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Minimum film boiling temperature for cooldown of insulated metals in saturated liquid

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Abstract—A theoretical study has been conducted to investigate an earlier transition from the film to the transition boiling, which may occur during the rapid cooldown of hot metals coated with a thin layer of insulating (low thermal conductivity) material. Direct liquid–solid contacts are assumed to occur intermittently in the film boiling regime. The transient contacting and subsequent evaporation of a thin microlayer of liquid bring forth a rapid decrease in the local surface temperature. If the local surface temperature falls below the lowest limit, an earlier onset of transition boiling occurs though the average wall temperature is quite high. The minimum film boiling temperature becomes higher with increasing thickness of insulating layer. The calculated results are in good agreement with experimental data for liquid nitrogen boiling on Teflon-coated copper plates.

INTRODUCTION

THE PROCESS of cooling a high temperature material with boiling liquid is widely encountered in metallurgy, cryogenic engineering, nuclear technology and other industrial applications. One of the problems of interest in such a cooling process is the assessment of the minimum temperature to maintain the film boiling. At this temperature, usually termed the minimum film boiling temperature T_{min}, the vapor film which separates the hot surface from the liquid becomes unstable and a transition from the film to the transition boiling occurs.

Several investigators [1–7] have reported that, for rapid cooldown of metals coated with a thin insulating (low thermal conductivity) layer, an earlier onset of transition boiling occurs at significantly higher T_{min} than that predicted by the hydrodynamic model of Berenson [8] or the maximum liquid superheat theory of Spiegler *et al.* [9]. Manson [10] supposed that this discrepancy was attributed to the thermal properties of the heated solid surface which played no part in both theories. He demonstrated with an analog computer that a periodic heat transfer coefficient produced local decreases in the surface temperature of the Teflon-coated metal and that an earlier onset of transition boiling possibly occurred while the average metal temperature was still high. On the basis of the experimental observations [11] of liquid–solid contacts, Henry [12] recognized the importance of surface properties by introducing the interface temperature upon contact and evaporation of a residual liquid microlayer to correct Berenson's equation. Baumeister and Simon [13] extended the theory of Spiegler *et al.* to take into account the thermal properties of the surface, and in addition, the surface energy which was related to wetting characteristics.

These theories, however, ignore the effect of the thickness of insulating layers, which was experimentally demonstrated in refs. [4–7]. This led the present authors to carry out a theoretical study of the effect of the insulating layer thickness on rapid cooldown of metals in boiling liquid. A theoretical model, which assumes the occurrence of local and intermittent liquid–solid contacts in the film boiling regime, is proposed for predicting the actual T_{min} for the coated metals. The calculated results are compared with the experimental data for Teflon-coated copper plates cooled in liquid nitrogen.

THEORETICAL ANALYSIS

1. *Model and assumptions*

Visual observations of film boiling [14] show that vapor bubbles depart from the antinodes of the surface waves on the liquid–vapor interface, and that the thickness of the vapor film is of the same order of magnitude as the wave amplitude. The thickness of the vapor film, therefore, varies periodically at any given point of the solid surface and there possibly exist the direct liquid–solid contacts on local portions of the solid surface. Experimental evidence of liquid–solid contacts in the film boiling regime was reported by Bradfield [11] and recently by Yao and Henry [15].

Based on these experimental observations, the physical pictures are proposed for the film boiling, as shown in Fig. 1. As the bubble departs from the antinode [Fig. 1(a)], the liquid rushes toward the solid surface, and then contacts the local portion of the surface [Fig. 1(b)]. The rapid evaporation of a residual microlayer of liquid (superheated on the surface) occurs [Fig. 1(c)]. To formulate a model describing these processes, the film boiling regime is divided into three periods: (a) dry period, (b) conduction period and (c) evaporation period.

(*a*) *Dry period* ($t < 0$). A dry condition is always maintained on the most areas of the solid surface, which are cooled with the film boiling heat transfer coefficient

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NOMENCLATURE

a	thermal diffusivity
c	specific heat
g	acceleration due to gravity
h_{fb}	film boiling heat transfer coefficient
h_{fg}	latent heat of vaporization
h_g	contact coefficient between coating material and metal
h_{nb}	transition boiling heat transfer coefficient
K_w	overall heat conductance defined in equation (A6)
k	thermal conductivity
q	heat flux
q_e	evaporation heat flux
q_{max}	critical heat flux
S	effective heat transfer area
T	temperature
T_g	temperature at back surface of coating layer
T_{iso}	isothermal minimum film boiling temperature
T_{sat}	saturation temperature
t	time
V	volume
x	co-ordinate normal to heated surface.

Greek symbols

Δ	difference
δ	thickness of coating layer
δ_0	thickness of metal plate
ε	weighted parameter of heat capacity of coating material
μ	viscosity
ρ	density
σ	surface tension
τ_c	duration of conduction period
τ_e	duration of evaporation period.

Subscripts

l	liquid
min	minimum film boiling point
o	metal
v	vapor
w	wall.

Superscripts

I	initial condition in dry period
J	initial condition in conduction period
K	initial condition in evaporation period.

h_{fb}. The local portions, which will later experience liquid–solid contacts, are also cooled with h_{fb} during the dry period.

(*b*) *Conduction period* ($0 \leqslant t < \tau_c$). When the cold liquid (T_{sat}) suddenly comes into direct contact with the hot surface (T_w), the interface temperature T_w^J is determined by

$$T_w^J - T_{sat} = (T_w - T_{sat})/[1 + \sqrt{\rho_1 c_1 k_1/(\rho_w c_w k_w)}], \quad (1)$$

which is valid for the coated and the uncoated plates [6]. During the initial but very short conduction period, the flow of heat in each section, even in liquid, obeys the heat conduction and the interface temperature is maintained at the value given by equation (1).

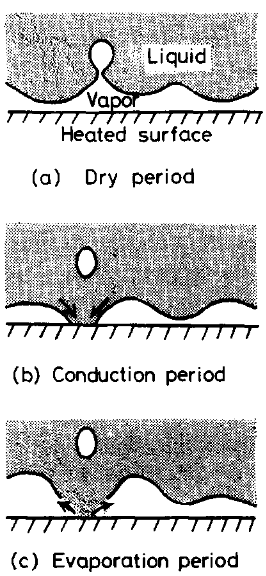

FIG. 1. Intermittent liquid–solid contact model: (a) dry period; (b) conduction period; (c) evaporation period.

