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FILM BOILING IN LAMINAR BOUNDARY-LAYER FLOW ALONG A HORIZONTAL PLATE SURFACE

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Abstract—A mathematical model is presented to cover the effect of a pressure gradient caused by the increasing vapor film thickness along the flow direction. Approximate heat transfer solutions are obtained analytically for laminar film boiling of a liquid deviating greatly from critical state. It is shown that, the heat transfer rate thus calculated may be obviously improved as compared with the results from previous formulae reported in the literature, especially for the region of low flow velocity.

NOMENCLATURE

- a thermal diffusivity
- c_p specific heat
- g gravitational acceleration
- h_{fg} latent heat
- Nu Nusselt number
- p pressure
- Pr Prandtl number
- q local heat transfer rate per unit area
- Re Reynolds number
- t temperature
- t_s saturation temperature
- u, v velocity component in x- and y-directions, respectively.

Greek symbols
- α local heat transfer coefficient
- δ thickness of vapor film
- μ absolute viscosity
- ν kinematic viscosity
- ρ density.

Subscripts
- w at surface
- ∞ at infinite distance from plate surface
- 1 vapor
- 2 liquid.

1. INTRODUCTION

THE FORCED-convective film boiling on a horizontal surface has attracted many researchers for a long time. Bradfield [1] analyzed this subject using the integral method. As regard to the laminar-flow film boiling of a saturated liquid on a flat plate, an approximate relation was reported by Cess and Sparrow [2] as

$$\frac{Nu}{\sqrt{Re_1}}\left(\frac{\mu_1}{\mu_2}\right) = 0.5\left[\frac{(\rho u)_2}{(\rho u)_1}\frac{c_{p_1}\Delta t}{h_{fg}Pr_1}\right]^{-1/2}, \qquad (1)$$

for the case $[(\rho u)_2/(\rho u)_1]^{1/2} \gg 1$ and a constant surface temperature, where subscripts '1' and '2' refer to vapor and liquid, respectively. Cess and Sparrow also analyzed the subcooled forced-convective film boiling on a horizontal surface [3], and for the boundary condition $q_w = \text{const.}$ [4]. Ito and Nishikawa [5] solved numerically this two-phase boundary-layer problem and compared their results with those reported by Cess and Sparrow [2, 3]. Later, Jordan [6] and Kalinin [7] reviewed the works in this field, and recommended equation (1) for predicting laminar-flow film boiling on a horizontal plate surface.

However, as indicated by equation (1), the dimensionless Nusselt number, Nu, approaches zero when the free-stream velocity becomes smaller and smaller, this is obviously not true in accordance with the real situation of pool film boiling. It had been pointed out that, the available heat transfer data on convective film boiling on a horizontal plate surface are regularly much higher than those obtained from theoretical analysis [1, 8, 9].

In this paper, we present, possibly for the first time, the effect of a pressure gradient caused by an increase in the vapor film thickness along the flow direction. It was found that this effect will be prominent for low-velocity laminar film boiling on a horizontal plate surface, especially for a large ratio between the density of the liquid and that of the vapor.

2. MATHEMATICAL MODEL

The basic assumptions adapted are as follows:

(1) The flow is steady and laminar in the boundary layer, with a smooth interface between the liquid and the vapor film.

(2) The thermophysical properties of the liquid and the vapor phase are considered as constants.

(3) The surface temperature is kept constant over all of the heated plate.

