}$ is the maximum material density. Various construction designs have been developed to ensure the constancy of shot size [9]. The mass flow rate of the screw plasticating unit depends on the revolution number of the screw and on back pressure. However, when thermosetting plastics are processed, the mass flow rate depends only slightly on back pressure, while in cases when thermoplastics or elastomers are used the mass flow rate decreases with increasing back pressure.

Where the shot size limits the shaping cycle it is advisable to increase the revolution number and to reduce the back pressure.

By satisfying the third requirement it is possible to reduce heating time in the mould, and thus the cycle time can be reduced.

The fourth and the fifth requirements are closely interrelated. In parts of the material where the temperature is higher, decomposition or cross-linking can begin. To satisfy the previous requirements, an increase in the revolution number of the screw is advisable, which is limited by the fourth and fifth requirements. The material temperature is determined by the heat transmitted by the walls of the barrel and by the heat of dissipation. (The latter is the heat evolved due to deformation in the case of thermoplastics or elastomers, while in the case of thermosetting materials it is the heat evolved due to friction against the walls of the barrel.) During phases of transport and melting of the solid material, heat is transferred from the surface of the barrel and from the surface of the screw to the plastic, in the melt-transporting zone, this process is often reversed and heat is transferred from the polymer to the surface of the barrel while the temperature of the plastic material becomes 15–35 °C higher than the temperature of the barrel. The temperature of the melt upon exit from the screw channel is given by:

$$T_{\text{out}} = T_b + aN + b_1 P \quad (9.2)$$

where a and b_1 are constants. A more precise temperature dependence may be derived based on the energy equation, thus:

$$\pi_T = I_2 \exp \frac{b_0}{\pi_T + 1} \quad (9.3)$$

where

$$\pi_T = \frac{T_{\text{out}} - T_b}{T_b}; \quad I_2 = \frac{\mu_1 V^{1+n} H^{1-n}}{12k T_b}; \quad b_0 = \frac{b}{T_b}$$

It is clear from the above relationship that to increase the melt temperature it is necessary to increase the revolution number. The limiting value of the revolution number increase is the point at which the temperature of the material reaches the temperature of cross-linking. The temperature is given by the J_* criterion relationship:

$$J_* = \int_0^{t_*} \exp\left(-\frac{E}{RT(t)}\right) dt \quad (9.4)$$

where E is the activation energy of cross-linking and t_* is the time lapse from the melting of the material to the exit from the screw channel.

The residence time and the temperature profiles of individual polymer particles differ from each other, hence, it is necessary to determine the maximum value of the J_* criterion. Figure 9.6 shows the shape of the temperature/time curve for two melt particles, one of which, particle A enters the space in front of the screw at the beginning of the plasticating cycle, while particle B enters the space in front of the screw at the end of the plasticating cycle. The shape of this curve depends primarily on the ratio of the volume of the screw channel and the volume of the shot. For the sake of simplicity assume that this ratio is 2, in other words, it is assumed that in each cycle half of the material leaves the screw channel. This means that particle A entered the screw channel in the previous cycle (cycle I), at the beginning of the plasticating cycle (point a), while particle B entered the screw channel at the end of the cycle. Let the initial temperature of particle A be T_0 , this temperature increases by the end of the first plasticating cycle, the material particle reaches point b (at time 4). During

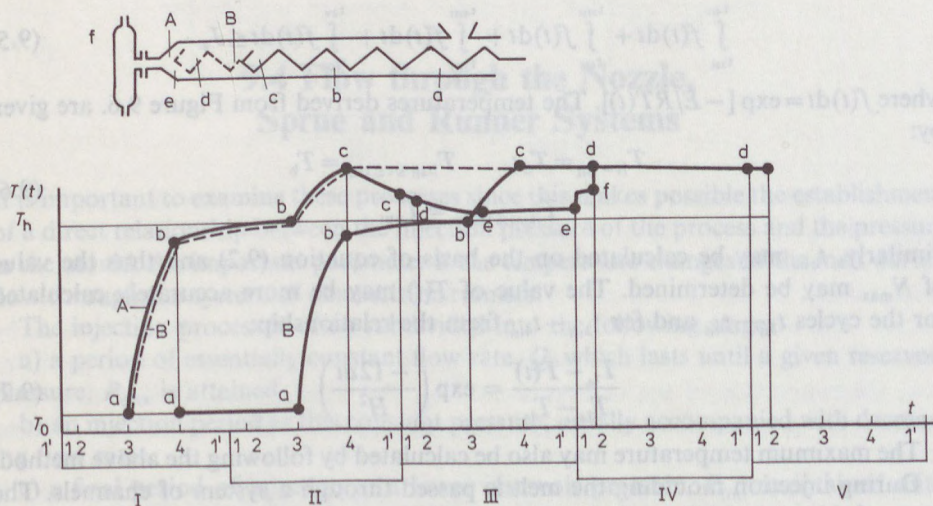


Fig. 9.6. Temperature vs. time diagram for a reciprocating plasticating unit
I to IV represent cycle numbers

1-2 injection, 2-3 packing, 3-4 plasticating, 1'-1 intermission

injection, the screw moves forward in axial direction to point *c* and remains there until the beginning of the next plasticating cycle (time 3_{II}), while its temperature increases due to heating. In the second plasticating cycle (3_{II} – 4_{II}) particle *A* reaches point *d*, its exit point from the screw channel. This material particle remains in this position until the injection of the third cycle (point 1_{III}), meanwhile, it cools down due to its contact with the cooler wall surface of the barrel. At the time of the next injection the particle is shifted to position *e* and is cooled further until the beginning of the plasticating cycle (point 3_{III}). During plasticating, since the particle is now at the end of the screw channel, it is not heated, but is shifted to the edge of the space in front of the screw (point *f*). The particle stays here, until the next injection (point 1_{IV}) and finally it enters the die during the following injection (points *f* and 2_{IV}).

Particle *B* undergoes similar temperature changes as was the case with particle *A*. Particle *B* enters the screw channel at the end of the plasticating cycle (at time 4_I), thus this particle stays here until the beginning of the following plasticating cycle (time 3_{II}) and is heated only during the second cycle. During the third plasticating cycle (time interval 3_{III} to 4_{III}) the particle is heated to a temperature well above the temperature of the walls of the barrel, due to heat dissipation (point *e*). The material particle stays there until the next injection (point 1_{IV}) and practically it does not cool down, since the reservoir filled with the melt in front of the screw is substantially larger in diameter than the channel depth, the melt is not in direct contact with the surface of the barrel, thus, intense heat conduction does not take place. During injection (1_{IV} – 2_{IV}) the particle is moved forward in the space in front of the screw to the nozzle.

Particle *B* is subjected to higher temperatures for a longer time than particle *A*. Here, particles *A* and *B* represent the limiting cases, all other particles fall in between these two extremes. The criterion parameter must be calculated for particle *B*:

$$\int_{t_{3II}}^{t_{4II}} f(t)dt + \int_{t_{4II}}^{t_{3III}} f(t)dt + \int_{t_{3III}}^{t_{4III}} f(t)dt + \int_{t_{4III}}^{t_{2V}} f(t)dt \leq J_* \quad (9.5)$$

where $f(t)dt = \exp[-E/RT(t)]$. The temperatures derived from Figure 9.6. are given by:

$$T_{|t=t_{3II}} = T_0; \quad T_{|t_{4II} \leq t \leq t_{3III}} = T_b \\ T_{|t_{4III} \leq t \leq t_{2V}} = T_{out} \quad (9.6)$$

Similarly, t_{out} may be calculated on the basis of equation (9.2) and thus the value of N_{max} may be determined. The value of $T(t)$ may be more accurately calculated for the cycles t_{3II} – t_{4II} and for t_{3III} – t_{4III} from the relationship:

$$\frac{T_{t_4} - T(t)}{T_{t_4} - T_{t_3}} = \exp\left(\frac{-12at}{H^2}\right) \quad (9.7)$$

The maximum temperature may also be calculated by following the above method.

During injection moulding the melt is passed through a system of channels. The parts of this system of channels are:

- the reservoir in front of the screw tip,
- the injection nozzle through which the molten polymer is forced,

- the main channel, the sprue connected with,
- the system of channels serving to distribute the injected material to the various mould cavities,
- the gates through which the polymer melt flows into the cavities.

The geometry of the system of cavities can be represented by a series of circular tubes (of uniform or slowly varying cross sections) and disc-like or planar narrow channels with slowly varying depth, connected with each other by bends or deliberately made constrictions.

The description of the flow processes is greatly facilitated by the method of the dimensionless criterion parameters. In the flow processes the inertia and the gravitational forces are negligible compared with the pressure and viscosity forces, so that only those members of the impulse equation need to be taken into account which contain forces of pressure and viscosity. As a rheological state equation, it suffices to consider only the viscous fluid equation, although, in some processes such as the introduction of the melt into the die the Deborah number may be important, and in examining the effects of the process the equation of viscous-elastic fluids may be necessary. The greatest variety is shown by the energy equation. It is advisable to take into consideration the following cases [10–14]:

- Gz and $G \gg 1$ the flow is thermally undeveloped, with significant viscosity variations due to viscous heating,
- $Gz \gg 1$, $G \ll 1$ thermally undeveloped flow with essentially constant viscosity,
- $Gz \approx 0$, $G \ll 1$ flow developing thermally with practically constant viscosity,
- $Gz \ll 1$, $G \approx 0$ thermally fully developed flow with significant viscosity variations due to heat dissipation,
- $Gz \ll 1$, $G \ll 1$ thermally fully developed flow with practically constant viscosity.

The above cases are examined in detail [13] for flow in a tube.

9.4 Flow through the Nozzle, Sprue and Runner Systems

It is important to examine these processes since this makes possible the establishment of a direct relationship between the injection pressure of the process and the pressure in the mould. An important parameter is the temperature changes of the melt during flow through the system of channels or runners.

The injection process is often subdivided into the following stages:

- a) a period of essentially constant flow rate, Q , which lasts until a given reservoir pressure, $P_{\max}$ is attained,
- b) an injection period at this constant pressure, usually accompanied with decreasing flow rates,
- c) a final period of injection at a lower reservoir pressure, P_{fin} , maintained until the mould is filled completely, at which stage,
- d) a mould holding pressure, P_{hold} is maintained until the polymer in the mould cavity is either solidified or cured.

First, let us examine the pressure drop across the nozzle. On the basis of a simplified theoretical analysis [15], the nozzle pressure is related to the hydraulic pressure according to the equation:

$$P_N = \frac{A_p}{A_f} P_H - \frac{F_s}{A_f} \quad (9.8)$$

where P_N is the nozzle pressure, P_H is the hydraulic pressure, A_p is the cross-sectional area of the ram piston, A_f is the cross-sectional area of the screw flight, and F_s represents the shearing force exerted by the polymer on the screw. The shearing force estimate is made on the basis of a model, the axial annular Couette flow:

$$F_s = \frac{2\pi\mu_1 L}{R^{n-1}} \left[\frac{U}{\frac{n}{n-1} \left(\varepsilon \frac{n-1}{n} - 1 \right)} \right]^n \quad (9.9)$$

where μ_1 and n are the parameters of the power-law viscosity equation, U is the injection velocity, L is the screw length, R is the internal barrel radius and ε is the ratio of the flight radius to the internal radius of the barrel.

Equation (9.9) approximates to a linear relationship, confirmed experimentally [15]. The relationship between the pressure drop and volume flow of the flow through the nozzle, for isothermal flow [7] is given by:

$$\Delta P = \mu_1 Q^n (a_1 + a_2) \quad (9.10)$$

where:

$$a_1 = \frac{4L_s D}{1 + e/W} \left[1 + \frac{e}{W} \left(\frac{H}{C_r} \right)^n + \frac{3 \sin^2 \Theta \left(1 - \frac{C_r}{H} \right)^2}{1 + \frac{W}{e} \left(\frac{C_r}{H} \right)^{2+n}} \right] \quad (9.11)$$

$$\cdot \left(\frac{4}{\pi H D^2} \right)^n \quad a_2 = \frac{l_r}{d_r} \left[\frac{8(3n+1)}{n\pi d_r^3} \right]^n$$

D is the internal diameter of the barrel, W is the width of the screw channel, e is the flight width, H is the depth of the screw channel, C_r represents the clearance between the screw flight and the surface of the barrel, Θ is the helix angle, L_s is the displacement of the screw, and l_r is the length, while d_r is the diameter of the nozzle. The relationship (9.10) may be applied to the runner channel system by appropriate choice of a_2 . The runner system consists of channels of various diameter, the connection of the various sections of the channel; the pressure drop also includes the pressure drop at entry of the melt, which is related to normal stresses, hence:

$$\Sigma \Delta P = \Sigma \Delta P_{\text{stac}} + \Sigma \Delta P_{\text{entry}} \quad (9.12)$$

The pressure drop upon entry of the melt is given by the relationship:

$$\Delta P = \xi (\tau_{w1} - \tau_{w2})^m \quad (9.13)$$

where ξ and m are the parameters of the power-law equation for normal stress difference versus shearing rate curve, while τ_{w1} and τ_{w2} represent the shearing stresses along the walls prior to and after entry of the melt, respectively.

Taking the energy equation into account, the specific case is examined when $Gz \gg 1$; that is, heat convection is the dominant process.

If the Griffith number is small the temperature increase in a channel of length L may be written as:

$$T = T_0 + \Delta T \left[1 - \exp \left(-\frac{\varepsilon L}{v} \right) \right] \quad (9.14)$$

where T_0 is the initial temperature, $\Delta T = T_p - T_w$, T_p is the temperature of the polymer melt in front of the screw tip, T_w is the wall temperature of the given melt

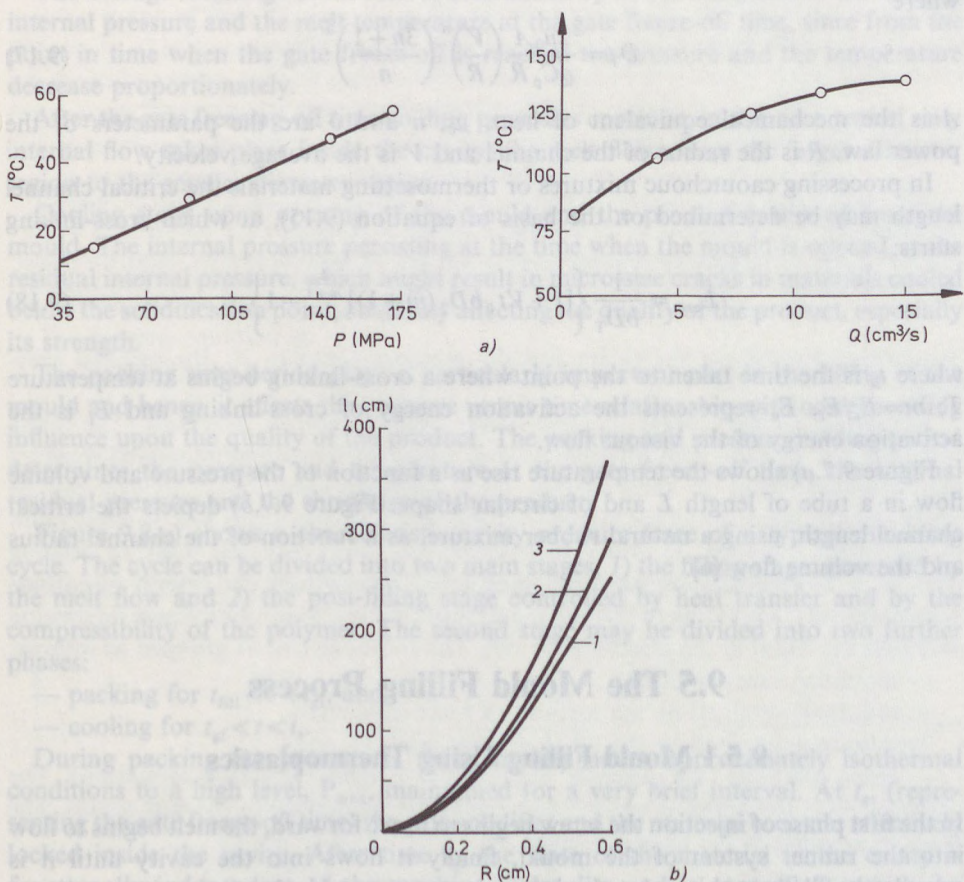


Fig. 9.7. Temperature increase and critical path length using a caoutchouc mix

a) Temperature increase as a function of pressure and volume flow,

b) Critical channel length as a function of the radius of the channel

1. $Q = 10$ cm³/s, 2. $Q = 20$ cm³/s, 3. $Q = 30$ cm³/s

transport channel

$$\varepsilon = \frac{8k}{\varrho C_p R^2} \frac{5n+1}{7n+1}$$

and v is the average velocity of the melt flow in the given section of the channel.

Where the Griffith number is large, so that viscous dissipation plays an important role:

$$T = T_0 + \frac{1}{b} \ln(1 + bD_T L) \quad (9.15)$$

the pressure drop is given by:

$$P = P_0 - \frac{\varrho C_p}{bA} \ln(1 + bD_T L) \quad (9.16)$$

where

$$D_T = \frac{2\mu_0 A}{\varrho C_p R} \left(\frac{V}{R} \right)^n \left(\frac{3n+1}{n} \right)^n \quad (9.17)$$

A is the mechanical equivalent of heat, μ_0 , n and b are the parameters of the power law, R is the radius of the channel and V is the average velocity.

In processing caoutchouc mixtures or thermosetting materials the critical channel length may be determined on the basis of equation (9.15), at which cross-linking starts:

$$L_{\text{crit}} = \frac{1}{bD_T} \left\{ [1 + Vt_0 bD_T(m+1)]^{\frac{1}{m+1}} - 1 \right\} \quad (9.18)$$

where t_0 is the time taken to the point where a cross-linking begins at temperature T , $m = E_n/E_f$, E_n represents the activation energy of cross-linking and E_f is the activation energy of the viscous flow.

Figure 9.7.a) shows the temperature rise as a function of the pressure and volume flow in a tube of length L and of circular shape. Figure 9.7.b) depicts the critical channel length, using a natural rubber mixture, as a function of the channel radius and the volume flow [6].

9.5 The Mould Filling Process

9.5.1 Mould Filling Using Thermoplastics

In the first phase of injection the screw begins to move forward, the melt begins to flow into the runner system of the mould, finally it flows into the cavity until it is completely filled; at this point the internal pressure suddenly reaches its maximum value.

After the cavity is filled to capacity the screw remains under pressure, this is the packing period (it includes a period of pressure increase as well). Due to the increased

pressure the volume of the melt in the cavity decreases. Concurrently, the mould itself is cooled externally, which also contributes to the drop in volume of the melt.

These two phenomena take place at the same time and make it possible to accommodate additional quantities of the melt in the cavity of the mould.

This means that in the packing period the melt continues to flow in reasonable quantities, but flows with a substantially smaller volume velocity. This packing period is terminated when plastification takes place with the aid of the screw and the screw begins its movement in the reverse direction.

Due to the initially applied pressure a substantial pressure continues to persist in the mould cavity, and due to the differences in pressure some of the melt is pushed out of the mould. This phenomenon is the so-called "back flow" that results in a considerable drop of pressure in the cavity. The back flow continues until the melt solidifies in the constriction of the melt channel. This is the gate freeze-off point.

The average shrinkage of the melt is determined by two factors, that of the existing internal pressure and the melt temperature at the gate freeze-off time, since from the point in time when the gate freeze-off is reached the pressure and the temperature decrease proportionately.

After the gate freezing-off time cooling processes continue, in this time period only internal flow takes place inside the cavity, the melt flows from the larger diameter region to the smaller diameter region.

Cooling stops upon opening of the mould and the product is moved from the mould. The internal pressure persisting at the time when the mould is opened, is the residual internal pressure, which might result in micro-size cracks in materials cooled below the solidification point, adversely affecting the quality of the product, especially its strength.

The packing time period plays a particularly important part in the filling of the mould and hence, it affects the pressure versus time relationship with corresponding influence upon the quality of the product. The packing and pressure-holding period determines the pressure and temperature at the gate freeze-off time, the internal residual pressure and the shrinkage of the product.

Figure 9.8.a) shows a characteristic cavity pressure trace of a typical moulding cycle. The cycle can be divided into two main stages, 1) the filling stage, governed by the melt flow and 2) the post-filling stage controlled by heat transfer and by the compressibility of the polymer. The second stage may be divided into two further phases:

- packing for $t_{\text{fill}} < t < t_{\text{gf}}$, and
- cooling for $t_{\text{gf}} < t < t_c$.