(*c*) *Evaporation period* ($\tau_c \leqslant t \leqslant \tau_c + \tau_e$). A thin film of cold (saturated) liquid has been superheated by conduction from the heated solid surface for the former conduction period. For the subsequent evaporation period, the superheated microlayer continues to cool locally the surface through rapid evaporation. For simplicity, during the evaporation period, the unknown time-dependent heat flux is represented by a time-averaged heat flux designated q_e [16].

If the local surface temperature falls below the lowest value T_{iso}* of limit while the average wall temperature is quite high, the vapor generation rate will not be sufficient to maintain the film boiling and an onset of transition boiling will occur, resulting in an im-

* T_{iso} is the minimum film boiling temperature measured for an isothermal surface which does not experience any temperature drop due to liquid–solid contacts. In the present study T_{iso} is assumed to equal the value measured for the uncoated copper.

provement of heat transfer from the bulk surface. On the other hand, if the local fall in the surface temperature is not too severe, a film of vapor is formed on the heated surface again and a dry condition is recovered.

The contribution of liquid–solid contact heat transfer to the overall film boiling heat transfer (h_{fb}) is neglected since the direct contact occurs on the local portions of the surface during a short time and the frequency of contacts is very low under the film boiling condition.

2. *Basic equations*

(*i*) *Dry period* ($t < 0$). If a film boiling condition is established, the Teflon-coated copper plate is cooled down with the film boiling heat transfer coefficient h_{fb}. With the coordinate system shown in Fig. 2, the flow of heat in both Teflon and copper sections obeys the one-dimensional equation of heat conduction

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2}, \tag{2}$$

where a is the thermal diffusivity.

The boundary conditions are

$$x = 0: \quad k_w \frac{\partial T}{\partial x} = h_{fb}(T - T_{sat}), \tag{3}$$

$$x = \delta: \quad k_0 \left.\frac{\partial T}{\partial x}\right|_{copper} = k_w \left.\frac{\partial T}{\partial x}\right|_{Teflon} = h_g(T_{copper} - T_{Teflon}), \tag{4}$$

$$x = \delta + \delta_0: \quad \frac{\partial T}{\partial x} = 0. \tag{5}$$

The physical properties of both Teflon and copper are assumed to be constant. h_g is the contact coefficient between the Teflon and the copper sections.

According to some calculated results, the temperature transient is slow and a quasi-steady-state condition is maintained throughout the dry period, except at the initial but short time when the coated plate is submerged into liquid nitrogen. The temperature distribution through the Teflon layer is linear since the layer thickness is very thin. In the copper region, however, a uniform temperature distribution is dominant because of its extremely high thermal conductivity.

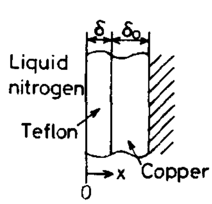

FIG. 2. Coordinate system.

If the copper temperature T_0 is assumed to be uniform, the temperature distribution in the Teflon layer is, with good accuracy, given by a simple equation

$$T - T_{sat} = \frac{(1 + h_{fb}x/k_w)(T_0 - T_{sat})}{1 + h_{fb}/h_g + h_{fb}\delta/k_w}. \tag{6}$$

(*ii*) *Conduction period* ($0 \leqslant t < \tau_c$). Consider a cold liquid of uniform temperature T_{sat} suddenly coming into direct contact with the local portion of the hot surface of a Teflon-coated copper plate. Although the contact portion is localized on the heated surface, the governing energy equation for the Teflon layer is simplified into the one-dimensional form of equation (2) since the thermal conductivity of Teflon is extremely low and the layer is so thin that two-dimensional (circumferential) conduction effects on the temperature transients can be neglected.

The boundary conditions are

$$x = 0: \quad T - T_{sat} = (T_0 - T_{sat})/\{(1 + h_{fb}/h_g + h_{fb}\delta/k_w)[1 + \sqrt{\rho_1 c_1 k_1/(\rho_w c_w k_w)}]\}, \tag{7}$$

$$x = \delta: \quad k_w \frac{\partial T}{\partial x} = h_g(T_0 - T), \tag{8}$$

where T_0 is the uniform copper temperature.

(*iii*) *Evaporation period* ($\tau_c \leqslant t \leqslant \tau_c + \tau_e$). The energy equation becomes the same form as equation (2). The boundary conditions are

$$x = 0: \quad k_w \frac{\partial T}{\partial x} = q_e, \tag{9}$$

$$x = \delta: \quad k_w \frac{\partial T}{\partial x} = h_g(T_0 - T), \tag{10}$$

where the uniform temperature of copper is assumed again.

3. *Calculation procedure*

Numerical methods are applied to transient conduction problems in each period. The relevant differential equations are reduced to finite-difference equations. An explicit method is used to calculate the unknown temperature distribution after a time interval.

EXPERIMENTS

1. *Experimental apparatus*

The apparatus used is shown schematically in Fig. 3. The test specimen is a 3-mm-thick copper plate,* whose surface is coated with a thin Teflon layer. The thickness of the Teflon layer is varied from 14 to 144 μm. The back

* In order to investigate the effect of geometrical configurations on boiling phenomena, a copper cylinder (20 mm in diameter) was also used as the test specimen.

