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POOL BOILING CRISIS

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ABSTRACT

The transition from the simultaneous superheated liquid and latent heat transport of developed nucleate boiling to the purely latent heat transport of transient film boiling is marked by an increase in the heat transfer rate to a maximum. This maximum - the critical heat flux - occurs when the total amount of incoming fluid is just vaporized at the heater surface. The crisis is consequently hydrodynamic in nature. This, it is shown, implies that the critical heat flux can be determined from the conservation laws for the mass, energy and momentum. Moreover, by taking into account the effect of subcooling in the energy equation, the maximum achievable heat flux can also be determined for subcooled boiling conditions.

РЕЗЮМЕ

При переходе от развитого пузырькового кипения с переносом перегретой жидкости и скрытого тепла к нестационарному пленочному кипению с переносом скрытого тепла получается максимум в теплоотдаче. Этот максимум - критический тепловой поток - возникает тогда, когда жидкость приходящая к поверхности нагрева, полностью испаряется. Отсюда следует, что кризис теплообмена имеет гидродинамическую природу. Записиваются законы сохранения массы, энергии и импульса для жидкого объема окруженного контрольными поверхностями, в том числе поверхностью нагрева, и определяется критический тепловой поток. Для расчета максимальной тепловой нагрузки при поверхностном кипении получается соотношение, которое учитывает недогрев жидкости.

KIVONAT

A kifejlett buborékos forrás egyidejü tulhevitett folyadék és rejtett hő-transzportjából az átmenet a tranziens filmforrás tisztán rejtett hő-transzportjába maximumot eredményez a hőátvitelben. A maximum - a kritikus hőfluxus - akkor adódik, amikor a fütőfelületre beérkező folyadék éppen teljes egészében elgőzölög. A krizis tehát hidrodinamikai természetü. Felirva egy a fütőfelületet magába foglaló ellenőrző felülettel körülvett folyadéktérre a tömeg-, energia és impulzusmegmaradási törvényeket, meghatároztuk a kritikus hőfluxust. Az aláhütés hatásának az energiaegyenletben történt figyelembe vételével az aláhütött folyadék forralásakor elérhető maximális hőterhelés számitására alkalmas összefüggés adódott.

INTRODUCTION

The considerable general importance of theoretical and experimental investigations of the crisis in the boiling process, and in particular the determination of the maximum attainable heat flux, holds for pool boiling as for other conditions. For in heat-flux-controlled systems, like an electric heater submerged in a pool of liquid or a fuel element of a nuclear reactor, if power is increased after the critical heat flux has been achieved, there is a sudden jump in the surface temperature of the heater, which is very often sufficient to deteriorate the surface material and so is manifested in burn out. Safety in operation demands the setting of a limit flux before the crisis above which the system will not pass. Before we can prescribe the necessary safety limits, of course, we have to know the value of the critical heat flux, and it is the calculation of this value which forms the subject of the present paper.

REVIEW

Researchers investigating pool boiling have proposed several empirical or semiempirical relationships for the calculation of critical heat flux. The best known of these and at the same time the ones best correlating the experimental results are the equations published by Rohsenow[1] Kutateladze [2] and Zuber[3].

Rohsenow's starting point is the consideration that when the critical heat flux is reached the heater surface becomes saturated with bubbles, and on this basis he got the following correlating equation:

$$\frac{q''_{cr}}{\rho'' L} = 43.6 \left(\frac{\Delta\rho}{\rho''}\right)^{0,6} g^{1/4} \left[\frac{m}{s}\right] \qquad /1/$$

This reproduced the measured points with an average deviation of 11%.

Kutateladze, on the other hand, supposed the crisis was hydrodynamic in nature. In his opinion the crisis occurs when the equilibrium in the two-phase boundary layer is disrupted, which is the case when the vapour velocity reaches some critical value. By dimensional analysis he obtained for the critical heat flux

$$q''_{cr} = \text{const} \cdot \sqrt{\rho''}\, L\, \sqrt[4]{\sigma g \Delta\rho}^{\,*} \quad [\text{kcal/m}^2,\text{sec}] \qquad /2/$$

The best agreement with the experiments was found for const = 0.16.