During packing the pressure is rising rapidly under approximately isothermal conditions to a high level, P_{max} , maintained for a very brief interval. At t_{gf} (representing the gate freeze-off time) the gate solidifies and the material becomes effectively locked inside the cavity. After time t_{gf} the state of the material in the cavity is functionally independent of the machine hydraulics and is controlled entirely by the dynamics of cooling. At t_{cool} the material passes through the innermost point of the cavity, T_g , at $t > t_{\text{cool}}$ the material in the cavity is fully solidified. As the system approaches thermal equilibrium (at $t = t_{\text{eq}}$), the temperature becomes evenly

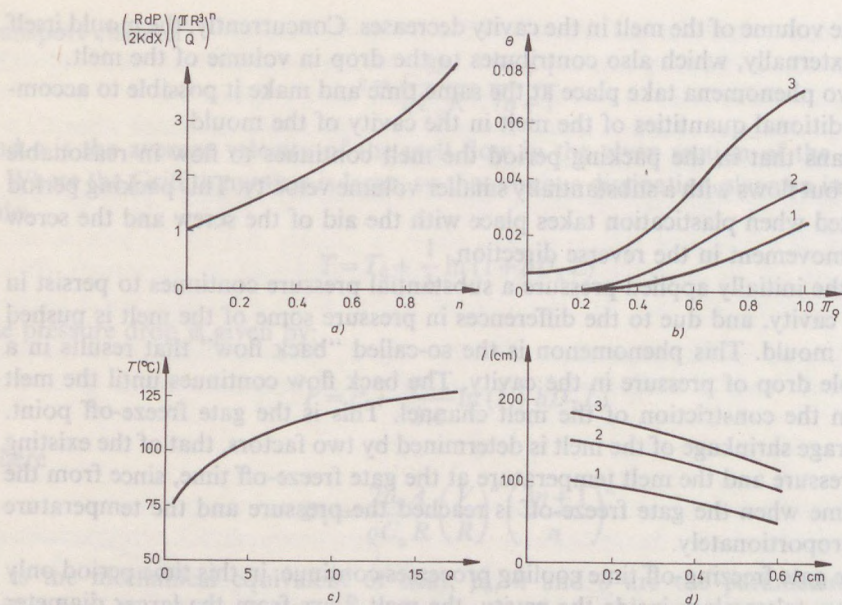


Fig. 9.8. The pressure and temperature increase of flow through the nozzle

a) Pressure gradient, exponential [7], b) Dimensionless temperature increase as a function of radial coordinates, in various positions, in the direction of the axis of the nozzle [7]. 1. $X=0.01$, 2. $X=0.02$, 3. $X=0.05$, c) The dependence of increased temperature upon the injection pressure [9], d) The critical length as a function of the radius [9] at vulcanization temperature at 160°C and at 100 MPa injection pressure. 1. $Q=10 \text{ cm}^3/\text{s}$, 2. $Q=20 \text{ cm}^3/\text{s}$, 3. $Q=30 \text{ cm}^3/\text{s}$.

distributed throughout the cavity and the pressure drops to P_r , the residual pressure.

The mould filling process is a non-steady, non-isothermal melt flow. The filling processes for moulds with different shapes and sizes cannot be expressed in exact mathematical terms. In spite of this, fairly accurate quantitative models can be established by subdividing the moulds into simple geometric forms and by application of numerical methods. In order to describe the filling and the pressure holding process, it is necessary to solve the continuity, momentum and energy equations simultaneously, according to the initial and final limiting conditions. Some interesting solutions are listed in the references [6–50]. The solutions can be grouped as follows:

- simplified exact solutions,
- solutions obtained by the method of finite differences,
- solutions obtained by the finite element method, and

— other solutions (for example, application of conformal transformation). The solution given for a planar section and a tube [9] is included in the first group. The drop of pressure in the mould is given by:

$$\frac{\Delta P_s}{L} = 2\mu_0 \exp[b(T_s - T_0)] \left\{ \frac{\frac{2n+1}{n} 2Q}{B(H-2\delta) \frac{2n+1}{n}} \right\}^n \quad (9.19)$$

$$\frac{\Delta P_t}{L} = 2\mu_0 \exp [b(T_b - T_0)] \left\{ \frac{\frac{3n+1}{n} Q}{\pi(r-\delta) \frac{3n+1}{n}} \right\}^n \quad (9.20)$$

The thickness of the solidified melt layer along the walls is:

$$\delta_s = 3.36 \sqrt{at} \left(1 - \sqrt{1 - \frac{T_m - T_s}{T_p - T_s}} \right) \quad (9.21)$$

$$\delta_t = 4.25 \sqrt{at} \left(1 - \sqrt{1 - \frac{T_m - T_s}{T_p - T_s}} \right) \quad (9.22)$$

where T_p represents the temperature of the polymer entering the mould, T_m is the melting point of the polymer, T_s is the temperature of the mould, a is the thermal diffusivity, Q is the volume flow rate, B is the width, H is the height of the mould, and r is the radius of the tube-shaped mould. It is a common practice to divide the moulds into simple elements for examination [30 to 50].

Let us now examine the flow in a rectangular cavity as can be seen in Figure 9.9.

The expression of the velocity distribution is:

$$v_x = v_x(y) \quad (9.23)$$

where x is the coordinate of the cavity in the direction of the injection, while y is the coordinate perpendicular to x .

The motion equation is:

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_{yx}}{\partial y} \quad (9.24)$$

The viscosity equation is given by:

$$\tau_{yx} = \mu(T) \left(-\frac{dv_x}{dy} \right)^n \quad (9.25)$$

where the term $\mu(T)$ is a temperature dependent multiplication factor.

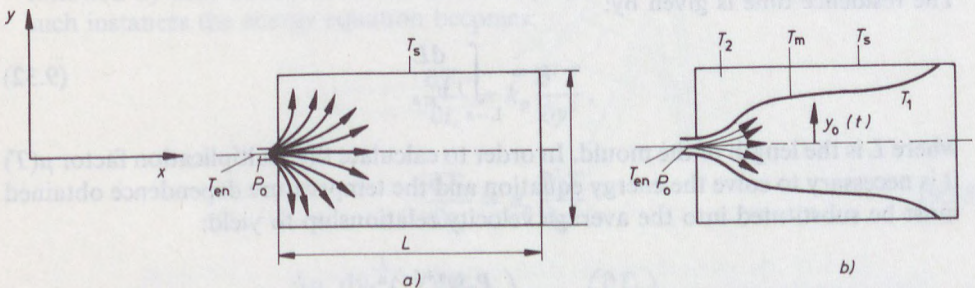


Fig. 9.9. Mould cavity filling in the cases of (a) amorphous and (b) crystalline polymers [20]

The energy equation is:

$$\frac{\partial T}{\partial t_x} = k_p \frac{\partial^2 T}{\partial y^2} \quad (9.26)$$

where k_p is the heat conductivity and t_x is the residence time in the cross-section of the cavity. The boundary conditions of the above system of equations (9.25) and (9.26) are as follows. The flow is free from sliding on the wall, thus

$$v_x \left(\frac{w}{2} \right) = 0 \quad (9.27)$$

where w represents the width of the mould, hence $w/2$ represents the coordinate of the mould wall.

The flow is symmetrical, thus

$$\frac{dv_x}{dy} = 0, \text{ provided } y=0 \quad (9.28)$$

The temperature of the melt upon entry is constant, (T_{in}), thus

$$T(y, t_x = 0) = T_{in} \quad (9.29)$$

The temperature of the polymer at the wall of the mould represents the glass transition, hence:

$$T \left(y = \frac{w}{2}, t_x \right) = T_g \quad (9.30)$$

The system of equations (9.23) through to (9.26) are solved by taking into account the boundary conditions expressed by equations (6.34) to (6.37). First the average velocity is established to determine the residence time, this is followed by the solution of the motion and the viscosity equations. The velocity is:

$$v_{x,a} = \frac{2}{w} \left(\frac{dP}{dx} \right)^{\frac{1}{n}} \int_0^{\frac{w}{2}} \left[\frac{y^{n+1}}{\mu(T)} \right]^{\frac{1}{n}} dy \quad (9.31)$$

The residence time is given by:

$$t_x = \int_{L-x}^L \frac{dL}{v_{x,a}} \quad (9.32)$$

where L is the length of the mould. In order to calculate the multiplication factor $\mu(T)$ it is necessary to solve the energy equation and the temperature dependence obtained must be substituted into the average velocity relationship to yield:

$$v_{x,a} = \left(\frac{P_0 w^{n+1}}{4 \cdot 6^n L \mu_j} \right)^{\frac{1}{n}} \quad (9.33)$$

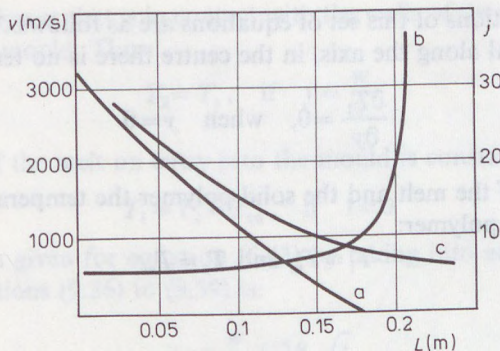


Fig. 9.10. Flow velocities as function of mould length

a. The velocity of non-isothermal flow, b. The 'j' value, c. The velocity of isothermal flow as function of mould length

where P_0 represents the pressure in the mould channel, while j is expressed as:

$$j = \frac{1}{L} \int_0^L \exp \left\{ \left(\frac{b}{T_b - T_s} \right) \left[\exp \left(- \frac{10\alpha_p t_x}{w^2} \right) - \left(\frac{T_g - T_s}{T_b - T_s} \right) \right]^{-1} \right\} dx \quad (9.34)$$

Further solution of equation (9.33) depends on whether the injection velocity or the injection pressure is constant. For the latter case the average velocity and the j values are depicted in Figure 9.10. as functions of the mould length, where *a*) values represent the velocity of the non-isothermal flow, *b*) contains the j values, while *c*) shows the velocity of the isothermal flow (μ is independent of the temperature). It seems obvious that in the initial phase of fill, when the degree of cooling is small (small j values), the flow velocities of isothermal and non-isothermal flows are close to each other. Upon cooling of the melt the deviation of the curves from each other becomes increasingly more evident.

Where crystalline polymers are used the energy equation undergoes certain modifications in the system of equations shown above. In such instances it must be taken into account that a solid layer of polymer adheres to the walls of the mould, thus heat transfer takes place first between the polymer melt and the solidified polymer layer, followed by heat transfer between the solid polymer and the walls of the mould. In such instances the energy equation becomes:

$$\begin{aligned} \frac{\partial T_1}{\partial t_x} &= k_p \frac{\partial^2 T}{\partial y^2}, \\ \frac{\partial T_2}{\partial t_x} &= \alpha_p \frac{\partial^2 T}{\partial y^2} \end{aligned} \quad (9.35)$$

$$\frac{\Lambda \varrho}{\alpha_p} \frac{dy_0}{dt} = \left(\frac{\partial T_2}{\partial y} \right)_{y=y_0(t)} + \left(\frac{\partial T_1}{\partial y} \right)_{y=y_0(t)}$$

The boundary conditions of this set of equations are as follows. The melt flow in the mould is symmetrical along the axis, in the centre there is no temperature gradient:

$$\frac{\partial T_1}{\partial y} = 0, \quad \text{when } y = 0 \quad (9.36)$$

At the interface of the melt and the solid polymer the temperature is equal to the melting point of the polymer:

$$T_1 = T_m \quad \text{and} \quad T_2 = T_m \quad (9.37)$$

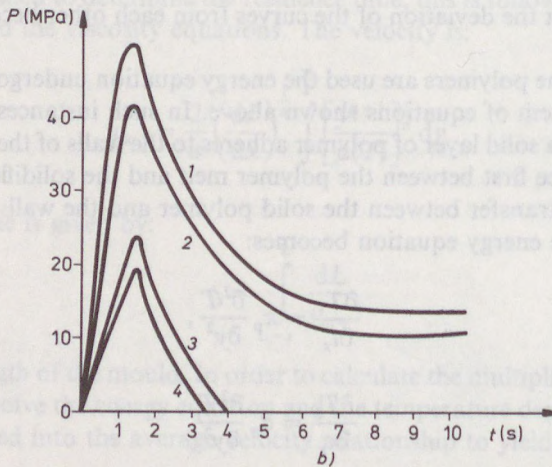
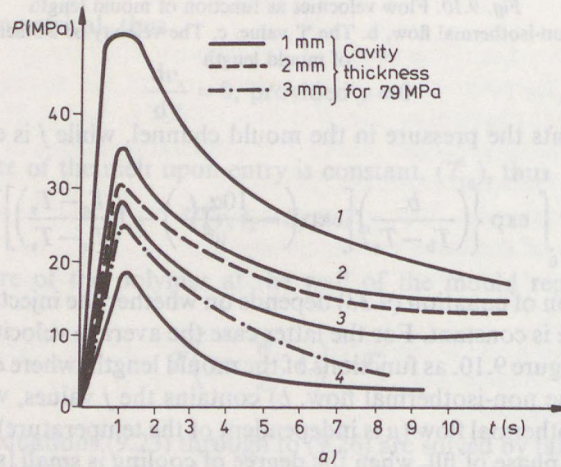


Fig. 9.11. The effects of injection pressure on the existing pressure in the mould
a) Polystyrene, 1. 158 MPa, 2. 79 MPa, 3. 72 MPa, 4. 62 MPa. b) Polyethylene, 1. 152 MPa, 2. 124 MPa, 3. 67.5 MPa, 4. 63.9 MPa

That part of the polymer that is in contact with the walls of the mould is at the same temperature as the mould. Thus:

$$T_2 = T_s, \quad \text{if } y = \frac{w}{2} \quad (9.38)$$

The temperature of the melt on entry into the mould is constant:

$$T_1 = T_2 = T_{\text{en}}, \quad \text{if } t = 0 \quad (9.39)$$

Hence, the solution given for equation (6.43) by taking into account the boundary conditions of equations (9.36) to (9.39) is:

$$y_0 = \frac{w}{2} - 2\beta \sqrt{t} \quad (9.40)$$

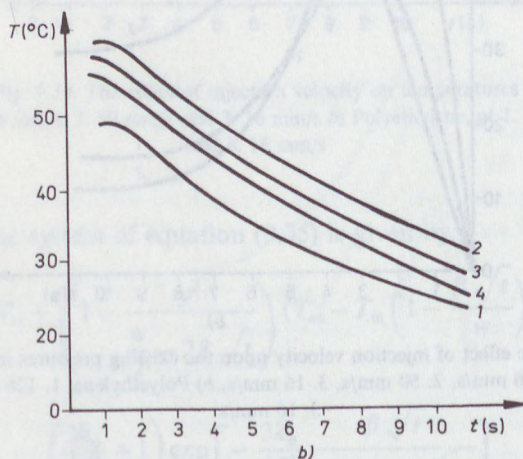
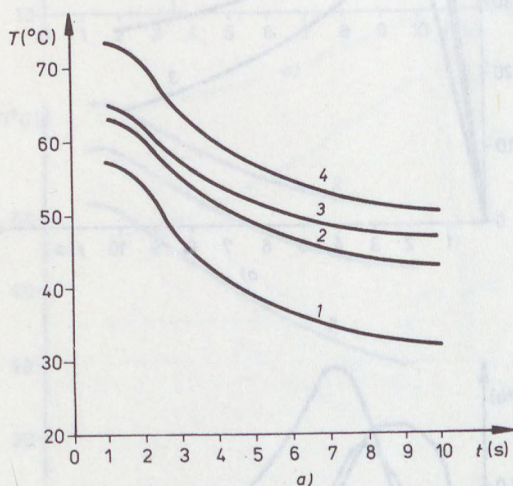


Fig. 9.12. Temperature curves as functions of injection pressure. Mould' temperature = 30°C
a) Polystyrene, b) Polyethylene. Curve numbers as in Fig.9.11.

where β is a constant which can be determined from the system of equations (9.35), dependent on the melting point of the material, on the heat conductivity, on the injection temperature of the polymer and on the wall temperature of the mould. The filling time $t_{\max}$ necessary to fill the maximum length of the mould $L_{\max}$, provided $y_0=0$, can be determined from equation (9.39).

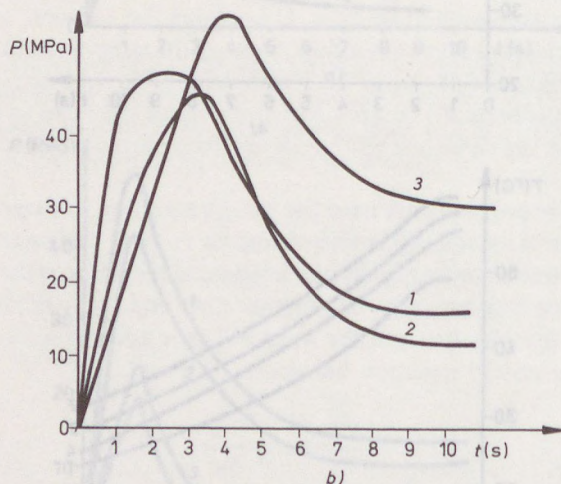
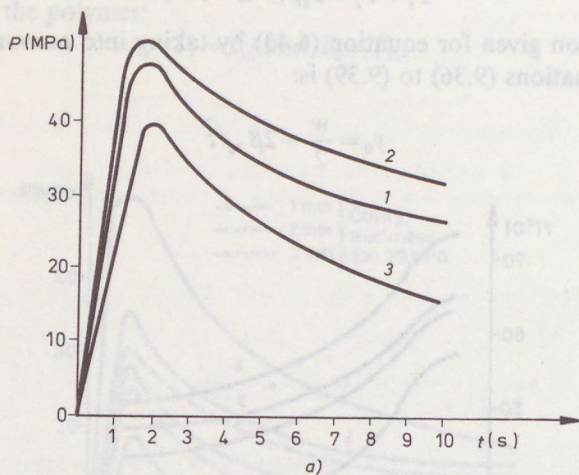
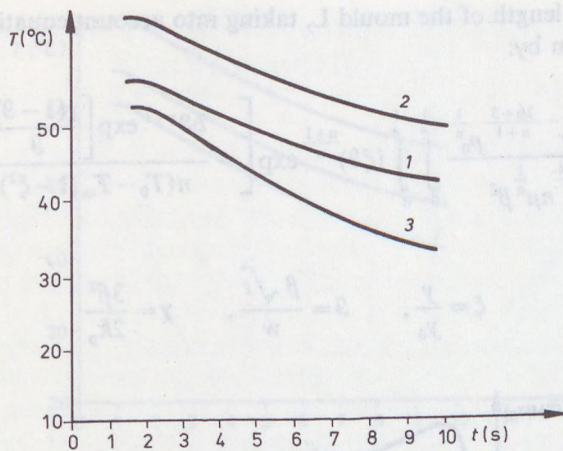
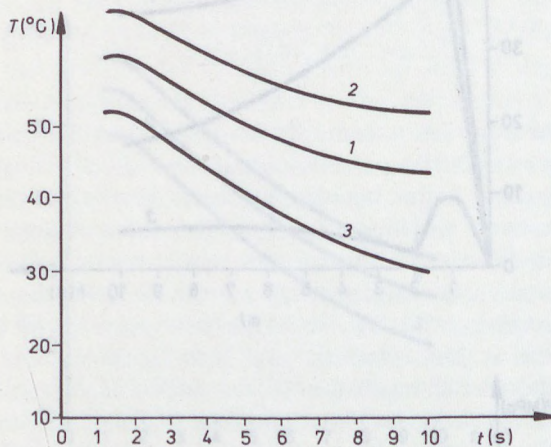


Fig. 9.13. The effect of injection velocity upon the existing pressures in the mould
a) Polystyrene, 1. 386 mm/s, 2. 50 mm/s, 3. 16 mm/s, b) Polyethylene, 1. 126 mm/s, 2. 35 mm/s, 3. 16 mm/s



a)



b)

Fig. 9.14. The effect of injection velocity on temperatures

a) Polystyrene, at 1. 386 mm/s, 2. 50 mm/s and 3. 16 mm/s b) Polyethylene, at 1. 126 mm/s, 2. 35 mm/s and 3. 16 mm/s

The solution of the system of equation (9.35) is given by:

$$T_1 = T_m + \left(1 - \frac{y^2}{\frac{w}{2} - 2\beta\sqrt{t}}\right) (T_{en} - T_m) \left(1 - \frac{\beta\sqrt{t}}{w}\right) - \left(\frac{3k_p}{2\beta^2} + 1\right) \exp\left[-\frac{3k_p}{2\beta^2} \frac{\beta\sqrt{t}}{w\left(1 - \frac{\beta\sqrt{t}}{w}\right)}\right] \quad (9.41)$$

The actual filling length of the mould L , taking into account equations (9.32), (9.33) and (9.40) is given by:

$$L = \left\{ \frac{(n+1)w^{-\frac{2n+3}{n+1}} p_0^{\frac{1}{n}}}{2^{\frac{3n+4}{n+1}} n \mu^{\frac{1}{n}} \beta^2} \int_0^1 \int_0^1 (\xi \vartheta)^{\frac{n+1}{n}} \exp \left[- \frac{b \vartheta^{x+1} \exp \left[\frac{\chi(1-\vartheta)}{\vartheta} \right]}{n(T_0 - T_m(1-\xi^2))} \right] d\xi d\vartheta \right\}^{\frac{1}{n+1}} \quad (9.42)$$

where

$$\xi = \frac{y}{y_0}, \quad \vartheta = \frac{\beta \sqrt{t}}{w}, \quad \chi = \frac{3\beta^2}{2k_p}$$

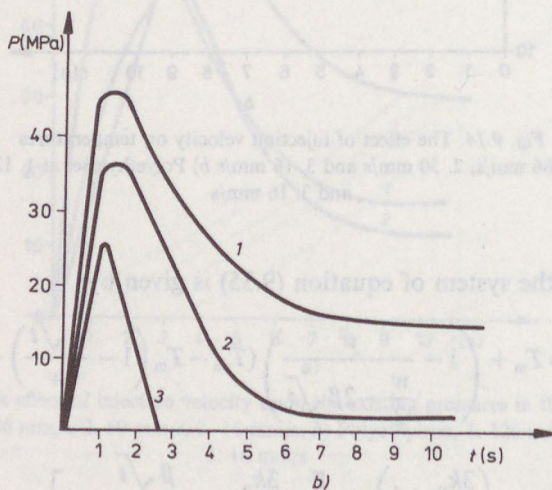
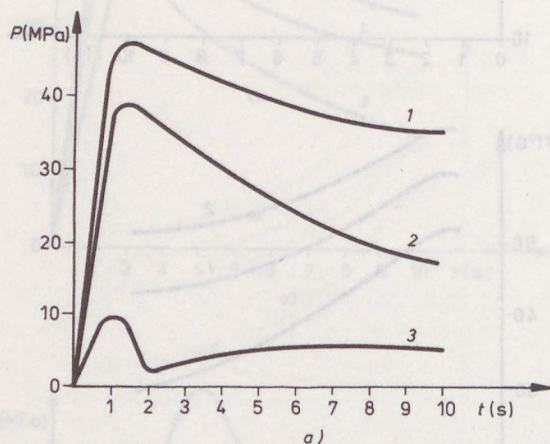


Fig. 9.15. The effects of the variation of the shot size on the mould pressure

a) Polystyrene, at 1. 7.2 g, 2. 6.2 g and 3. 5.8 g weights, b) Polyethylene, at 1. 5.8 g, 2. 5.3 g and at 3. 4.7 g weights

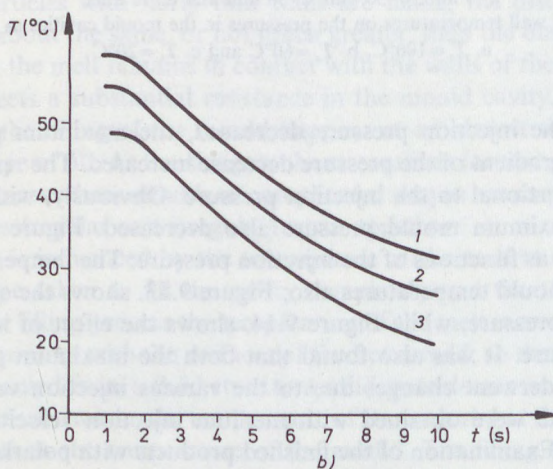
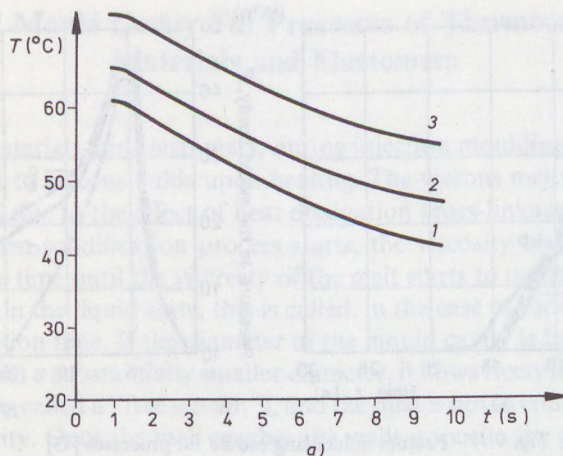


Fig. 9.16. The effects of the weight of the material added on the material temperature
a) Polystyrene, 1. 72. g, 2. 6.2 g b) Polyethylene 1. 5.8 g, 2. 5.3 g and 3. 4.7 g

The double integral above is evaluated numerically. Practical experience shows that the filling process is complete if the actual value of j is higher by a factor of 1.5–2 than its value at entry.