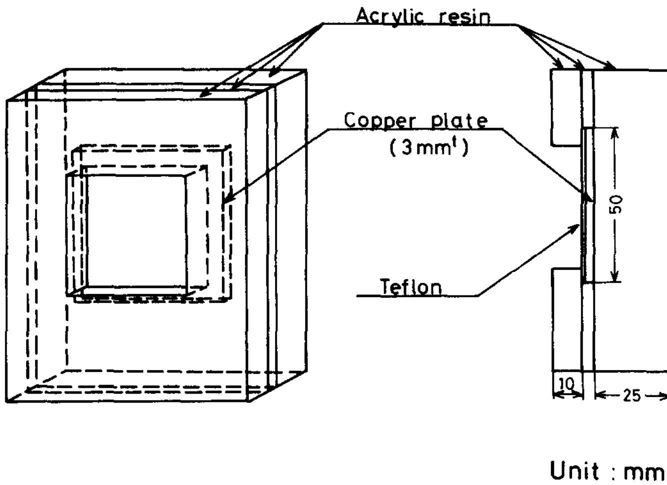

FIG. 3. Schematic arrangement of apparatus.

surface of the copper plate is tightly in contact with a thick acrylic plate, and is kept in an adiabatic condition. A copper–constantan thermocouple (0.1 mm in diameter), which monitors the temperature T_0 of the copper plate, is buried with solder in a groove on the back surface.

The test specimen is vertically submerged in liquid nitrogen inside a stainless-steel Dewar, and is cooled down to the saturation temperature of liquid nitrogen. The output signal from the thermocouple is recorded on a strip chart. During the runs the liquid nitrogen is maintained at the saturation temperature under atmospheric pressure.

2. *Data reduction*

For the uncoated copper plate, the slope of the temperature–time trace of the back surface of the copper plate in the film boiling regime yielded the heat transfer coefficient h_{fb}. Because of the high thermal conductivity of copper, the film boiling Biot number of the plate was very small ($\sim 1 \times 10^{-3}$). Assuming the plate as a lumped-parameter system, i.e. an isothermal one, the heat transfer coefficient was calculated using the following equation

$$q = h_{fb}\Delta T_0 = \rho_0 c_0 \frac{V_0}{S_0}\left|\frac{dT_0}{dt}\right|, \qquad (11)$$

where V_0 and S_0 are the volume and the effective heat transfer area, respectively, of the plate. ΔT_0 is defined as $\Delta T_0 = T_0 - T_{sat}$.

For the Teflon-coated plate, however, the transient conduction equation in the two-layer plate should be solved using a finite-difference scheme since a discrepancy between the surface temperature T_w and the copper temperature T_0 occurs and is more enlarged with increasing the Teflon-layer thickness.

The temperature at which the slope of the temperature–time trace rapidly increased was taken to be the minimum film boiling temperature $T_{min,0}$ of the copper plate with and without Teflon coating.

RESULTS AND DISCUSSION

1. *Cooling curve*

Figure 4(a) shows a typical calculated result of temperature transients for a Teflon-coated copper plate (3 mm in thickness) cooled in liquid nitrogen. The thickness of the Teflon layer is 0.05 mm. The abscissa is the elapse of time, and the ordinate is the superheat defined as $\Delta T = T - T_{sat}$. The isothermal minimum film boiling superheat ΔT_{iso} and the film boiling heat transfer coefficient h_{fb} are taken as 35 K and 85 W m^{-2} K^{-1}, respectively, which are based on the experimental results of the uncoated plate.

Violent oscillations are observed for the surface temperature (ΔT_w) at the side facing the liquid nitrogen, while the temperature (ΔT_0) of the copper plate decreases slowly with no fluctuations. These oscillations are caused by intermittent liquid–solid contacts. The details of a rapid temperature change associated with the liquid–solid contact are shown in the right portion of this figure. When the cold liquid suddenly comes into contact with the local portion of the Teflon surface ($\Delta T_w = 114.4$ K) at $t = 110$ s, the interface temperature falls stepwise to 68.9 K and remains constant for a while. This local temperature drop is followed by the second decrease of 27.6 K for 0.25 s. The time interval between 110 s and 110.1 s corresponds to the conduction period, and the interval between 110.1 s and 110.35 s is the evaporation period. The local surface temperature increases after 110.35 s and again a dry condition is recovered.

When another contact occurs at 120 s, the local surface temperature rapidly decreases to the lowest value of limit ($\Delta T_{iso} = 35$ K) at which a transition from

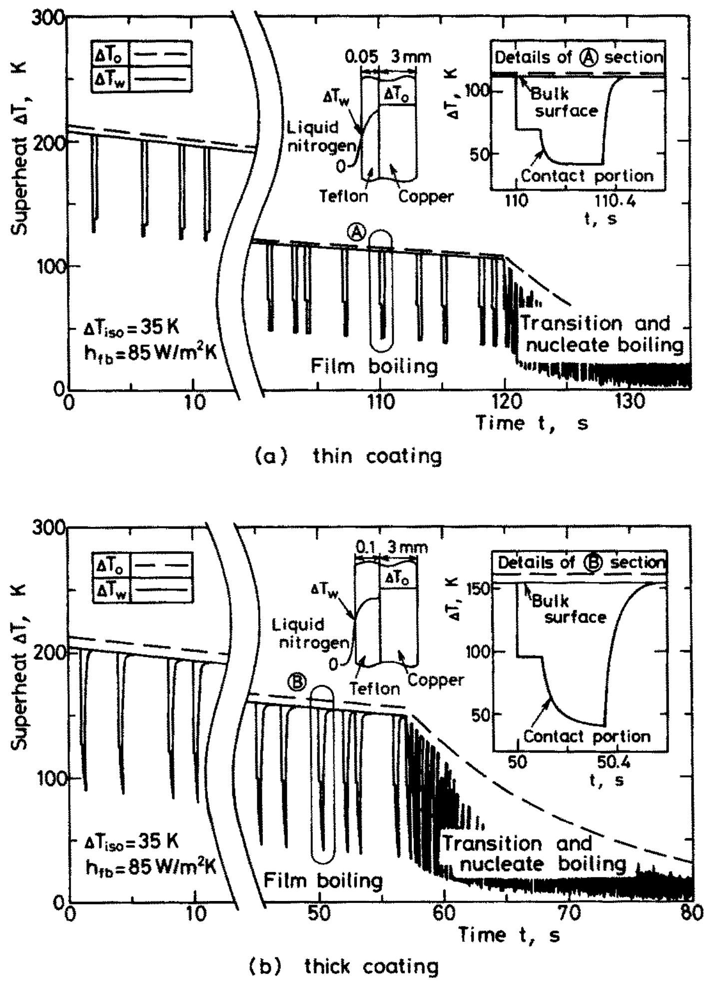

FIG. 4. Calculated temperature change during cooldown: (a) thin coating; (b) thick coating.

the film boiling to the transition boiling occurs. However, the bulk surface and copper temperatures, which are taken to be the minimum film boiling temperatures ($\Delta T_{min,w} = 105.5$ K and $\Delta T_{min,O} = 108.1$ K, respectively), are much higher than the limit value of 35 K.

