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Predictions of parametric effect on transition boiling under pool boiling conditions

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Abstract—Using the theoretical model developed by the authors, important parametric effects, such as cavity size distribution, coating thickness, substrate thermal properties, system pressure, and liquid subcooling level, on transition boiling are investigated. The model predicts the same trend as experimental observations. If suitable data are available, direct comparisons show reasonable quantitative agreement. The theoretical model is the first in the literature that has the ability to predict such a wide range of parametric effects on transition boiling, including the critical and minimum heat flux points.

INTRODUCTION

TRANSITION boiling is of significant importance in the safety analysis of water-cooled nuclear reactors and in the heat treatment of metals. Several parameters, such as surface coating, oxidation, or deposition, surface wettability, substrate thermal properties, system pressure, liquid subcooling level, etc., have been experimentally found influencing transition boiling significantly. In the literature, there is no single model or correlation that can predict all of these parametric effects. This paper presents a theoretical model which can predict most of the parametric effects listed above.

For upward facing flat plates, there is strong evidence [1–3] that the pool boiling near the critical heat flux is characterized by the presence of a thin liquid film between the heating surface and the hovering bubble with vapour stems penetrating the film providing vapour to the growing bubble. The liquid film is referred to as the 'macrolayer'. Recently, Haramura and Katto [4] developed a new hydrodynamic model for the critical heat flux based on the formation and dryout of the macrolayer. In their model critical heat flux occurs when the liquid film evaporates away at the end of the bubble hovering period. In the transition boiling regime, which is introduced naturally after the critical heat flux if the surface temperature is the controlling variable, it is reasonable to postulate that a similar mechanism, i.e. the formation and dryout of the macrolayer, is present; transition boiling is the situation that the macrolayer would dryout before the hovering bubble leaves. On the basis of this concept, a theoretical model for transition boiling under pool boiling conditions has been developed by the authors [5]. The model treats transition boiling by incorporating transient conduction, boiling incipience, macrolayer evaporation, and vapour film boiling. Macrolayer evaporation is found to be the dominant contributor to the transition boiling heat flux except in the region of high wall superheats near the minimum film boiling point where vapour film boiling becomes dominant.

The present model is developed primarily for upward facing flat plates. Haramura and Katto [4] extended their critical heat flux model for other geometries. It is believed that the basic mechanism, i.e. the formation and dryout of the macrolayer, is similar for other geometries and the present model can be applied with some modifications.

In this paper, important parametric effects, such as cavity size distribution, coating thickness, substrate thermal properties, system pressure, and liquid subcooling level, on transition boiling are investigated by the theoretical model developed in ref. [5]. If suitable data are available, direct comparisons between model predictions and the experimental results are made. Otherwise, only parametric trends are demonstrated.

Recently, the mode of heat transfer to obtain the transition boiling curve, i.e. heating or cooling mode, has been found to influence the transition boiling curves and the existence of so-called two-transition boiling curves has been proposed in the literature [6]. However, the mechanism of heat transfer in one mode or the other is still unclear at this stage [7]. Therefore, in this paper, there is no intention to distinguish between the heating and cooling modes of heat transfer. In addition to the effect of the mode of heat transfer, it has been shown experimentally that surface wettability plays an important role in transition boiling [8]. With some modifications, the present model is able to predict such a wettability effect. This feature of the model is presented in another paper [9].

BACKGROUND

In the literature, important parametric effects on transition boiling from extensive experimental studies have been presented. However, much scattering in

NOMENCLATURE

C_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
g	gravitational constant [m s^{-2}]
H_{fg}	latent heat of evaporation [J kg^{-1}]
Ja	Jacob number, $C_p\Delta T_{sub}/H_{fg}$
K	empirical constant in equation (1)
k	thermal conductivity [W m^{-1} K^{-1}]
$k\rho C_p$	thermal effusivity [W^2 s m^{-4} K^{-2}]
P	system pressure [Pa]
q''_{CHF}	critical heat flux [W m^{-2}]
q''_{min}	minimum film boiling heat flux [W m^{-2}]
r_c	surface cavity radius [m]
T	temperature [K]
ΔT_{max}	wall superheat at critical heat flux [K]
ΔT_{min}	wall superheat at minimum heat flux [K]
ΔT_{sat}	surface (wall) superheat [K]
ΔT_{sub}	liquid subcooling level [K]
t	time [s]
v_{fg}	specific volume difference between saturated vapour and liquid [m^3 kg^{-1}]
v_1	volumetric growth rate of hovering bubble [m^3 s^{-1}]
x	distance from wall [m].

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
Δ	coating thickness [m]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
τ	bubble hovering period [s].

Subscripts

b	bulk
c	coating
h	heater
l	liquid
sat	saturation
v	vapour
w	wall.

data exists and theoretical models in correlating these data are not very successful. In the following, important parametric effects on transition boiling under pool boiling conditions will be reviewed. Several parametric effects have recently been reviewed by Hsu and Kim [10].

Surface roughness

Berenson [11] first observed a profound surface roughness effect on the transition boiling curve and indirectly demonstrated the existence of liquid–solid contacts. However, recent studies conducted by Chowdhury and Winterton [12] indicated that the surface roughness does not play an important role. In contrast, Bui and Dhir [13] reported that the surface roughness has significant effects on transition boiling. Shoji and Witte [14] also reported effects of surface roughness on transition boiling. However, the effect is only moderate compared to the nucleate boiling region.

Thermal properties of substrate

The effects of thermal properties of substrate on pool boiling have been systematically investigated by Lin and Westwater [15] by quenching spheres and flat plates of the same configurations of different materials (Cu, Al, Zn, Pb and Bi) using liquid nitrogen as the fluid. These data show that the transition boiling curve is moved to the right as the value of $\rho C_p k$ of the substrate is decreased. Westwater *et al.* [16] recently proposed some correlations for the critical heat flux point as well as for the minimum heat flux as a function of $\rho C_p k$.

Surface coating/deposition

Surface coatings, oxidation, and/or deposits may be applied to a heating surface or be formed on it by nature. It has been well recognized that the presence of the surface layer has a profound effect on transition boiling. Bui and Dhir [13] reported that surface oxidation or deposition on a vertical heating surface significantly shifts the transition boiling curve toward higher wall superheats. They attributed this effect to the improvement in surface wettability. The model evaluation by the present authors [5] indicates that the thermal properties and thickness of the surface layer may play an equally important role. This model prediction is, at least, supported by the following three observations: (1) significant effects caused by substrate thermal properties as reported by Westwater and co-workers [15, 16], and (2) significant difference in the transition boiling curves from surfaces with light and heavy deposits, respectively, as reported by Bui and Dhir [13]; if the surface wettability is the only controlling parameter, the thickness of the deposition should not introduce such a profound effect as reported by Bui and Dhir [13], (3) significant effects of coating (Teflon) thickness on moving the boiling curve to the right as reported by Chandratilleke *et al.* [17].

System pressure

The system pressure has a very significant effect on pool boiling. In the nucleate boiling region, the curve is pushed to the left as the system pressure is increased. This system pressure effect on nucleate boiling is correctly predicted by the Rohsenow correlation. The critical heat flux is also a strong function of system pressure and the maximum value appears at a reduced system pressure of about 0.3 [18] and can be accurately predicted by Zuber's model [19]. The pressure dependence of minimum film boiling (Leidenfrost point) heat flux is similar to that for the critical heat flux and a maximum value appears at a reduced pressure of about 0.3 [18]. The experimental observations of the effect of system pressure on transition boiling have been reported by Hesse [20] using refrigerants as working fluids. As for the nucleate boiling curve, the transition boiling curve is moved to the left as the system pressure is elevated.

Subcooling of bulk liquid

The effect of liquid subcooling on transition boiling has recently been investigated experimentally by Shoji and Witte [14]. The whole boiling curve is pushed upward and to the right by increasing the subcooling level. The effect of liquid subcooling on the liquid contact duration during transition boiling for some fluids has been reported by Kostyuk *et al.* [21]. It was found [21] that the liquid contact duration increases with increasing the liquid subcooling level.

