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PREDICTION OF BUBBLE GROWTH RATES AND DEPARTURE VOLUMES IN NUCLEATE BOILING AT ISOLATED SITES

N. S. SRINIVAS* and R. KUMAR
Department of Chemical Engineering, Indian Institute of Science, Bangalore 560012, India

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Abstract—A model has been developed to predict heat transfer rates and sizes of bubbles generated during nucleate pool boiling. This model assumes conduction and a natural convective heat transfer mechanism through the liquid layer under the bubble and transient conduction from the bulk liquid. The temperature of the bulk liquid in the vicinity of the bubble is obtained by assuming a turbulent natural convection process from the hot plate to the liquid bulk. The shape of the bubble is obtained by equilibrium analysis. The bubble departure condition is predicted by a force balance equation. Good agreement has been found between the bubble radii predicted by the present theory and the ones obtained experimentally.

NOMENCLATURE

A	surface area [m^2]
a, b, c	axes of ellipsoid [m]
C	specific heat [J kg^{-1} K^{-1}]
D	cavity diameter [m]
d	bubble equivalent diameter [m]
g	acceleration due to gravity [m s^{-2}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
ΔP	excess pressure [N m^{-2}]
Q	volumetric flow rate [m^3 s^{-1}]
Q_{cond}	conductive heat transfer rate [W]
Q_{conv}	convective heat transfer rate [W]
Q_{trans}	transient conduction heat transfer rate [W]
q	heat flux [W m^{-2}]
R_1, R_2	principal radii of curvature [m]
r	radius [m]
T	temperature [K]
$(\Delta T)_l$	temperature difference, $(T_w - T_v)$ [K]
$(\Delta T)_m$	temperature difference, $(T_l - T_v)$ [K]
t	time [s]
V	volume of bubble [m^3]
v	velocity of bubble base [m s^{-1}]
x, y, z	distance coordinates [m]
$\bar{y}$	average distance in y-direction [m].

Dimensionless groups

Gr	Grashoff number, $\beta g(\Delta T)_l y^3 \rho_l^2/\mu_l^2$
Nu	Nusselt number, hy/k_l
Pr	Prandtl number, $C_l\mu_l/k_l$
Ra	Rayleigh number, $\beta g(\Delta T)_l y^3 \rho_l^2 C_l/\mu_l k_l$.

Greek letters

α	thermal diffusivity [m^2 s^{-1}]
β	coefficient of cubical expansion [K^{-1}]
γ	surface tension [N m^{-1}]
ε	defined in equation (14)
θ	contact angle [degrees]
λ	latent heat of evaporation [J kg^{-1}]
μ	viscosity [N s m^{-2}]
ρ	density [kg m^{-3}]
ϕ	deformation term as given in equation (1).

Subscripts

b	bulk
ct	critical
l	liquid
m	mean
o	cavity
p	plate
t	at any time
v	vapour (or bubble).

INTRODUCTION

THE EXISTENCE of a thin liquid layer at the base of the bubble, in pool boiling, which evaporates quickly and contributes significantly to the overall heat transfer, has been reported and confirmed by several investigators [1–13]. However, there are conflicting reports regarding its thickness.

Further, the shape of the liquid layer has been taken as conical by some investigators [8–11], whereas the experimental findings of others [14, 15] show the bubble to be an oblate spheroid with smooth contours. The thickness of the liquid layer increases along the radius of the bubble base in a nonlinear fashion.

Most of the investigators assume that the heat transport through the liquid layer takes place through conduction alone. However, in regions where the film thickness is high, natural convection effects could be expected to contribute to the heat transfer. Further, heat will also be transferred over the remaining surface of the bubble, making its own contribution to bubble growth.

A number of expressions [1, 16–21] have appeared in the literature for predicting the bubble departure volumes generated at nucleating sites. Some of these are theoretical whereas others are semi-theoretical in nature. The various parameters affecting the bubble departure volume are the liquid superheat, cavity size,

* Present address: Research and Development, Walchandnager Industries Ltd., Walchandnager 413114, India.

surface tension, density of the liquid and the rate of bubble expansion. None of the expressions available in the literature takes all these parameters into account.

An attempt is made in this paper to consider the heat transfer from both the liquid layer underneath the bubble and from the remaining upper portion of the bubble. A model is also presented to predict the bubble departure volume and its dependence on various parameters mentioned above.

