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Film boiling heat transfer from a horizontal surface in low forced convection and saturated conditions under an interfacial instability model

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The author examine the film boiling heat transfer enhancement in low forced convection from horizontal surface into the framework of Taylor–Helmholtz Hydrodynamic instabilities. Utilizing a simplified geometrical model, an analytical expression for the heat transfer coefficient was derived. The above equation agree with the available experimental measurements made on R113 within ±15 percent.

1. Introduction

Knowledge of low forced convection film boiling heat transfer for relatively low flow rates from a horizontal surface has played an important role in industrial heat transfer processes such as macroscopic heat transfer exchangers in fossil and nuclear power plants (for example the reflooding phenomenon during the emergency cooling in a water-cooled nuclear reactor). The object of this work was to analyze film boiling heat transfer from a horizontal surface in low forced flow into the framework of Taylor–Helmholtz instabilities theory. Forced convection film boiling heat transfer from a horizontal cylinder in cross flow of liquid was studied by several workers (Bromley et al., 1953 [1]; Motte and Bromley, 1957 [2]; Epstein and Hauser, 1980; Chou and Witte, 1992 [3]; Liu et al., 1992a,b) [4]. On the other hand, there have been some theoretical analysis on forced convection film boiling heat transfer from a horizontal flat plate according to laminar boundary layer theory (Cess and Sparrow, 1961a,b; Ito and Nishikawa, 1966). Cess and Sparrow (1961a) presented a correlation for saturated forced flow film boiling heat transfer based on their theoretical solution. However, applicability of these theoretical solutions and correlation to real film boiling have not been studied experimentally until quite recently. In many of these papers are discussions of the state of the interface, nothing the formation of waves and vapor bubbles in a low forced convection. there has been only one theoretical model on forced flow film boiling heat transfer for the formation of waves as far as the authors know. Budov et al., 1981 examined the influence of a moving liquid on the parameters of interphase surface waves under film boiling and presented a correlation for wavelength profile, on the other hand they assumed that an increase of the liquid velocity leads to an increase of the phase velocity and a decrease of the wavelength. This change of the parameters of interphase surface waves intensifies convective mixing, and, as a result, the amount of heat transmitted is increased, compared with the case of boiling of a stationary liquid however and no correlation of film boiling heat transfer was given. However in a vertical surfaces, the independency of the heat transfer intensity, at some distance from the leading edge, of the height of the surface and the peculiar behavior in the heat transfer coefficient in low forced convection (reduction of heat transfer) have provide the basis for assuming that Taylor–Helmholtz can be the dominant process (Sakurai and Shiotsu, 1992 [7]). As mentioned above a rigorous theoretical analysis is justified from a horizontal surface into the framework of Taylor–Helmholtz instabilities theory because although the consequence in the heat transfer coefficient can be quantitatively similar, the mechanisms are very different and in some special situation such as when g is much less than earth gravity $g0$, it could very well a difference large enough to warrant careful consideration to a design of a power plant for space applications.

1.1. Pool film boiling

At or near boiling crisis a film boiling occurs when the heat surface is blanketed with vapor film and the heat transfer coefficient rapidly decreases, the film hinders heat transfer, and resulting

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heat flux is usually small compared with the values observed during nucleate boiling. In most industrial process for vaporizing liquids, film boiling is avoided. However, when large temperature differences are encountered, such as when an ordinary liquid contacts a very hot solid or when vapor is used to heat liquids with low boiling points, film boiling may occur. However film boiling has received much less attention than nucleate boiling; yet the film-type phenomenon appears to be more susceptible to attack from the theoretical viewpoint.

1.2. Assumptions

We have a heat surface which is blanketed with a vapor film with constant density ρ_v; and velocity u_v, the film is separated of the rest of the saturated liquid (upper region) by the boundary layer, which is at saturation temperature. On the other hand the upper region (saturated liquid) with a constant density ρ_l and velocity u_l. The actual shape of the liquid–vapor interface, and the coordinates in the model used in the analysis are shown in Fig. 1.