Double q''–ΔT maxima

Shoji and Witte [14] also reported a soluble q''–ΔT maxima between film boiling and nucleate boiling for water on mirror finished and #100 emery paper polished surfaces. The double maxima phenomenon was explained by the presence of nucleate–transition boiling [6], and the absence of this phenomenon for another fluid, such as R-113, was attributed to the predominance of the film–transition curve which also involved solid–liquid contacts but not as violent as nucleate–transition boiling.

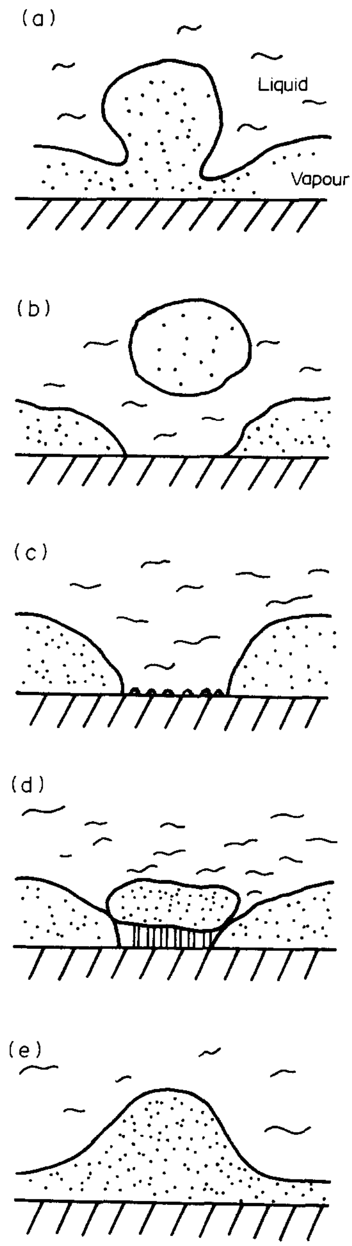

FIG. 1. Transition boiling model: (a) bubble departing; (b) transient conduction; (c) boiling incipience and heat transfer; (d) macrolayer evaporation; (e) vapour covering.

SUMMARY OF THE MODEL

A model for transition boiling has been developed by the authors in ref. [5] and is briefly summarized below. As shown in Fig. 1, transition boiling is modelled by incorporating transient conduction, boiling incipience and heat transfer, macrolayer evaporation, and vapour film boiling. The theoretical model involves several unique features: (a) effects of surface coating (oxidation and/or deposition) are considered and a time-dependent surface temperature during the transient conduction period is derived, which is quite different from that without considering the effect of surface coating; (b) the inherently turbulent nature, due to the large wall superheat (temperature head) and bubble disturbance, of the contacting liquid is taken into account and an effective liquid thermal conductivity is derived; (c) boiling heat transfer is considered to be in the high heat flux region, which is characterized by the formation of vapour jets rather than discrete bubbles at lower heat fluxes; (d) the bulk coolant is displaced due to the Helmholtz instability and a liquid film, referred to as a macrolayer, is left on the surface; (e) the boiling heat flux and thus the macrolayer thickness are determined based on the temperature at the end of the transient conduction, which is much lower than the pre-contact temperature. The displacement of the bulk liquid and the evaporation of the macrolayer explain the termination of each liquid–solid contact. The model treats the two transitions in the boiling curve, namely, critical (maximum) and minimum heat fluxes, as natural translations from transition boiling to nucleate boiling and to film boiling, respectively. Therefore, both transitions can be predicted.

Model evaluation

The model has been carefully evaluated in ref. [5], which concludes the following. (a) The inherent liquid turbulence is an important parameter in transition boiling and can be predicted by a simple mixing theory incorporating buoyancy force and bubble agitation. (b) Wall temperature drop at the end of the transient conduction period increases approximately linearly with an increase in wall temperature before liquid contact. Experimental observations of temperature drop as high as 125 K [22] are explained by the model. (c) Liquid contact duration and contact-time fraction decreases very rapidly with increasing wall superheat. (d) Surface coatings (oxidation or deposition) have very significant effects on transition boiling and cannot be neglected. (e) The improvement of transition boiling due to the presence of a thin surface oxidation or deposition may be explained, at least partially, by the oxide or deposit having poorer thermal properties than the heater material. (f) The model predictions indicate that the presence of a thin-insulating layer significantly increases the wall superheats at both the critical heat flux and the minimum film boiling points.

Modification for subcooling of liquid

The model developed in ref. [5] is basically for saturated boiling. To investigate the effect of liquid subcooling on transition boiling, the model must be modified accordingly. Pasamehmetoglu and Gunnerson [23] found that liquid subcooling influences the hovering period of the massive bubble on the liquid film. In fact, the hovering period has been modified [23] as the bubble growth period during which the bubble may depart or collapse for subcooled boiling. Experimental observations indicate that the bubble growth period decreases with increasing the liquid subcooling level and Pasamehmetoglu and Gunnerson [23] have extended the model of Haramura and Katto [4] for the critical heat flux. The vapour hovering period given by equation (12) in ref. [5] (see Appendix A) should be modified to include the subcooling effect as follows [23]:

$$\tau_{\rm sub} = \frac{1+K^*\,Ja^*}{(1+0.102Ja^*)^3}\,\tau \qquad (1)$$

$$K^* = \frac{K}{(\rho_l/\rho_v)^{3/4}} \qquad (1a)$$

$$Ja^* = \left(\frac{\rho_l}{\rho_v}\right)^{3/4} Ja \qquad (1b)$$

$$Ja = \frac{C_{pl}\Delta T_{\rm sub}}{H_{fg}}. \qquad (1c)$$

In the above equation, τ is the bubble hovering period and is given by equation (12) in ref. [5]. Setting the empirical constant, K, equal to 10 results in good agreement between model predictions and experimental measurements of heat flux [23].

UNIFORM SURFACE CAVITY SIZE DISTRIBUTION VERSUS OPTIMAL CAVITY SIZE DISTRIBUTION

The cavity size distribution has been well recognized as a primary parameter influencing boiling incipience. In transition boiling, the incipient boiling time influences the length of the transient conduction period which controls the surface temperature at the end of transient conduction and the length of the macrolayer evaporation period and so affects the transition boiling curve. Two kinds of cavity size distribution are considered in this paper: uniform cavity size and optimal cavity size. The uniform cavity size assumes that the surface has only one size of cavity. This assumption is unrealistic because a real surface will contain cavities having a size distribution. The uniform cavity size may be considered as the maximum cavity size in a continuous size spectrum that is smaller than the optimal cavity size evaluated on the basis of the assumption that the surface has a sufficiently wide range of cavity sizes available; for these small cavities the boiling incipience is actually controlled by the maximum cavity size. On the other hand, if a surface has a sufficiently wide range of cavity sizes available, using the optimal cavity size, which is the size of the cavity that gives the shortest time for boiling incipience at a given pre-contact wall superheat, is more reasonable than using a uniform cavity size for model predictions.

The optimal cavity size at a given pre-contact wall superheat can be determined using equations (8a) and (8b) in ref. [5] (see Appendix B) in the following procedure. Setting, $x = r_c$ in equation (8a) and then combining it with equation (8b) will result in an equation for the incipient time for that cavity size. The optimal cavity size can then be found by searching the size that gives the shortest incipient time. This procedure is similar to that used in Hsu's model [24]. Schematically, the optimal cavity size is the size of the vapour temperature tangent to the transient liquid temperature distribution as shown in Fig. 2. The optimal cavity size thus evaluated, as a function of pre-contact wall superheat, for a copper surface with and without a surface layer (Al_2O_3) is shown in Fig. 3. It can be seen that the optimal cavity sizes decrease with increasing wall superheat.