Finally, Zuber, starting from essentially the same principles as Kutateladze, supposed that the critical velocity of the vapour leaving the surface in the form of jets is simultaneously determined by the Taylor and Helmholz instabilities, on which basis he derived the relationship

$$q''_{cr} = \text{const}\sqrt{\rho''}\, L\, \sqrt{g\sigma\Delta\rho}\, \sqrt{\frac{\rho'}{\rho''+\rho'}}^{\,*} \quad [\text{kcal/m}^2,\text{sec}] \qquad /3/$$

The value of the constant - according to the stability criteria - has to lie between 0.12 and 0.157, so that a regular scattering of the measured critical heat flux data can be expected.

The proposed correlating equations /1/, /2/ and /3/ are similar in form and, in fact, they cover substantially the same physical ground, as even Rohsenow's equation supposes that after a very high bubble population is reached the surface will become inaccessible to sufficient quantities of incoming liquid.

The expression evaluated in this paper is essentially the same as that of Kutateladze but a scattering field like Zuber's is found. Moreover by a simple modification the equation can be successfully extended to the subcooled boiling condition too.

EXPLANATION OF THE BOILING CURVE

The mechanism of saturated nucleate boiling has already been dealt with in ref. [4]. According to the model described there, the heat transferred in developed nucleate boiling, if we disregard the insignificant convection, may be attributed to two fundamental factors:

1/ the latent heat transport of bubbles, and
2/ the enthalpy of the superheated liquid layer removed by bubbles on departure.

Fig. 1 shows a typical boiling curve. Along the segment of developed nucleate boiling, B - C, the heat flux increases sharply as a consequence of

*in Eqs. /2/ and /3/ the surface tension σ is in N/m.

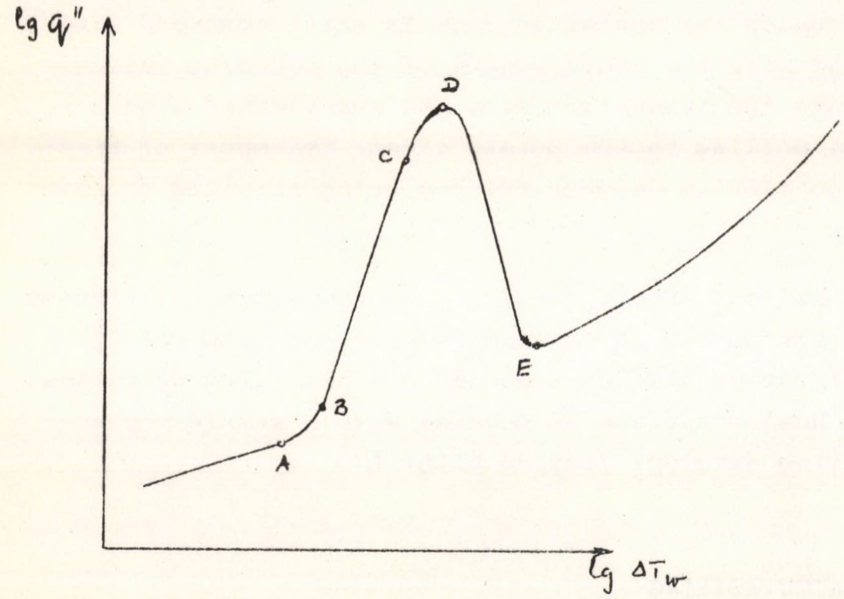

Fig. 1 Typical boiling curve

the rapid growth of the bubble population brought about by rising wall superheat. The heat is in this regime transported according to both pathways 1 and 2. Now, although it was set up originally to account for developed nucleate boiling, this same heat transfer model makes it possible to explain the other parts of the boiling curve.

Up to point A heat transfer is due solely to convection, because superheats less than ΔT_A are not enough to activate any bubble-generating centres.