Figure 4(b) shows the calculated cooling curve under a thicker Teflon-coating condition (0.1 mm in thickness). Local temperature drops due to liquid–solid contacts are much larger compared with the former thinner coating case. The local surface temperature falls to the limit of 35 K at 57 s and an earlier onset of transition boiling occurs. The minimum film boiling temperatures become higher and attain $\Delta T_{min,w} = 149.4$ K and $\Delta T_{min,O} = 155.5$ K, respectively.

Figure 5 shows a comparison of theoretical and experimental results of cooling curves of a copper plate (3 mm in thickness) for four Teflon-layer thicknesses. The Teflon coating gives a great improvement of heat transfer since the minimum film boiling temperature becomes higher with increasing the layer thickness δ and an earlier onset of transition boiling occurs. The experimental results agree well with the theoretical calculations, in which the film and the transition boiling heat transfer coefficients are assumed to be $h_{fb} = 85$ W m^{-2} K^{-1} and $h_{nb} = 2 \times 10^3$ W m^{-2} K^{-1}, respectively.

In the above calculations several parameters concerning liquid–solid contacts are also assumed that $q_e = 2.5 \times 10^5$ W m^{-2}, $\tau_e = 0.25$ s, $\tau_c = 0.1$ s and $h_g = 10^4$ W m^{-2} K^{-1}. A way to determine these parameters will be described in the following section.

2. *Minimum film boiling temperature*

The minimum film boiling temperatures are indicative of the general level of the enhancement of heat transfer in cooldown processes. The minimum film boiling superheats $\Delta T_{min,O}$ for the Teflon-coated and the uncoated plates are brought together in Fig. 6. The abscissa is the thickness δ of Teflon layer. The figure also contains the measured values of Nishio [7] for a 2-mm-thick copper plate. The $\Delta T_{min,O}$ is higher with thicker δ for both the present and Nishio's data.

The experimental results are compared with the

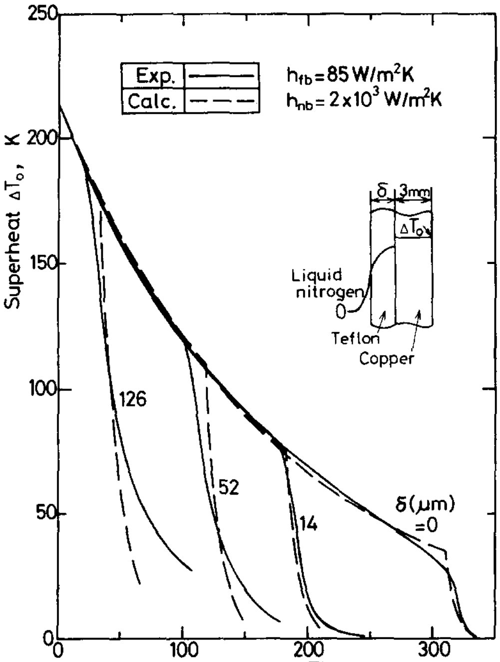

FIG. 5. Effect of coating thickness on temperature change during cooldown.

theoretical calculations by the present liquid–solid contact model. Calculations were performed for three evaporation heat fluxes q_e. The calculated curve for $q_e = 2.5 \times 10^5$ W m^{-2} agrees well with the measured values. The q_e of 2.5×10^5 W m^{-2} is equal to or slightly higher than the critical heat flux q_{max} in saturated nucleate boiling of liquid nitrogen. For example, a conventional correlation of Kutateladze [17], which

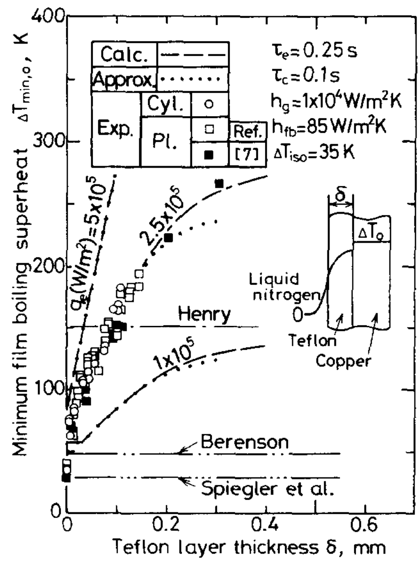

FIG. 6. Effect of evaporation heat flux on minimum film boiling superheat.

was derived from a hydrodynamic stability model for a flat horizontal surface, is given by

$$q_{max} = 0.16(\pm 0.03) h_{fg} \rho_v \left[\frac{g\sigma(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}. \quad (12)$$

Introduction of thermophysical properties of nitrogen into the equation gives

$$q_{max} = 2.0(\pm 0.4) \times 10^5 \text{ W m}^{-2}.$$

This value is almost equal to the q_e in the present study.

The dotted lines in Fig. 6 are the approximate solutions which were obtained under the assumption of a linear temperature distribution in the Teflon layer, as described in the Appendix. The approximate solutions are in good agreement with the exact numerical solutions, especially in the region of thin Teflon coating.

In this figure are also indicated the minimum film boiling temperatures T_{min} predicted by other investigators. Based on a hydrodynamic model of the film boiling process, Berenson [8] has derived a correlation for the minimum film boiling superheat

$$\Delta T_{min} = 0.127 \frac{\rho_v h_{fg}}{k_v} \left[\frac{g(\rho_l - \rho_v)}{\rho_l + \rho_v} \right]^{2/3} \times \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \left[\frac{\mu_v}{g(\rho_l - \rho_v)} \right]^{1/3}. \quad (13)$$

On the other hand, Spiegler *et al.* [9] assumed that the T_{min} corresponds to the maximum liquid superheat predicted by the Van der Waals equation of state. Their theory indicates that at pressures well below the critical pressure

$$T_{min} = \frac{27}{32} T_{crit}, \quad (14)$$

where T_{crit} is the critical temperature of the fluid.