As shown in Fig. 1, if p_{δ_x} and $p_{\delta_{(x+\Delta x)}}$ are the pressure at the interface of x and $(x+\Delta x)$, respectively, then

$$\Delta p = p_{\delta_{(x+\Delta x)}} - p_{\delta_x} = -(\rho_2-\rho_1)g\Delta\delta. \qquad (2)$$

Since the vapor film thickness, δ, is a function of x only, we obtain

$$\frac{\partial p}{\partial x} = -(\rho_2-\rho_1)g\frac{d\delta}{dx}. \qquad (3)$$

The momentum equation in the vapor film can thus be

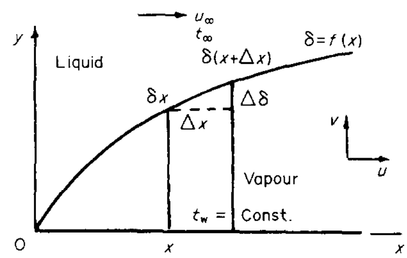

FIG. 1. Analytical model.

expressed as

$$u_1 \frac{\partial u_1}{\partial x} + v_1 \frac{\partial u_1}{\partial y} = \nu_1 \frac{\partial^2 u_1}{\partial y^2} + \frac{\rho_2 - \rho_1}{\rho_1} g \frac{d\delta}{dx}. \quad (4)$$

For a liquid deviating greatly from the critical state, i.e. $(\rho_2 - \rho_1)/\rho_1$ has a large value, for example, water at a pressure of 1 Pa, the order of magnitude $O[(\rho_2 - \rho_1)/\rho_1]$ is about 10^3. Hence, the term $[(\rho_2 - \rho_1)/\rho_1]g(d\delta/dx)$ in equation (4) may be of the same order of magnitude as the rest of the terms.

Continuity and energy equations in the vapor film are

$$\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y} = 0, \quad (5)$$

$$u_1 \frac{\partial t_1}{\partial x} + v_1 \frac{\partial t_1}{\partial y} = a_1 \frac{\partial^2 t_1}{\partial y^2}. \quad (6)$$

Continuity, momentum and energy equations in the liquid region are

$$\frac{\partial u_2}{\partial x} + \frac{\partial v_2}{\partial y} = 0, \quad (7)$$

$$u_2 \frac{\partial u_2}{\partial x} + v_2 \frac{\partial u_2}{\partial y} = \nu_2 \frac{\partial^2 u_2}{\partial y^2}, \quad (8)$$

$$u_2 \frac{\partial t_2}{\partial x} + v_2 \frac{\partial t_2}{\partial y} = a_2 \frac{\partial^2 t_2}{\partial y^2}. \quad (9)$$

The boundary conditions are

$$y = 0, \qquad u_1 = v_1 = 0, \qquad t_1 = t_w, \quad (10)$$

$$y \to \infty, \qquad u_2 = u_\infty, \qquad t_2 = t_\infty, \quad (11)$$

and the matching conditions at the liquid–vapor interface, $y = \delta$, will be

$$t = t_s, \quad (12)$$

$$u_1 = u_2, \quad (13)$$

$$\mu_1 \frac{\partial u_1}{\partial y} = \mu_2 \frac{\partial u_2}{\partial y}, \quad (14)$$

$$\rho_1\left(u_1 \frac{d\delta}{dx} - v_1\right) = \rho_2\left(u_2 \frac{d\delta}{dx} - v_2\right) = \dot{m}, \quad (15)$$

$$-\lambda_1 \frac{\partial t_1}{\partial y} = -\lambda_2 \frac{\partial t_2}{\partial y} + \dot{m} h_{fg}, \quad (16)$$

where $\dot{m}$ is the mass flux across the interface.

3. SIMILARITY TRANSFORMATION

For the liquid region, similar variables used usually for the single-phase flow along a flat plate [10] are introduced as below

$$\xi = y\sqrt{(u_\infty/\nu_2 x)}, \qquad F(\xi) = \frac{\psi}{\sqrt{(\nu_2 u_\infty x)}}, \quad (17)$$

where ψ is the stream function of the liquid flow, and

$$u_2 = \frac{\partial \psi}{\partial y} = u_\infty F', \quad (18)$$

$$v_2 = -\frac{\partial \psi}{\partial x} = \frac{1}{2}\sqrt{\left(\frac{\nu_2 u_\infty}{x}\right)}(\xi F' - F). \quad (19)$$