The section between A and B is the region of partial boiling, which marks the transition from convection to boiling. Bubbles growing in these conditions prove the heat transfer through their qualitatively better heat transport, in spite of the fact that that part of the surface covered by them becomes inaccessible to convection. In this transitional region the number of growing and departing bubbles increases first slowly, then more and more rapidly, as wall superheat is elevated. At the same time the convective heat transfer rate falls until its contribution becomes negligible compared to the effective heat transport of bubbles, and developed nucleate boiling is achieved.

Regime C - D is another transitional part of the boiling curve and may be thought of in these terms. Because of a large increase in the bubble population the area of the heating surface not influenced by bubbles is reduced quickly until in the end it becomes approximately zero. In this state bubbles remove the total transient boundary layer which is developed in the average cycle time $t_w + t_d$ /point C/. On further increasing the wall superheat the number of active centres, of course, continues to rise, but bubbles now begin grow at each other's expense and so the number of active sites becomes independent of the bubble population because of the frequent bubble coalescence. The total heat flux increases both because the enthalpy of the transient boundary layer becomes higher, and because the bubble generation frequency and boundary layer thickness are also influenced. The above changes proceed until all the heat is being transferred according to pathway 1, i.e. only by latent heat transport of bubbles. At this point the amount of liquid allowed to reach the heater surface is still just sufficient to cover the mass, energy and momentum requirements of the outgoing vapour. Thus regime C - D represents the transition from the superheated liquid + vapour transport of nucleate boiling to the purely vapour transport of transition film boiling, with equilibrium between the two being attained at point D.

In transition film boiling itself /D-E/ the hydrodynamic equilibrium no longer holds. The heater surface is at first partially and temporarily covered by vapour but as the vapour blanket enlarges the heat flux decreases until eventually the entire heater surface is covered with a stable vapour blanket and stable film boiling develops /beyond point E/.

CRITICAL HEAT FLUX IN SATURATED BOILING

With the explanations of the different regimes of the boiling curve outlined in the previous section we can now go on to determine the physical conditions describing the heat transfer crisis. The crisis is of a hydrodynamic nature and occurs - as Kutateladze [2] and Borishanskii [5] pointed out - when the hydrodynamic equilibrium of the two-phase flow past the heater surface stops. Accordingly we ought to be able to evaluate the maximum heat flux from the conservation laws for energy, mass and momentum which express the state of equilibrium.

We shall assume we are dealing with a definite liquid volume surrounding the heater. The conservation of energy can be expressed as

$$G_v = \frac{q''_{cr,sat}}{L} \qquad /4/$$

where it has been supposed that all the transported heat is carried away in the latent heat of bubbles.*

Conservation of mass expresses here the condition that the mass of the incoming liquid must be equal to the mass of outgoing vapour:

$$G_\ell = (1 - \alpha)\rho' v_\ell = G_v \qquad /5/$$

*It is also assumed that the boiling process is steady state, the heater surface is a horizontal plane and the effect of viscosity may be neglected.

For the conservation of momentum, finally, we can write

$$\rho'(1-\alpha)\ v_\ell^2 = \rho''\alpha V_v^2 \qquad /6/$$

Solution of equations /4/, /5/ and /6/ yields

$$q''_{cr,sat} = \sqrt{\alpha(1-\alpha)}\ \sqrt{\rho'\rho''}\ L\ V_v \qquad /7/$$

As the vapour is released from the surface in the form of bubbles and continuous vapour columns develop only later, we must use for the vapour velocity in Eq./6/ the terminal bubble rise velocity, only the control surface surrounding the investigated liquid volume has to be chosen close enough to the heating surface.

$$q''_{cr,sat} = \sqrt{\alpha(1-\alpha)}\ \sqrt{\rho'\rho''} L v_\infty \qquad /8/$$