In analyzing film boiling from a horizontal tube one knows that the vapor flows up around the tube, departing as bubbles from the top of the tube. The vapor generated in the vicinity of a given growing bubble flows in toward the bubble location, combines, and departs. This process repeats itself continuously, leading to a steady stream of individual bubbles departing from the liquid vapor interface. For stability analysis applied to three dimension one bubble is generated in an area $\lambda/2$, referring to Fig. 1, this condition can be expressed as:

$$\pi r_2^2 = \frac{\lambda^2}{2} \tag{1}$$

On the other hand, the required pressure difference required to sustain the flow, yield the following result Berenson, 1961 [8].

$$p_2 - p_1 = \frac{\beta\mu_\upsilon\kappa_\upsilon\Delta T}{g0a^4\rho_\upsilon\Delta h}\int_{r_1}^{r_2}\frac{\lambda^2/2-\pi r^2}{2\pi r}\,\mathrm{d}r \tag{2}$$

The meaning of the various terms in the above equation is defined in Nomenclature.

1.3. Wavelength profile in low forced convection

Note that equation (2) allow to compute 'mechanistically' the pressure difference if we know the interfacial wavelength and radio bubble r_1. It is easily shown Berenson [8] that in the absence of forced convection the wavelength which maximizes the instability is given by:

$$\lambda_0 = 2\pi\sqrt{\frac{3g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}} \tag{3}$$

However under forced convection, it is plausible to suppose a certain influence on equation (3) from velocity field, in other words a more accurate expression can be expressed as

$$\lambda = \lambda_0\cdot\Phi \tag{4}$$

Where the function $\Phi = 1$ when the liquid velocity $u_\iota = 0$. On the other hand, bubble radio $r_1 = R$ and the average height of the bubble δ above the vapor film is given by semi-empirical equations obtained in experimental measurements, Borishansky [9] with an error above $\pm10\%$

$$r_1 = R = 2.35\sqrt{\frac{g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}};\quad \delta = 3.2\sqrt{\frac{g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}} \tag{5}$$

with equation (5), (4) and equation (3), in equation (2) gives the final pressure difference

$$p_2 - p_1 = \left[\frac{8\beta}{\pi}\frac{\mu_\upsilon\kappa_\upsilon\Delta T}{g_0a^4\rho_\upsilon\Delta h}\frac{g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}\right]\cdot\Pi \tag{6}$$

where

$$\Pi = \frac{3}{8}\pi^2\Phi^2\ln(1.84\cdot\Phi) - \frac{3\pi^2}{16}\Phi^2 + 0.54 \tag{7}$$

The pressure difference in equation (6) must be supplied by the difference in gravity head and the surface tension according to the following equation, derived in Appendix A.

$$p_2 - p_1 = 2.34\frac{g}{g_0}(\rho_\iota-\rho_\upsilon)\sqrt{\frac{g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}} \tag{8}$$

Equating equation (6) to equation (8) multiplying by the ratio of the total surface area to the area between the bubbles 1.4, and taking into account the two extreme values of β we obtain the average vapor film thickness for the entire surface.

$$a = a_0\cdot\Pi^{\frac{1}{4}} \tag{9}$$

where a_0 is naturally, the vapor film thickness found by Berenson which is given by

$$a_0 = 2.35\left[\frac{1.09\mu_\upsilon\kappa_\upsilon\Delta T}{\Delta h\rho_\upsilon g(\rho_\iota-\rho_\upsilon)}\sqrt{\frac{g_0\sigma}{g(\rho_\iota-\rho_\upsilon)}}\right]^{\frac{1}{4}} \tag{10}$$

Many expressions can be used in a theoretical study on the effect of liquid velocity on the wavelength λ, however in the present paper, the work of V. Budov et al. [6]., is specially useful where the parameter Φ in equation (4) yields the following result.