Introducing a dimensionless variable $\Theta = (t_2 - t)/(t_s - t)$, we obtained from equations (7)–(9)

$$2F''' + FF'' = 0, \quad (20)$$

$$\frac{2}{Pr}\Theta'' + F\Theta' = 0, \quad (21)$$

with the corresponding boundary conditions

$$\xi \to \infty, \qquad F' \to 1, \quad (22)$$

$$\Theta \to 0. \quad (23)$$

For the vapor film, as reported by Sparrow and Yu [11] to analyze the mixed convection problem, the following variables are defined

$$\varepsilon = \varepsilon(x), \qquad \eta = y\sqrt{(u_\infty/\nu x)},$$

and

$$f(\varepsilon, \eta) = \phi(x, y)/\sqrt{(\nu_1 u_\infty x)}, \quad (24)$$

where ϕ is the stream function in the vapor film, or

$$u_1 = \frac{\partial \phi}{\partial y} = u_\infty \frac{\partial f}{\partial \eta}, \quad (25)$$

$$v_1 = -\frac{\partial \phi}{\partial x} = -\left[\frac{1}{2} f\sqrt{(\nu_1 u_\infty/x)} + \sqrt{(\nu_1 u_\infty x)}\left(-\frac{1}{2}\frac{\eta}{x}\frac{\partial f}{\partial \eta} + \frac{\partial f}{\partial \varepsilon}\varepsilon'\right)\right]. \quad (26)$$

Noting $\eta = \eta_\delta$ at $y = \delta$

$$\frac{d\delta}{dx} = \frac{\eta_\delta}{2}\sqrt{\left(\frac{\nu_1}{u_\infty x}\right)}. \quad (27)$$

We define

$$\varepsilon(x) = \frac{1}{2}\sqrt{\left(\frac{\nu_1 x}{u_\infty}\right)} g \frac{(\rho_2 - \rho_1)}{\rho_1} = \frac{Ar}{Re_1^{5/2}}, \quad (28)$$

where $Ar = g(\rho_2 - \rho_1)x^3/(\rho_1 \nu_1^2)$, is the Archimedes number and $Re_1 = u_\infty x/\nu_1$, is the Reynolds number. Introducing a dimensionless variable, $\theta = (t_1 - t_s)/(t_w - t_s)$, and substituting equations (25)–(27) into equations (5) and (6), we obtained

$$2\frac{\partial^3 f}{\partial \eta^3} + f\frac{\partial^2 f}{\partial \eta^2} + \eta_\delta \varepsilon = \varepsilon\left[\frac{\partial f}{\partial \eta}\frac{\partial}{\partial \varepsilon}\left(\frac{\partial f}{\partial \eta}\right) - \frac{\partial^2 f}{\partial \eta^2}\frac{\partial f}{\partial \varepsilon}\right], \quad (29)$$

$$\frac{2}{Pr}\frac{\partial^2\theta}{\partial\eta^2}+f\frac{\partial\theta}{\partial\eta}=\varepsilon\left[\frac{\partial f}{\partial\eta}\frac{\partial\theta}{\partial\varepsilon}-2\frac{\partial\theta}{\partial\eta}\frac{\partial f}{\partial\varepsilon}\right], \tag{30}$$

with boundary conditions

$$\text{at } \eta=0, \quad t_1=t_w \text{ or } \theta=1,$$

$$u_1=0 \text{ or } \frac{\partial f}{\partial\eta}=0,$$

$$v_1=0 \text{ or } f+\varepsilon\frac{\partial f}{\partial\varepsilon}=0. \tag{31}$$