The majority of the models used in practice are numerical models.

Some of the author's own experimental results are now discussed. The mould investigated was a rectangular cavity mould with adjustable height. The entry of the melt took place at the centre of the shorter side, where one of the temperature sensors was positioned, opposite to this a manometer was positioned with a built-in temperature sensor.

Figure 9.11. shows the effect of injection pressure on the pressure in the mould, for three different mould thicknesses using polystyrene, for one mould thickness using

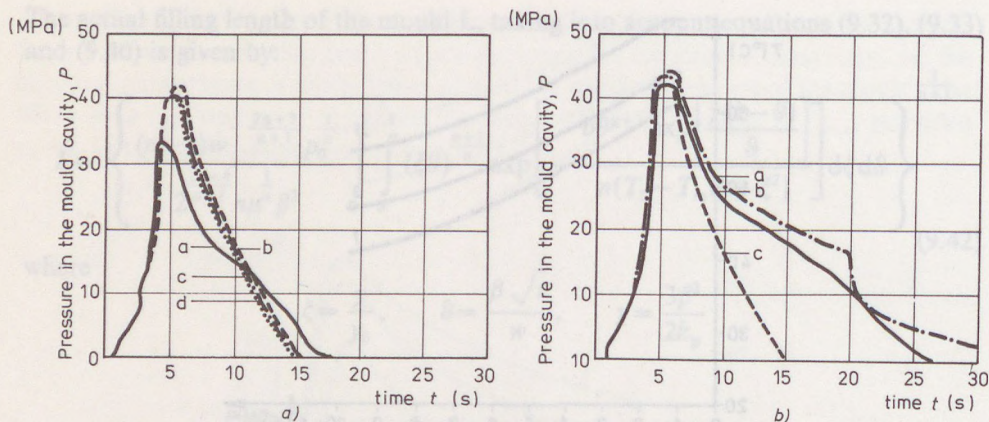


Fig. 9.17. Factors influencing mould fill processes [43]

- a) The effect of the size of the cushion on the pressure in the mould cavities with time, with cushion of a. 0 mm, b. 30 mm, c. 50 mm and d. 70 mm.
- b) The effect of mould wall temperatures on the pressures in the mould cavities as a function of time, a. $T_s = 100^\circ\text{C}$, b. $T_s = 60^\circ\text{C}$ and c. $T_s = 20^\circ\text{C}$

polyethylene. As the injection pressure decreased, the maximum pressure created decreased and the gradient of the pressure decrease increased. The remaining residual pressure was proportional to the injection pressure. Obviously, with increased wall thicknesses the maximum mould pressure also decreased. Figure 9.12. shows the temperature curves as functions of the injection pressure. The temperature curves are influenced by the mould temperatures also. Figure 9.13. shows the effect of injection velocity upon the pressure, while Figure 9.14. shows the effect of injection velocity upon the temperature. It was also found that both the maximum pressure and the pressure curves underwent changes due to the various injection velocities applied. Maximum pressures were obtained with medium injection velocities with highest residual pressures. Examination of the finished products with polarized light showed that greater injection velocity resulted in a greater degree of orientation. Figures 9.15. and 9.16. depict the effects of shot size changes within ranges so that the finished articles remained complete after injection. It is worth noting that with decreased quantities the pressure gradient also decreased drastically with time.

The effects of a cushion and mould temperature were examined by Reuss [43]. Just in front of the screw a cushion must remain after the development of the total injection pressure. The size of this cushion depends on factors such as the accuracy of the shot size, the temperature of the melt, and the efficiency of shut-off valve which impedes reverse flow. Figure 9.17.a) shows the effects of cushions of various dimensions on the pressure in the mould cavity. If the size of the cushion is approximately zero, in other words, if the movement of the screw is unhindered by the residual material, the effects of injection pressure and of the residual pressure are also negligible. The mould wall temperature also affects the pressure gradient as is shown by Fig. 9.17.b). The lower is the mould temperature, the more rapid is the decrease of pressure.

9.5.2 Mould Cavity Fill Processes of Thermosetting Materials and Elastomers

Thermosetting materials and elastomers, during injection moulding, are transformed from a solid state to viscous fluids upon heating. The viscous melts are injected into a hot mould, and due to the effect of heat dissipation cross-linkages are formed and they solidify. When solidification process starts, the viscosity of the melt increases substantially. The time until the viscosity of the melt starts to increase is the time the material remains in the liquid state; this is called, in the case of caoutchouc mixtures, the pre-vulcanization time. If the diameter of the mould cavity is large, the stream of material enters with a substantially smaller diameter, it flows freely in a relatively large space (hence this is called a “free stream”), and the melt is not in contact with the walls of the mould cavity. Once the melt reaches the walls opposite the gate, an irregular, turbulent flow develops, followed by solidification at an increasingly rapid rate. In instances when articles with fairly thin walls are made, the distance between the opposite walls is about the same, or not much greater, than the diameter of the gate, which means that the melt remains in contact with the walls of the die continuously. The melt flow meets a substantial resistance in the mould cavity, the melt front is deformed, hence the filling of the mould happens at an almost steady rate. This is called a regular type of fill. At the slot gate the streamlines formed are almost parallel to each other. In cases where moulds of complicated shapes are employed, both kinds of filling processes (regular and irregular) occur together.

The fill process is influenced by the temperature of the melt at entry, the velocity of the fill, the time taken to fill the cavity completely and the temperature of the mould. During the filling process the temperature of the melt increases due to intense deformation and contact with the surfaces of the hot mould, so the time taken for the melt to be transformed from a fluid state to a solid state decreases. Where articles of small wall thickness are made, the temperature of the material at the time of injection is usually higher than the temperature of the mould. The filling time of the mould cavity is inversely proportional to the average injection velocity. If the injection pressure is reduced, the average injection velocity also decreases. If the viscosity of the material increases, the time taken to fill the mould also increases. The fill time is inversely proportional to the resistance of the mould cavity and the resistance of the runner, the sprue and the gate. The filling time of the cavity and the time that the melt remains in the fluid state represent the basic parameters of the process and exert major influences upon the quality of the product.

In packing, after the filling of the mould cavity, the pressure increases, and this higher pressure prevents the absorption of small molecular weight substances and the formation of a porous material structure. At this phase the pressure in the mould equalizes. The pressure curves obtained are shown in Figure 9.18. The first phase (*I*) represents the mould fill phase, phase (*II*) is the packing phase, phase (*III*) is the hardening or the vulcanization phase. The relative maximum pressure value (at point 8), ranges from 2–4 MPa for elastomers, in cases where thermosetting materials are used these values are of the order of 20–40 MPa. In the packing phase the density of

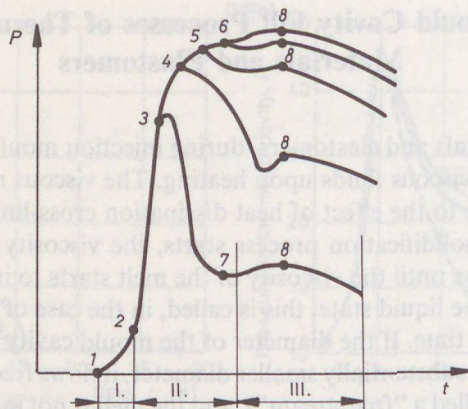


Fig. 9.18. Development of pressure in the mould using thermosetting materials for injection [42] 1-2 injection takes place, 2-3 fill of the mould, 3-4 total fill of the mould, 4-6 cross linking process under pressure, 7 the end of inward flow

the material in the runner and in the mould cavity undergoes slow changes, due to compressibility and due to heat expansion, while the axial movement of the screw becomes slower. In order to compensate for this phenomenon a higher pressure must be maintained and most of the modern machines can be switched to higher pressure to control the pressure in the packing phase. The magnitude of pressure and the length of the packing period are two basic technological features of this process. The packing phase is finished when the material in the gate begins to solidify and further material flow stops. The formation of the cross-linking structure may be controlled by adjusting the cure time, one of the characteristic features of the process. The cure time must be such that the optimum material structure of the product is obtained. The degree of the cross-linking is a decisive factor in the physical and mechanical properties of the product.

9.5.2.1 Jet-Stream Mould Filling Processes

The jet-stream filling processes take place in two stages. In the first stage the material flow from the runner to the mould takes the jet-stream with a cross section similar to that of the gate. As the melt flow reaches the end of the channel opposite the gate the configuration of the cross section of the jet-stream changes and takes up a coil shape. As a result, at this phase the pressure in the mould is $P \approx 0$, the speed of the process is governed by the combined resistance of the gate, sprue, runner system and of the nozzle. The first phase takes place under a constant injection pressure, P_i , while the volume flow, Q , remains constant. Towards the end of this first phase the density of the flowing material increases. In the second phase the entrapped air in the melt is expelled, the density of the melt increases, the pressure $P_0(t)$ begins to rise and by the end of the filling process the pressure reaches the value P_v . The part-process of mould filling can be regarded as isothermal due to the minute degree of heat dissipa-

tion and the low conductivity of polymers. The degree of mould filling is expressed by porosity β (the ratio of entrapped air and the material per unit volume), and the mould filling velocity can be characterized by the rate of decrease of the porosity of the material. The pressure in the mould during the first phase of the process, $P_0(t)$, is the same throughout the mould cavity. In general, the degree of porosity is below the value of $\beta^* \approx 0.2$, which according to experimental data, characterizes the end of the first phase of the mould filling process.

The characteristic volume flow rate of these two stages is given by:

$$Q = -V_m \frac{d\beta}{dt} \quad (9.43)$$

where V_m is the volume of the mould.

The characteristic porosity volume change of the process is expressed as:

$$\frac{d\beta}{dt} = \frac{-\beta P_0}{\mu \Psi(\beta)} \quad (9.44)$$

where $\Psi(\beta) = \Psi_0$ if $\beta \rightarrow 0$. The function describes the compactness of the arrangement of the particles. As a general rule $\Psi(\beta) \approx 1.15$. Expressing the shearing rate by the change of the pore volume and describing the viscosity in terms of the power law, equation (9.43) takes the form:

$$-\frac{d\beta}{dt} = \left[\frac{\beta P_0}{\Psi \mu_1 (1-\beta)^{1-n}} \right]^{\frac{1}{n}} \quad (9.45)$$

Here, the term $P_0 = P_0(t)$ is a time function and is dependent on the external injection pressure and on the pressure drop of the melt flow through the nozzle, the runner and the gate. Experimental results show that $\Delta P = P_f - P_0 \approx \omega P_f$, where the value of ω is constant. The volume flow rate is given by:

$$Q = \mu_1 [P_f(1-\omega) - P_0]^{\frac{1}{n}} \quad (9.46)$$

The pore-volume change in the first phase is given by:

$$V \frac{d\beta}{dt} = \mu_1 [P_f(1-\omega)]^{\frac{1}{n}} \quad (9.47)$$

Solving the equation with the initial condition $\beta(0) = 1$ in the region of $0 \leq t \leq t^*$:

$$t^* = V(1-\beta^*) \{ \mu_1 [P_f(1-\omega) - 1] \}^{\frac{1}{n}} \quad (9.48)$$

In the second phase (when $t > t^*$) the initial conditions are:

$$\beta(t=t^*) = \beta^* \text{ and } P_0(t=t^*) = P_0^*$$

being the parameters at the end of the first phase. Figure 9.19. depicts the development of pressure.

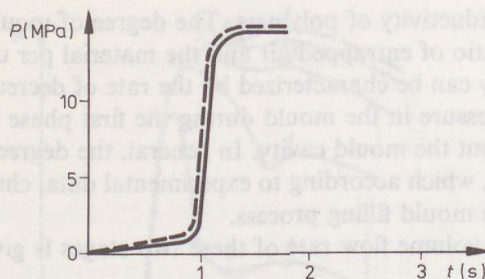


Fig. 9.19. The characteristic curve illustrating the mould fill process using thermoplastic material
The mould fill pressure versus time, where —: calculated values,
---: experimental values

9.5.2.2 Regular Mould Filling

The process of regular mould filling also takes place in two phases. The first phase lasts until the melt reaches the opposite wall of the mould and hence, filling is complete. Pressure increase occurs in the second phase. The process is well illustrated by Figure 9.20. In the first phase the melt slows down due to its contact with the walls of the mould and moves forward in a plug-like flow with a given pore volume given by $\beta = \beta^* = 0.2$.

In instances when thermosets are used one of the features of the process is the sliding of the material along the walls of the mould. The characteristic parameters of the mould filling process are the pressure, $P(x, t)$, the velocity, $v(x, t)$ and the porosity $\beta(x, t)$.

The continuity equation is:

$$-\frac{\partial \beta}{\partial t} + V \frac{\partial(1 + \beta)}{\partial x} = 0 \quad (9.49)$$

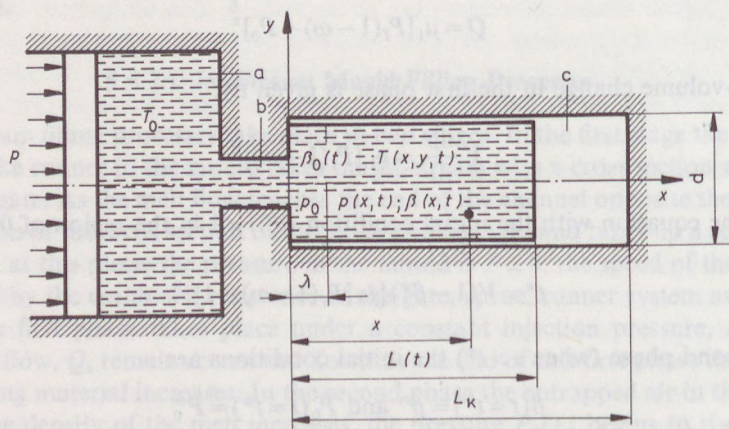


Fig. 9.20. A regular mould fill process using thermoplastic materials
a. the melt reservoir in front of the screw, b. runner and sprue, c. cavity of the mould

the momentum equation is given by:

$$(1 - \beta)\mu v^s = -\frac{H}{2} \frac{\partial P}{\partial x} \quad (9.50)$$

the boundary conditions are:

$$\begin{aligned} \beta(x=0) &= 0 & \beta(x=l_1) &= \beta_0 \\ v(x=0) &= \frac{Q}{WH}; & v(x=l_1) &= v \end{aligned} \quad (9.51)$$

thus, the continuity equation derived for the mixing zone for section l_1 is given by:

$$\beta H \left[1 - \beta_0(t) \frac{dl}{dt} \right] = k_f [P(1 - \omega) - P_0]^{\frac{1}{s}} \quad (9.52)$$

Solving the momentum equation using boundary conditions of:

$$P(-\infty < x < \infty) = P(x, t) \text{ and } P(x=l(t)) = 0$$

gives:

$$P(x, t) = \frac{2}{H} \mu (v_x(t))^n \int_x^{l(t)} \beta(x, t) dx \quad (9.53)$$

substituting the new coordinate $d[l(t) - x] = -dx$ the pressure on entry into the mould is expressed as:

$$P_0(t) = \frac{2}{H} \mu \left[\frac{dl(t)}{dt} \right]^n \left\{ \int_0^t l(t) - \int_0^{l(t)} \beta_0[l(t) - x] \frac{dl(t)}{dt} \right\} dt \quad (9.54)$$

where

$$v_x(t) = v(t) = \frac{d[l(t) - x]}{dt}$$

Introducing the dimensionless quantities:

$$\begin{aligned} \pi_p &= \frac{P_0(t)}{P(1 - \omega)} \\ \pi_t &= \frac{[P(1 - \omega)]^{1/n}}{\Psi_0 \mu} t; \\ \pi_L &= \left\{ \frac{2\mu}{P(1 - \omega)d} \left[\frac{P(1 - \omega)}{\Psi_0 \mu} \right]^{s/n} \right\}^{\frac{1}{1+n}} l(t) \end{aligned} \quad (9.55)$$

and the expression:

$$F_1 = \frac{1}{b} \left(\frac{2}{H} \right)^{\frac{s+2}{s+1}} (\mu \phi_0)^{\frac{1}{n(s+1)}} [\mu(T)]^{\frac{1}{s}} k_f^{\frac{1}{s(s+1)}} [p(1 - \omega)]^{\frac{n-s}{ns(1+s)}} \quad (9.56)$$

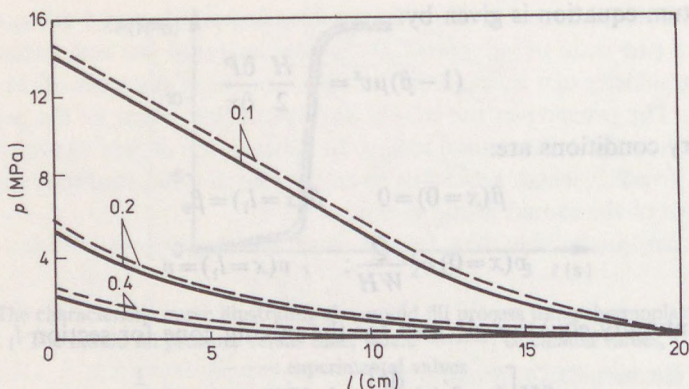


Fig. 9.21. Pressure vs. channel length relationship curves in mould of various thicknesses, using pheno-plast mixtures at 160°C
—: calculated values
---: experimentally obtained values

the equations will assume the following shapes:

— the pore change in the region $x = l_1$:

$$-\frac{d\beta_0}{d\pi_L} = \left[\frac{\beta_0 \pi_p}{(1-\beta_0)^{1-n}} \right]^{\frac{1}{n}} \quad (9.57)$$

— the pressure:

$$\frac{\pi_p(1-\beta_0)}{1-\pi_p} = F_1^{\frac{s+1}{s}} \int_0^{\pi_l} (1-\pi_p)^{\frac{1}{s}} d\pi_l \quad (9.58)$$

— the change of the length of the section filled with the melt is:

$$\frac{dl}{d\pi_T} = F_1 \left(\frac{1-\pi_p}{1-\beta_0} \right)^{\frac{1}{s}} \quad (9.59)$$

The boundary conditions to solve the system of equations given above are:

$$\pi_l = 0; \quad \pi_L(t=0) = 0 \quad \text{and} \quad \beta_0(t=0) = \beta_* = 0.2$$

The solution may be obtained numerically. The above system of equations can be made applicable to the second phase by using the boundary condition $v(x=L)=0$.

Figure 9.21. compares the calculated and measured values of $P(l)$.

9.6 The Processes of Packing and Hardening

During the packing stage the density and pressure of the material in the mould increases. The process of hardening of the material under pressure begins when the

material in the gate becomes solid. During the hardening process the viscosity of the material increases, the material acquires a solid state upon cooling or by forming a cross-linked structure.

9.6.1 Packing and Solidification of Thermoplastics

The solidification of amorphous thermoplastics takes place by cooling below the glass temperature, while solidification in the case of crystalline materials takes place by cooling below their crystallization temperatures. In the case of the former group the viscosity of the melt increases gradually during cooling, while in the case of crystalline materials the viscosity increases at a sudden rate near the crystallization temperature.