EXPERIMENTAL SET-UP

In this investigation bubbles were generated on artificial sites formed on copper strips. The experimental set-up is shown in Fig. 1 and consists of: (a) a bubble formation section, (b) a heating system, and (c) a vapour capsizing section.

Bubble formation section

A Pyrex glass beaker of 500 ml capacity contained the superheated liquid and an artificial site (the method of preparation of the site is given in the next section) made on a copper plate was immersed in it. The liquid temperature was measured with a sensitive mercury in-glass thermometer ($\pm 0.01\,^{\circ}C$ accuracy).

Heating system

Two infrared (IR) radiation lamps (250 W each) and an auxiliary heater (1000 W) were used to superheat the liquid. These were connected to a 230 V AC line supply.

Vapour capsizing section

Vapour generated due to bubble formation was sent to a water cooled condenser and the condensate collected.

PREPARATION OF THE NUCLEATION SITE

The nucleating site was made by pressing a sharp needle on a copper plate. This artificial site (cavity) was polished with fine emery powder and the cavity was observed through a travelling microscope to confirm that there were no irregularities present in it and also to measure its diameter. The cavity was cleaned with ethanol to remove any grease present and was stored in triple distilled water.

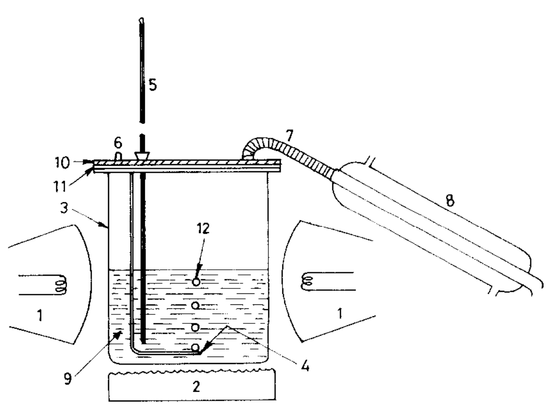

FIG. 1. Experimental set-up: (1) IR radiation lamps; (2) auxiliary heater; (3) beaker; (4) artificial nucleus; (5) thermometer; (6) vent to manometer; (7) vapour vent; (8) condenser; (9) liquid; (10) s.s. lid; (11) cork gasket; (12) bubbles.

EXPERIMENTAL PROCEDURE

The liquid under investigation was degassed and transferred to the bubble forming beaker to a predetermined level. The heating was started through IR lamps and the auxiliary heater. When the liquid reached near boiling conditions, the auxiliary heater was switched off and the superheating was done through IR radiation lamps alone. The amount of radiation absorbed by the thermowell of the thermometer was neglected as suggested by Dergarabedian [22]. As soon as the liquid attained the required superheat, the artificial nucleating site was introduced into the liquid. The vapour generated was condensed and weighed. A blank run was conducted under identical conditions but without the nucleating site. The difference in the two condensates collected was taken as the contribution of the bubbles. The frequency of bubble formation was measured by a strobometer [23]. For the same superheat, the experiments were repeated by taking different liquid heights above the cavity and bubble sizes determined. The bubble size generated at the cavity was determined by extrapolating the values obtained at different heights to zero height.

The range of variables studied is given in Table 1.

QUALITATIVE DISCUSSION OF THE MODEL

When bubbles are generated from heating surfaces in nucleate pool boiling, heat transfer takes place partly through the liquid layer trapped under the growing bubble and the heating surface and partly from the bulk liquid. Thus the bubble vicinity is divided into two sections, namely, the liquid layer part and the free surface part as shown in Fig. 2. The thickness of the liquid layer depends on the shape of the bubble. Through the liquid layer, heat is assumed to flow through conduction (for very small film thicknesses) and through natural convection (for large film thicknesses). The rest of the bubble surface receives heat from the bulk liquid through the transient conduction process. The bulk liquid in turn obtains heat from the heating surface through turbulent natural convection, set in both by temperature differences and bubble movement.

Table 1. Range of variables studied

Systems	Water, acetone and chloroform
Superheats	2.0–9.0 °C
Cavity diameters	0.04–0.13 cm

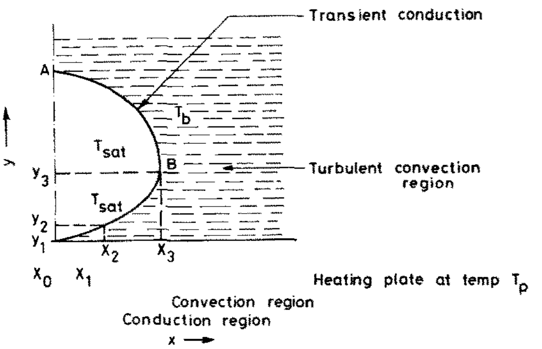

FIG. 2. Schematic representation of conduction, convection and transient conduction regions.