$$\frac{1}{\Phi} = \left[1+\frac{3}{2}f\right]\cdot\left[\frac{3f^3+8f^2+7f+2}{54(1+f)\left(\frac{1}{3}+\frac{1}{2}f\right)^3}\right]^{1/2} \tag{11}$$

and the parameter f is established in:

$$f = \frac{1}{g(\rho_\iota-\rho_\upsilon)a_0}\left(\frac{\rho_\iota u_\iota^2\gamma}{2}+ju_\iota\right) \tag{12}$$

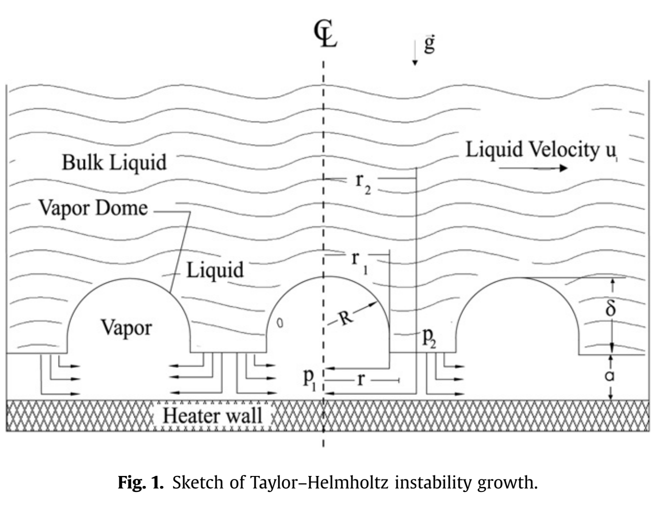

Fig. 1. Sketch of Taylor–Helmholtz instability growth.

During film boiling under conditions of natural convection or low forced convection the vapor velocity is small, and hence, as shown Kutateladze [10] can be neglected, so equation (12) may be written

$$f = \frac{\rho_\iota u_\iota^2 \gamma}{2a_0 g(\rho_\iota - \rho_v)} \tag{13}$$

A heat transfer coefficient may be defined by applying the following equation.

$$h = \frac{\kappa_v}{a} \tag{14}$$

upon employing equation (9) this leads to

$$\frac{h}{h_0} = \Pi^{-1/4} \tag{15}$$

where h_0 is the value of the heat transfer coefficient when $u_\iota = 0$ and naturally is the obtained by Berenson [8]. Although equation (15) was derived from horizontal surface, it is plausible to assume that the effect of forced convection is qualitative and quantitatively similar for a horizontal tubes, corrected only by scale factors, for example Berenson [8] compared his theoretical model for film boiling heat transfer from a horizontal surface with that Bromley (1948) [11] for horizontal tubes.

$$h_0 = 0.425\left[\frac{\kappa_v^3 \Delta h \rho_v(\rho_\iota - \rho_v)}{\mu_v \Delta T\sqrt{\frac{g_0\sigma}{g(\rho_\iota - \rho_v)}}}\right]^{\frac{1}{4}}; \quad \text{Berenson} \tag{16}$$

$$h_0 = 0.62\left[\frac{\kappa_v^3 \Delta h \rho_v(\rho_\iota - \rho_v)}{\mu_v \Delta T D}\right]^{\frac{1}{4}}; \quad \text{Bromley} \tag{17}$$

where the major difference is the substitution of $\sqrt{g_0\sigma/g(\rho_\iota - \rho_v)}$ for the tube diameter D. These are the geometrical scale factors for horizontal plates and tubes, respectively.

2. Comparison with experiment

To obtain some idea of the effect on the heat transfer predicted by equation (15), we can derive a simplified expression for (11) by performing Taylor series expansion on $f \to 0$, in this way, one obtains for the parameter Π in equation (7).

$$\Pi = 1 - 2.25\cdot f + 3.18\cdot f^2 - 3.80\cdot f^3 + 4.26\cdot f^4 - 2.47\cdot f^5 + \cdots \tag{18}$$