Due to the small flow velocity, the dissipation and heat transfer across the wall can be ignored, thus, the energy equation is:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial y^2} \quad (9.60)$$

the initial and the boundary conditions are:

$$T(t=0) = T_0, \quad T(y = \pm H/2) = T_m \quad \text{and} \quad \frac{\partial T}{\partial y}(y=0) = 0 \quad (9.61)$$

— the momentum equation is:

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_{yx}}{\partial y} \quad (9.62)$$

with boundary conditions:

$$P(x=0) = P_0 \quad \text{and} \quad P(0 < x < L) = P(x, t) \quad (9.63)$$

— the continuity equation is given as:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x} \bar{\rho} \bar{V} = 0 \quad (9.64)$$

where $\bar{\rho}$ is the averaged melt density for the cross section, while $\bar{V}$ is the average velocity, expressed as follows:

$$\bar{\rho} = \frac{2}{H} \int_0^{H/2} \rho(y) dy; \quad \bar{V} = \frac{2}{H} \int_0^{H/2} v(y) dy \quad (9.65)$$

The pressure dependence of average density expressed in terms of the Spencer-Gilmore relationship is:

$$\bar{\rho} = \frac{2}{H\omega} \int_0^{H/2} \frac{P + \pi}{(P + \pi) + \frac{RT}{M\omega}} dy \quad (9.66)$$

where ω and π are constants, characteristic of the polymer used.

The solution of the momentum equation is:

$$v = \left(\frac{1}{\mu}\right)^{\frac{1}{n}} \left(-\frac{\partial P}{\partial x}\right)^{\frac{1}{n}} \int_y^{H/2} y^{\frac{1}{n}} \exp\left[-\frac{b}{n(T-T_0)}\right] dy \quad (9.67)$$

The balance equation system may be solved numerically, or, in some simple cases in an exact way. The following dimensionless quantities are substituted into the above relationship:

$$\begin{aligned} Y &= \frac{2y}{H}; & X &= \frac{2x}{H}; & \Phi &= \frac{P(x, t) + \pi}{P_0 + \pi} \\ \tau &= \frac{(H/2)^2 t}{a}; & \Theta &= \frac{T(Y, t)}{T_w}; & \bar{\Theta} &= \frac{\bar{T}}{T_w} \end{aligned} \quad (9.68)$$

The solution of the momentum equation has the form:

$$\Phi(X, \tau) = e^{-\lambda(\tau)X} \quad (9.69)$$

with initial and boundary conditions of:

$$\begin{aligned} \Phi(\tau, X=0) &= 1; & \Phi(X, \tau) &= e^{-\lambda_0 X} \\ \frac{\partial \Phi}{\partial X} \left(X = \frac{2L}{H}\right) &= 0 \end{aligned} \quad (9.70)$$

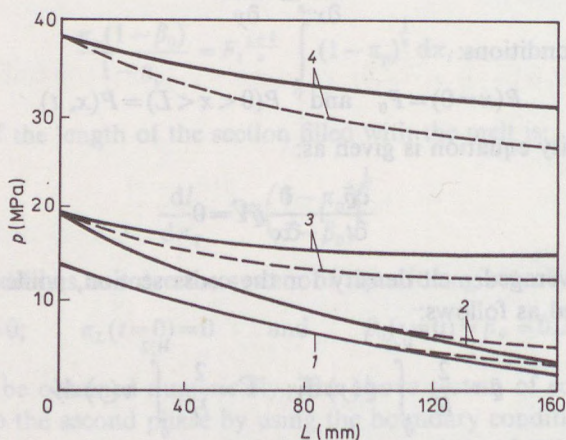


Fig. 9.22 Pressure vs. channel length relationship curves for phenoplastics

— : calculated values
 --- : experimentally obtained values

Number	T_0 (in °C)	P_t (in MPa)	P_0 (in MPa)	H (in mm)	t^* (s)
1	170	43.5	12.6	4	2.5
2	210	34.5	20.0	2	1.5
3	210	38.5	20.0	4	3.0
4	210	62.5	37.5	4	3.8

and

$$\lambda(\tau) = \Theta(\tau)^{-1} \left[\left(\frac{T_w/T_0}{\lambda_0(\tau)} \right)^{\frac{1+n}{n}} - \frac{1-n}{n} \int_0^\tau \left(\frac{\Theta(\tau)}{F_2(\tau)} \right)^{\frac{-2+n}{n}} d\tau + \frac{n+1}{2(2n+1)} \int_0^\tau \frac{F_3(\tau)\Theta(\tau)}{F_2(\tau)} d\tau \right]^{\frac{-n}{n+1}} \quad (9.71)$$

where

$$F_2(\tau) = \frac{4a\mu^{1/n}}{(P_0 + \pi)^{1/n} H^2} \left\{ \Theta(\tau)^{1-\frac{1}{n}} \left[\int_0^1 Y^{\frac{1}{n}} \exp \frac{-b dY}{nT_w[\Theta(\tau)-1]} \int_0^Y \Theta(\tau) dY \right]^{-1} \right\} \quad (9.72)$$

$$F_3(\tau) = \frac{(P_0 + \pi)M\omega}{T_w R} \left\{ \Theta(\tau) \frac{\int_0^1 Y^{\frac{1+n}{n}} \exp \frac{-b}{nT_0[\Theta(\tau)-1]} dY}{\int_0^1 Y^{\frac{1}{n}} \exp \frac{-b dY}{nT_w[\Theta(\tau)-1]} \int_0^Y \Theta(\tau) dY} \right\} \quad (9.73)$$

The values of $\Theta(\tau, Y)$ may be determined from the heat conduction equation. Figure 9.22. gives the calculated and experimental values.

9.6.2 The Cooling Processes of Thermoplastics

Due to the low conductivity of the polymer melt, the cooling phase forms the main part of the moulding cycle.

Considering the macro-balance of heat transfer (see Figure 9.23.), the heat flow between the injection mould and its surrounding environment may be expressed by the following equation:

$$Q_p = Q_c + Q_r + Q_s + Q_n \quad (9.74)$$

where Q_p represents the heat flow from the molten polymer to the mould, thus:

$$Q_p = \frac{m_p}{t_c} \int_{T_{ej}}^{T_{inj}} C_p(T) dT \quad (9.75)$$

where m_p is the mass of the product, t_c is the cycle time, $C_p(T)$ is the temperature-dependent specific heat of the polymer, while T_{inj} and T_{ej} are the respective injection and ejection temperatures.

Q_c is the heat flow from the mould to the heat transfer medium:

$$Q_c = \alpha A (T_{s, ch} - T_c) \quad (9.76)$$

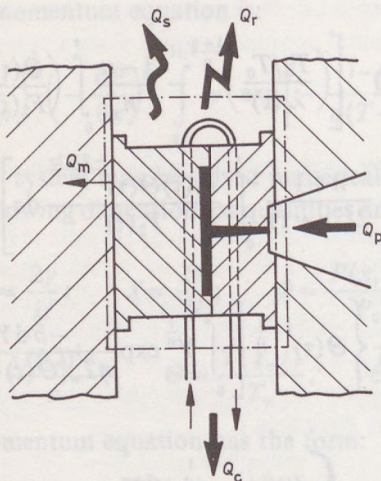


Fig. 9.23. Macro balance of heat transfer in an injection mould

where α is the convection coefficient, A is the surface area of the cooling channels, $T_{s, ch}$ is the average surface temperature of the cooling channel, and T_c is the averaged temperature of the cooling medium. On the other hand, the heat flow Q_c can also be expressed in terms of the coolant as:

$$Q_c = C_c \dot{m}_c (T_{out} - T_{in}) \quad (9.77)$$

where C_c and $\dot{m}_c$ represent the specific heat and the mass flow of the cooling medium, T_{in} and T_{out} are the inlet and the outlet temperatures of the cooling medium.

The radiative heat flow, Q_r , may be expressed by the Stefan-Boltzmann law of radiation. The radiative heat flow is very small (2–5% of the total heat flow) and hence, may be neglected in the majority of cases for the heat transfer calculations.

The heat flow due to conduction, Q_m from the mould to the injection moulding machine can be calculated from the expression:

$$Q_m = k_m A_m \frac{T_m - T_{mm}}{s} \quad (9.78)$$

where k_m and A_m are the heat conductivity and the fixing area of the base plates of the mould, T_{mm} is the temperature of the injection moulding machine at the mould fixing point, and s is the thickness of the base plate. Q_m can be reduced to almost zero by using special isolation plates between the mould and the machine.

The heat flow, Q_s , on the mould surface can be expressed by the equation:

$$Q_s = \alpha_s A_s (T_m - T_s) \quad (9.79)$$

where α_s is the convection coefficient of the mould surface and other terms are defined as above. Convection on the mould surfaces and conduction into the moulding machine are of only minor importance, accounting for 5–15% of the total heat flow.

Heat transfer from the polymer melt to the mould takes place by conduction. This may be described by the energy equation, which has been solved by using various methods and boundary conditions [59–70]. Due to the importance of the cooling design, several computer programmes are available now, to control cooling [62–65]. Most of them are based on a semi-analytical treatment of the heat transfer problems. One approach is to divide the mould into several cooling segments and a one-dimensional steady-state solution of the heat transfer problem is applied to each segment. New, more advanced solution methods are introduced, based either on two-dimensional finite differences, or on finite elements [70].

The different times, characterizing the solidification processes, need to be calculated, based on the cooling model. The analysis is intended to generate estimates of t_{cool} , t_{eq} and t_{gf} . Here, the cavity is approximated as a finite disc. The melt, occupying the cavity is initially at a temperature T_{melt} , and the cavity surfaces are at T_{mould} . It is further assumed that the boundary temperature remains constant throughout the moulding cycle. The energy equation is:

$$a \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] = \frac{\partial T}{\partial t} \quad (9.80)$$

where a is the thermal diffusivity of the polymer. The solution to this isothermal boundary problem is well known [69]:

$$\begin{aligned} \frac{T - T_{\text{mould}}}{T_{\text{melt}} - T_{\text{mould}}} = & \frac{8}{\pi R} \sum_{n=0}^{\infty} \sum_{m=1}^{\infty} \left\{ \frac{(-1)^n J_0(r\beta_m)}{(2n+1)\beta_m J_1(R\beta_m)} \times \right. \\ & \left. \times \cos \left[\frac{(2n+1)\pi y}{H} \right] \exp \left[-at \left[\beta_m^2 + \frac{(2n+1)^2 \pi^2}{H^2} \right] \right] \right\} \end{aligned} \quad (9.81)$$

where J_0 and J_1 are the zeroth and the first-order Bessel functions, and β_m are the roots of the zeroth order Bessel function.

The time t_{cool} represents the time at which the material solidifies in the cavity, this is achieved as soon as the temperature exceeds the glass transition temperature, T_g , at the centre of the cavity. Thus, substituting $T = T_g$ and $r = z = 0$ into equation (9.81) gives the following relationship for t_{cool} :

$$\begin{aligned} \frac{T_g - T_{\text{mould}}}{T_{\text{melt}} - T_{\text{mould}}} = & \frac{8}{\pi R} \sum_{n=0}^{\infty} \sum_{m=1}^{\infty} \frac{(-1)^n}{(2n+1)\beta_m J_1(R\beta_m)} \times \\ & \times \exp \left\{ -at_{\text{cool}} \left[\beta_m^2 + \frac{(2n+1)^2 \pi^2}{H^2} \right] \right\} \end{aligned} \quad (9.82)$$

In a similar way an equation for t_{eq} can also be derived by substituting $t = t_{\text{eq}}$, $r = z = 0$ and $T = T_{\text{mould}} + 1$.

The gate freeze-off time, t_{gf} is equal to t_{cool} . The thermal boundary conditions for the gate are somewhat different from those for the cavity. The gate is usually represented as a short cylinder open at both ends. Thus, the heat transfer along the

gate axis will be much smaller than in the radial direction, hence, the gate may be considered as a cylinder of infinite size, i.e., H , the gate length is given some arbitrarily large value, and equation (9.81) is solved for $t_{\text{cool}} = t_{\text{gf}}$, for a specific gate radius.

9.6.3 The Packing and the Curing Process of Thermosetting Materials

Concurrently with the packing process, formation of the cross-linkages commences.

Due to the cross-linking process it is necessary to modify the energy equation, thus:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial y^2} + \frac{q_0}{\rho c_0} \frac{\partial \xi}{\partial t} \quad (9.83)$$

where q_0 represents the quantity of heat liberated during curing.

The cross-linking reaction is expressed by the equation:

$$\frac{\partial \xi}{\partial t} = k_0 e^{\frac{-u}{RT}} (1 - \xi)^m \quad (9.84)$$

Due to cross-linking, the rheological state equation is modified:

$$\eta = \eta_0(0) \varphi(\xi) e^{\frac{U_T}{RT}} \left(\frac{\dot{\gamma}}{\dot{\gamma}_0} \right)^{\frac{1-k}{k}} \quad (9.85)$$

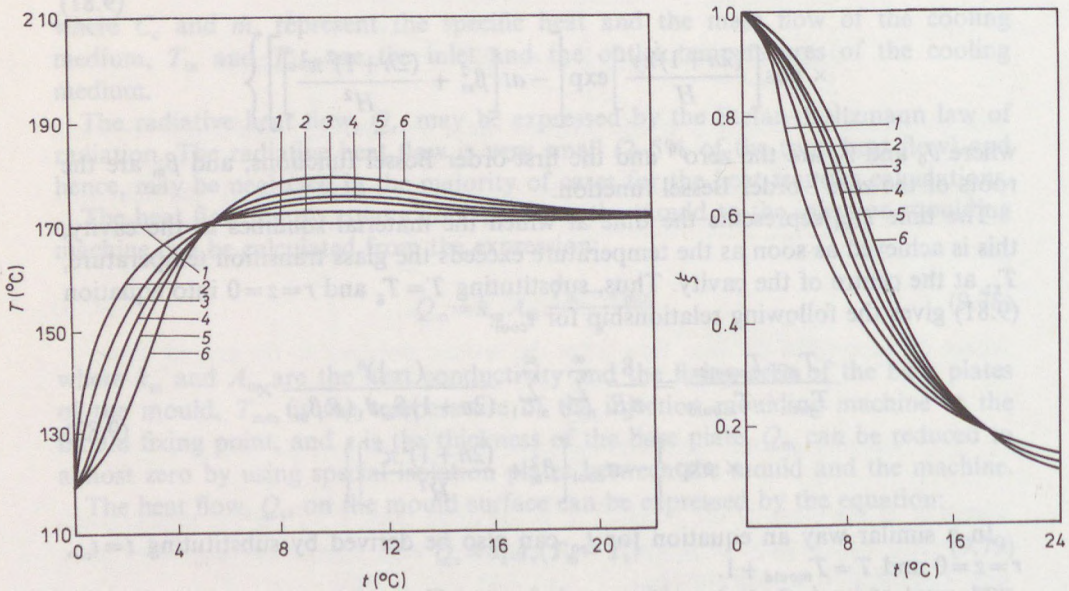


Fig. 9.24. Temperature distribution in the mould during the curing process of phenoplastic material

$T_m = 170^\circ\text{C}$, $T_0 = 125^\circ\text{C}$, $H = 2 \text{ mm}$

1. 0.5 H, 2. 0.4 H, 3. 0.3 H, 4. 0.2 H, 5. 0.1 and 6. 0.0 H.

$$\varphi(\xi) = \begin{cases} 1; \xi \leq \xi_* \\ 1 + \frac{(\xi - \xi_*)^{n_1}}{(1 - \xi)^{n_2}}; \xi \geq \xi_* \end{cases} \quad (9.86)$$

At ξ_* degree of cross-linking, the viscosity suddenly increases.

The energy equation, in conjunction with the chemical reaction, is solved numerically. Figure 9.24. shows some of the results obtained. Examination of the temperature curves leads to the conclusion that due to the exothermic nature of cross-linking the temperature of the melt will be higher than that of the walls of the mould.

Knowing $T(t, y)$ and $\xi(t, y)$ it is possible to solve equations (9.62) to (9.64), using initial and boundary conditions as follows:

$$P(x=0) = P_0; \quad \frac{\partial P}{\partial x}(x=L) = 0; \quad P(t=0) = P_0(x)$$

Due to the modification of the rheological state equation the average velocity becomes:

$$\bar{V} = \left(\frac{\partial p}{\partial x} \right)^k \left(\frac{H}{2} \right)^{k+1} \frac{\dot{\gamma}_0^{1-k}}{\eta_0(0)^k} b(t') \quad (9.87)$$

where

$$b(t') = \int_0^1 \frac{(y)^{k+1}}{\varphi(\xi)^k} e^{-\frac{U_T k}{RT}} dY \quad (9.88)$$

$$t' = \frac{4a}{H^2} t$$

The continuity equation is:

$$\frac{\partial \pi_p}{\partial t'} = \frac{K \dot{\gamma}_0^{1-k} p_0^{k-1} (H/2)^2 b(t')}{\eta_0(0)a} \frac{\partial}{\partial x} \left(\frac{\partial \pi_p}{\partial x} \right) \quad (9.89)$$

Introducing the new variable:

$$L = \int_0^{t'} \frac{b(t') K \dot{\gamma}_0^{1-k} p_0^{k-1} (H/2)^2}{\eta_0(0)a} dt' \quad (9.90)$$

the form of equation (9.89) becomes

$$\frac{\partial \pi_p}{\partial L} = \frac{\partial}{\partial x} \left(\frac{\partial \pi_p}{\partial x} \right)^k \quad (9.91)$$

with the following initial and boundary conditions:

$$\pi_p(L=0) = \pi_{p_0}(x); \quad \pi_p(x=0) = 1$$

$$\frac{\partial \pi_p}{\partial x}(x=L) = 0$$

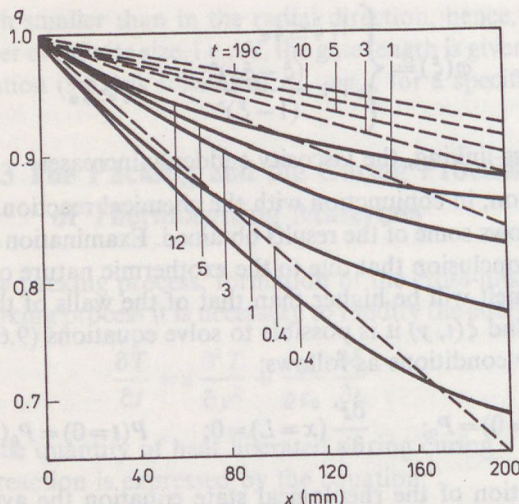


Fig. 9.25. The dimensionless pressure as a function of the channel length (note: the dashed lines are calculated values)

$T = 190^\circ\text{C}$, $H = 4$ mm, $P_i = 80$ MPa. The numbers alongside the curves denote the times (expressed in seconds)

The solution of the differential equation is:

$$\pi_p = \begin{cases} 1 - \left(\frac{k-1}{2k} \right)^{\frac{1}{k-1}} \int_0^\mu (\mu_0^2 - \mu^2)^{\frac{1}{k-1}} d\mu; & \mu < \mu_0 \\ 0; & \mu \geq \mu_0 \end{cases} \quad (9.93)$$

where

$$\mu = \left(\frac{1}{k+1} \right)^{1/(k+1)} \frac{x}{(L + L_0)^{1/(k+1)}} \quad (9.94)$$

and

$$\mu_0 = \left(\frac{2k}{k-1} \right)^{\frac{1}{k+1}} \left[\int_0^1 (1-v^2)^{\frac{1}{k-1}} dv \right]^{-\frac{k-1}{k+1}} \quad (9.95)$$

The constant, L_0 , may be determined from the initial pressure distribution.

The steps in solving the system of equations are:

- determination of the terms $T(y, t)$ and $\xi(y, t)$,
- determination of $b(t)$,
- calculating L ,
- calculating μ , in order to do this the value of L must be chosen,
- calculating π_p .

The calculated versus experimental values are shown in Figure 9.25.

9.7 Qualitative Characteristics of the Products Made by Injection Moulding and their Relationship to Technological Parameters

The most important quality aspects of the products are the size, shape, the strength indices and the surface properties of the articles made by injection moulding. Related to the above properties are the shrinkage, the internal stresses, the state of orientation and the fine structure of the article. This latter list of properties are considered in relationship to the manufacturing parameters employed.

Shrinkage of the product is one of the most important factors that determines the standard deviation of the size of products made by injection moulding [71 to 78].

9.7.1 Shrinkage of Injected Articles

In the case of thermoplastics and elastomers thermal and structural shrinkages can be distinguished. The thermal shrinkage of plastic materials is governed by the fact that their volume decreases during cooling in an extent determined by the linear heat expansion factor and the compressibility factor. The structural shrinkage is related to the reduction of volume which occurs in the material during cooling and is connected with crystallization, orientation and relaxation disorientation.

In principle the thermal shrinkage can be calculated from the differences in the volume heat expansion factor and the compressibility factor at the time of injection moulding and the removal from the die. This, however, is not a practical approach since the above coefficients are constant only in narrow ranges of temperature and pressure.

Shrinkage is given by:

$$S_v = \left(1 - \frac{V_p}{V_m}\right) = 1 - (1 - S_L)(1 - S_w)(1 - S_T) \quad (9.96)$$

where V_p is the volume of the injected article, V_m is the volume of the die, S_L is the shrinkage in the lengthwise direction, S_w is the shrinkage of the width, and S_T is the shrinkage in thickness of the article.

The degree of shrinkage is decisively influenced by the pressure and temperature in the mould.

The degree of shrinking of crystalline polymers is greater than that of amorphous polymers. The crystallization process takes place at a slow rate. The development of the super-molecular structure also involves volume changes during the injection process. At slow rates of cooling, larger crystalloids and larger spherulites are formed, while the residual stresses, the degree of crystallization and the density and shrinkage will be greater. The crystallization degree of the material, apart from the degree of shrinkage, also affects the mechanical, chemical and dielectric properties of the product.