Theoretical results given by equations (13) and (14) are significantly different from the measured values for the Teflon-coated copper. This large discrepancy can not be explained by the temperature drop ($= T_0 - T_w$) across the Teflon layer since the temperature drop across a 0.1-mm-thick layer is of the order of only 6 K in the vicinity of the minimum film boiling point.

Henry [12] postulated that liquid–solid contacts might exist in the film boiling regime and proposed a correlation for T_{min} over a wide range of thermal properties and subcoolings, given by

$$\frac{T_{min} - T_{m,B}}{T_{min,B} - T_l} = 0.42 \left(\sqrt{\frac{\rho_l c_l k_l}{\rho_w c_w k_w}} \frac{h_{fg}}{c_w \Delta T_{min,B}} \right)^{0.6}, \quad (15)$$

where $T_{min,B}$ (or $\Delta T_{min,B}$) is the isothermal minimum film boiling temperature (or superheat) predicted by Berenson's formulation of equation (13). Henry's equation is likely to represent the average value of the present data for various thicknesses of Teflon layers, but it cannot explain a strong dependency of T_{min} on the thickness of Teflon layer.

Figure 7 shows the effect of the duration τ_e of the evaporation period on the minimum film boiling

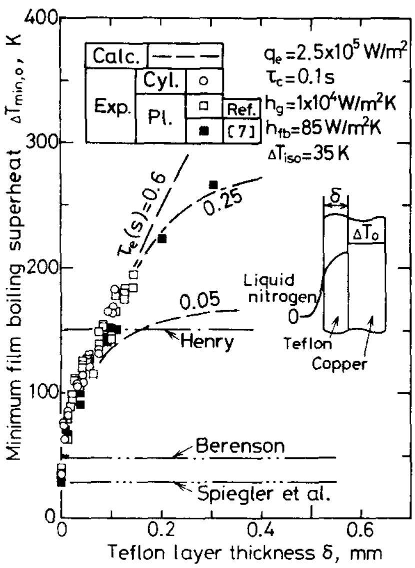

FIG. 7. Effect of duration of evaporation period on minimum film boiling superheat.

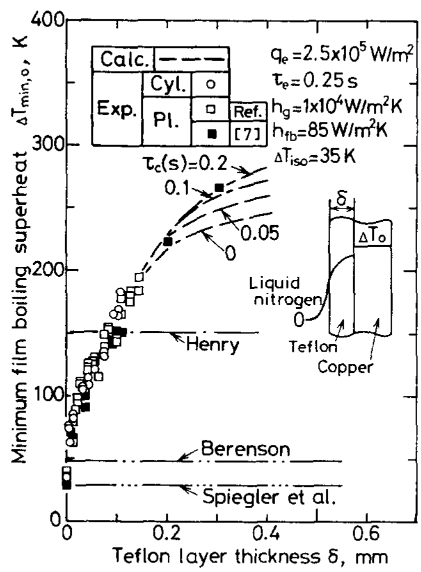

FIG. 8. Effect of duration of conduction period on minimum film boiling superheat.

superheat $\Delta T_{min,o}$. The $\Delta T_{min,o}$ is higher with longer time of evaporation, especially in the thick Teflon-layer region, because the local surface temperature drop due to liquid–solid contacts becomes larger with increasing τ_e. The calculated results for $\tau_e = 0.25$ s agree well with the measured values.

The τ_e of 0.25 s is much longer than the contacting time ($\sim$20 ms) for water, which was measured in the liquid pool experiment [15] as well as the liquid drop experiments [18–20] in the vicinity of the minimum film boiling (or Leidenfrost) point. This long duration is attributed to the good wetting characteristics of liquid nitrogen. Cryogenic liquids, including liquid nitrogen, completely wet Teflon as well as copper (zero angle of contact) [10].

Figure 8 shows the effect of the duration τ_c of the conduction period on $\Delta T_{min,o}$. There are no strong dependencies of $\Delta T_{min,o}$ on τ_c. The reference value of τ_c is, therefore, taken as 0.1 s [16].

A thermal resistance between the Teflon layer and the copper plate cannot be neglected since the evaporation heat flux is high ($q_e = 2.5 \times 10^5$ W m^{-2}) and the temperature difference possibly appears between the back surface of the Teflon layer and the copper plate. Figure 9 shows a dependency of $\Delta T_{min,o}$ on the contact coefficient h_g between the Teflon and the copper. In the thin-layer region there exists a strong effect of h_g on $\Delta T_{min,o}$ and then the $\Delta T_{min,o}$ is higher with lower h_g. No thermal resistance (complete contact) conditions correspond to $h_g = \infty$. The calculation for $h_g = 10^4$ W m^{-2} K^{-1} agrees well with the experimental data.

Consequently, the parameters q_e, τ_e, τ_c and h_g have been determined well as constants. This suggests that the assumptions and formulations of the present theoretical model is valid for predicting the effect of a thin insulating layer on the T_{min} of liquid nitrogen. Figure 10 shows the calculated results of minimum film boiling superheats $\Delta T_{min,o}$ and $\Delta T_{min,w}$ for three kinds of coating materials. Calculations were performed for the same conditions: $q_e = 2.5 \times 10^5$ W m^{-2}, $\tau_e = 0.25$ s, $\tau_c = 0.1$ s, $h_g = 10^4$ W m^{-2} K^{-1}, $h_{fb} = 85$ W m^{-2} K^{-1} and $\Delta T_{iso} = 35$ K. It can be seen from the figure that both $\Delta T_{min,o}$ and $\Delta T_{min,w}$ increase with increasing coating thickness δ. The augmentation of minimum film boiling superheats is more accentuated as the

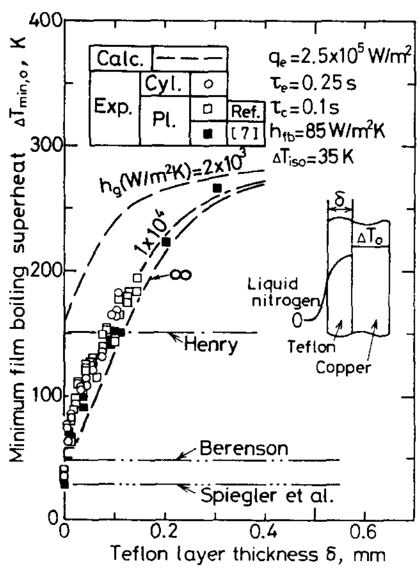

FIG. 9. Effect of contact coefficient between Teflon and copper on minimum film boiling superheat.