The corresponding matching conditions at the liquid–vapor interface are

$$\text{from equation (12)}, \quad \theta=0, \quad \Theta=1, \tag{32}$$

$$\text{from equation (13)}, \quad \frac{\partial f}{\partial\eta}=F', \tag{33}$$

$$\text{from equation (14)}, \quad F''=\sqrt{\left(\frac{\mu_1\rho_1}{\mu_2\rho_2}\right)}\frac{\partial^2 f}{\partial\eta^2}, \tag{34}$$

from equation (15),

$$F=\sqrt{\left(\frac{\mu_1\rho_1}{\mu_2\rho_2}\right)}\left(f+\varepsilon\frac{\partial f}{\partial\varepsilon}\right), \tag{35}$$

from equation (16),

$$\frac{\partial\theta}{\partial\eta}=\frac{\lambda_2(t_s-t_\infty)}{\lambda_1(t_w-t_s)}\sqrt{\left(\frac{\nu_1}{\nu_2}\right)}\Theta' -\frac{1}{2}\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w-t_s)}\left(f|_{\eta=\eta_\delta}+\varepsilon\frac{\partial f}{\partial\varepsilon}\right). \tag{36}$$

According to the analysis of mixed convection [11, 12] it is reasonable to assume that $\partial f/\partial\varepsilon$, $(\partial/\partial\varepsilon)(\partial f/\partial\eta)$, and $\partial\theta/\partial\varepsilon$ are negligibly small, and equations (29) and (30) can thus be simplified as

$$2\frac{\partial^3 f}{\partial\eta^3}+f\frac{\partial^2 f}{\partial\eta^2}+\eta_\delta\varepsilon=0, \tag{37}$$

$$\frac{2}{Pr}\frac{\partial^2\theta}{\partial\eta^2}+f\frac{\partial\theta}{\partial\eta}=0, \tag{38}$$

while the boundary and matching conditions, equations (31), (32), and (36), can be reduced to

$$\text{at } \eta=0, \quad \theta=1, \quad \frac{\partial f}{\partial\eta}=0, \quad f=0; \tag{39}$$

$$\text{at } \eta=\eta_\delta, \quad F=\sqrt{\left(\frac{\mu_1\rho_1}{\mu_2\rho_2}\right)}f, \tag{40}$$

$$\frac{\partial\theta}{\partial\eta}=\frac{\lambda_2(t_s-t_\infty)}{\lambda_1(t_w-t_s)}\sqrt{\left(\frac{\nu_1}{\nu_2}\right)}\Theta'-\frac{1}{2}\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w-t_s)}f|_{\eta=\eta_\delta}. \tag{41}$$

Equations (20), (21), and (36), (37), together with corresponding boundary and matching conditions, provide a complete set of equations for determining the four unknown variables, F, f, Θ, and θ, so that the temperature and velocity distribution, as well as the heat transfer flux on the surface, may be calculated numerically.

4. A SIMPLIFIED HEAT TRANSFER SOLUTION

If attention is limited to film boiling for a liquid deviating greatly from its critical state, which often occurs in engineering practice, we can follow Cess and Sparrow's suggestion [2] to set aside the inertia and energy convection terms in the vapor film, then equations (37) and (38) can be reduced further to the following equations

$$2\frac{\partial^3 f}{\partial\eta^3}+\eta_\delta\varepsilon=0, \tag{42}$$

$$\frac{\partial^2\theta}{\partial\eta^2}=0. \tag{43}$$

The solution of equation (42) combined with the corresponding boundary conditions is given as

$$f=\frac{1}{2}F''(0)\sqrt{\left(\frac{\rho_2\mu_2}{\rho_1\mu_1}\right)}\eta^2+\frac{1}{4}\eta_\delta^2\varepsilon\eta^2-\frac{1}{12}\eta_\delta\eta^3. \tag{44}$$

Changing the ordinate referring to the liquid–vapor interface, i.e. taking $\xi=0$ at $\eta=\eta_\delta$, the following relation can be derived from equations (44) and (33)

$$F''(0)\sqrt{\left(\frac{\rho_2\mu_2}{\rho_1\mu_1}\right)}\eta_\delta+\frac{1}{4}\eta_\delta^3\varepsilon=F'(0). \tag{45}$$