Uniform cavity size effect

The effect of cavity size on the transition boiling curve is shown in Fig. 4. This is the case for a copper heater overlaid with an Al_2O_3 coating having a thickness of 16 μm, which is to simulate the heater used in ref. [22]. With the presence of a coating, the cavities are on the coating surface. It can be seen that at higher wall superheats, there is no significant cavity size effect. However, at lower superheats significant effects exist for cavity sizes ranging from 1 to 2 μm. Within this range, the heat flux increases with increasing the cavity size. In addition, a slope change in boiling

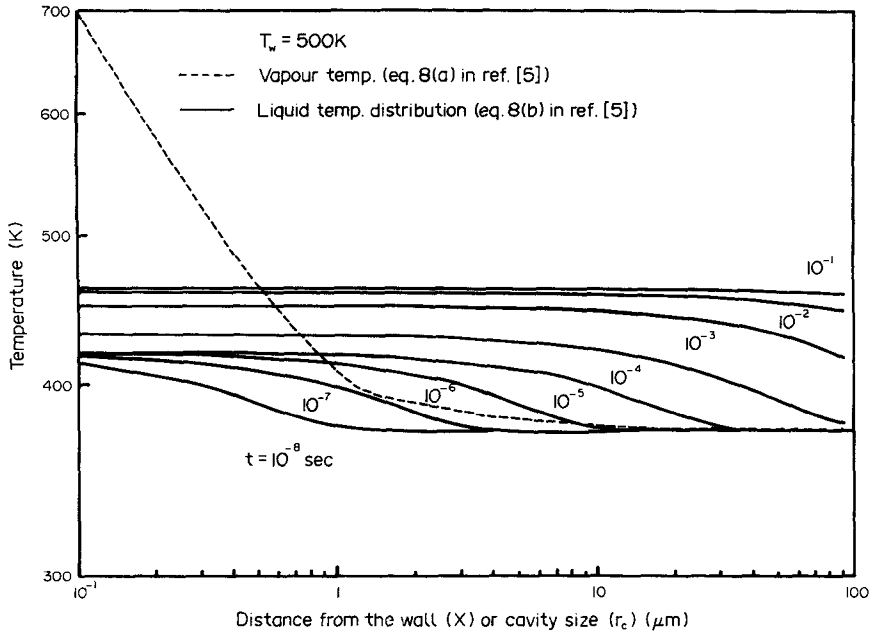

FIG. 2. Determination of the optimal cavity size at a given pre-contact wall superheat.

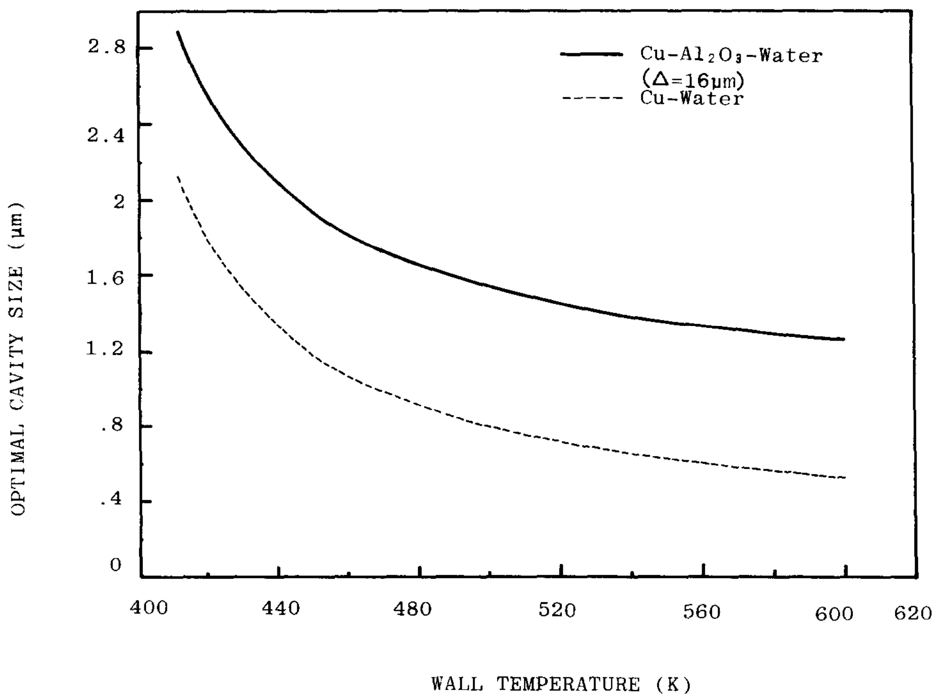

FIG. 3. Optimal cavity size as a function of temperature.

curve, which is similar to the double peaks reported in the literature [14], appears. These effects are primarily due to the presence of coating and can be explained as follows using Fig. 5 as the reference.

Figure 5 shows the interface (surface) temperature of water contacting with a copper heater overlaid with a thin layer of Al_2O_3, with a thickness of 16 μm, as a function of time. The heater and the layer have a pre-contact wall superheat of 60 K. The vertical dashed lines show the boiling incipient time at various cavity sizes. It can be seen that the interface temperature changes rapidly from a constant low value, which

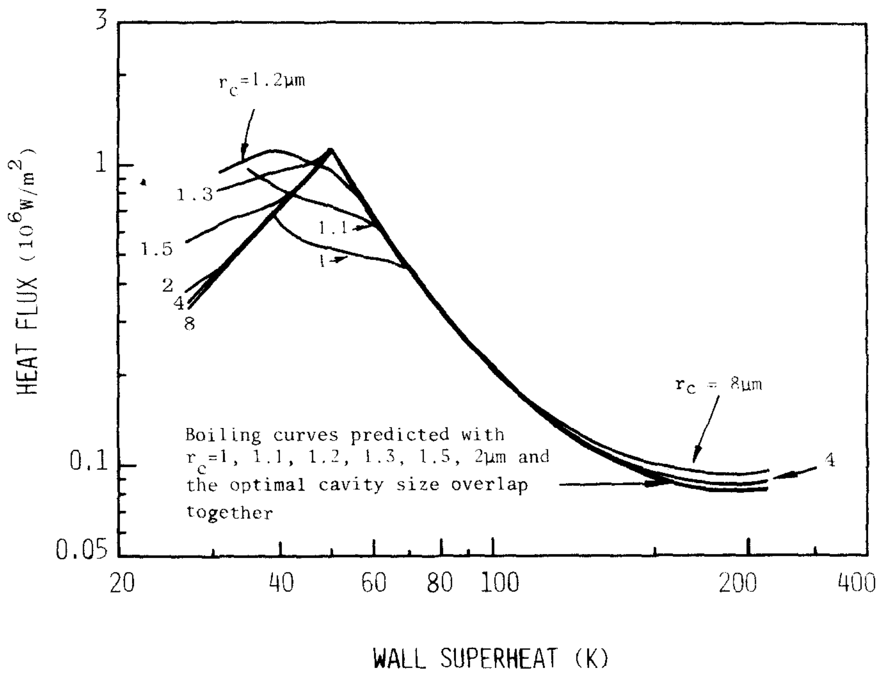

FIG. 4. Effect of cavity size on transition boiling on a copper surface overlaid with Al_2O_3, where $\Delta = 16$ μm.