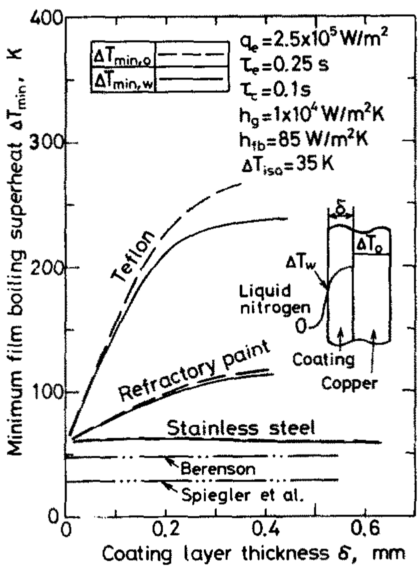

FIG. 10. Minimum film boiling superheat for liquid nitrogen on various kinds of coating materials.

thermal conductivity of a coating material becomes lower.

In the thin region ($\delta \leqslant 0.2$ mm) of Teflon coating, both $\Delta T_{\min,o}$ and $\Delta T_{\min,w}$ increase sharply with increasing δ. In the thick region ($\delta > 0.2$ mm), however, the augmentation of minimum film boiling superheats are attenuated and the $\Delta T_{\min,w}$ attains the highest limit of approx. 240 K in the thicker region than 0.35 mm since the effect of liquid–solid contacts is localized in the portions near the surface and the portions in the interior of thick Teflon experience no temperature changes for the short time of $\tau_e = 0.25$ s.

In the stainless-steel coating, the overestimated values are given for both $T_{\min,o}$ and $T_{\min,w}$ since the present one-dimensional model ignores a circumferential conduction effect on the temperature transients associated with local liquid–solid contacts although the thermal conductivity of stainless steel is much higher than that of Teflon. A two-dimensional model is, therefore, needed for better understanding the $T_{\min}$ for higher thermal conductivity materials.

CONCLUSIONS

A theoretical model has been proposed for explaining the rapid cooldown of metals coated with a thin insulating layer, for which an earlier transition from the film to the transition boiling occurs at unaccountably high temperatures. Based on analytical and experimental results published in the literature, intermittent liquid–solid contacts are assumed to occur in the film boiling regime. Transient contacting and subsequent microlayer evaporation bring forth a rapid decrease in the local surface temperature and an earlier onset of transition boiling is caused while the bulk surface temperature is still high. The minimum film boiling temperature is higher with thicker insulating layer and the calculated results agree well with measured values for liquid nitrogen boiling on Teflon-coated copper plates.

Minimum film boiling temperatures predicted by the present model are shown in Fig. 10 for liquid nitrogen over a wide range of thermal properties and thicknesses of coating materials. Upgrading of the present one-dimensional model to a two-dimensional model is useful for better prediction of the minimum film boiling temperature for coating materials of higher thermal conductivity as well as the Leidenfrost temperature in liquid drop experiments.

Application of the present model to other fluids, for example, water and liquid metals, is now being undertaken. The calculated results for these fluids will be reported in a sequel to the present paper.

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APPENDIX: APPROXIMATE SOLUTION

1. *Assumptions*

In order to obtain the approximate solution, the following assumptions are made:

(I) There is no temperature gradient through the copper plate because of its extremely high thermal conductivity.

(II) The temperature distribution through the Teflon layer is linear.

The second assumption is exactly true only in the steady-state condition where the copper temperature is constant and where transient effects due to a change in the wall temperature have vanished. But the approximation should be satisfactory for the present study since the copper temperature decreases slowly in the film boiling regime and the Teflon layer is very thin. For each period of liquid–solid contacts, the governing equations may be obtained by considering heat balance for system sketched in Fig. A1.

2. *Dry period*

In the dry period the surface is cooled with the film boiling heat transfer coefficient h_{fb}. The governing equations are

$$\varepsilon c_w \rho_w \delta \frac{dT_w}{dt} = \frac{k_w}{\delta}(T_g - T_w) - h_{fb}(T_w - T_{sat}), \tag{A1}$$

$$(1-\varepsilon) c_w \rho_w \delta \frac{dT_g}{dt} = h_g(T_0 - T_g) - \frac{k_w}{\delta}(T_g - T_w), \tag{A2}$$

$$c_0 \rho_0 \delta_0 \frac{dT_0}{dt} = -h_g(T_0 - T_g), \tag{A3}$$

where ε is the weighted parameter of the heat capacity of the Teflon layer and is varied from 0 to 1. The reference value of ε is taken as 0.5.

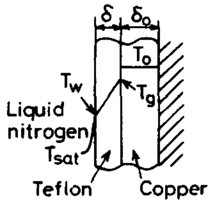

FIG. A1. Coordinate system.