The average shrinkage may be expressed by Spencer–Gilmore state equations:

$$\bar{S} = 1 - \sqrt[3]{Y} \quad (9.97)$$

and

$$Y = \frac{MV_0(P + \pi_1)}{RT + M\omega(P + \pi_1)} \quad (9.98)$$

where V_0 represents the volume of the polymer at room temperature and normal pressure, M is the molecular weight of the polymer, ω is a constant which is temperature and pressure dependent, and π_1 is the internal pressure. Equation (9.98) provides only a limited scope in practical application since it does not include the effects of crystallization, orientation and relaxation. The equation is suitable for the calculation of thermal shrinkage.

The tolerances of the plastic article made are determined by three factors, namely, the size and the tolerance of the mould and the shrinkage [72 and 77], expressed mathematically:

$$2\delta = 2\Delta + H(S_{\max} - S_{\min}) \quad (9.99)$$

where 2δ is the nominal tolerance range of the plastic article, 2Δ is the corresponding tolerance range of the die, and the difference $S_{\max} - S_{\min}$ represents shrinkage. The size tolerance is thus obviously related to shrinkage.

Two of the most important aspects that govern the plasticating processes are the average temperature and the homogeneity of the melt in front of the tip of the screw. With increased average temperature of the melt the standard deviation of the size and the weight of the article is reduced. The die temperature plays an important role where partially crystalline thermoplastics are used in injection moulding. The die temperature, together with the material temperature and the injection velocity exerts a decisive influence on the partially crystalline structure and orientation of the material of the article. The degree of post shrinkage is a measure of the degree of orientation and of the crystalline equilibrium. With increased mould temperature the degree of post shrinkage is also reduced.

The injection pressure applied must be high enough to fill the mould with the melt: this pressure ceases, or is switched to post pressure, on termination of the injection. At this pressure the article begins to solidify, and the residual post pressure thus partly compensates for volume shrinkage. The magnitude of post pressure exerts a substantial influence on the mechanical properties of the injected article. On application of excessive pressures considerable internal stresses may occur, conversely, if the applied pressure is excessively small, depressions result in the finished article.

The packing time continues to influence the shrinkage of the injected article until the melt is solidified at the gate. It therefore follows that one can adjust the packing time such that the weight of the resulting article becomes the maximum possible. This optimum packing time is a function of the material temperature, the mould temperature, the wall thickness and the size of the melt stream upon entry. The size of the gate must be chosen so that the thickness of the solidified material is at least two thirds the thickness of the wall. Under such conditions, i.e. with a given injection pressure and various wall thicknesses, the degree of shrinkage of the article remains nearly the

same. The injection time should be reduced to the minimum since, generally, a rapid injection results in a smaller degree of orientation in the finished product. Where the size of the nozzle and the cross sectional area of the gate are excessively small (i.e. a needle gate is employed), the molecular chains of the thermoplastics may degrade due to temperature increase due to excessive injection velocities. Correspondingly, the strength of the injected article is reduced, together with its resistance to corrosion. The velocity of injection does not, however, influence size tolerances of the article made.

Shrinkage of Thermosetting Materials

Shrinkage of thermosetting materials depends on the type of material used, on the quality of the filler and other auxiliary materials used, on the interaction of the resin with the additives, on the preparatory steps in making the mixture and on the shaping process employed. The degree of shrinkage is determined by the processes which take place in the plasticating unit and in the closed mould, from the production of the melt to the filling of the mould, from the course of the curing process through to formation of by-products. The volume deformation of thermosetting materials may be described by the same kind of relationships as for thermoplastics.

The volume changes of thermosets occur in the short time between the closure of the mould and the removal of the product from the mould. After reduction of pressure the material "remembers" the compression during mould filling and packing and the deformation of the filler. Furthermore, at this moment the product suffers a thermal shock (the actual temperature difference is 150–180° C) and cooling takes place at an

Table 9.1. Factors influencing shrinkage

Factors influencing shrinkage during processing	The degree of the effect upon plastic materials		
	amorphous	crystalline	thermosets
Characteristic shrinkage			
Flowability	+	+	+
Quality of fillers (additives)			
Tendency for anisotropic shrinkage			
Wall thickness	0	+	0
Distance from the point of entry	0	+	0
The direction of injection	0	+	+
Terminal affects	—	0	
The geometry of entry	0	+	
Material temperature	+	+	0
Mould temperature	+	+	+
Injection time (duration)	0	+	—
Duration of pressure holding	—	0	—
Duration of cooling	—	0	—
The pressures in the mould	+	+	0

Legend: + substantial effect, 0 medium effect, — small effect.

uneven rate, hence anisotropic shrinkage occurs. The shrinkage of thermosetting materials is governed by the plasticating process, the filling of the mould and by the curing processes. In the plasticating process, just as in the case of thermoplastics, the most essential factor influencing thermosets is the thermal homogeneity of the melt, however, the residence time plays a more important part. The mould filling of thermosets is also similar to those of thermoplastics, but the dissipation heat production must also be taken into account, since this can initiate the curing processes. Curing of the material commences in the injection channel, then the plasticating unit is removed from the mould and further curing takes place without the flow of additional material. At a given temperature, the sum of heat transported by the material during injection and liberated in the exothermal curing reaction is constant. In an ideal case, the melt and the mould are thermally homogeneous which results in the most favourable conditions for shrinkage.

The shrinkage of thermosetting materials decreases with increasing injection pressure and time taken for curing especially in radial directions. With an increased mould temperature, shrinkage increases together with the anisotropy of shrinkage.

The parameters involved in shrinkage are shown in Table 9.1. [73-76].

9.7.2 Orientation and Internal Stresses in Articles Made by Injection Moulding

During injection moulding a substantial degree of orientation takes place. Due to the orientation, the properties of the articles are direction dependent, thus, the tensile strength of the article is higher while breaking strain is lower in the direction of orientation than in the direction perpendicular to it. Similarly, in the direction of orientation shrinkage is greater, compared with shrinkage in a direction perpendicular to it. This phenomenon is responsible for warping of the products. In the cross section of the product, in a direction from the walls of the mould towards the bulk of the article, the degree of orientation is always uneven. The reason for this is, primarily, the uneven shearing velocity distribution developed during filling in the melt flow profile, secondly, it is due to temperature changes at different points of the flow profile during the injection cycle. The internal stresses between the molecules, the "frozen" mechanical stresses, the orientation and the internal stresses caused by the mould occur independently of one another, however, the over-all properties of the finished article are determined by their combined effects. A quantitative description of orientation during injection is given by Tadmor [79], who assumed, after examination of the flow taking place at the slot mould, that orientation was due to the flow of the melt. The polymer melt, in contact with the cold walls solidifies, the orientation originating from elongation flow developing in the moving melt front becomes fixed. The flow of the polymer in the middle part of the melt front is slowed down when approaching the layer in contact with the cold surface and this produces an elongation flow. Behind the melt front, and between the two solidified melt layers a simple shearing flow develops. In thicker layers relaxation reduces the degree of orientation.

The surface orientation is expressed as:

$$\varepsilon_f = 1 - \frac{1}{\sqrt{1 + \left[\left(\frac{1}{1 - \varepsilon_0} \right)^2 - 1 \right] \exp \left(\frac{y^2}{A^2 \lambda} \right)}} \quad (9.100)$$

the internal orientation parameter is:

$$\varepsilon_b = 1 - \frac{1}{\sqrt{1 + \left[\left(\frac{1}{1 - \varepsilon_0^*} \right)^2 - 1 \right] \exp \left[(y^2 - y_f) A^2 \lambda \right]}} \quad (9.101)$$

where ε_0 and ε_0^* are stretch-dependent coefficients, y is the cross coordinate, y_f is the coordinate of the solid polymer layer, λ is the characteristic relaxation time, and A is coefficient calculated from the heat balance.

In the cross section of articles made by injection processes, in a direction, starting from the wall of the die and proceeding towards the bulk of the product, non-uniform orientation develops. This is due partly to the non-uniform shearing rate and shearing stress values developing in the flow profile of the melt during filling the mould, partly to the temperature changes during the injection cycle at different points of the flow profile. The internal stresses between the molecules, the fixed-in mechanical stresses, the orientation and the internal stresses brought about by the shaping processes all are produced independently of each other, but they determine the properties of the polymer articles in conjunction.

The internal stresses result in deteriorating the strength properties of the product and cause size variation and shape distortions of the finished article. Qualitative, and especially quantitative determination of internal stresses are rather cumbersome; their reduction or elimination is more than difficult. As a general rule, elimination or a substantial reduction of internal stresses can be achieved by the correct choice and optimization of the technological parameters. It is advisable to eliminate the internal stresses in the finished product, since the longer these stresses persist in the product, the greater is its deterioration in quality.

The development of internal stresses and the related quantitative correlations are usually based on the most frequent cause, that is, the uneven cooling. In an attempt to determine the internal stresses developed in a given polymer and their relationships with the other properties of the polymer (such as shrinkage and strength), a circular disc with a central inlet is used as a model.

Figure 9.26. shows a finished article, made by injection moulding, in which a radial stress, σ_r , and a tangential stress, σ_t act on a given element; this forms the basis of the most frequently applied shrinkage examinations. Upon mould cavity filling in the centre of the article a flow process takes place, terminated during packing. At the beginning of the second phase of packing, the defined conditions exist in the mould, since the flow of material is stopped. Now, the internal pressure is in equilibrium with the mould clamping pressure and it is the same at all points of the article, thus, $\Delta P_{x,y,z} = 0$. At the beginning of cooling the temperature distribu-

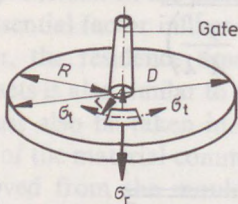


Fig. 9.26. Internal stresses developed in a disc-shaped object

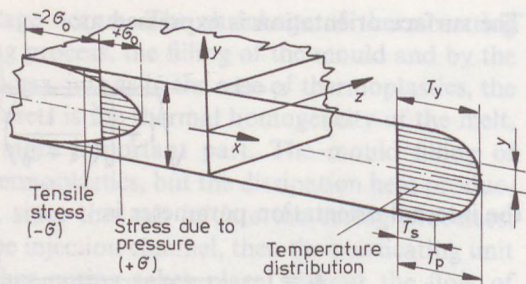


Fig. 9.27. Internal stresses developed in the cross-section segment of an injected object, due to uneven temperature distribution

tion inside the injected article is as shown in Figure 9.27., since filling of the space took place under the condition $T_p > T_s$. At a distance y from the centre line the temperature is T_y , this may be expressed by the following equation using the designations in Figure 9.26, thus:

$$T_y = T_p - (T_p - T_s) \left(\frac{y}{w/2} \right)^2 \quad (9.102)$$

At the beginning of the cooling process the melt pressure in the mould presses the external surface layers against the walls of the mould. Now, due to contraction in volume, but not later than the time when the object is removed from the mould, the balance of stresses exists not between the internal pressure of the article and the mould, but between the internal pressure of the article and the surface crust of the object, in which a tensile stress arises being in equilibrium with the compressive stress in the core. When $T_p = T$ (where T is an experimental value, which is, in general, by 30°C below the melting temperature T_m), the stresses developed within the body may be expressed by the following relationship:

$$\sigma_x - \sigma_z = - \frac{\alpha_h E_y (T - T_s)}{1 - \mu_p} \left[\left(\frac{2y}{w} \right)^2 - \frac{1}{3} \right] \quad (9.103)$$

where α_h is the heat expansion coefficient, E_y is the Young modulus and μ_p is the Poisson number. For maximum stress values it is:

$$\sigma_0 = \frac{\alpha_h E_y (T - T_s)}{3(1 - \mu_p)} \quad (9.104)$$

Since $T_p > T$, due to the viscoelastic state existing inside the injected article, internal equilibrium stress does not occur, because at this stage, the internal stresses are hydrostatic stresses in equilibrium with the walls of the mould. Hence, from the point of view of the article, external stresses predominate.

The crust layer produced from the melt entering the mould solidifies in the initial phase of filling at a relatively low pressure. During solidification of the subsequent layers a pressure maximum appears inside the mould owing to the increase in injection

pressure. Upon completion of the filling cycle and compression of the melt, the pressure decreases, thus the still fluid parts of the melt undergo cooling to the point of solidification under small pressure, or with no pressure applied, or even in a vacuum (holes form in the product). From the point in time when the available space in the cavity is completely filled to the state of total solidification of the melt the temperature decreases continuously, while the pressure of the melt passes over maximum as mentioned earlier. In those material portions which solidified under the highest pressures a relative excess quantity of material is present.

In the cross section of the article made by injection, according to the internal pressure and the cooling processes in the mould, there are two limiting cases of the development of stresses: 1. in the surface layers elongational stresses, and in the internal "core" compression stresses develop, or 2. vice versa. Under favourable equilibrium conditions it is also possible that the article solidifies free of internal stresses.

Without exception, warping and distortion of plastic articles are due to internal stresses. These stresses may be due to three possible causes:

a) It occurs frequently that the cooling rates of the two major surfaces of the object are different. With moulds equipped with inserts it is possible that, due to a reduced rate of heat conductivity, the insert becomes hotter than the mould. The surface of the object in contact with a hotter die surface cools slower and less than that in contact with a cooler surface of the mould. Upon removal of the article from the mould as a consequence of cooling to the same ambient temperature, the originally hotter surface shrinks more than the cooler surface, resulting in a concave shape.

b) Moving away from the entry orifice of the object made by injection moulding, the average temperature and the average pressure change from one point to the next together with their relative relationship to one another. If the heat expansion and compression are not in equilibrium, a non-equilibrium state develops. In the disc with an orifice at its centre, illustrated in Figure 9.26., two kinds of non-equilibrium states may occur, shown by Figures 9.28.a) and 9.28.b). The first is so-called "membrane" effect, due to the presence of a relative excess of material, brought about by the inequality $\Sigma \alpha \Delta T < \Sigma \beta \Delta P$ in the central zone. In the opposite situation a relative excess of material occurs at the edges giving rise to the so-called "propeller" effect (Figure 9.28.b)).

Uneven orientation often manifests itself in warping. In the section of the concentric circles in Figure 9.26., stresses in two different directions develop during shrinkage depending on whether the radial ϵ_r , or the tangential ϵ_t shrinkage dominates. This phenomenon may also occur even if the volumes are the same, since, owing to radial orientation the radial heat expansion coefficient will be smaller than the tangential one. This means that due to the inequality $\alpha_{h,t} < \alpha_{h,r}$ the effects are analogous to the membrane effect, except that the extent of bending is smaller. Under favourable circumstances the membrane effect caused by orientation and the propeller effect brought about by the inequality of the volume change state function, may balance each other out; in such instances warp-free articles are produced.

c) The following inequilibrium is also known in practice, once again brought about by the fact that shrinkage in the direction of the orientation is greater than shrinkage

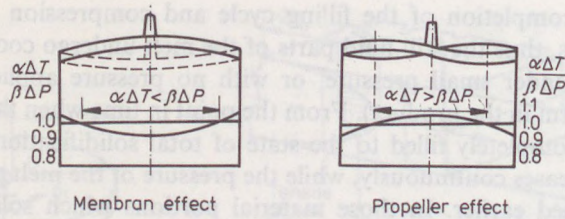


Fig. 9.28. Different stress states

in a crosswise direction [18 and 23], hence, in the case of the disc $\varepsilon_r > \varepsilon_t$. Based on the above, according to the equation:

$$\sigma_t = E_y \frac{1 + \mu_p}{1 - \mu_p} [\varepsilon_t - \varepsilon_r + (\bar{\alpha}_{h,t} - \bar{\alpha}_{h,r}) \Delta T] \quad (9.105)$$

tangential stretching or compression stresses occur due to temperature differences and the resultant vector of the heat expansion coefficient and the shrinkage values; again in an extreme, no stretching and compression stresses develop at all [13]. One of the extreme conditions would be, for example, if a greater shrinkage occurred in a region in the immediate vicinity of the inlet orifice, due to radial orientation, but this would be precisely balanced by a relatively higher pressure.

9.8 Control Application for Injection Moulding Processes

The part processes of injection moulding have been described above. As was mentioned earlier, the quality aspects of the objects made by injection processes are:

- dimension tolerances,
- reliable mechanical properties,
- surface qualities;

all of these depend on the properties of the material(s) used and on the technical quality of the processes.

Table 9.2. Quality aspects of injection moulded objects

Size	Surface	Strength
Dimension tolerance	surface lustre	strength
Shrinkage	smooth surfaces	even strength
Warping	even surfaces	resistance to stresses developing through corrosion
Inward retraction	even colour (transparency)	lack of internal stresses
Twisting	freedom from cracks	

In ideal process control it is necessary to assess the quality of the product immediately and directly. During injection moulding these requirements cannot be met, hence, process criteria must be chosen, which connect directly with the quality of the product. The relationship between the quality criteria of the product and the parameters of the process applied are collected in Table 9.2.; the methods employed to influence these quality criteria are shown in Table 9.3. From Table 9.3. it is evident that the quality of the product is influenced by the following items:

- the duration of the individual technological steps (the injection time, packing time, the cooling time and the supplementary time),

Table 9.3. Technical parameters which influence the quality of injection moulded objects

Fault in quality	The technical parameters that bring about these said faults
Incomplete formation	- Incorrect quantities of material added - Excessively small injection pressure - Incorrect material temperatures - Incorrect mould temperatures - Small plasticating capacity
Indentations	- Incorrect material quantities added - Excessively small injection pressure - Incorrect material temperatures - Incorrect mould temperatures - Excessively small plasticating temperatures - The product is removed from the mould at an excessively high temperature - The pressure-holding time is incorrect - Injection velocity is excessively small
Cut-off formation	- Quantities of material added are excessive - Excessive injection pressure - The material used is too cold - Duration of pressure holding is excessively short - The injection velocity is excessively large - Incorrect mould closure
Hair-line cracks	- The material used is excessively cold - The mould temperatures are excessively low - The duration of pressure holding is excessively long - The injection velocity is much too low
Warping	- Incorrect material temperatures - Incorrect mould temperatures - The duration of pressure holding is excessive - The work cycle is excessively short
Flow tracks (marks)	- The injection pressure is excessively small - The material temperatures are too low - The mould temperature is excessively low - The injection velocity is much too low

- the temperatures of the melt and of the product (influenced by the temperature distribution in the plasticating unit and the temperature of the mould),
- the pressure values attained in the production phases (the pressure in the mould, the pressure during the plasticating process, the residual pressure and the mould clamping pressure),
- the properties of the material used in injection moulding (its rheological and thermal properties).

From the above it is evident that in order to interfere with the processes for control purposes the following parameters are available for manipulation: the temperature, the pressure, the speed of the process and time.

The control levels of the injection process are given in Figure 9.29.

As a first level, a control plan is prepared, and this plan is carried out by the machine. This level consists of open-loop process controls. Here, process control consists of control of predetermined values as the first level; the hydraulic pressure, the time cycles, the displacement of the mould, and the clamping forces are adjusted manually, while these adjusted values are, more or less, maintained by the machine during production. The temperature of the mould, for example, is kept constant as the cycles follow each other as far as it is possible to maintain the temperatures of the heating fluid at a constant value. The temperature conditions of the injection machine are stabilized by the temperature control systems of the plasticating unit and the nozzle. Such controls are representative of the traditional injection machines.

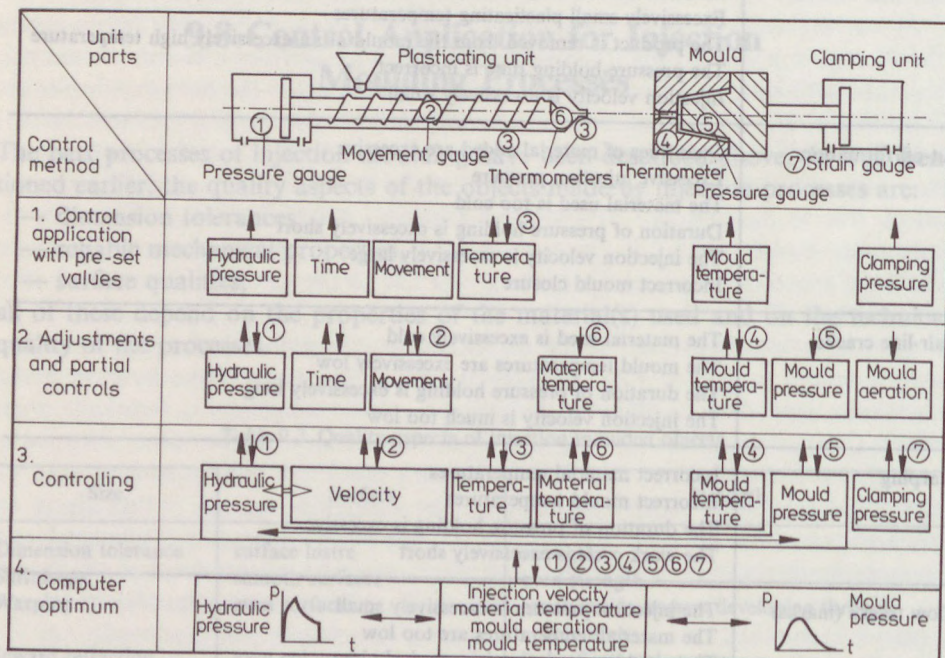


Fig. 9.29. Different control levels in injection mouldity

Table 9.4. Measuring, controlling and command of the various injection parameters

Process parameters	Measuring	Control	Command
Closure speed			X
Closure pressure	X		X
Injection velocity	X	X	
Injection pressure			X
Mould pressure	X		
Packing pressure	X	X	
Opening velocity			X
Barrel temperature	X	X	

The second level of process control involves mixed control modes, where both closed-loop and open-loop control exist side by side. This level consists of control according to the momentary values measured. Here, machine parameters of traditional control modes are not included. The most important "momentary value" is the pressure in the mould. The material temperature and the mould temperature must be known, the hydraulic oil pressure and aeration of the mould must also be known. Control is based on the set and the measured mould pressure. This second level of process control is the closed loop control, in which some parameters of the process are maintained at predetermined values. A more advanced control method compared with simple control is one which uses adaptive controls, where disturbances are corrected by an adaptive control system. Here, the speed of injection, the pressure in the mould, the temperatures of the mould and of the polymer melt are controlled. In addition to this, the temperature of the hydraulic oil is also controlled.