An approximate solution to equation (20) for liquid under the condition of $(\rho_2\mu_2/\rho_1\mu_1)^{1/2}\gg 1$ was suggested by Cess and Sparrow [2] as

$$F''(0)=\frac{1}{\sqrt{\pi}}[1-F'(0)]. \tag{46}$$

From equations (45) and (46), by eliminating $F'(0)$, we obtain

$$F''(0)=\frac{1-(1/4)\eta_\delta^3\varepsilon}{\sqrt{\pi}+\sqrt{(\rho_2\mu_2/\rho_1\mu_1)}\eta_\delta}. \tag{47}$$

As given by Cess and Sparrow [3] for the case $Pr\approx 1$, from the similarity between the momentum equation (20) and energy equation (21)

$$\Theta=\frac{F'-1}{F'(0)-1} \quad \text{or} \quad \Theta'|_{\xi=0}=\frac{F''(0)}{F'(0)-1}. \tag{48}$$

Solving equations (40), (44), and (46)–(48), and ignoring the value of $\sqrt{\pi}$ as compared with $\sqrt{(\rho_2\mu_2/\rho_1\mu_1)}\eta_\delta$ in the denominator of equation (47) for the first approximation, we get

$$\frac{1}{\eta_\delta}=\frac{\lambda_2(t_s-t_\infty)}{\lambda_1(t_w-t_s)}\sqrt{\left(\frac{\nu_1}{\nu_2}\right)}\frac{1}{\sqrt{\pi}}+\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w-t_s)}\left(\frac{1}{4}\eta_\delta+\frac{1}{48}\eta_\delta^4\varepsilon\right). \tag{49}$$

The solution of equation (43), combined with its boundary conditions, will be

$$\theta=1-\frac{1}{\eta_\delta}\eta. \tag{50}$$

It is clear from Fourier's law that

$$q = -\lambda_1 \frac{\partial t_1}{\partial y}\bigg|_{y=0} = \lambda_1(t_w - t_s)\sqrt{\left(\frac{u_\infty}{v_1 x}\right)}\frac{1}{\eta_\delta}. \quad (51)$$

Let $Nu = \alpha x/\lambda_1$, where $\alpha = q/(t_w - t_s)$ is the local heat transfer coefficient based on the temperature difference taken as $(t_w - t_s)$. Hence, from equations (49) and (51)

$$Nu^5 = \frac{1}{\sqrt{\pi}}\left(\frac{\rho_2\mu_2}{\rho_1\mu_1}\right)^{1/2}\frac{c_{p_2}(t_s - t_\infty)}{c_{p_1}(t_w - t_s)}\frac{Pr_1}{Pr_2}\sqrt{Re_1}\,Nu^4 + \frac{1}{4}\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w - t_s)}Re_1\,Nu^3 + \frac{1}{48}\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w - t_s)}Ar. \quad (52)$$

5. DISCUSSION AND CONCLUSIONS

For saturation film boiling, $t_\infty = t_s$, equation (52) can be simplified to

$$\left(\frac{Nu}{\sqrt{Re_1}}\right)^5 = \frac{Pr_1\,h_{fg}}{c_{p_1}(t_w - t_s)}\left[\frac{1}{4}\left(\frac{Nu}{\sqrt{Re_1}}\right)^3 + \frac{1}{48}\varepsilon\right]. \quad (53)$$

It can be shown that, as $\varepsilon \to 0$, i.e. the effect of the pressure gradient on the buoyancy force can be neglected, equation (53) will be the same as equation (1) which was derived by Cess and Sparrow [2].

Figure 2 shows the variation of Nu as function of Re_1 and ε in equation (53). It is obvious that a smaller free-stream velocity, coinciding with a greater ε, could lead to an important effect on the heat transfer rate.