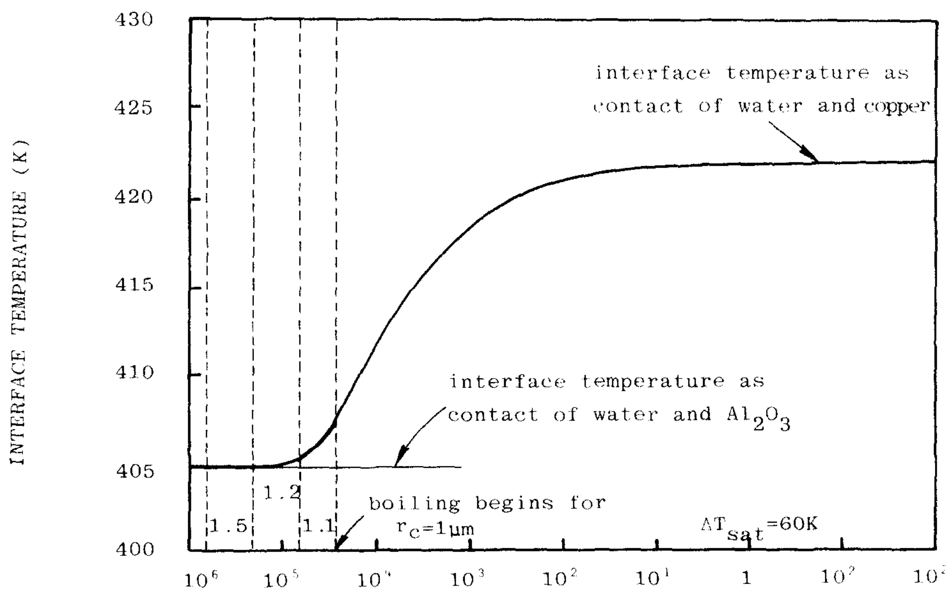

FIG. 5. Surface wall temperature during transient conduction between water and copper overlaid with Al_2O_3, where $\Delta = 16$ μm.

corresponds to the interface temperature for the transient contact of water and Al_2O_3, to a constant high value, which corresponds to the interface temperature as the transient contact of water and copper. The actual surface temperature is determined by the time at which boiling begins. In a certain range of cavity sizes, e.g. around 1 μm under the conditions of Fig. 5, boiling begins during the changing period of surface temperature. Within the cavity size range of around 1 μm, the heat flux increases with increasing the cavity size, because the boiling incipient time increases with decreasing cavity size and the prolonged incipient time significantly elevates the surface temperature at the moment of boiling incipience as shown in Fig. 5. The elevated surface temperature at the time of boiling incipience increases the boiling heat flux and so reduces the macrolayer thickness. The macrolayer thickness is inversely proportional to the square of

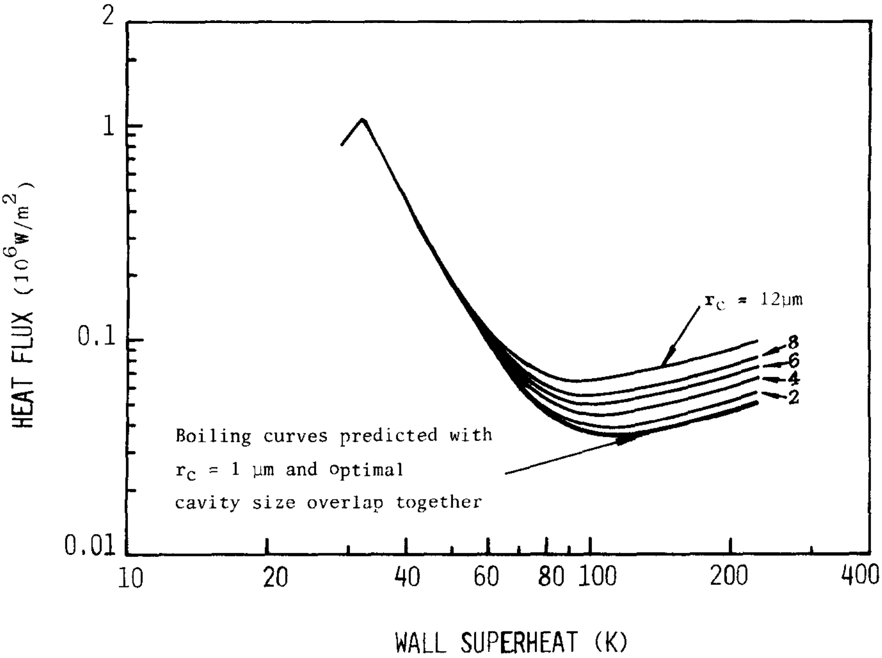

FIG. 6. Effect of cavity size on transition boiling on a copper surface.

the boiling heat flux [4, 5]. Overall, the elevated surface temperature reduces the total transition boiling heat flux because the macrolayer evaporation is the major contributor [5].

The slope change in boiling curves of cavity sizes ranging from 1 to 2 μm may be explained in a similar manner. The boiling incipient time is also a function of pre-contact wall superheat. With a given cavity size, there is a certain range of pre-contact wall superheat for which the boiling incipient time could fall within the changing period of the surface temperature as shown in Fig. 5. A decrease in pre-contact wall superheat increases the boiling incipient time and so increases the surface temperature at the moment of boiling incipience. As discussed previously, the elevated surface temperature reduces the total transition boiling heat flux. Consequently, a sharp change in boiling curve slope is expected when the pre-contact wall superheat results in an incipient time which is within the changing period of surface temperature after liquid contact.

As is well known, the transient conduction between two semi-infinite bodies results in a time-independent interface temperature. Thus, for a heater without a coating, boiling incipient time does not influence the surface temperature at the moment of the boiling incipience and there should be no cavity size effect. Figure 6 shows that this is exactly the situation at lower pre-contact wall superheats. However, cavity size effects appear at higher pre-contact wall superheats where vapour film boiling is dominant. Figure 4 also shows a cavity size effect in the film boiling regime. This is somewhat surprising. This unrealistic result is caused by the unrealistic assumption of uniform cavity size distribution. In Figs. 4 and 6, the cavity sizes showing the effect on the film boiling regime is much larger than the optimal cavity size. For these cavity sizes the boiling incipience is controlled by the optimal cavity size if small cavities are available. From Fig. 4, it can be seen that there is no cavity size effect on film boiling if the uniform cavity size, e.g. r_c = 1–1.5 μm, is smaller than the optimal cavity size.

In summary, the cavity size effect on transition boiling, in general, is insignificant; for a surface overlaid with an insulating layer having small cavities, a slope change in the boiling curve may be present.

Boiling curve from optimal cavity size

It is recognized that the cavity size distribution depends on surface preparation. If the cavity size distribution is specified, the model can be applied by simply using the given cavity size distribution. For a surface without a specified cavity size distribution, it may be assumed that there is a sufficiently wide range of cavity sizes available and using the optimal cavity size, which gives the shortest time for boiling incipience at a given pre-contact wall superheat, is more reasonable for model predictions. Figures 4 and 6 also include the boiling curve predicted by using the optimal cavity size distribution. In Fig. 4, the curve almost overlaps the curves of $r_c \leqslant 2$ μm at high wall superheats. In Fig. 6, the curve almost overlaps the curve of r_c = 1 μm. For a surface without a specified cavity size distribution, using the optimal cavity size

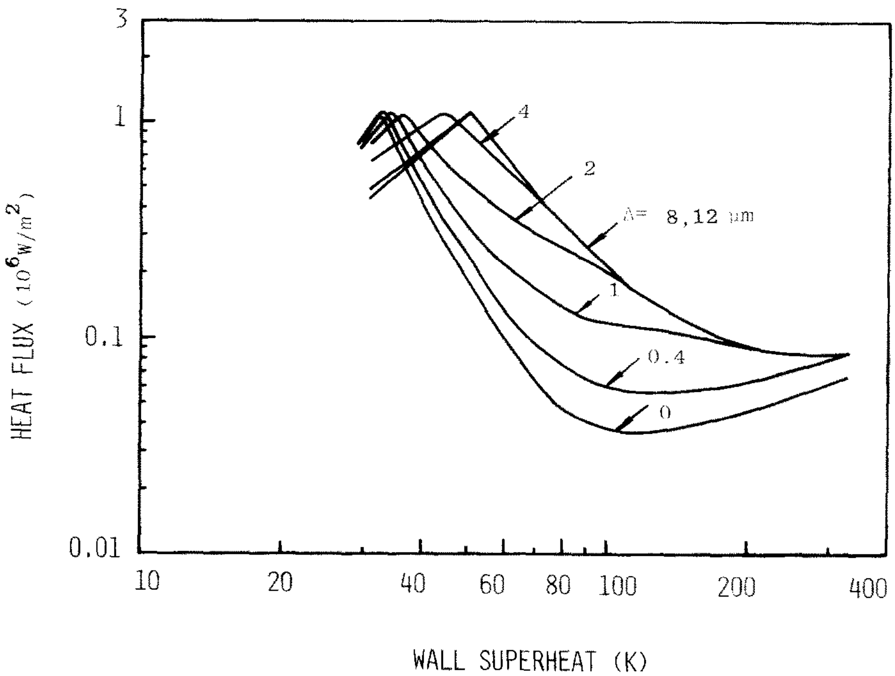

FIG. 7. Effect of coating thickness on transition boiling on a copper surface overlaid with Al_2O_3.

distribution is more reasonable than using an arbitrary cavity size. Consequently, the optimal cavity size distribution will be used hereafter.