TERMINAL BUBBLE RISE VELOCITY

To determine the terminal bubble rise velocity the bubble was assumed to be a solid sphere. Since the range of Reynolds' numbers characteristic for bubble rise generally lies in the turbulent region, the Stokes' equation is not applicable, so we took the flow resistance coefficient from ref. [6]. According to this the flow resistance coefficient can be calculated accurately enough from the following expression if the Reynolds' number is between 10 and 12.000

$$\zeta = 0.5 + \frac{40}{R_e} = 0.5 + \frac{20\nu_\ell}{R_d v_\infty} \qquad /9/$$

Taking the flow resistance force and putting it equal to the buoyancy force, the therminal bubble rise velocity is obtained as

$$v_\infty = -\frac{20\nu_\ell}{R_d} \pm \sqrt{\left(\frac{20\nu_\ell}{R_d}\right)^2 + \frac{16}{3}\ g\ R_d\ \frac{\Delta\rho}{\rho'}} \qquad /10/$$

In most boiling systems the bubble departure radii are large enough for us to be able to neglect the viscosity term in Eq/10/, and so we may write

$$v_\infty \approx \pm\sqrt{\frac{16}{3}\ g\ R_d \frac{\Delta\rho}{\rho'}} = \pm\ B_o\ \sqrt{R_d\ \frac{\Delta\rho}{\rho'}} \qquad /11/$$

where only the positive root has a real physical meaning. Unlike solid spheres, however, bubbles can be deformed as a consequence of the hydrostatic pressure difference between their bottom and top, and the deformation increases as they grow in size. Owing to the deformation the resistance against bubble rise is greater and so the bubble rise velocity decreases. The value determined by Eq./11/ is thus the maximum velocity theoretically attainable by bubbles and, of course, the real velocity is always less.

In pool boiling the vapour transport may be considered as a slug flow in a channel above the nucleating site with a size about the bubble departure diameter. In slug-flow conditions the best value for the constant in Eq./11/ was determined by Nicklin and Davidson [7] to be

$$B_o = 0.35\sqrt{2g} \qquad /12/$$

The bubble departure size can be evaluated well from the Fritz correlation

$$R_d = B_1 \sqrt{\frac{\sigma}{\Delta\rho}} \qquad /13/$$

Though measurement by Semeria show a significant deviation from the radii predicted by Eq./13/, the deviation is the greatest in the region of developed nucleate boiling [8]. At higher heat fluxes, when bubble coalescence prevails, the trend of Semeria's data approaches that of Fritz's results.

By substituting /12/ and /13/ into /11/, the bubble rise velocity can be expressed as

$$v_\infty = 0.35 \sqrt{\frac{2gB_1}{\rho'}} \sqrt[4]{\sigma\Delta\rho} \left[\frac{m}{sec} \right] \qquad /14/$$

CRITICAL HEAT FLUX CORRELATION

Using Eq./14/ as the rise velocity of the vapour conglomerate leaving the heater surface near critical conditions, the maximum heat flux in saturated pool boiling is found to be

$$q''_{cr,sat} = \sqrt{\alpha(1-\alpha)}\ 0.35\cdot 3600 \sqrt{2gB_1} \sqrt{\rho''}\ L \sqrt[4]{\sigma\Delta\rho} \qquad /15/$$

The constant B_1 can be determined from the rough approximation that the bubble departure radius at 1 atm. is about 1 mm, and we gain

$$q''_{cr,sat} = 3540 \sqrt{\alpha(1-\alpha)} \sqrt{\rho''} L \sqrt[4]{\sigma\Delta\rho} \qquad /16/$$

The void fraction α is that proportion of the control surface covered by vapour when critical heat flux is reached. It was determined in this case on consideration of the statistical emission of bubble-generating sites and obviously takes such extreme values as bound all the possible cases.