In general, Ar is large, for example it reaches 10^{10}–10^{12} for water under atmospheric pressure. As the free-stream velocity decreases to zero, i.e. for pool film boiling, equation (53) can be reduced to

$$Nu^5 = \frac{1}{48}\frac{Pr_1\,h_{fg}}{c_{p_1}(t_w - t_s)}Ar. \quad (54)$$

Figures 3 and 4 describe respectively the effect of buoyancy force and subcooling of liquid on the heat transfer rate. For highly subcooled film boiling, the last two terms on the RHS of equation (52) may be

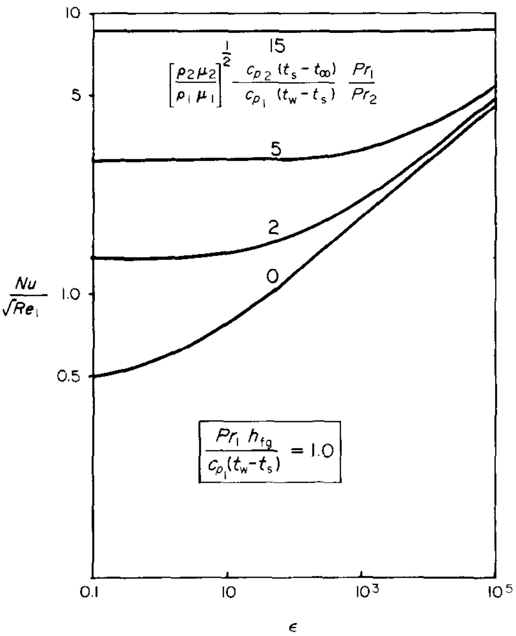

Fig. 3. Effect of buoyancy force on laminar film boiling heat transfer.

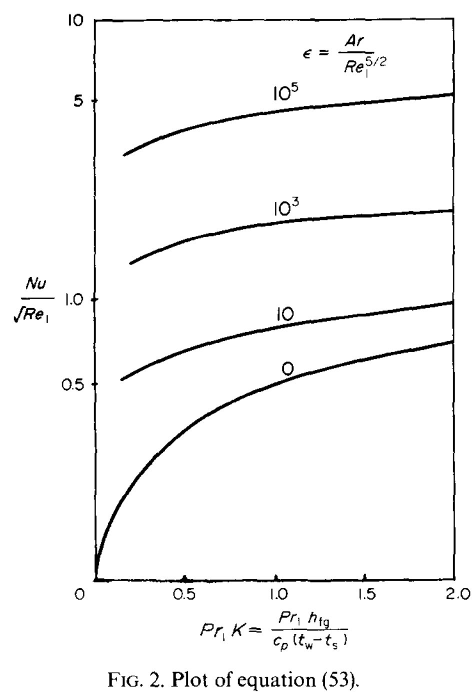

Fig. 2. Plot of equation (53).

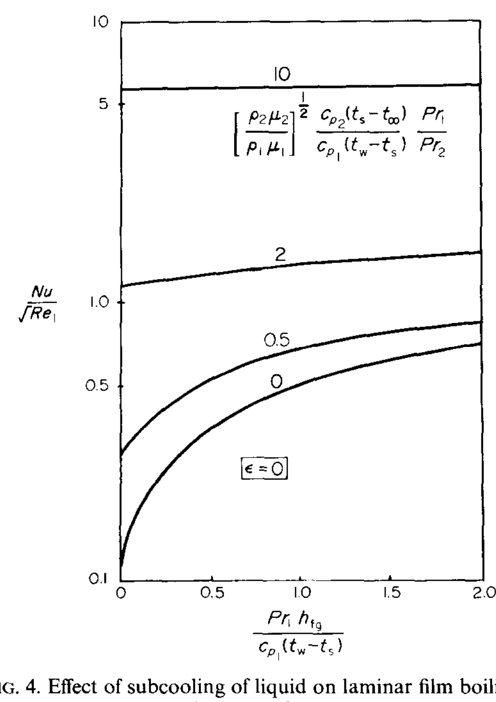

Fig. 4. Effect of subcooling of liquid on laminar film boiling heat transfer.