PARAMETRIC EFFECTS

Several important effects on transition boiling have been investigated using the theoretical model developed in ref. [5] and are presented in what follows. These parameters include coating thickness, substrate thermal properties, system pressure, and liquid subcooling level. Unless it is clearly specified, the evaluation is based on saturated water at 1 atm pressure.

Effect of coating thickness

The effect of coating thickness on transition boiling is presented in Fig. 7. It can be seen that the boiling curve is moved to the right by increased coating thickness. The wall superheat at the critical heat flux point increases with increasing the coating thickness. The wall superheat at the minimum film boiling point is also somewhat elevated. For coating thicknesses greater than 4 μm, there is no significant thickness effect under the conditions being considered. In the literature, Bui and Dhir [13] reported a similar effect of coating thickness moving the boiling curve upward and to the right for pool boiling with a vertical heating surface. More recently, Chandratilleke *et al.* [17] investigated the effect of Teflon coating thickness on the pool boiling heat transfer to saturated liquid helium from flat surfaces. Their results also show the effect of coating thickness pushing the boiling curve to the right.

Effect of substrate thermal properties

Westwater and co-workers [15, 16] investigated experimentally the effect of substrate thermal properties on the transition boiling on a thick flat plate using nitrogen as the working fluid. Five substrates, namely, Al, Bi, Cu, Pb, and Zn, were used. Figure 8 shows the model prediction of boiling curves for nitrogen at atmospheric pressure on the above five substrate metals. The general trend predicted by the model agrees with that of the experimental results in ref. [15]. The comparison between model predictions and experimental measurements for the critical heat flux point using the thermal effusivity, $k\rho C_p$, a dimensional group, as the variable is shown in Fig. 9. Westwater *et al.* [16] first used this dimensional group to correlate their critical and minimum heat flux points. In the present model predictions $k\rho C_p$ is considered temperature dependent. The present model as well as Zuber's predictions show that there is no effect of substrate effusivity on the critical heat flux. However, the data show that the critical heat flux increases with increasing effusivity. This discrepancy is probably due to the surface wettability and mode of heat transfer (cooling vs heating). Neither of these effects are considered in the present paper. It should be noted that the data were taken during a quenching process.

The model prediction of the wall superheats at the critical heat flux for various substrate metals agrees well, both qualitatively and quantitatively, with the experimental measurements as shown in Fig. 9. The wall superheat at the critical heat flux increases with decreasing effusivity.

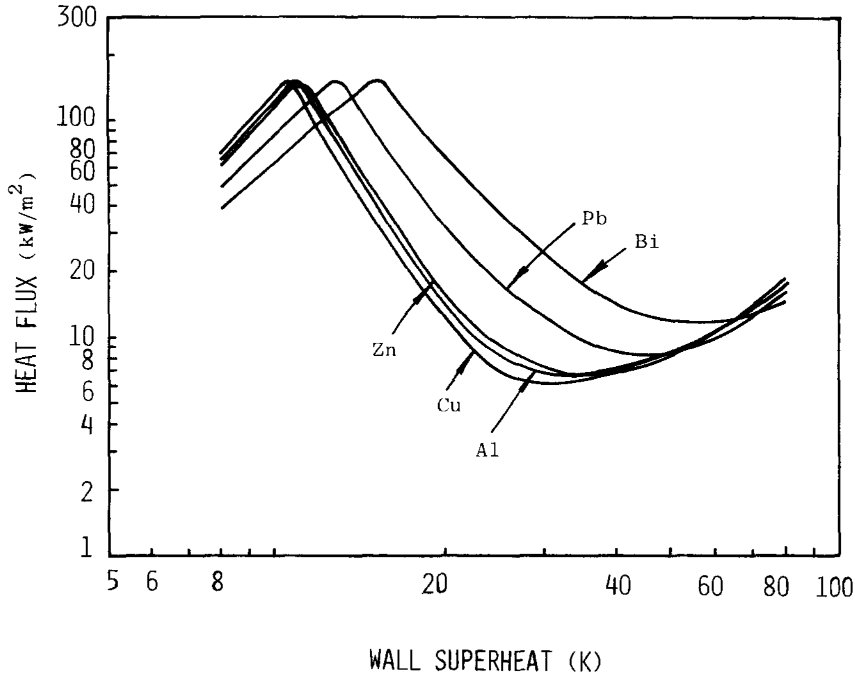

FIG. 8. Effect of substrate thermal properties on transition boiling for nitrogen.

The effects of substrate effusivity on the minimum heat flux point are shown in Fig. 10. The model predicts the same trend as experimental measurements. The wall superheat at the minimum heat flux increases with decreasing the substrate effusivity. The minimum heat flux is somewhat increased by decreasing the effusivity but the measurements are quite scattered.

Effect of system pressure

The model prediction of the effect of system pressure on the transition boiling curve of water is shown in Fig. 11. For both nucleate and transition boiling regimes as well as for the critical and minimum heat fluxes, the trends predicted by the model are in good agreement with experimental observations [18, 20]. The fluid being considered is water. The agreement of model predictions of the critical heat flux as a function of pressure between the current model and that of Zuber is shown in Fig. 12. A maximum value appears at a reduced pressure of about 0.3. Figure 12 also shows good agreement of the wall superheats at the critical heat flux predicted by the current model and that predicted by the Rohsenow correlation using Zuber's critical heat flux model. The effect of system pressure on the minimum heat flux and the minimum wall superheat is shown in Fig. 13. The current model prediction of minimum heat flux is far more insensitive to the change of system pressure than is the Zuber model prediction. Experimental data presented in ref. [18] for various refrigerants indicate that the minimum heat flux is insensitive to the system pressure for the reduced pressure range from 0.2 to 0.6. Reference [18] also shows that the predictions of the Zuber model are significantly higher than experimental measurements.

Figure 11 also shows that film boiling is sensitive to the variation of system pressure, which is in contrast to the behaviour observed by Hesse [20]. However, as film boiling is a function of the vapour properties, which are strongly pressure dependent, a significant effect will be expected. Superheated vapour properties at the film temperature have been used in the analysis in this paper. The predicted effect of pressure on film boiling agrees with the model of Breen and Westwater [25] as shown in Fig. 11.

Effect of liquid subcooling

The effect of liquid subcooling on transition boiling, predicted by the modified model, is shown in Fig. 14. It can be seen that an increase in liquid subcooling moves the boiling curve upward and to the right as is observed in experiments [14]. Critical heat flux increases with increasing liquid subcooling. Figure 15 shows good agreement of the current model prediction with that of the model of Ivey and Morris [26], which is widely used in the literature. The trends of the liquid subcooling effect on minimum film boiling temperature and film boiling predicted by the present model agree with the data and empirical correlation of Dhir and Purohit [27] for film boiling on spheres. The model prediction indicates that the liquid contact duration increases with increasing liquid subcooling, which is in agreement with experimental observations in ref. [21].