Near the critical heat flux the nucleating sites operate like jets, i.e. the ejected vapour conglomerates immediately follow one another. The area occupied by vapour reaches a maximum when the jets touch each other from the side. Hence α_{max} is determined by the maximum of the filling factor. On simple geometrical grounds it can be seen that

$$\alpha_{max} = \frac{\frac{R_d^2\pi}{2}}{\sqrt{3}\, R_d^2} = \frac{\pi}{2\sqrt{3}} \qquad /17/$$

Eq./17/ is equivalent to the case when the emission of slugs from the active nucleating sites is simultaneous. In this case the factor $\sqrt{\alpha(1-\alpha)}$ takes its minimum value because the free cross section for the incoming liquid is likewise minimal in these circumstances. As α must lie between 0 and 1, the expression has its maximum when α is equal to 0.5. This is obviously the other extreme value, corresponding approximately to the case when bubbles are released uniformly in time.

Statistically emitting bubble-generating centres can produce any optional point of the field $\alpha = 0.5 - 0.907$, therefore Eg./16/ may be changed into the form

$$q''_{cr,sat} = (1770 \div 1027) \sqrt{\rho''} L \sqrt[4]{\sigma\Delta\rho} \qquad /18/$$

Fig. 2 compares experimental results of Kazakova [9] and the boundaries calculated by Eq./18/. The agreement is very good; almost all the measured points lie within the interval determined by the factor $\sqrt{\alpha(1-\alpha)}$.

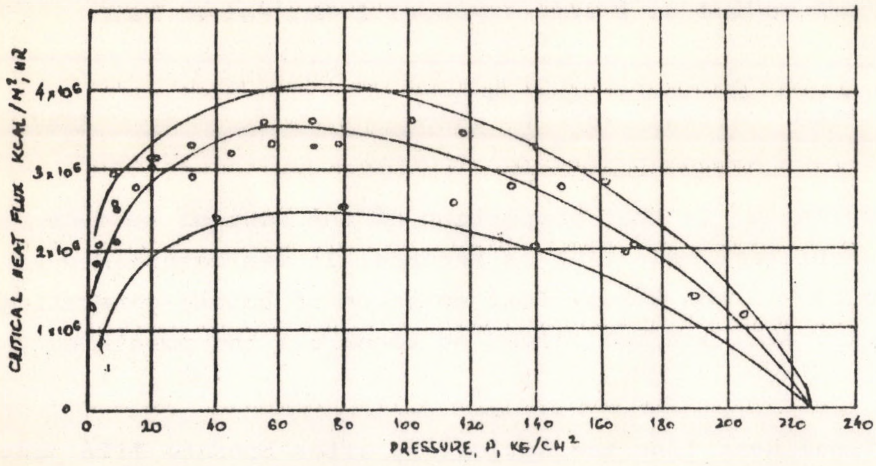

Fig.2 Critical heat flux in saturated pool boiling
o points of Kazakova —— lines calculated by eqs. /18/and/19/ respectively

According to the above considerations the most probable critical heat flux is determined by the expected value of the bubble emission process. The theoretical treatment of the problem, however, runs into serious difficulties. On the basis of Kazakova's measurements it was found that the points condense at 2/3 rd of the zone between the boundaries. Thus the best prediction for the critical heat flux seems to be

$$q''_{cr,sat} = 1520 \sqrt{\rho''}\, L\, \sqrt[4]{\sigma\Delta\rho} \qquad /19/$$

CRITICAL HEAT FLUX IN SUBCOOLED BOILING

The above detailed model can be extended to the investigation of subcooled boiling after the introduction of some additional assumptions.

The first assumption, which helps us to create the new conservation laws, is that at critical heat flux there is again only latent heat transport. If this is so, the amount of generated vapour can be determined as follows. In the boundary layer the incoming liquid will be heated from a temperature T_ℓ up to T_w, i.e.

$$q''_{cr,sub} = G_\ell c_\ell (T_w - T_\ell) = G_\ell c_\ell \, \Delta T_t \qquad /20/$$

This heat balance gives a liquid mass flow rate which can produce vapour only from its own superheat:

$$G_v L = G_\ell c_\ell \, \Delta T_w \qquad /21/$$

Expressing Eq./20/ and /21/ for G_v we obtain

$$G_v = \frac{q''_{cr,sub}}{L} \; \frac{\Delta T_w}{\Delta T_t} \qquad /22/$$

Consequently, in subcooled boiling the equation for the conservation of energy takes the form of /22/ instead of /4/.