The third and highest level of control includes the application of a computer to maintain near optimal controls. The computer interacts with the processes in accordance with a model. Table 9.4. shows the part played by each parameter in the application of a control system.

We now give an account of the methods to control the most important parameters, followed by an examination of complex control methods applied to injection moulding machines [80–124].

9.8.1 Temperature Control

The three parameters that require temperature control are:

- melt temperature,
- temperature of the mould, and
- temperature of the hydraulic oil.

The first two of these items affect directly the properties of the finished product. The hydraulic oil temperature indirectly affects the quality of the articles being moulded. All components of the hydraulic circuits are designed to work over a specific

range of oil temperatures. If the temperature of the oil falls outside a specified working range, it may result in damage to some of the hydraulic components and the system may begin to function in a non-linear manner. This means that speeds, pressures and positions set at one oil temperature may not be the same at another oil temperature. An open-loop hydraulic control system is more prone to manifest these fluctuations as defects in the moulded article than a closed-loop-controlled hydraulic system. The temperature control systems of plasticating units are generally DDC systems assigned to measure the temperature of the reservoir and of the barrel.

The temperature of the mould significantly influences the cooling and curing processes.

The two main methods available for control of the mould temperature are: controlling the temperature of the heat transfer fluid or controlling the temperature of the mould directly. The first alternative, by which the outlet temperature is controlled, is the more frequently employed (see Figure 9.30.a) and b)). The accuracy of regulation attained in this manner is sufficient for normal purposes; however, the second alternative may be preferred when the stability of the mould temperatures is high on the list of priorities (see Figure 9.30.c) and d)).

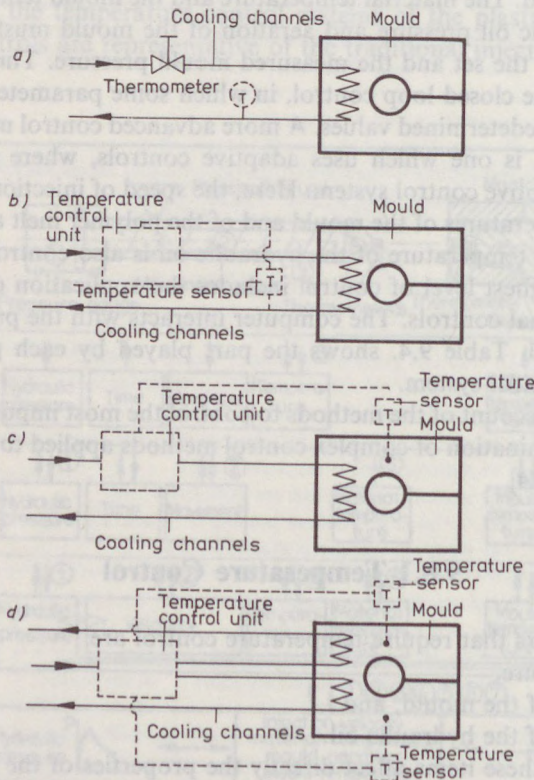


Fig. 9.30. Types of mould cooling control system: a) Manual regulation, b) Indirect control via the outlet temperature, c) One circuit direct control and d) Multicircuit multipoint direct control

The most advanced method of controlling the mould temperature is to use impulse cooling, based on the transient temperature field. In this method the flow of the heat transfer fluid is controlled as a function of time. This method also employs direct temperature measurement in the mould.

The mould temperature influences the quality of injection-moulded items during the filling phase by way of cavity surface temperatures and, naturally, in the cooling phase, by means of spatial uniformity of the cooling rate. The temperature of the mould determines the surface of the product (flow lines, joint lines, lustre), and the filling ratio of the piece (i.e. it affects flow resistance and pressure loss). Uneven mould temperatures during cooling affect the shrinkage, residual stresses and warpage of the moulded article. This effect is the greatest when crystalline polymers are used, since crystal growth influences the isotropy of the material properties. Excessively high mould temperatures during the cooling phase slow down production cycle unnecessarily.

9.8.2 Pressure Control

Injection pressure is the most important process variable since it relates directly to the degree of filling of the mould. Injection pressure relates to short shots and dimensional variations in parts. Proper control of the mould pressure can be a simple and cost-effective method of accomplishing the most benefit with the least cost.

One of the problems in monitoring and controlling plastics pressures is that it is not constant for all positions in the cavity, thus, the pressure in the mould cavity varies quite considerably due to variations in hydraulic pressure. It also varies with distance of flow. In practice the mould cavity pressure is actually a profile. The control of this plastics pressure profile is the key to successful control. The profile, that is, the change of cavity pressure across the mould cavity is determined by other variables such as the temperature of the melt, the flow rate, the cooling rate and the mould temperature. Where these variables are kept constant, a single cavity pressure sensing location is necessary to ensure proper control. However, in some applications, a mixed approach is employed in monitoring and controlling the process using cavity pressure measurements. This entails the use of one sensor near the gate to control the cavity pressure, with one or more sensors near the end of fill of one or more cavities to monitor pressure at the end of fill. By controlling the upstream in-cavity pressure and monitoring the last point to fill, the cavity pressure profile can be maintained. If, for any reason, monitored end of fill pressure varies, the resulting product is rejected and the cause of the profile variation is remedied.

The mould filling process may be divided into three distinct stages:

- the cavity filling stage,
- the compression phase, and
- the pressure holding phase.

During the cavity filling phase the important control factor is the injection speed. At the filling phase a fairly high hydraulic pressure is provided to give the required injection pressure, however, a much lower pressure usually suffices for the other two phases.

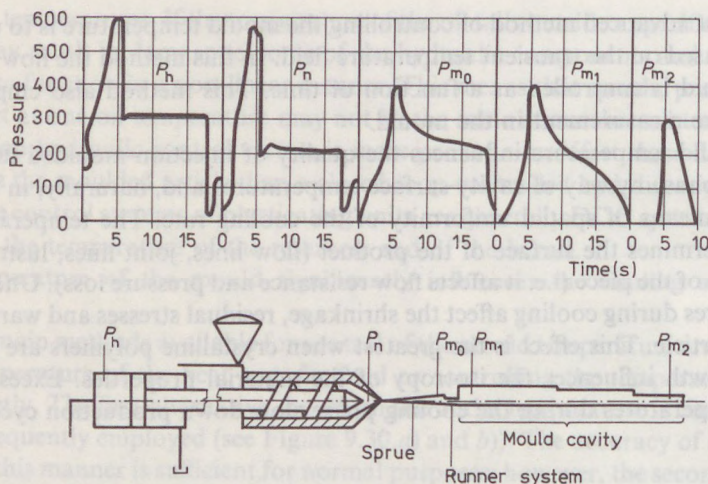


Fig. 9.31. The pressure profile of an injection machine

Figure 9.31. shows the pressure profile of an injection machine, the hydraulic pressure, the pressure curve of the plasticating unit, the pressures at the runner system and the pressure in the mould. This diagram may be regarded as showing a control action sequence, where the input value is the hydraulic pressure, and the output value is the pressure in the mould. The three units to which control is applied are the hydraulics, the plasticating unit and the mould. Disturbances affecting the pressure in the mould are collated in Table 9.5. From the Table it is evident that changes in the pressure profile may be brought about by both the hydraulic system and the plasticat-

Table 9.5. Factors influencing the pressures in the mould

Adjustable parameter	Influencing factors
1. Plasticating barrel wall temperatures ram pressure revolution number	material temperature temperature distribution of the material viscosity
2. Mould clamping unit pressure limitations closure speed	mould clamping forces aeration of the mould
3. Heating of the mould temperature of the cooling medium volume current of the cooling medium duration of heating	mould temperature
4. Injection unit injection pressure packing pressure switch-over time pressure-holding time	mould fill duration of cooling duration of pressure holding

ing unit. The pressure gradient at the mould filling phase depends on the velocity of injection, the geometry of the mould, the properties of the material used, the temperatures of the material and the mould. During injection the geometry of the mould and the properties of the material are fixed and pressure change can be brought about by the speed of injection, by the material and the mould temperatures and by changes in the rheological properties of the material. The most frequently occurring reasons for pressure fluctuations are variations in the speed of injection and temperature of the material. The maximum pressure value depends on the timing of the switch-over from injection pressure to packing, on the injection speed and on the material and the mould temperatures. The most important effect is that of the timing of pressure switch-over. If this happens too early, a too rapid pressure drop occurs; if the

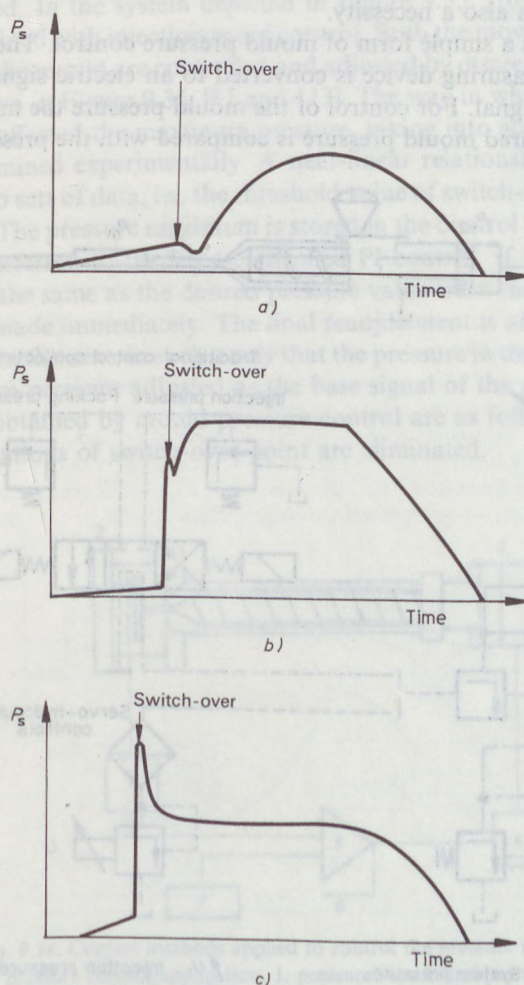


Fig. 9.32. The effect of pressure switch-over on the pressure in the mould [66]

a) Switch-over made excessively early, b) Early switch-over, c) Late switch-over

switch-over occurs too late, a high pressure surge is caused (see Figure 9.32.). The pressure surge is followed by a large pressure drop which causes a reverse flow, causing significant orientation. Following the injection phase, a switch-over to packing can be accomplished in a number of ways:

- using a time dependent system,
- using a path dependent system,
- using a system dependent on hydraulic pressure,
- using a system dependent on the pressure in the mould.

From the point of view of the process the last method seems to be the most promising. Pressure control obtained after switch-over is effected on the basis of the preset pressure versus time values. The control involves following a predetermined programme. Since the pressure values also undergo certain disturbances, control of the pressure values is also a necessity.

Figure 9.33. shows a simple form of mould pressure control. The signal given out by the stretching measuring device is converted to an electric signal and compared against the control signal. For control of the mould pressure the maximum pressure is chosen. The measured mould pressure is compared with the preset pressure, if the

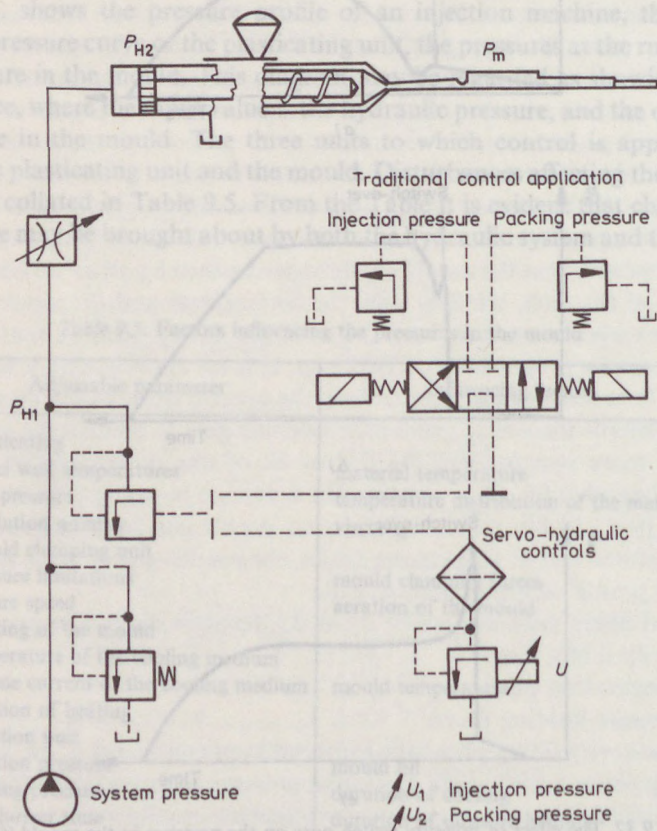


Fig. 9.33. Control method applied to control the pressure in the mould. Traditional controls

difference is greater than the preset limit, the servo-valve changes the hydraulic oil pressure, or the oil flow. This correction is made after the packing phase, and its effect appears in the next cycle. The actuating organ of controller system is a hydraulic valve adjustable by two setting points. The disadvantages of this control method are that the injection speed attainable is reduced and that the reproducibility of the pressure curve is not very good. Figures 9.34., 9.35. and 9.36. show improved versions of pressure controls. The solution in Figure 9.34. is the so-called "Dynac Controller"; this equipment also measures the hydraulic oil pressure, determines the pressure increase in the hydraulic system to draw conclusions regarding the maximum pressure occurring in the mould. If the pressure gradient is either greater or less than optimum, the equipment decreases or increases the injection pressure accordingly at the beginning of the mould filling cycle. The disadvantage of this system is that the injection time is increased. In the system depicted in Figure 9.35. [102], the mould pressure control is combined with injection speed control. Both the movement of the screw and the pressure in the mould are controlled and adjusted by discrete increments. Another solution is shown in Figure 9.36. [81 and 113]. The way in which the threshold value of switch-over affected the maximum pressure, taking into account various parameters, was determined experimentally. A near-linear relationship was found to exist between the two sets of data, i.e. the threshold value of switch-over and the maximum pressure [112]. The pressure maximum is stored in the control system. From here, the signal was transferred to the logic-controlled PI control. If the pressure inside the mould is to be the same as the desired pressure value from the control indicator, the switch-over is made immediately. The final readjustment is affected by an algorithm from one cycle to the next, in such a way that the pressure in the mould always is equal to the maximum pressure adjusted as the base signal of the control system.

The results obtained by mould pressure control are as follows:

— the fluctuations of switch-over point are eliminated,

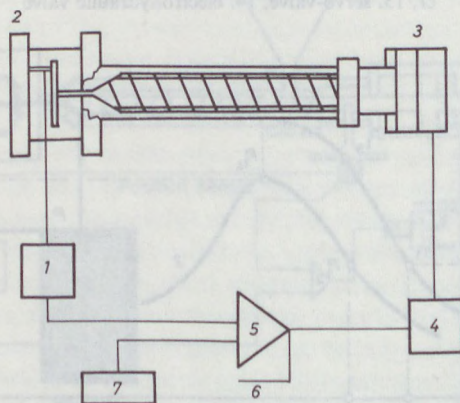


Fig. 9.34. Control methods applied to control the pressure in the mould
Simple Dynisco pressure control application. 1. pressure sensor and pre-amplifier, 2. mould with a built-in pressure gauge, 3. screw plasticating unit, 4. servo-valve, 5. programmable servo-system, 6. control signal, 7. pressure indicator

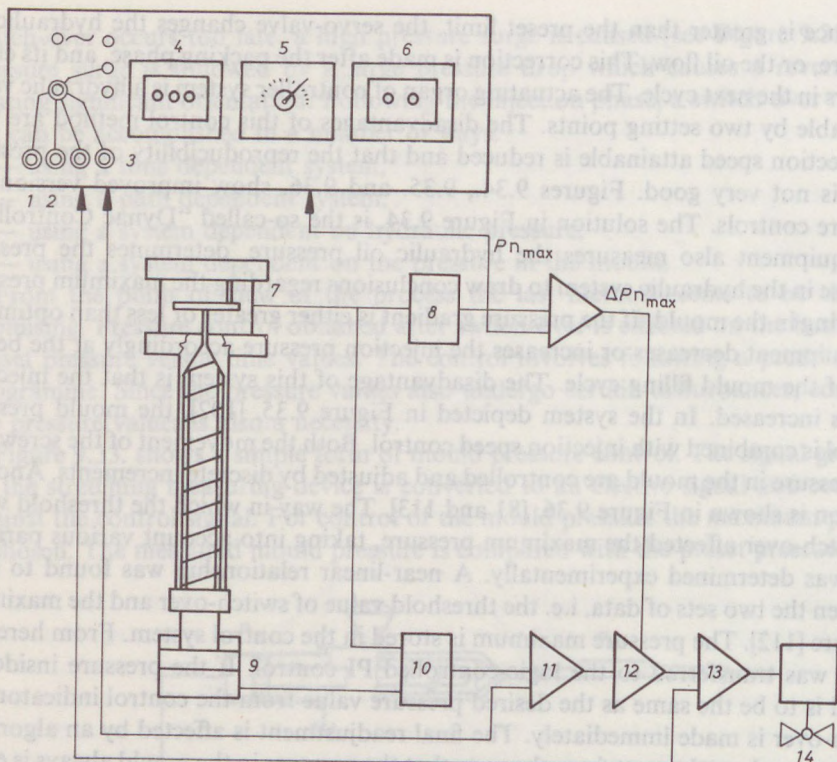


Fig. 9.35. Dynac-Controller pressure control method

1. adjustable potentiometer, 2. pressure control rotating dial, 3. calibrating knob, 4. system to control the pressure in the mould, 5. equipment used for control of packing pressure, 6. instrument to control the back pressure, 7. pressure sensor built into the mould, 8. comparison block, 9. manometer to measure the pressure in the hydraulics system, 10. logic equipment, 11. process type indicator, 12. controller, 13. servo-valve, 14. electrohydraulic valve

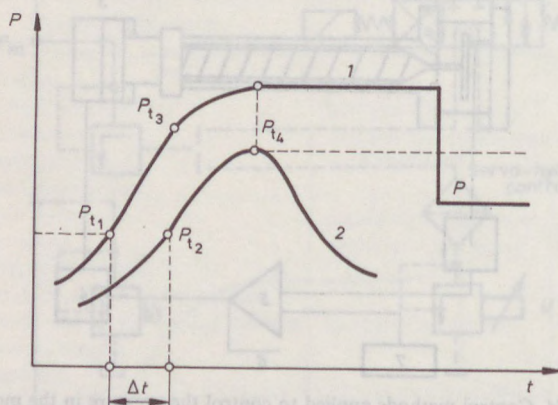


Fig. 9.36. The pressure in the mould

1. the pressures in the injection and the packing pressure phases, 2. the pressures of the hydraulic system

- the dimension tolerances of the finished product improve,
- the reject rate is reduced.

The difficulties experienced in pressure control are:

- pressure gauges must be installed in each of the moulds, and
- a problem lies in determining the correct pressure where moulds with several cavities are used.

9.8.3 Injection Speed Control Methods

The flow rate of plastic materials is the second most important variable after pressure, for a number of reasons. First, flow rate is not well controlled in conventional moulding machines. Second, the flow rate influences the viscosity and thus the plastics pressures in the mould in a machine not equipped with mould pressure controller. Third, flow rate variations alter the degree of orientation and molecular alignment of plastics during the filling process. This, together with the rate of cooling, determines the degree of orientation of the end products. The best measure of flow rate is to monitor the actual time it takes for the melt to fill the mould. This flow time, or fill time is a constant for a given mould. Unlike ram velocity, which must be different for the same mould used in a different sized machine, the fill time remains the same. Ram velocity monitoring will not detect variations to leakage of the non-return valve of the screw, which can be a significant variable in many instances. One approach to fill time control is to use a closed loop adaptive system. The closed loop system controls ram velocity and loop settings are now adopted in practice, based on the fill time to achieve the desired flow rate of the plastics into the mould.