Fig. 2 shows the experimental results of saturated flow film boiling heat transfer coefficients on a horizontal cylinder in cross flow of R113 by Liu et al. (1992b) [5] for subcooling degrees: 0 K and 20 K. referring to Fig. 2 it is clear that equation (15) is in a good agreement for saturated conditions (subcooling 0 K), which it is reasonable, due that in the present model only conductivity heat transfer mechanism is assumed, and the above assumption is not valid in subcooling conditions where additional natural convective heat transfer mechanism must be taken account. Furthermore, divergence (for $u_\iota > 0.25$ m/s) between experimental data for saturated conditions and equation (15) could be partially associated whit the Taylor expansion in equation (18) where additional terms of superior order (6...) are needed. Finally, the effect of the gravity field on heat transfer coefficient is briefly treated in Appendix B.

3. Summary and conclusions

The behavior of the heat transfer for the onset and development of Taylor–Helmholtz hydrodynamic instability from horizontal surface in low forced convection was discussed.

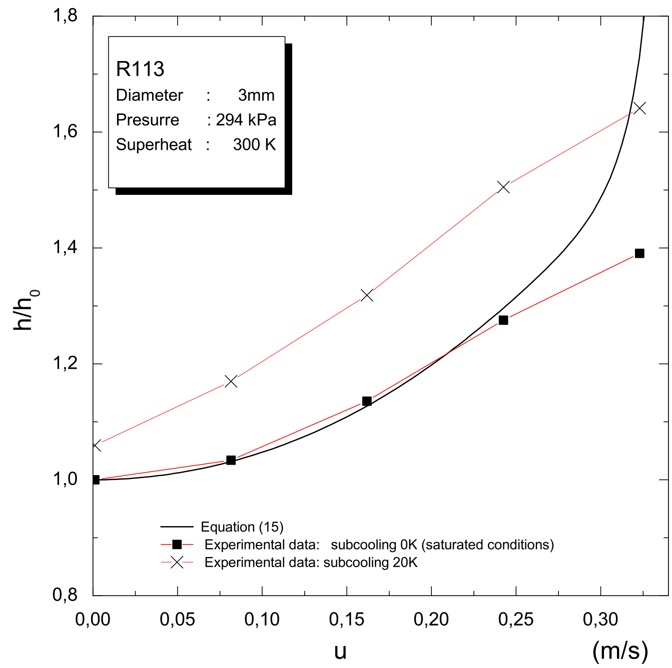

Fig. 2. Effect of flow velocity on h for a horizontal cylinder in cross flow of R113 by Liu et al., (1992b) [5] compared with equation (15).

(a) An analytical expression equation (15) was derived which predicts the heat transfer enhancement in low forced convection under Taylor–Helmholtz in stability, the above equation agree with the available experimental measurements made on R113 within ±15 percent. Extension to the present work from vertical surface is necessary.
(b) The above equation provides added confidence in the validity of the generalized model into the framework of Taylor–Helmholtz instabilities for horizontal and vertical surface in low forced convection.
(c) Finally, heat transfer coefficient increase with further increases of the gravity field and practically it is independent with further decreases of the gravity field.

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Appendix A. Pressure field

The pressure difference in equation (6) is supplied by the difference in gravity head. Referring to Fig. 1, at a height δ above the film, the pressure is independent of radius and equal to p_0. The following relations exist between p_0, p_1, and p_2.

$$p_2 - p_0 = \delta\rho_\iota\frac{g}{g_0};$$

$$p_1 - p_0 = \delta \rho_v \frac{g}{g_0} + \frac{2\sigma}{R} \tag{19}$$

Solving the above equation, the pressure differences gives,

$$p_2 - p_1 = \delta(\rho_\iota - \rho_v)\frac{g}{g_0} - \frac{2\sigma}{R} \tag{20}$$

where the radio of curvature R is equal to the bubble radio and δ the average bubble height given in equation (5), so the available pressure difference this becomes

$$p_2 - p_1 = 2.34\frac{g}{g_0}(\rho_\iota - \rho_v)\sqrt{\frac{g_0\sigma}{g(\rho_\iota - \rho_v)}} \tag{21}$$