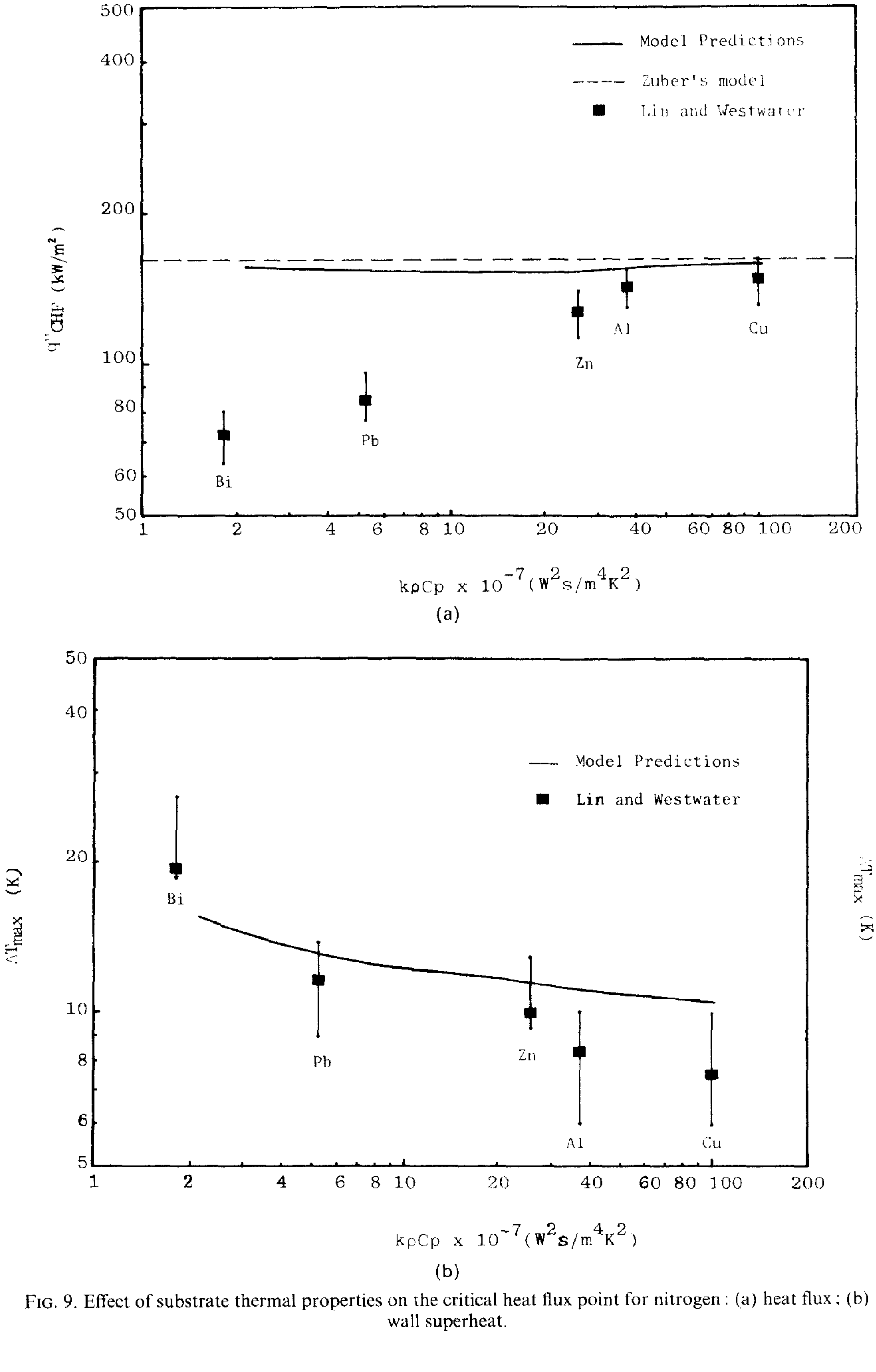

FIG. 9. Effect of substrate thermal properties on the critical heat flux point for nitrogen: (a) heat flux; (b) wall superheat.

SUMMARY AND CONDITIONS

Using the theoretical model developed by the authors [5], important parameter effects, such as cavity size distribution, coating thickness, substrate thermal properties, system pressure, and liquid subcooling, on transition boiling have been investigated. The model predicts the same trends in general as experimental observations. Several direct comparisons with experimental data also show reasonable quantita-

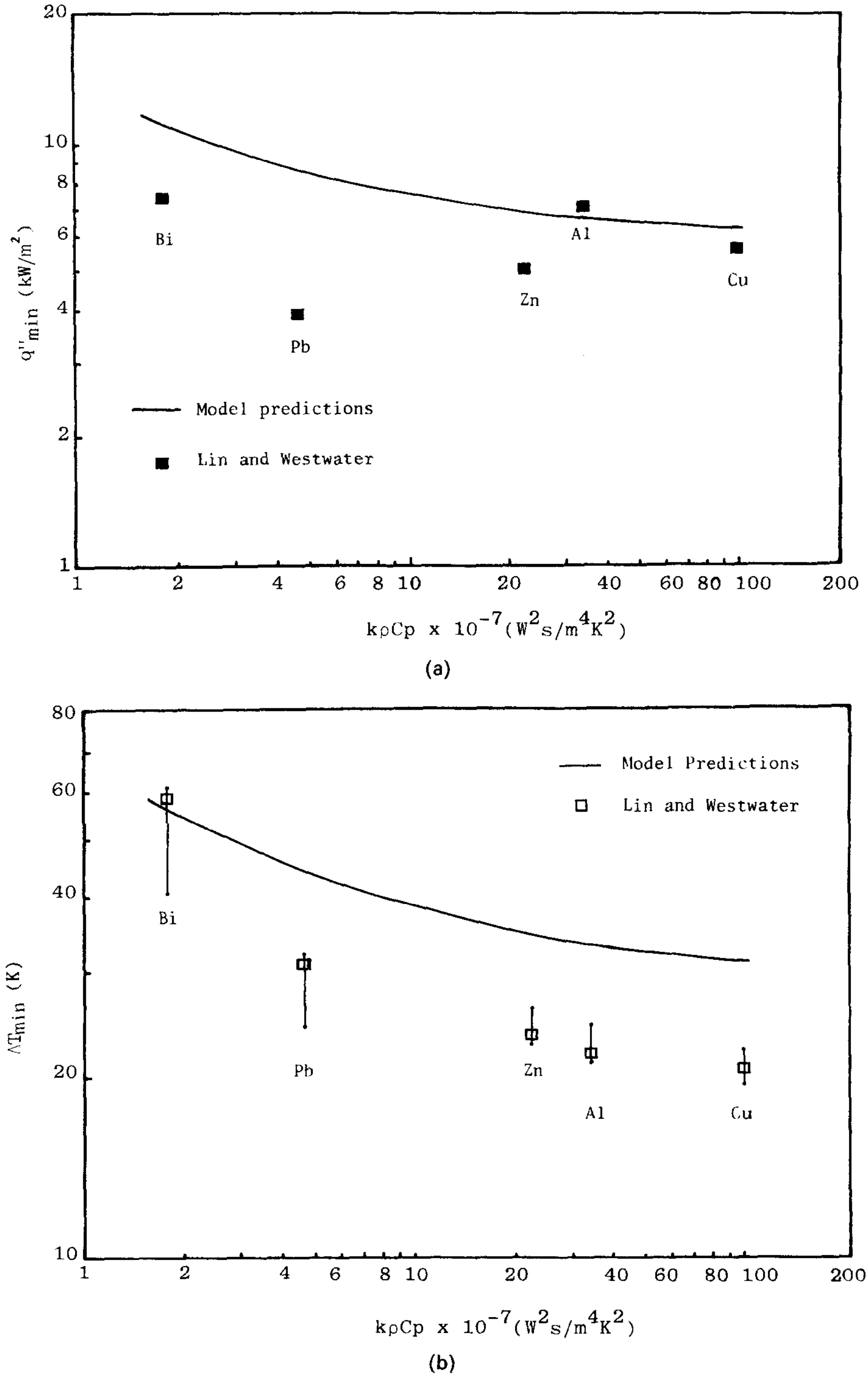

FIG. 10. Effect of substrate thermal properties on the minimum heat flux point for nitrogen: (a) heat flux; (b) wall superheat.

tive agreement. The theoretical model is the first in the literature that has the ability to predict such a wide range of parameter effects on transition boiling, including the critical and minimum heat flux points. The following is a summary of the model predictions of these parameter effects.