In the screw forward velocity control system shown in Figure 9.37, the forward

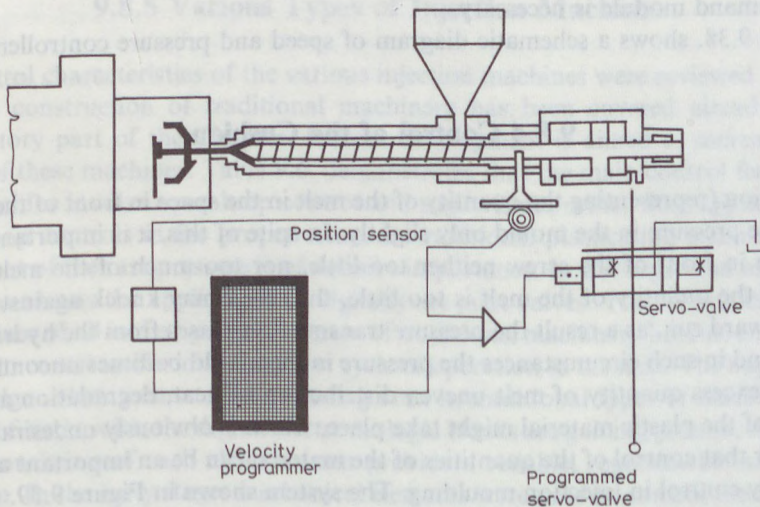


Fig. 9.37. Control methods applied to control the forward speed of the screw
A system to control the forward speed of the screw and the pressure in the mould

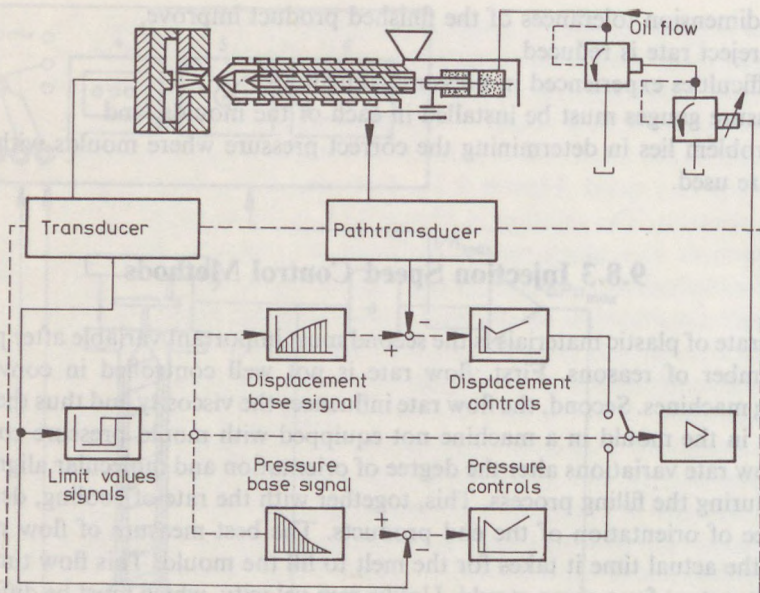


Fig. 9.38. Control system for the forward movement of the screw

velocity of the screw is produced by a ten-value path length controller. The measuring function is converted by the machine into an analogue form and, according to the programming, the forward movement of the screw is controlled in ten incremental steps. In medium size machines, the range of screw speed control generally extends from 1–1.4 s. Below these limiting values, due to control instability, the application of a command module is necessary.

Figure 9.38. shows a schematic diagram of speed and pressure controllers.

9.8.4 Control of the Cushion

The cushion (representing the quantity of the melt in the space in front of the screw), affects the pressure in the mould only slightly. In spite of this, it is important that in the space in front of the screw neither too little, nor too much of the melt should reside. If the quantity of the melt is too little, the screw may knock against the end of its forward run, as a result the pressure transmission ceases from the hydraulics to the die, and in such circumstances the pressure in the mould becomes uncontrollable. With an excess quantity of melt uneven distribution of heat, degradation and even burning of the plastic material might take place, which is obviously undesirable. It is thus clear that control of the quantities of the material can be an important aspect of subsidiary control in injection moulding. The system shown in Figure 9.39. controls the quantities of the melt to an optimum. The moment the pressure in the mould reaches the threshold level this control system defines the position of the screw and

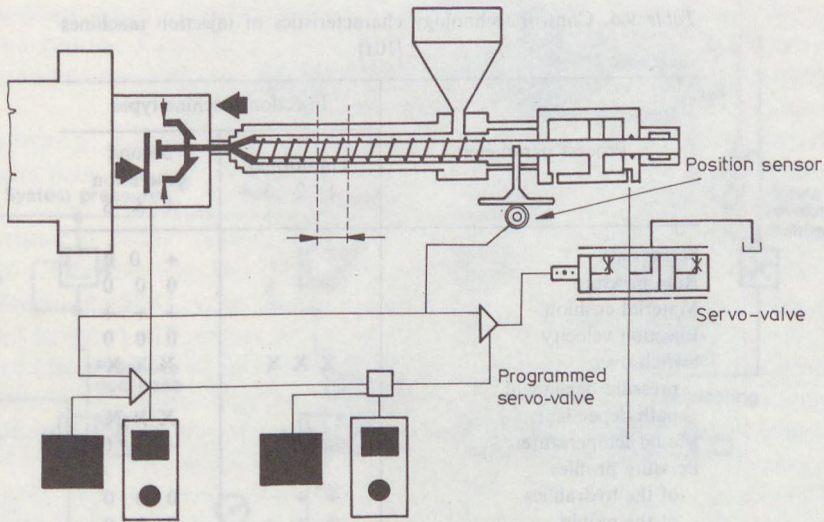


Fig. 9.39. System to control material cushion [81]

adjusts the desirable movement and appropriate amounts of the melt from one cycle to the next.

In the text above, the control of the separate parameters of injection machines have been outlined. Total control of injection moulding machines usually consists of several control loops and control cycles.

9.8.5 Various Types of Injection Machines

The control characteristics of the various injection machines were reviewed in Table 9.6. The construction of traditional machinery has been covered already in the introductory part of the Chapter. Present development is aimed at increasing the output of these machines. Table 9.6. demonstrates that the main control features of these machine involve open-loop control and supervision, rather than application of closed-loop controls in the proper sense. In traditional plasticating machinery, the adjustment of the ram pressure is of decisive importance. In this regard an important step forward was the application of digitally set pilot valves. The adjustment of the temperature of oil in the hydraulic system of traditional machinery became a common practice to ensure uniformity from one cycle of operation to the next. The application of cartridge valves seems to be spreading even in traditional types of machinery. In the field of electronics, the digital electronic logic blocks are gaining ground. A control system consisting of such elements can provide a reliable, reproducible and rapid operation. In the early stages mechanical elements were used to control the injection machinery. Cam conductor switches and control discs equipped with mobile nibs were used. These mechanical elements were later replaced by electro-mechanical switching

Table 9.6. Control technology characteristics of injection machines
[101]

Process parameters	Injection machine types					
	Traditional			Second generation		
	1	2	3	4	5	6
Screw path				+	0	0
Ram pressure	+	+		0	0	0
Material cushion				+	+	+
Injection velocity				0	0	0
Switch-over				X	X	X
pressure dependent		X	X			
path dependent				X	X	X
Mould temperature	+	+	+	+	0	0
Pressure profiles						
of the hydraulics	+	+		0	0	0
of the mould	+	+	+	0	0	0

Legend: + supervision

X command

0 controls

The numbers 1 to 6 represent the various types of machinery used.

elements, such as magnetic switches, terminal switches and time relay units, employed as the base units of the first generation of electronically controlled machinery.

With the advent of semi-conductors the magnetic switches and relays were replaced by electronic elements, thus eliminating all mechanical switches. The appearance on the scene of electronic elements constituted the second generation of machine control modes. Even today, a large number of injection machines are produced with relay controls, but electronic control seems to be gaining ground. The electronic controls are, as compared with relay controls, smaller in size, more durable, more rapid in response and have greater flexibility.

Digital controls are capable of adjusting all hydraulic parameters in the digital mode. The transfer of signals is electric and hydraulic. Before the operation of DC machines is described, it is appropriate to review the characteristic hydraulic systems of injection machines; one of the most widespread methods of inducing motion in injection machines is to use hydraulics. The hydraulic controls are therefore of great importance. The injection cycle requires rapidly changing and variable hydraulic energies.

The following values can be adjusted electrically in hydraulic injection machines: the temperatures, times and the required operating constants are adjusted on the control panel; the length of the stroke, the pressure values and the speeds are adjusted manually. A more advanced form of process control consists of electrical-hydraulic control loops, with essential construction elements of digital pressure and speed controls.

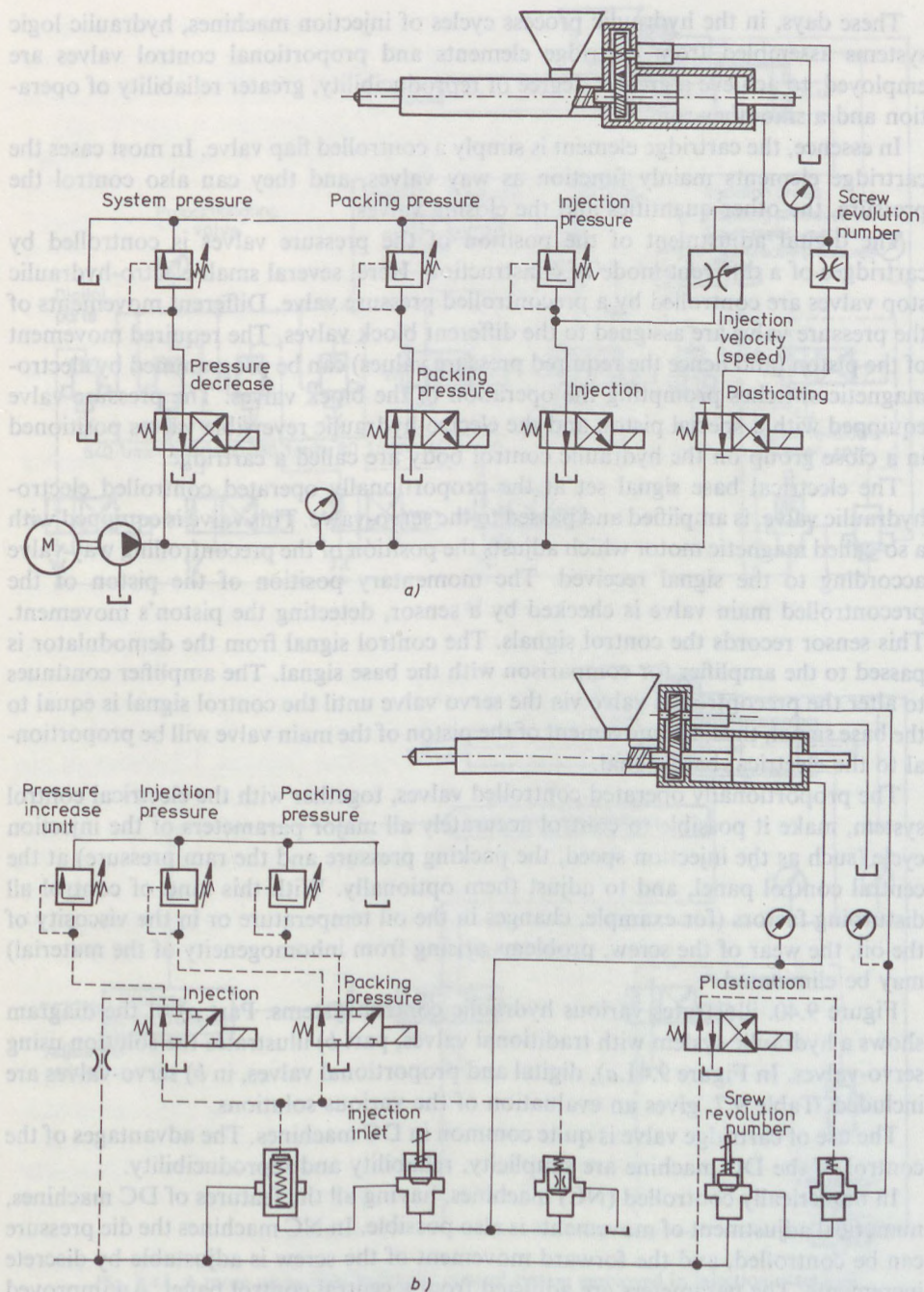


Fig. 9.40. Hydraulic control systems applied to injection machines
 a) Traditional system utilizing valves, b) Cartridge-valve system

These days, in the hydraulic process cycles of injection machines, hydraulic logic systems assembled from cartridge elements and proportional control valves are employed, to achieve a greater degree of reproducibility, greater reliability of operation and a smoother run.

In essence, the cartridge element is simply a controlled flap valve. In most cases the cartridge elements mainly function as way valves, and they can also control the pressure, the other quantities and the closing valves.

The digital adjustment of the position of the pressure valves is controlled by cartridges of a different mode of construction. Here, several small electro-hydraulic stop valves are controlled by a precontrolled pressure valve. Different movements of the pressure valve are assigned to the different block valves. The required movement of the piston (and hence the required pressure values) can be programmed by electro-magnetic switches prompting the operation of the block valves. The pressure valve equipped with a special piston and the electro-hydraulic reversible valves positioned in a close group on the hydraulic control body are called a cartridge.

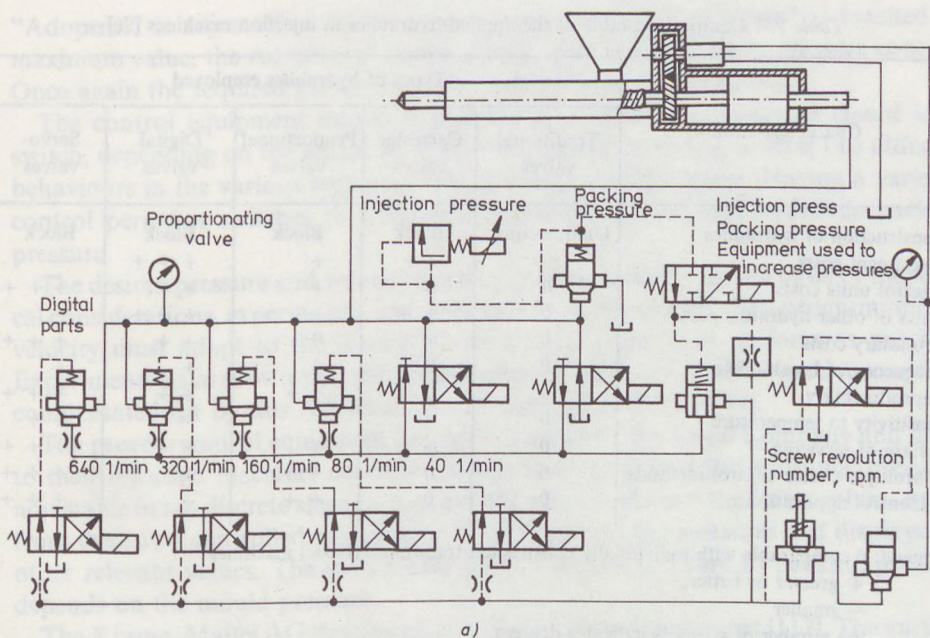
The electrical base signal set at the proportionally operated controlled electro-hydraulic valve, is amplified and passed to the servo-valve. This valve is equipped with a so-called magnetic motor which adjusts the position of the precontrolling way valve according to the signal received. The momentary position of the piston of the precontrolled main valve is checked by a sensor, detecting the piston's movement. This sensor records the control signals. The control signal from the demodulator is passed to the amplifier for comparison with the base signal. The amplifier continues to alter the precontrolled valve via the servo valve until the control signal is equal to the base signal, thus, the movement of the piston of the main valve will be proportional to the electrical base signal.

The proportionally operated controlled valves, together with the electrical control system, make it possible to control accurately all major parameters of the injection cycle (such as the injection speed, the packing pressure and the ram pressure) at the central control panel, and to adjust them optionally. With this kind of control all disturbing factors (for example, changes in the oil temperature or in the viscosity of the oil, the wear of the screw, problems arising from inhomogeneity of the material) may be eliminated.

Figure 9.40. illustrates various hydraulic control systems. Part *a*) of the diagram shows a hydraulic system with traditional valves, part *b*) illustrates the solution using servo-valves. In Figure 9.41.*a*), digital and proportional valves, in *b*) servo-valves are included. Table 9.7. gives an evaluation of the various solutions.

The use of cartridge valve is quite common in DC machines. The advantages of the control of the DC machine are simplicity, reliability and reproducibility.

In numerically controlled (NC) machines, having all the features of DC machines, numerical adjustment of movements is also possible. In NC machines the die pressure can be controlled, and the forward movement of the screw is adjustable by discrete increments. The parameters are adjusted from a central control panel. An improved version of NC control is the CNC control mode, which is superior to NC digital control, since here it is possible not only to check the control but also to correct the possible deviations. CNC controlled machines make it possible to compare the



a)

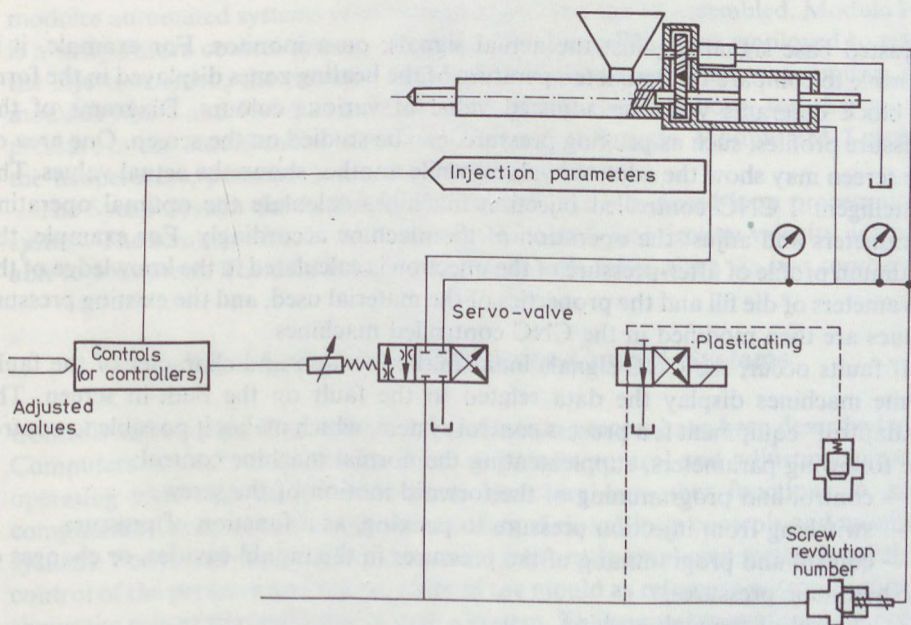


Fig. 9.41. A more up-to-date hydraulic control system employed in injection machines

a) Proportional valve system, b) Servo-valve system

Table 9.7. Comparison table of the applied hydraulics in injection machines [96]

Characterisation	Types of hydraulics employed				
	Traditional valves	Cartridge valves	Proportional valves	Digital valves	Servo-valves
Construction of hydraulics	Unique const.	Block	Block	Block	Block
Investment costs	0	++	+	+++	—
Control units costs	0	0	+	++	+++
Costs of other hydraulic parts	0	++	+	+++	—
Subsidiary costs	0	+	0	++	+++
Frequency of break-down	0	0	+	+	+
Reproducibility	0	0	++	++	+++
Sensitivity to temperature	0	—	—	—	++
Ease of servicing	0	+	+	++	+++
Multiple choice control methods	0	0	++	+	+++
Control application	0	0	++	+	+++

Legend: 0 comparable with individually constructed traditional (basic) machines

+ greater or better,

— smaller

the number of symbols indicates degrees.

adjusted base signals against the actual signals, on a monitor. For example, it is possible to compare the actual temperature of the heating zones displayed in the form of block diagrams with the adjusted value of various colours. Diagrams of the pressure profiles, such as packing pressure, can be studied on the screen. One area of the screen may show the adjusted values, while another shows the actual values. The “intelligent”, CNC controlled injection machines calculate the optimal operating parameters and adjust the operation of the machine accordingly. For example, the optimum profile of after-pressure of the injection is calculated in the knowledge of the parameters of die fill and the properties of the material used, and the existing pressure values are then modified in the CNC controlled machines.

If faults occur, the CNC signals indicate the location and character of the fault. Some machines display the data related to the fault on the built-in screen. The “Adaptrol” equipment is a process control system, which makes it possible to control the following parameters, supplementing the normal machine control:

- control and programming of the forward motion of the screw,
- switching from injection pressure to packing, as a function of pressure,
- control and programming of the pressures in the mould cavities, or changes of the hydraulic pressures,
- control of the melt cushion,
- control of the load on the screw.

Each of the above functions may be switched on or off as desired.

The injection speed is adjusted between various control points by interpolation on a plug board. The course of the program is monitored on a screen using LEDs. The

“Adoptrol” is adjustable: once the mould pressure of the machine has reached its maximum value, the Adoptrol is switched over from rate control to pressure control. Once again the required pressure profile is defined on a plug board.

The control equipment makes it possible by means of an internal closed loop switch, depending on the length of the pressure control period, to adapt to different behaviours in the various sections in the packing pressure phase. Having a variable control period it switches to a linearly decreasing or constant hydraulic packing pressure.

The desired pressure and velocity profiles are programmed on the basis of theoretical considerations, experiments, and subsequent quality control. The programming of velocity must adapt to the mould fill process to make it as uniform as possible. Experiments have shown that melt temperature changes of $\pm 10^{\circ}\text{C}$ were successfully compensated for by this Adaptrol control equipment [93 and 94].

The process control equipment Digital L2, made by the Engel Company and fitted to their injection machine, controls the injection speed and the hydraulic pressure; adjustable in ten discrete steps on a panel, the values influence the servo-valves. Apart from these two controlled parameters, the equipment also measures and displays the other relevant values. The switch-over from injection pressure to packing pressure depends on the mould pressure.

The Krauss-Maffei AG developed a modular control equipment [117]. The various modules are each capable of different control applications. With the aid of these modules automated systems of differing capabilities can be assembled. Module PM-1 is a temperature control system. Modules PM-2 and PM-3 are employed to control the injection speed, the pressure profile and the pressure switch-over timing, while modules PM-4 and PM-5 control the same parameters as above, together with the pressure in the mould cavity in a closed-loop control mode. Module PM-7 monitors the temperature, pressure, time and the melt cushion.

The Sycap-System developed by the Netstal AG is a closed-loop process control system. The screw speed, the hydraulic pressure and the injection velocity are adjustable in four steps. The interaction with the process takes place via two servo-valves.