By introducing the concept of the overall conductance of heat, equations (A1)–(A3) are transformed into the simplified form

$$\varepsilon c_w \rho_w \delta \frac{dT_w}{dt} = \frac{K_w}{\delta}(T_0 - T_w) - h_{fb}(T_w - T_{sat}), \tag{A4}$$

$$[(1-\varepsilon) c_w \rho_w \delta + c_0 \rho_0 \delta_0] \frac{dT_0}{dt} = -\frac{K_w}{\delta}(T_0 - T_w), \tag{A5}$$

where

$$1/K_w = 1/k_w + 1/(h_g \delta). \tag{A6}$$

The initial conditions are

$$T_w(0) = T_w^I, \quad T_0(0) = T_0^I. \tag{A7}$$

The solution of equations (A4) and (A5) with the initial conditions expressed by equation (A7) becomes somewhat lengthy but results in the expressions for the copper and the Teflon surface temperatures, respectively,

$$\Delta T_0 = T_0 - T_{sat} = A_1 e^{\phi_1 t} + A_2 e^{\phi_2 t}, \tag{A8}$$

$$\Delta T_w = T_w - T_{sat} = T_0 + (A_1 \phi_1 e^{\phi_1 t} + A_2 \phi_2 e^{\phi_2 t})/U_1, \tag{A9}$$

where

$$\phi_j = -[Y_1 + (-1)^j \sqrt{Y_1^2 - 4Z_1}]/2, \quad j = 1, 2, \tag{A10}$$

$$Y_1 = U_1 + K_w/(\varepsilon c_w \rho_w \delta^2) + h_{fb}/(\varepsilon c_w \rho_w \delta), \tag{A11}$$

$$Z_1 = U_1 h_{fb}/(\varepsilon c_w \rho_w \delta), \tag{A12}$$

$$U_1 = K_w/[(1-\varepsilon) c_w \rho_w \delta^2 + c_0 \rho_0 \delta_0 \delta], \tag{A13}$$

$$A_1 = [U_1(T_0^I - T_w^I) + \phi_2 \Delta T_0^I]/(\phi_2 - \phi_1), \tag{A14}$$

$$A_2 = [U_1(T_0^I - T_w^I) + \phi_1 \Delta T_0^I]/(\phi_1 - \phi_2), \tag{A15}$$

$$\Delta T_0^I = T_0^I - T_{sat}. \tag{A16}$$

3. *Conduction period*

During the conduction period the surface temperature is constant. The governing equations are

$$\frac{dT_w}{dt} = 0, \tag{A17}$$

$$(1-\varepsilon) c_w \rho_w \delta \frac{dT_g}{dt} = h_g(T_0 - T_g) - \frac{k_w}{\delta}(T_g - T_w), \tag{A18}$$

$$c_0 \rho_0 \delta_0 \frac{dT_0}{dt} = -h_g(T_0 - T_g), \tag{A19}$$

with the initial conditions

$$T_w(0) = T_w^J, \quad T_g(0) = T_g^J, \quad T_0(0) = T_0^J. \tag{A20}$$

The solutions of equations (A17)–(A19) with the initial conditions of equation (A20) become, after some manipulations,

$$T_w = T_w^J = \text{const.}, \tag{A21}$$

$$T_0 = T_w^J + A_3 e^{\phi_3 t} + A_4 e^{\phi_4 t}, \tag{A22}$$

$$T_g = T_0 + U_2(\phi_3 A_3 e^{\phi_3 t} + \phi_4 A_4 e^{\phi_4 t}), \tag{A23}$$

where

$$\phi_j = -[Y_2 + (-1)^j \sqrt{Y_2^2 - 4X_2 Z_2}]/(2X_2), \quad j = 3, 4, \tag{A24}$$

$$X_2 = (1-\varepsilon) c_w \rho_w \delta U_2, \tag{A25}$$

$$Y_2 = (1-\varepsilon) c_w \rho_w \delta + c_0 \rho_0 \delta_0 + U_2 Z_2, \tag{A26}$$

$$Z_2 = k_w/\delta, \tag{A27}$$

$$U_2 = c_0 \rho_0 \delta_0 / h_g, \tag{A28}$$

$$A_3 = [(T_0^{\mathrm{J}} - T_{\mathrm{g}}^{\mathrm{J}})/U_2 + \phi_4(T_0^{\mathrm{J}} - T_{\mathrm{w}}^{\mathrm{J}})]/(\phi_4 - \phi_3), \quad \text{(A29)}$$

$$A_4 = [(T_0^{\mathrm{J}} - T_{\mathrm{g}}^{\mathrm{J}})/U_2 + \phi_3(T_0^{\mathrm{J}} - T_{\mathrm{w}}^{\mathrm{J}})]/(\phi_3 - \phi_4). \quad \text{(A30)}$$

4. *Evaporation period*

In the evaporation period the surface heat flux q_e is constant. A heat balance at each point yields

$$\varepsilon c_{\mathrm{w}} \rho_{\mathrm{w}} \delta \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = \frac{k_{\mathrm{w}}}{\delta}(T_{\mathrm{g}} - T_{\mathrm{w}}) - q_e, \quad \text{(A31)}$$

$$(1-\varepsilon) c_{\mathrm{w}} \rho_{\mathrm{w}} \delta \frac{\mathrm{d}T_{\mathrm{g}}}{\mathrm{d}t} = h_{\mathrm{g}}(T_0 - T_{\mathrm{g}}) - \frac{k_{\mathrm{w}}}{\delta}(T_{\mathrm{g}} - T_{\mathrm{w}}), \quad \text{(A32)}$$

$$c_0 \rho_0 \delta_0 \frac{\mathrm{d}T_0}{\mathrm{d}t} = -h_{\mathrm{g}}(T_0 - T_{\mathrm{g}}). \quad \text{(A33)}$$

The initial conditions are

$$T_{\mathrm{w}}(0) = T_{\mathrm{w}}^{\mathrm{K}}, \quad T_{\mathrm{g}}(0) = T_{\mathrm{g}}^{\mathrm{K}}, \quad T_0(0) = T_0^{\mathrm{K}}. \quad \text{(A34)}$$