(1) The cavity size effect on transition is generally insignificant. However, for a heating surface overlaid by an insulator (Al_2O_3), the cavity size has a significant effect on the transition boiling curve at lower wall superheats. A slope change in the boiling curve, which is similar to the double-peak phenomena

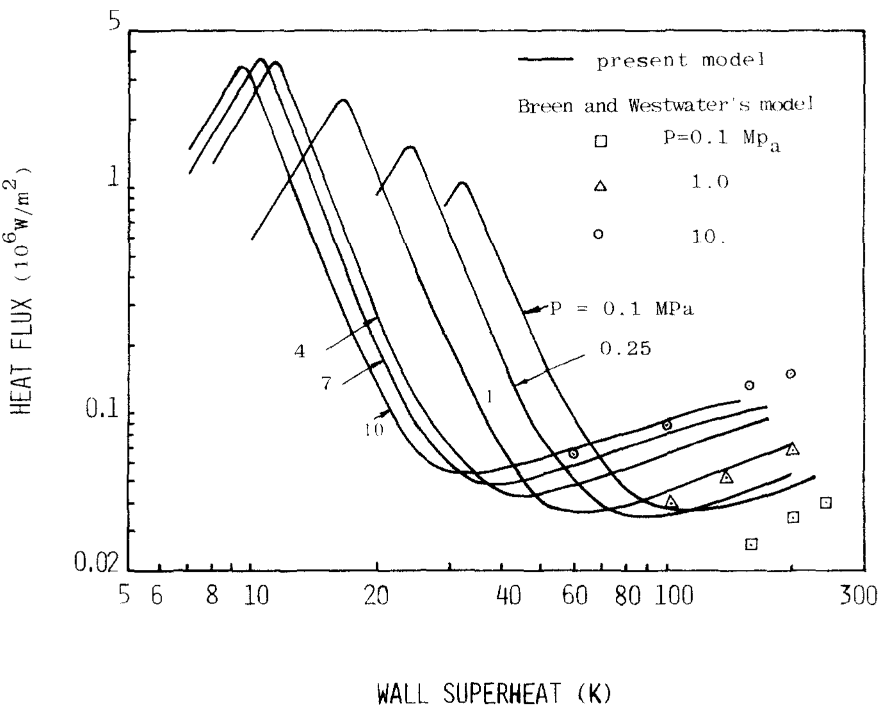

FIG. 11. Effect of system pressure on transition boiling of water on a copper surface.

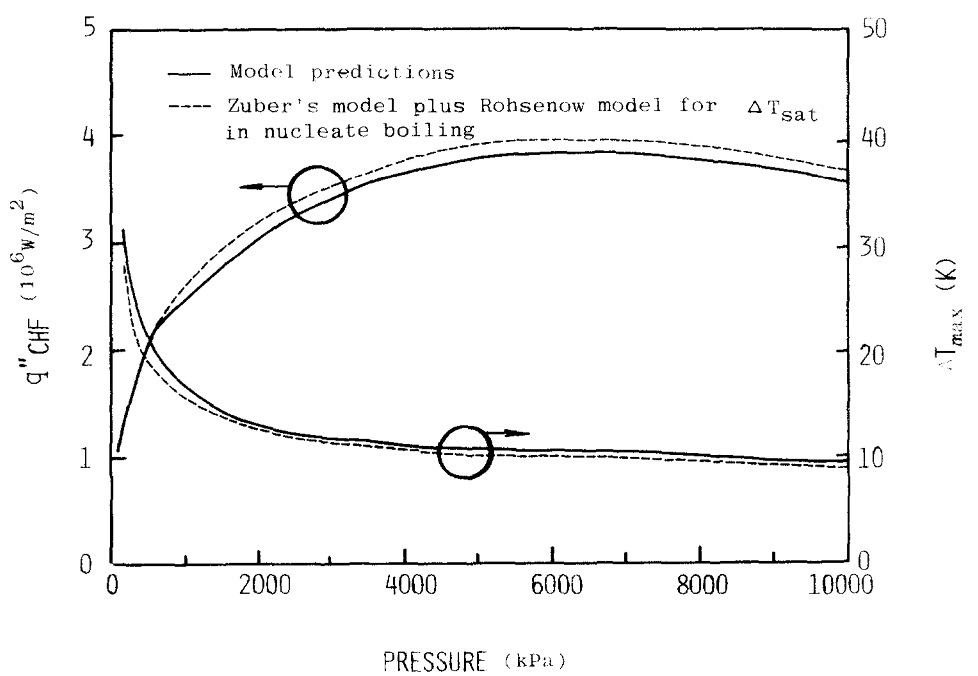

FIG. 12. Effect of system pressure on the critical heat flux point of water on a copper surface.

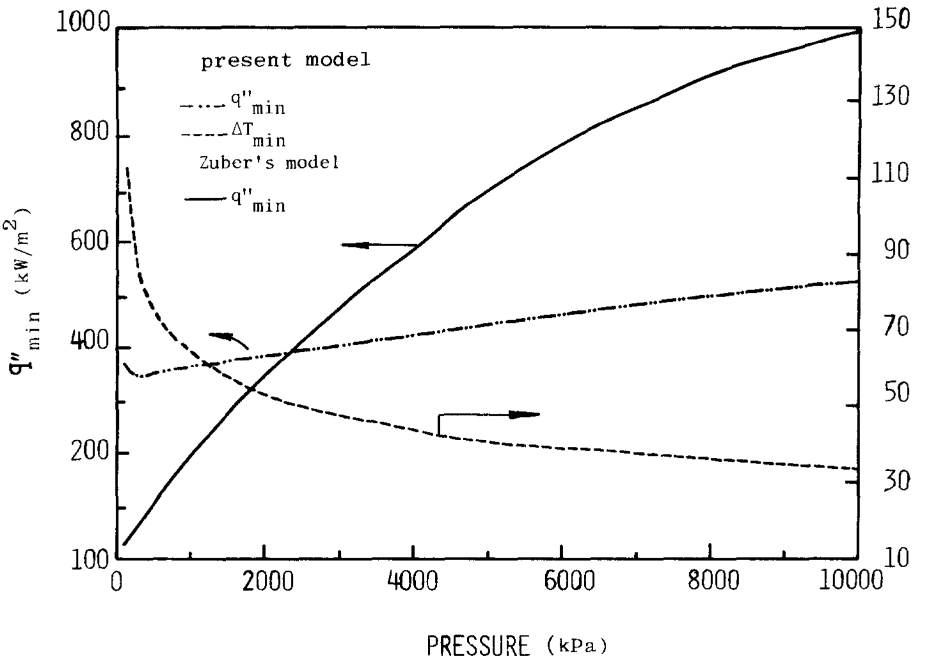

FIG. 13. Effect of system pressure on the minimum heat flux point of water on a copper surface.

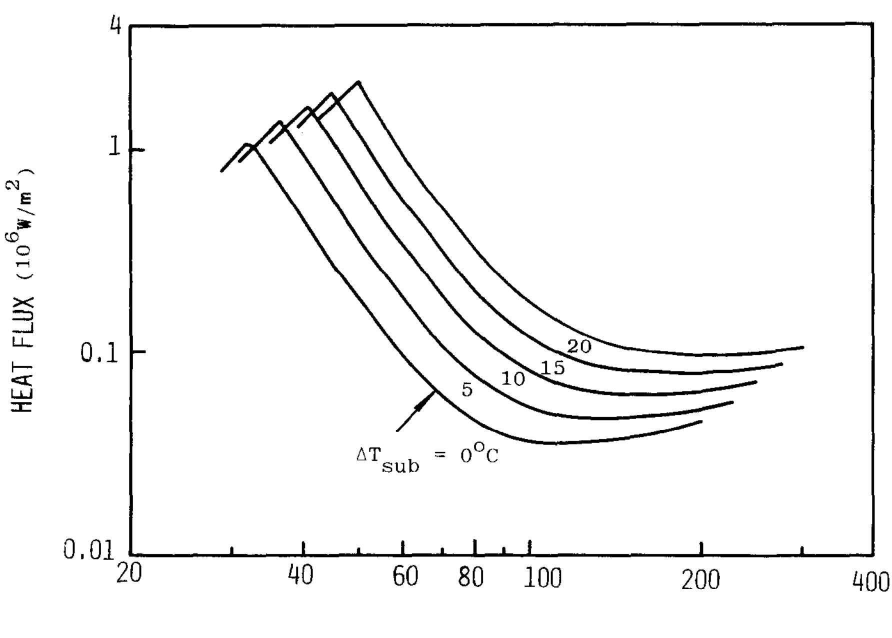

FIG. 14. Effect of water subcooling on transition boiling on a copper surface.

reported in the literature, is predicted for certain cavity sizes and can be explained by the model.