The equations for the conservation of mass and momentum are analogous to /5/ and /6/:

$$\rho'(1-\alpha)v_\ell = G_v \qquad /23/$$

and

$$\rho'(1-\alpha)\, v_\ell^2 = \rho''\alpha V_v^2 \qquad /24/$$

where the vapour velocity is again the terminal bubble rise velocity in the liquid.

It is presumably not a bad assumption if we suppose that the wall superheat in the subcooled boiling crisis does not deviate considerably from that of saturated boiling.[2] It can be expected then that the bubble departure size is also unchanged, so we may use the same expression for the vapour velocity and the same values for the void fraction in Eq./25/. This can now be written

$$q''_{cr,sub} = 1520\sqrt{\rho''}\; L\; \sqrt[4]{\sigma\Delta\rho}\; \frac{\Delta T_t}{\Delta T_w} \qquad /26/$$

or rather

$$q''_{cr,sub} = q''_{cr,sat} \cdot \frac{\Delta T_t}{\Delta T_w} \qquad /27/$$

If the total temperature difference is now divided into wall superheat and subcooling, we get

$$q''_{cr,sub} = q''_{cr,sat} \left(1 + \frac{\Delta T_{sub}}{\Delta T_w}\right) \qquad /28/$$

Though it was stated that the wall superheat in subcooled boiling approximately agrees with that in saturated boiling, we still have to introduce a correction factor into Eq./28/ to take into account the difference between the boiling curve slopes in subcooled and saturated conditions. The correction factor is needed to enable us to get a ΔT_w value in Eq./28/ that can be evaluated without difficulty.

2/ The wall superheat can not change sharply with respect to the subcooling because of the slope of the boiling curve.

It can be proved that the following equation expresses the heat flux in developed subcooled boiling:

$$q''_{sub} = B_3 \, \kappa \left(\frac{\rho' c_\ell}{\rho'' L} \right)^{n/2} \left(\frac{p'}{\sigma} \right)^m \Delta T_w^{\,m+\frac{n}{2}+2} \left(1 + \frac{\Delta T_{sub}}{\Delta T_w} \right) \qquad /29/$$

The heat flux in saturated boiling is [4]

$$q''_{sat} = B_3 \, \kappa \left(\frac{\rho' c_\ell}{\rho'' L} \right)^{n/2} \left(\frac{p'}{\sigma} \right)^m \Delta T_{w,sat}^{\,m+\frac{n}{2}+2} \qquad /30/$$

This means that the difference between the two types of boiling can be expressed in the same way in developed nucleate boiling and in critical conditions.

Thus by putting /29/ and /30/ equal to one another we can determine how much less wall superheat is necessary in subcooled boiling to reach the same heat flux:

$$\Delta T_w = \Delta T_{w,sat} \frac{1}{\left(1 + \frac{\Delta T_{sub}}{\Delta T_w} \right)^{1/(m+\frac{n}{2}+i)}} \qquad /31/$$

Introducing /31/ into /28/ and neglecting the difference between ΔT_w and $\Delta T_{w,sat}$ in the second brackets, we gain

$$q''_{cr,sub} = q''_{cr,sat} \left[1 + \frac{\Delta T_{sub}}{\Delta T_{w,sat}} \left(1 + \frac{\Delta T_{sub}}{\Delta T_{w,sat}} \right)^{\frac{1}{m+\frac{n}{2}+2}} \right] \qquad /32/$$

Before we can calculate the maximum heat flux from Eq./32/ it is necessary first to solve Eq./19/ and /30/ for $\Delta T_{w,sat}$. In the case of water $B_3 = 8.43 \cdot 10^{-5}$ and $(m+n/2+2) = 3.33$ were found from the data published by Kutateladze. These values give $\Delta T_{w,sat} = 20^oC$. The critical heat flux for subcooled boiling of water was calculated with these data in the function of subcooling and the results are presented in Fig. 3. The agreement with the measurements of Gunther and Kreith [10] and Ellion [11] /taken from ref. [3]/ is reasonably good.