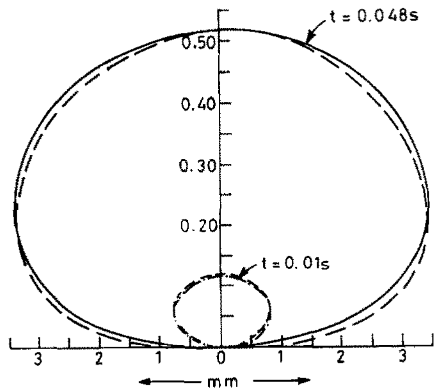

FIG. 3. Comparison of experimental and predicted bubble shapes. System: water; ---, theoretical; ——, Madhavan and Mesler [15]; —·—·—, Johnson *et al.* [14].

Due to the above mechanisms taking place simultaneously, the bubble volume increases and the bubble detaches from the cavity after the detaching forces have exceeded the downward forces holding the bubble to the cavity.

QUANTITATIVE DISCUSSION OF THE MODEL

Katto and Shoji [5], Hendrics and Sharp [4], Jawurek [8], Sharp [9] and Cooper and Lloyd [10] have assumed that when bubbles are formed on heating surfaces, the upper half of the bubble surface is hemispherical and the lower is conical in shape. However, from photographic observations of Johnson *et al.* [14] and Madhavan and Mesler [15], it is found that the bubbles are made up of two oblate spheroids with a common major axis and differing minor axes. It is also reported that the ratio of the major axis to the upper minor axis is 1.1, which is not too different from the ones assumed by earlier investigators. To derive expressions for finding out the actual bubble shapes, a distorted bubble is considered.

Bubble distortion takes place when the drag force generates a non-uniform pressure distribution around the bubble. The actual radii of curvature at any point depend on the excess pressure, which for a distorted bubble, is given by [24]

$$\Delta P = \gamma\left[\frac{1}{R_1}+\frac{1}{R_2}\right]$$
$$= \gamma\left[\frac{2}{r}-\frac{2\phi}{r}-\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left\{\sin\theta\frac{\partial\phi}{\partial\theta}\right\}\right], \quad (1)$$

where R_1 and R_2 are radii of curvature of the surface at any point (r, θ) and ϕ is the deformation term expressed as a function of r and θ.

The equation of the bubble with a common major axis a and minor axes b and c is given by [25]

$$y^2 = bc\left[1-\frac{x^2}{a^2}\right]+(b-c)y\left[1-\frac{x^2}{a^2}\right]^{1/2}. \quad (2)$$

By using equations (1) and (2) along with the drag force yields [25]

$$b-c = \frac{0.122\rho_l U_b^2 r^2}{\gamma}, \quad (3)$$

where $U_b = dr/dt$, is the bubble growth velocity.

Knowing dr/dt, the value of c is obtained. The bubble shapes, as calculated from equation (3) are compared with the experimental data of Johnson *et al.* [14] and Madhavan and Mesler [15] in Fig. 3, where a close agreement is observed.

The effect of bubble radial velocity on the rate of deformation is depicted in Fig. 4. It is evident that as the growth velocity decreases, the bubble assumes a spherical shape and at very large growth velocities the shape is nearly hemispherical. Thus, the liquid layer below the bubble can vary significantly in thickness depending on the rate of bubble growth.

MECHANISM OF HEAT TRANSFER TO THE GROWING BUBBLE

For the liquid layer below the bubble, the following heat transfer mechanism is assumed. In the region

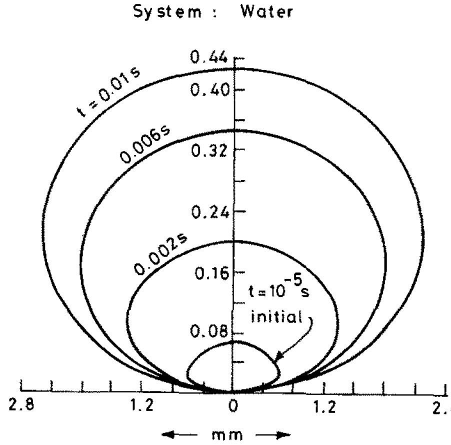

FIG. 4. Effect of bubble radial velocity on bubble shapes. System: water.