Appendix B. Gravity effect on heat transfer coefficient

An interesting analysis is the gravity effect on parameter $\Pi^{-1/4}$ compared with the gravity effect of h_0 studied by Berenson [8]. Let us re-write equation (12) as

$$f = \frac{g_0}{g} f_0 \tag{22}$$

being

$$f_0 = \frac{\rho_\iota u_\iota^2 \gamma}{2a_0 g_0(\rho_\iota - \rho_v)} \tag{23}$$

in this manner, equation (18) can be re-write as

$$\Pi = 1 - 2.25\cdot\left[\frac{g_0}{g}\right] f_0 + 3.18\cdot\left[\frac{g_0}{g}\right]^2 f_0^2 - 3.80\cdot\left[\frac{g_0}{g}\right]^3 f_0^3 + 4.26\cdot\left[\frac{g_0}{g}\right]^4 f_0^4 - 2.47\cdot\left[\frac{g_0}{g}\right]^5 f_0^5 + \cdots \tag{24}$$

On the other hand, it is easy to see, that the gravity effect on the classical expression for h_0 equation (16) is scaled as $[g_0/g]^{-1/8}$, then, the total partial gravity effect on heat transfer coefficient will be scaled as $[g_0/g]^{-1/8}\ \Pi^{-1/4}$ where Π is given by equation (24).

Fig. 3 it is a plot of $\Pi^{-1/4}$, $[g_0/g]^{-1/8}$ and total effect $[g_0/g]^{-1/8}\cdot\Pi^{-1/4}$ for a typical value of $f_0 = 0, 2$. referring to Fig. 3, it is easy to see that heat transfer coefficient increase with further increases of the gravity field and practically it is independent with further decreases of the gravity field.

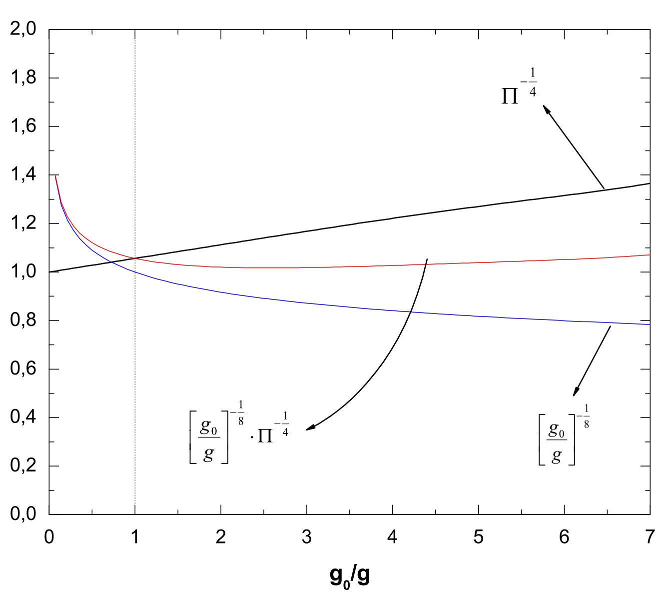

Fig. 3. Plot of partial gravity field effect on heat transfer coefficient.

Nomenclature

a	vapor film thickness, m
D	diameter, m
g	gravity acceleration, m/s^2
h	heat transfer coefficient W/m^2K
j	transverse mass flow, kg/m^2s
p	pressure, standardized with gravity, kg/m^2
R	curvature radius of the bubble, m
u	velocity parallel to the wall, m/s
ΔT	$T_w - T_{sa}$
Δh	average enthalpy difference between vapor and liquid, m^2/s^2

Greek and symbols

δ	average height of the bubble, m
η	perpendicular distance to the liquid vapor interface, m
κ	thermal conductivity, $W/m\kappa$
λ	wavelength, m
μ	dynamical viscosity, kg/ms
υ	kinetic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, standardized with gravity, kg/m
Δ	difference
γ	friction coefficient
Π	multiplier factor of heat transfer coefficient equation (7)

Subscripts

1	liquid
o	initial or reference value
r	radial component
sa	saturation
v	vapor
w	wall heater

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