neglected, and the following simplified relation can thus be obtained

$$Nu = \frac{1}{\sqrt{\pi}}\left[\frac{\rho_2\mu_2}{\rho_1\mu_1}\right]^{1/2}\frac{c_p(t_s-t_\infty)}{c_{p_1}(t_w-t_s)}\frac{Pr_1}{Pr_2}\sqrt{Re_x}. \quad (55)$$

Let $\widetilde{Nu} = \tilde{\alpha}x/\lambda_2$, where $\tilde{\alpha} = q/(t_w-t_s)$. Then

$$\widetilde{Nu} = \frac{1}{\sqrt{\pi}}\sqrt{\left(\frac{u_\infty x}{v^2}\right)}, \quad (56)$$

which is almost the same as the heat transfer relation for single-phase fluids with laminar boundary-layer flow [10] except the constant coefficient in equation (56) increased to $1/\sqrt{\pi} = 0.564$.

In conclusion, it may be summarized as follows:

(1) For a liquid deviating greatly from its critical state and flowing with a low velocity, the pressure gradient caused by a great density ratio between the liquid and vapor phase has an important effect on the film boiling heat transfer rate, and can be predicted approximately by equation (54) as the free-stream velocity is close to zero.

(2) The heat transfer rate for film boiling in a laminar boundary-layer flow with a greater subcooling of the liquid and at a higher free-stream velocity may be predicted from equation (55).

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EBULLITION EN FILM DANS UN ECOULEMENT A COUCHE LIMITE LE LONG D'UNE SURFACE PLANE HORIZONTALE

Résumé—On présente un modèle mathématique pour couvrir les effets du gradient de pression causé par l'accroissement d'épaisseur du film de vapeur dans la direction de l'écoulement. Des solutions approchées du transfert thermique sont obtenues analytiquement pour l'ébullition en film laminaire d'un liquide loin de l'état critique. On montre que le flux thermique ainsi calculé peut être clairement amélioré en comparaison des résultats donnés par des formules disponibles dans la bibliographie, spécialement pour la région des faibles vitesses d'écoulement.

FILMSIEDEN BEI LAMINARER GRENZSCHICHTSTRÖMUNG LÄNGS EINER HORIZONTALEN PLATTENOBERFLÄCHE

Zusammenfassung—Es wird ein mathematisches Modell vorgestellt, das den Einfluß des Druckgradienten aufgrund der zunehmenden Filmdicke in Strömungsrichtung mit berücksichtigt. Für den Wärmeübergang beim laminaren Filmsieden einer Flüssigkeit fern vom kritischen Zustand werden analytisch Näherungslösungen gewonnen. Es wird gezeigt, daß der derart berechnete Wärmeübergang im Vergleich mit Rechenwerten nach früher veröffentlichten Beziehungen deutlich besser ist, dies speziell für kleine Strömungsgeschwindigkeiten.

ПЛЕНОЧНОЕ КИПЕНИЕ ПРИ ЛАМИНАРНОМ ТЕЧЕНИИ В ПОГРАНИЧНОМ СЛОЕ НА ГОРИЗОНТАЛЬНОЙ ПЛАСТИНЕ

Аннотация—Представлена математическая модель для описания влияния на пленочное кипение градиента давления, вызванного ростом толщины пленки пара по направлению течения. Получены приближенные аналитические решения уравнения теплопереноса для процесса кипения ламинарной пленки жидкости в далеком от критического режима состоянии. Показано, что рассчитанная таким образом плотность теплового потока является более точной по сравнению с результатами, получаемыми по ранее использованным представленным в литературе формулам, особенно для области с небольшой скоростью течения.