With the use of this initial condition the solutions for equation (A31)–(A33) become

$$T_0 = A_5\, \mathrm{e}^{\phi_5 t} + A_6\, \mathrm{e}^{\phi_6 t} - U_3 t + C_3/Z_3, \quad \text{(A35)}$$

$$T_{\mathrm{g}} = T_0 + D_3(\phi_5 A_5\, \mathrm{e}^{\phi_5 t} + \phi_6 A_6\, \mathrm{e}^{\phi_6 t} - U_3), \quad \text{(A36)}$$

$$T_{\mathrm{w}} = -D_3 E_3(\phi_5 A_5\, \mathrm{e}^{\phi_5 t} + \phi_6 A_6\, \mathrm{e}^{\phi_6 t} - U_3) - (E_3 + F_3)T_0 - G_3 t + B_3, \quad \text{(A37)}$$

where

$$\phi_j = -[Y_3 + (-1)^j \sqrt{Y_3^2 - 4X_3 Z_3}]/(2X_3), \quad j = 5, 6, \quad \text{(A38)}$$

$$X_3 = (1-\varepsilon) c_{\mathrm{w}} \rho_{\mathrm{w}} \delta D_3, \quad \text{(A39)}$$

$$Y_3 = (1-\varepsilon) c_{\mathrm{w}} \rho_{\mathrm{w}} \delta + c_0 \rho_0 \delta_0 + k_{\mathrm{w}} D_3/(\varepsilon\delta), \quad \text{(A40)}$$

$$Z_3 = [1 + c_0 \rho_0 \delta_0/(c_{\mathrm{w}} \rho_{\mathrm{w}} \delta)] k_{\mathrm{w}}/(\varepsilon\delta), \quad \text{(A41)}$$

$$B_3 = T_{\mathrm{w}}^{\mathrm{K}} + F_3 T_0^{\mathrm{K}} + E_3 T_{\mathrm{g}}^{\mathrm{K}}, \quad \text{(A42)}$$

$$C_3 = Y_3 U_3 + k_{\mathrm{w}} B_3/\delta, \quad \text{(A43)}$$

$$D_3 = c_0 \rho_0 \delta_0 / h_{\mathrm{g}}, \quad \text{(A44)}$$

$$E_3 = (1-\varepsilon)/\varepsilon, \quad \text{(A45)}$$

$$F_3 = c_0 \rho_0 \delta_0/(\varepsilon c_{\mathrm{w}} \rho_{\mathrm{w}} \delta), \quad \text{(A46)}$$

$$G_3 = q_e/(\varepsilon c_{\mathrm{w}} \rho_{\mathrm{w}} \delta), \quad \text{(A47)}$$

$$U_3 = q_e/(c_{\mathrm{w}} \rho_{\mathrm{w}} \delta + c_0 \rho_0 \delta_0), \quad \text{(A48)}$$

$$A_5 = [(T_0^{\mathrm{K}} - T_{\mathrm{g}}^{\mathrm{K}})/D_3 + \phi_6(T_0^{\mathrm{K}} - C_3/Z_3) - U_3]/(\phi_6 - \phi_5), \quad \text{(A49)}$$

$$A_6 = [(T_0^{\mathrm{K}} - T_{\mathrm{g}}^{\mathrm{K}})/D_3 + \phi_5(T_0^{\mathrm{K}} - C_3/Z_3) - U_3]/(\phi_5 - \phi_6). \quad \text{(A50)}$$

TEMPERATURE MINIMALE D'EBULLITION EN FILM LORS DU REFROIDISSEMENT DE METAUX DANS UN LIQUIDE SATURE

Résumé—On conduit l'étude théorique d'une transition prématurée entre l'ébullition en film et celle de transition qui peut apparaître pendant le refroidissement rapide de métaux chauds recouverts d'une fine couche d'isolant (faible conductivité thermique). Des contacts directs liquide–solide sont supposés exister de façon intermittante dans le régime d'ébullition en film. Le contact transitoire et l'évaporation résultante d'une fine microcouche de liquide amène une rapide diminution de la température locale de la surface. Si cette température chute au dessous de la limite la plus basse, une ébullition de transition anticipée apparait bien que la température moyenne de la surface soit élevée. La température minimale d'ébullition en film est plus élevée lorsque l'épaisseur de la couche isolante augmente. Les résultats calculés sont en bon accord avec les données expérimentales pour l'azote liquide en ébullition sur des plaques recouvertes de Teflon.

DIE MINIMALE FILMSIEDETEMPERATUR BEIM ABKÜHLEN VON ISOLIERTEN METALLEN IN GESÄTTIGTER FLÜSSIGKEIT

Zusammenfassung—Eine theoretische Studie wurde durchgeführt, um den vorzeitigen Wechsel vom Film- zum Übergangssieden zu untersuchen, der während des schnellen Abkühlens von heißen Metallen, die mit einer dünnen Schicht schlecht wärmeleitenden Materials beschichtet sind, auftreten kann. Es wird angenommen, daß der Kontakt zwischen Flüssigkeit und fester Oberfläche im Filmsiedebereich pulsierend auftritt. Der kurzzeitige Kontakt und die anschließende Verdampfung einer dünnen Flüssigkeits-Mikroschicht führen zu einem starken Absinken der lokalen Oberflächentemperaturen. Unterschreitet die lokale Oberflächentemperatur eine untere Grenze, so setzt das Übergangssieden vorzeitig ein, obwohl die mittlere Wandtemperatur noch relativ hoch ist. Die minimale Filmsiedetemperatur steigt mit dicker werdender Isolierschicht. Die berechneten Ergebnisse stimmen gut mit experimentellen Daten für die Verdampfung von flüssigem Stickstoff an teflonbeschichteten Kupferplatten überein.

МИНИМАЛЬНАЯ ТЕМПЕРАТУРА ПЛЕНОЧНОГО КИПЕНИЯ ДЛЯ ОХЛАЖДЕНИЯ ТЕПЛОИЗОЛИРОВАННЫХ МЕТАЛЛОВ В НАСЫЩЕННОЙ ЖИДКОСТИ

Аннотация—Проведено теоретическое исследование раннего перехода от пленочного кипения к переходному, который может иметь место при резком охлаждении горячих металлов, покрытых тонким слоем изолирующего материала, обладающего низкой теплопроводностью. Предполагается, что при пленочном кипении прямые контакты жидкости и твердого тела имеют пульсирующий характер. Нестационарные контакты и последующее испарение тонкого микрослоя жидкости приводят к быстрому снижению локальной температуры поверхности. В случае, если локальная температура поверхности падает ниже наименьшего предела, несмотря на то, что средняя температура стенки достаточно высока, возникает более раннее переходное кипение. Минимальная температура пленочного кипения растет с увеличением толщины изолирующего слоя. Результаты расчета хорошо согласуются с экспериментальными данными, полученными для кипения жидкого азота на медных пластинах, покрытых тефлоном.