9.8.6 Computerized Process Control Systems

Controls and command modules for the injection process have been described above. Computers can take over the functions of process control and adjustment from the operating staff and, at the same time, can carry out other functions. A simple, computerized process control system consists of closed-loop controls and monitoring systems. For closed-loop controls, the most frequently employed methods involve the control of the pressure and temperature of the mould as reference points. Figure 9.42. shows the role of the computer in such a system. The computer monitors the pressure profile established experimentally and realizes a following control. If the cycle time is too short, it is not possible to exercise sufficient control during one cycle owing to the inertia of the machine, here, the computer assumes the existence of a constant characteristic profile. The parameters are determined by the computer with the aid of

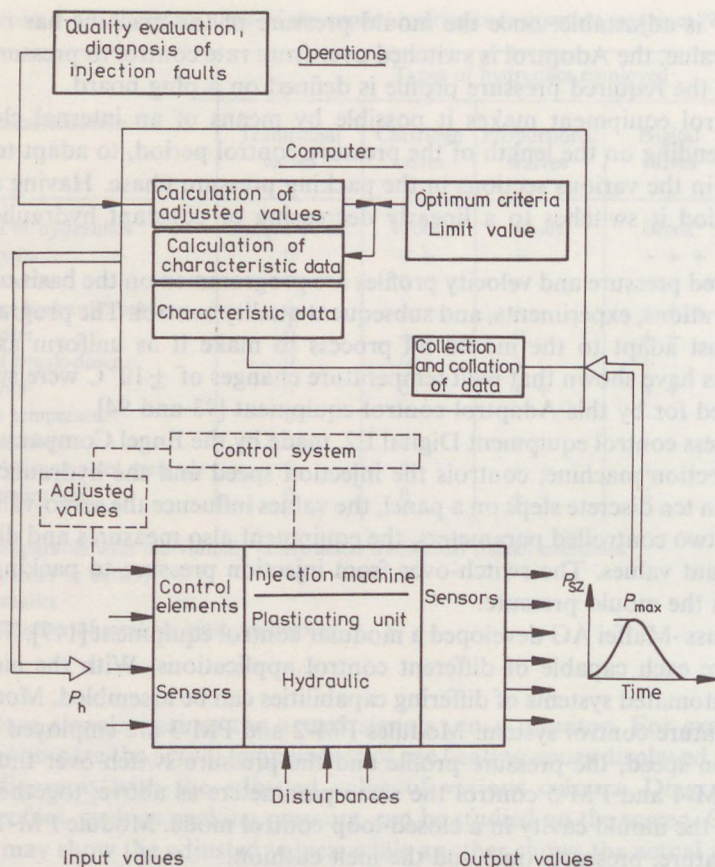


Fig. 9.42. Computerized control of the mould pressure

a suitable programme from the data measured during the process. The computer compares the data obtained against the desired values. Figure 9.43. shows a block diagram indicating the computer control of the basic processes of injection moulding, such as plasticating, injection, packing and cooling. All input data and the determination of all the process parameters are handled by the computer. The computer carries out optimum control, processing the data by an adaptive control algorithm [98 to 100].

The computer may be involved in completely automatic, semi-automatic or manual operation. Here, the computer plus injection machine combination operates completely automatically from the start of the process until termination of the process in the case of automatic operation, while in semi-automatic operation the machine stops at the end of each cycle, until the operator opens and closes the safety screen of the machine. In manual operation it is possible to interfere with the processes of the machine, the mould may be opened and closed, plasticating and the injection cycle may be started, the operator can remove from the machine the product or can place an insert in the mould. The steps in computerized data processing are: introduction

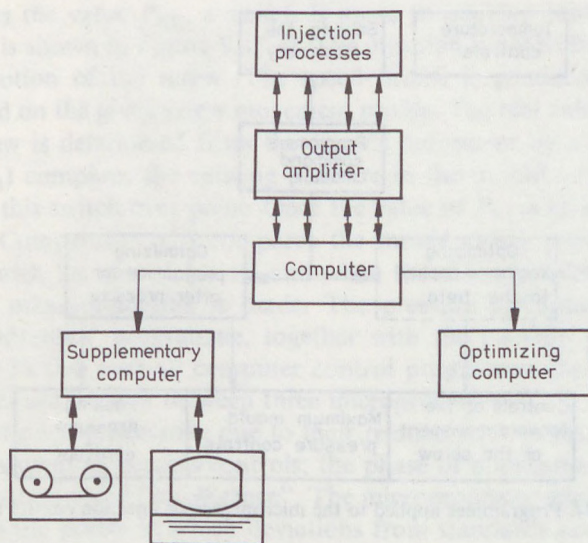


Fig. 9.43. The flow sheet diagram of the injection processes controlled by a computer

of new input data, alteration of the data stored and displaying the data obtained on the screen. The first step consists of making a choice of the specific parameter, the value of which is to be changed, it carries out this desired change and checks it. A similar procedure applies where the data stored are to be changed. The operator can display or print out the data stored. The computer uses two software systems for process control, the first is the so-called action software, the other is the sequencing software. The former controls the entire process and the data flow, the latter ensures automatic accomplishment of injection moulding. The main parts of the sequential software are: the plasticating control programme, the mould movement programme, the injection programme, the packing-pressure programme, the adaptive ram stroke programme and the adaptive melt temperature control programme. The plasticating programme determines and adjusts the revolution number of the screw according to the plasticating time programmed, taking the ram pressure into account. The computer checks the speed of the movement of the screw to agree with the required plasticating time, it also monitors all the relevant variables, such as speed, movement, pressure and time; it calculates the plasticating time and carries out any adjustment required. The programme prevents the over-load of the motor-drive at the maximum of r.p.m. and pressure, and it switches the machine off and gives fault signals. The mould movement programme governs the opening and closing of the mould, measures the distance between the half moulds and their speed. In contrast to solutions normally employed, the mould movement here is not governed by terminal switches, but is adjusted on the control panel. The injection speed and packing pressure programmes make it possible to adjust the speed profile using ten speed increment values, however, in addition to these ten increments the computer can interpolate another ten speed values. When the forward movement of the screw reaches the

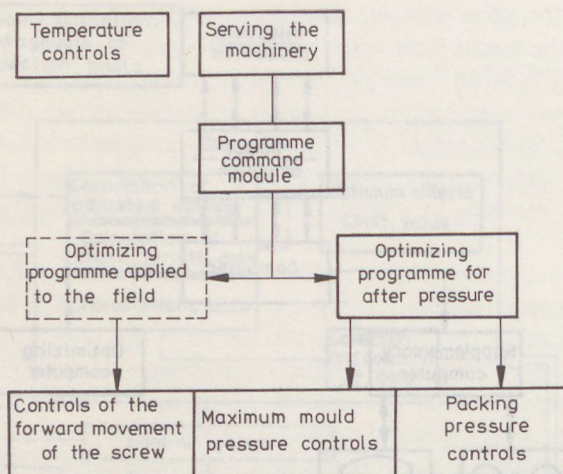


Fig. 9.44. Programmes applied to the microprocessor injection control system

required cushion size, the computer switches to packing-pressure mode. The adaptive stroke-length control programme maintains the size of the melt cushion at the desired value. The computer checks the position of the screw ram at the end of the packing, compares this with the desired value and makes a correction to the stroke length in the next cycle, if any deviation is detected. The computer indicates the size of the cushion to the operator. The adaptive temperature control system is similar to that introduced in Chapter 4. In the control system of the IKV injection machine, three M 6800 type microprocessors are used. One of them controls the inlet and the outlet analogue and digital data flow and it controls the injection process. The second is an optimizing microprocessor to control the optimal mould pressure profile. The third microprocessor is the application microprocessor, it organizes the traffic and flow of data between the control computer and its memory. The system is illustrated in Figure 9.44. The process control programmes of the microprocessor consist of the profile programme, the hydraulics control programme, the adaptive programme and the temperature control programmes. The sequential programme controls the steps of the injection cycle, shown in Figure 9.45.a). This programme provides the control signals for the individual steps of the cycle. Further, it originates fault signals in the case of certain disturbances in the injection cycle. The hydraulics control programme controls the forward movement of the screw, the maximum mould pressure, the packing-pressure and the size of the melt cushion. Figure 9.45.b) shows the flow sheet for the forward movement control of the screw. The system is a digital version of the previously shown forward movement control of the screw. The switch-over from injection pressure to packing-pressure is pressure dependent, as shown in Figure 9.45.c). The pressure curve is represented in four regions, where region A represents the injection phase controlled through the forward movement of the screw. At pressure P_{BA} (region B) the control is switched from injection control to the switch-over pressure control. Region C is a transfer to pressure controls, and when the

pressure reaches the value P_{KU} , a switch is made to packing control. The switch-over controller is shown in Figure 9.45.d). The injection is controlled via the rate of the forward motion of the screw. The speed profile is produced by a function generator, based on the given screw movement profile. The real value of the forward rate of the screw is determined from the screw's movement by a differentiator. A comparator (C_1) compares the existing pressure in the mould with the P_{AB} value determined for this switch-over point. Once the value of P_{BA} is attained, the switch-over is made. Comparator (C_2) compares the mould cavity pressure gradient at the P_{KU} point with the zero value set and when the difference decreases to zero a switch over to pressure-holding is made. The pressure optimization programme controls the hydraulics' programme, together with the packing pressure and the cooling phases. In this over-all computer control programme the functions of the central computer are divided between three microprocessors.

The spread of microprocessors, due to their relatively low costs, launched a new phase of development in process controls; the phase of application of new control equipment with subdivided "intelligence". The microprocessor applies control functions directly to the points at which deviations from standards occur, using digital controls of divided intelligence.

Where central large computers are employed, problems may be caused by the high costs and the potential problems associated with the breakdown of such a large central computer. The advantages of divided intelligence are:

- cost advantage; it is cheaper to use microprocessors than large computers,
- greater reliability,
- the ease of fault location,
- the possibility of transfer of information to the central microprocessor; the role of the central microprocessor is data collection, in-process control and information recording,
- the process can be divided into part systems, which represent individual control cycles.

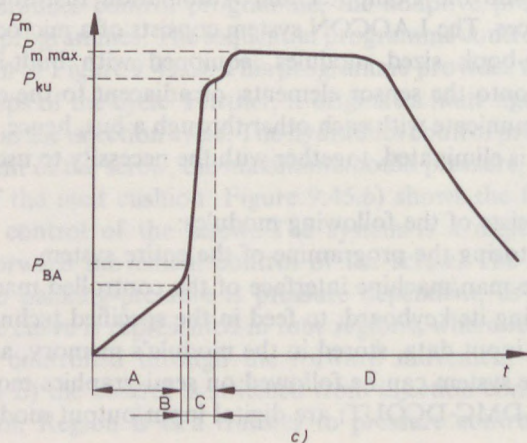
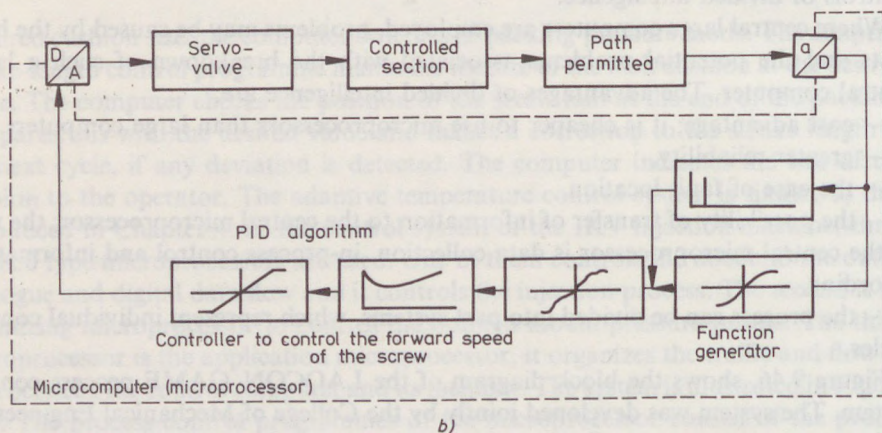
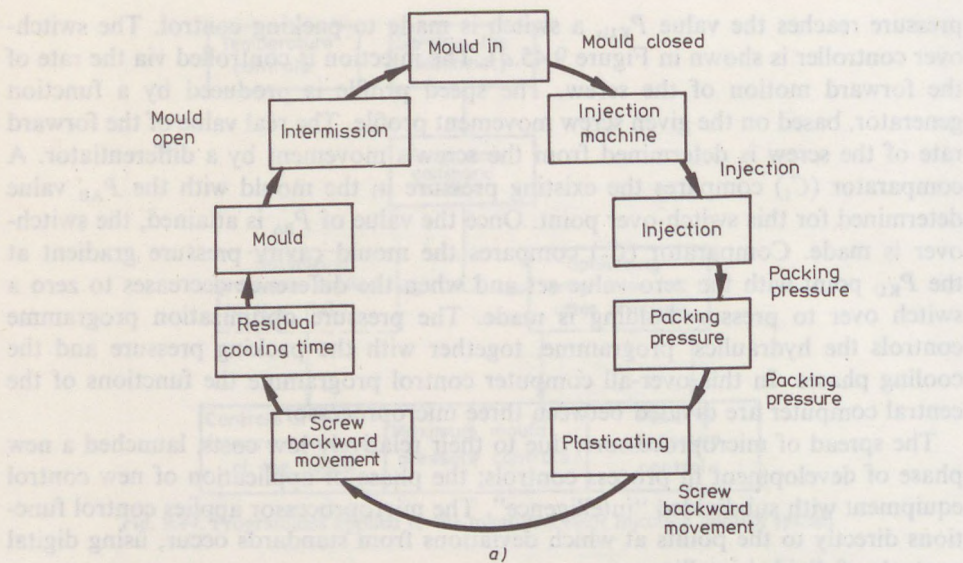
Figure 9.46. shows the block diagram of the LAOCON-GAMF process control system. The system was developed jointly by the College of Mechanical Engineering and Automation and the Computer and Automation Institute of the Hungarian Academy of Sciences. The LAOCON system consists of a microcomputer controlled system with note-book sized modules, equipped with built-in microcomputers, mounted directly onto the sensor elements, or adjacent to the control devices. The modules can communicate with each other through a bus, hence, the need for special cable connections is eliminated, together with the necessity to use a central processor control computer.

The system consists of the following modules:

DMC-Store: for storing the programme of the entire system.

DMC-MMI/S: the man/machine interface of the controlled machine. It is possible, using its keyboard, to feed in the specified technological parameters as input data, stored in the module's memory, and the operation of the system can be followed on semi-graphics monitor.

DMC-DCIN and DMC-DCOUT: are digital input/output modules.



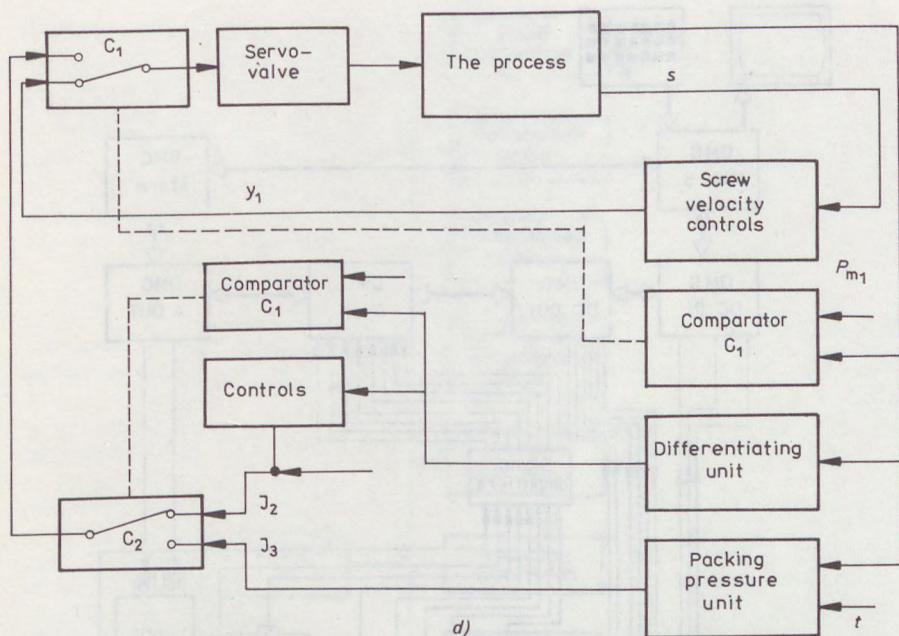


Fig. 9.45. The operation of a microprocessor control system

a) A programme to control the entire operation, b) Control system to control the forward movement of the screw, c) Pressure curve with indications of the points of switch-over, d) A system to control switch-over

DMC-A IN: analogue signal receiver.

DMC-A OUT: applied to handle the analogue outputs.

Equipment frequently used in the chemical industry is, for example, the Honeywell Automation TDC-2000 machine [100].

The microprocessor system of divided intelligence used in the control of injection moulding processes consists of the following control loops [71]:

- the temperature control system,
- the control system to control the injection speed and the die pressure,
- a programmable logic unit,
- an alarm signal system, and
- a product registering unit.

One of the most important requirements is the capability of the temperature control system to receive information from the computer. These include control of the temperature of the walls of the barrel, of the nozzle, of the inlet orifice for the melt, control of the die temperature, the conditioning of the feed hopper, the temperature control of the material in front of the screw through the wall temperatures in a cascade control mode.

The injection and the packing pressure unit control the rate, the switch-over and the packing pressure in the same way as described earlier. The position of the screw-ram is determined, and by differentiating the position signal, the actual speed

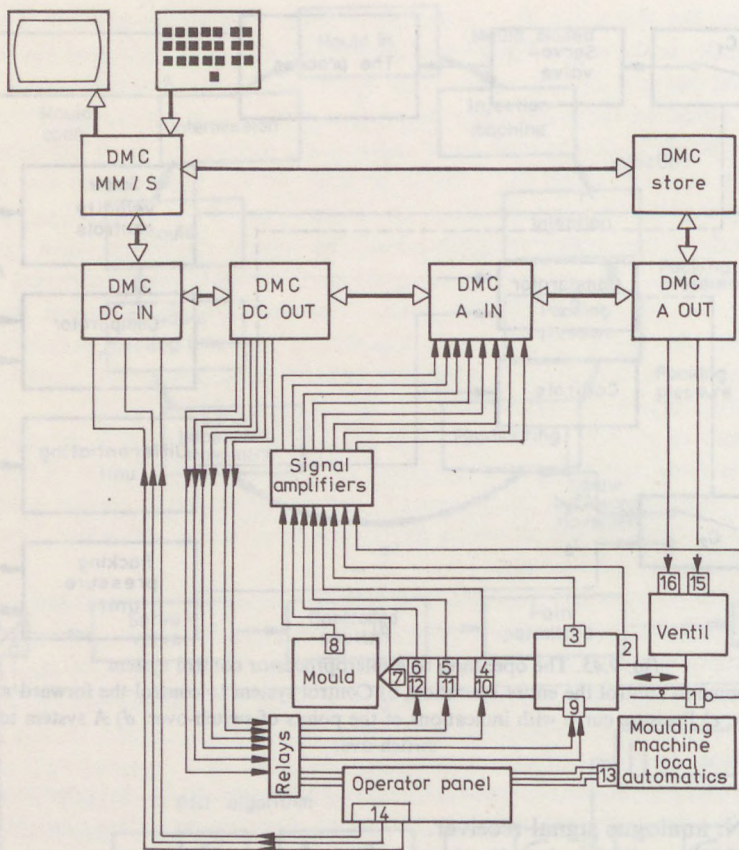


Fig. 9.46. Block diagram of the LAOCON®-GAMF Process Control System

is obtained. Adjustment is performed by the hydraulic servo-valve. Continuous monitoring of the pressure curve is possible either by measuring the pressure in the mould, or by measuring the hydraulic pressure. A more reliable value is obtained by measuring the pressure in the mould. The control system of the injection process often contains a cushion control loop as well.

One of the tasks assigned to the programmable logics is to fit the operation of the injection and the packing-pressure control systems to the mould unit. The unit receives digital signals from the terminal switches, timing signals from the control panel and from the central microprocessor, digital signals from the system choosing the operation mode and from the control panel; it determines queuing of the signal traffic and the sequence of interference. Finally, it should send signals from the control loop to the control units of the mould unit. The task assigned to the alarm device is to indicate overloading of the motor, to indicate incorrect mould positioning, etc., and to interrupt operation of the machine. The product registering unit provides information on the process. Such information may include the name of the product and its

compares the characteristic features of computer controls with traditional controls. It is clear that the quality of the products made under computerized control is superior to those made by exercising traditional controls. The Table shows that reject rates are reduced, in the case of computerized control application, both at start up of production and during production. In general, the application of computerized control is advantageous financially when several machines are controlled simultaneously.

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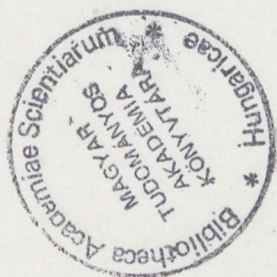
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With the general growth in demand for an ever-increasing range of articles manufactured by the plastics industry, the use of computers to control not only equipment and machines but even entire production lines is a development of great importance in the constant search for optimum output and high quality. In addition, the need to minimize energy requirements is another obvious target for computer technology, given the ability of a computer to make near-instant decisions on the complex interactions of many factors.

This work is the first publication, specific to plastic manufacturing, where the focus is placed on computer-controlled technology. The author approaches the application of control processes by computer from aspects of the processes employed; commencing from theoretical considerations he examines those processes which influence product quality, and summarizes the various control processes as an overview.

This work is intended particularly to be a source book for scientists and engineers engaged in plastic manufacturing. Experts dealing with control engineering especially in the processing industry will gain the most benefit from this book.



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Control methods in polymer processing