(2) The boiling curve is moved to the right by increasing the insulator (Al_2O_3) layer thickness. The wall superheat at the critical heat flux increases with increasing layer thickness.

(3) The boiling curve is moved to the right by decreasing the effusivity of the substrate material. The

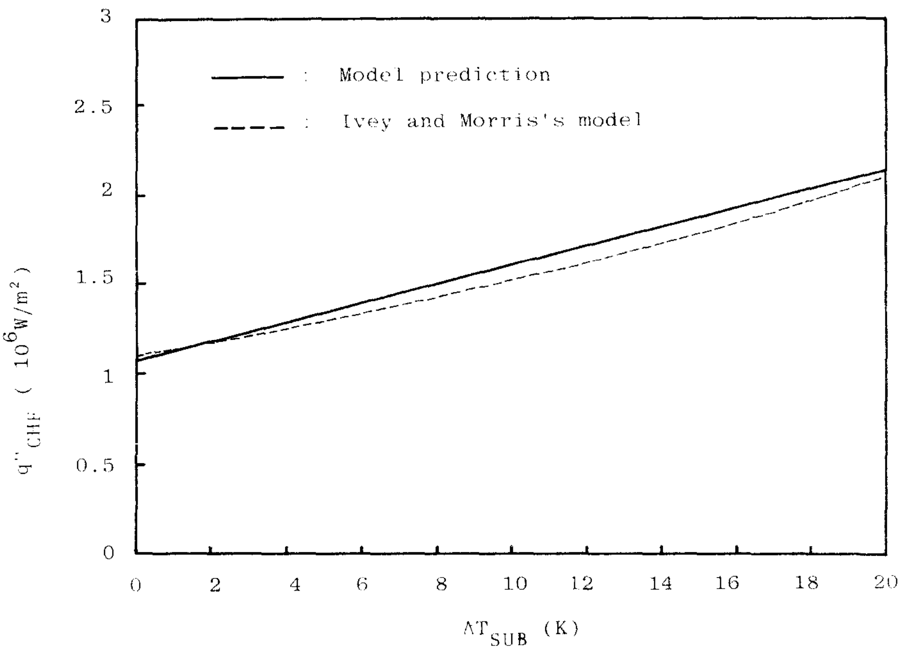

FIG. 15. Effect of water subcooling on the critical heat flux.

model predicts that critical heat flux is basically independent of substrate effusivity and minimum heat flux is somewhat increased by decreasing effusivity. The wall superheats at the critical and minimum heat fluxes increase with decreasing the substrate effusivity and may be correlated using the effusivity as the variable.

(4) The transition boiling curve is moved upward and to the left by increasing the system pressure. The critical heat flux at various pressures predicted by the model agrees well with Zuber's model. For the minimum heat flux points, the model predicts the same trend as is observed in experiments.

(5) The transition boiling curve is moved upward and to the right by increasing the liquid subcooling level. The critical heat flux predicted by the current model agrees well with the model of Ivey and Morris [26].

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APPENDIX A. BUBBLE HOVERING TIME

The hovering time for a bubble of volumetric growth rate v_l is given as [4]

$$\tau = \left(\frac{3}{4\pi}\right)^{1/5}\left[\frac{4(\frac{11}{16}\rho_l+\rho_v)}{g(\rho_l-\rho_v)}\right]^{3/5} v_l^{1/5}. \qquad \text{(A1)}$$

APPENDIX B. BOILING INCIPIENCE MODEL

Boiling incipience is predicted by the model of Hsu [24], which requires that for boiling incipience the liquid temperature at the bubble tip be greater than or equal to the vapour temperature

$$T_l(x=r_c,t) \geqslant T_v = T_{sat}+\frac{2\sigma}{r_c}\frac{T_{sat}v_{fg}}{H_{fg}}. \qquad \text{(B1a)}$$

The liquid temperature is given by

$$T_l(x,t) = T_b+\frac{(T_w-T_b)}{(1+b_1)(1+b_2)} \times\left\{b_2(1+b_1)\sum_{n=0}^{\infty}\left[\frac{(1-b_1)(1-b_2)}{(1+b_1)(1+b_2)}\right]^n \times \operatorname{erfc}\left(\frac{x}{2\sqrt{(\alpha_l t)}}+\frac{n\Delta}{\sqrt{(\alpha_c t)}}\right) + b_2(1-b_1)\sum_{n=0}^{\infty}\left[\frac{(1-b_1)(1-b_2)}{(1+b_1)(1+b_2)}\right]^n \times \operatorname{erfc}\left(\frac{x}{2\sqrt{(\alpha_l t)}}+\frac{(n+1)\Delta}{\sqrt{(\alpha_c t)}}\right)\right\} \qquad \text{(B1b)}$$

where

$$b_1 = (k\rho C_p)_c^{1/2}/(k\rho C_p)_h^{1/2}, \quad b_2 = (k\rho C_p)_c^{1/2}/(k\rho C_p)_l^{1/2}.$$

PREDICTION DE L'EFFET PARAMETRIQUE DE L'EBULLITION TRANSITOIRE DANS LES CONDITIONS D'EBULLITION EN RESERVOIR

Résumé—On étudie par un modèle théorique les effets importants sur l'ébullition transitoire des paramètres tels que la forme de la cavité, l'épaisseur du revêtement, les propriétés thermiques du substrat, la pression du système et le niveau de sous-refroidissement du liquide. Le modèle prédit les mêmes tendances que les observations expérimentales. Quand des données sont disponibles, des comparaisons directes montrent un accord quantitatif raisonnable. Le modèle théorique est le premier actuellement qui possède la capacité de prédire les effets des paramètres sur l'ébullition de transition, en incluant les points de flux critique et minimal.

BERECHNUNG DES EINFLUSSES UNTERSCHIEDLICHER GRÖSSEN AUF DAS ÜBERGANGSSIEDEN UNTER DEN BEDINGUNGEN DES BEHÄLTERSIEDENS

Zusammenfassung—Mit Hilfe eines von den Autoren entwickelten theoretischen Modells werden wichtige Einflüsse auf das Übergangssieden untersucht: Verteilung der Keimstellengröße, Dicke und Stoffeigenschaften der Beschichtung, Systemdruck sowie Flüssigkeitsunterkühlung. Die Vorhersagen des Modells werden qualitativ von Versuchsergebnissen bestätigt. Soweit Versuchsdaten zur Verfügung stehen ergibt ein direkter Vergleich eine befriedigende quantitative Übereinstimmung. Das vorgestellte theoretische Modell ist das erste, welches den Einfluß derart vieler Größen auf das Übergangssieden vorausberechnen kann—hierzu gehören auch die Punkte der kritischen und der minimalen Wärmestromdichte.

РАСЧЕТЫ ВЛИЯНИЯ ПАРАМЕТРОВ НА ПЕРЕХОДНОЕ КИПЕНИЕ В БОЛЬШОМ ОБЪЕМЕ

Аннотация—С использованием разработанной авторами данной работы теоретической модели исследуется влияние на переходное кипение таких параметров, как распределение размеров полости, толщина покрытия, тепловые свойства подложки, давление в системе и уровень недогрева жидкости. Предсказываемая моделью тенденция наблюдается и экспериментально. При наличии соответствующих данных прямые сравнения показывают удовлетворительное качественное согласие. Разработанная теоретическая модель является первой, опубликованной в литературе, которая дает возможность определять влияние такого широкого диапазона параметров на переходное кипение, включая точки критического и минимального тепловых потоков.