It should be noted that Eq./32/ correctly describes the very clear trend of the measurements, displaying the same slight deviation from linearity in the relationship between subcooling and critical heat flux.

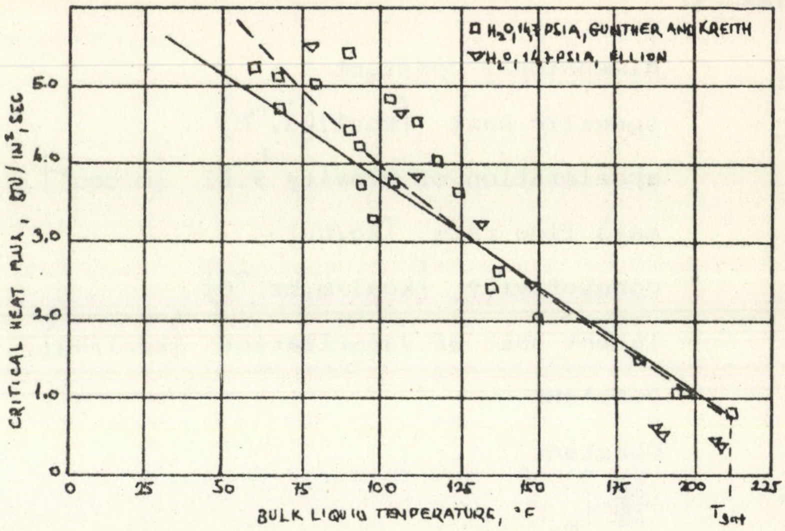

Fig. 3 Critical heat flux in subcooled boiling
—— line proposed by Zuber
---- line according to Eq.(32)

DISCUSSION

The explanations of the boiling curve and the equations of hydrodynamic stability have given us the possibility of determining the critical heat flux in saturated pool boiling. The method could be extended to subcooled boiling with relative ease.

The agreement between calculated and measured data supports the assumptions made and the applicability of the conservation laws for solving the problem. Checks of the relationships for liquids other than water would be desirable, especially in subcooled boiling conditions.

The demonstration rests, for the sake of simplicity, on the assumption of a horizontal plane surface. A detailed check of the results for vertically situated and other geometries would require further elaboration.

The model might be extendible to flow boiling conditions by treating the absolute vapour velocity as the sum of the average liquid and relative vapour velocities. However, a suitable departure size correlation would also be needed, and this raises further difficulties.

SYMBOLS:

B_i	dimensional constant
c	specific heat $[kcal/kg,^{o}C]$
g	acceleration of gravity 9.81 $[m/sec^2]$
G	mass flow rate $[kg/hr]$
k	conductivity $[kcal/m,hr,^{o}C]$
L	latent heat of vaporization $[kcal/kg]$
m	constant
n	constant
p'	$\left.\frac{\partial p}{\partial T}\right\|_{Ts}$
q"	heat flux $[kcal/m^2,hr]$
R_d	departure radius of bubble $[m]$
R_e	Reynolds' Number
T	temperature $[^{o}C]$
ΔT	temperature difference $[^{o}C]$
ΔT_{sub}	subcooling $[^{o}C]$
ΔT_w	superheat $[^{o}C]$
v	velocity $[m/sec]$
v_∞	terminal bubble rise velocity $[m/sec]$

GREEK LETTERS:

α	void fraction
ν	kinematic viscosity $[m^2/sec]$
ρ	density $[kg/m^3]$
ρ	density of saturated liquid $[kg/m^3]$
ρ	density of saturated vapour $[kg/m^3]$
$\Delta\rho$	$\rho' - \rho''$
σ	surface tension $[kp/m]$
ξ	flow resistance coefficient

INDECES:

cr	refers to critical conditions
l	refers to liquid
sat	refers to saturated conditions
sub	refers to subcooled conditions
t	means total
v	refers to vapour
w	refers to wall

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