x_0–x_1, the liquid layer will be extremely thin and will evaporate immediately, making a negligible contribution to the overall heat transfer. In the region x_1–x_2, heat transfer is assumed to take place through conduction, whereas between x_2 and x_3, the heat is assumed to be transferred through natural convection. Finally, in the region AB, transient conduction heat transfer is assumed to take place. The temperature distribution in the surrounding liquid is obtained from the turbulent natural convection heat transfer mechanism. The actual thickness of the liquid film beyond which natural convection heat transfer takes place is related by the following equation [26]

$$Nu = 1 = \frac{g\beta(\Delta T)_l y^3 \rho_l^2 C_l}{k_l \mu_l}. \tag{4}$$

In equation (4), y gives the limiting thickness of the liquid layer up to which the conduction mechanism is important and permits the evaluation of y for any $(\Delta T)_l$. Through the rest of the liquid layer, heat transfer occurs through natural convection.

The heat transfer equations for the regions discussed above are formulated as follows.

Heat transfer through the liquid layer

In the region x_1–x_2, x_1 corresponds to the cavity radius. In this region conduction heat transfer predominates and the heat flux at any thickness is given by

$$q = \frac{k_l(\Delta T)_l}{y}. \tag{5}$$

Since the thickness of the layer increases in the x-direction, the average thickness $\bar{y}$ of the layer is obtained and thus equation (5) becomes

$$q = \frac{k_l(\Delta T)_l}{\bar{y}}. \tag{6}$$

The value of $\bar{y}$ works out to be [25]

$$\bar{y} = \frac{1}{(x_2 - x_1)}\left\{c(x_2 - x_1) - \left[\frac{c}{a}\frac{x_2}{2}\sqrt{(a^2 - x_2^2)} + \frac{a^2}{2}\sin^{-1}\frac{x_2}{a} - \frac{x_1}{2}\sqrt{(a^2 - x_1^2)} - \frac{a^2}{2}\sin^{-1}\frac{x_1}{a}\right]\right\}. \tag{7}$$

The expression for heat transport through this section of the layer becomes

$$Q_{\text{cond}} = k_l \pi (x_2^2 - x_1^2)(\Delta T)_l / \bar{y}. \tag{8}$$

Heat transfer through natural convection

In the regions x_2–x_3, heat transmission takes place through natural convection. The average heat transfer coefficient is obtained to predict the amount of heat transfer in this region. The natural convection between two horizontal plates separated by a distance y is given by Coulson and Richardson [26] as

$$Nu = 0.15(Gr\,Pr)^{0.25}. \tag{9}$$

Equation (9) on rearrangement becomes

$$h = 0.15\left[\frac{\beta g(\Delta T)_l \rho_l^2 C_l k_l^3}{\mu_l}\right]^{0.25} y^{-1/4}. \tag{10}$$

The rate of heat transfer between regions x_2 and x_3 works out to be

$$Q_{\text{conv}} = 0.2\pi\left[\frac{\beta g(\Delta T)_l \rho_l^2 C_l k_l}{\mu_l}\right]^{1/4} \times \frac{(y_3^{3/4} - y_2^{3/4})}{(y_3 - y_2)}(x_3^2 - x_2^2)(\Delta T)_l. \tag{11}$$

The total heat transfer rate in the lower section of the bubble is obtained as

$$Q_{\text{lower}} = Q_{\text{cond}} + Q_{\text{conv}}. \tag{12}$$

Heat transfer through the upper section

To find out the amount of heat transfer in the upper section, the temperature distribution in the bulk liquid is required. Malkus' [27] expression is used to obtain the temperature distribution in the liquid. The dimensionless temperature as a function of dimensionless distance is given by

$$T(\varepsilon) - T_m = \frac{\Delta T}{2}\left[1 - \frac{2}{\pi}\left\{\sin(2\varepsilon) - \frac{\sin^2 \varepsilon}{\varepsilon}\right\}\right], \tag{13}$$

where

$$T = T_1 - T_2 \quad \text{and} \quad T_1 > T_2$$

$$T_m = \frac{T_1 + T_2}{2}.$$

and ε is given as

$$\varepsilon = \frac{y\pi}{10.87}\left[\frac{\rho_l^2 C_l g(\Delta T)_m d^3 \beta}{\mu_l k_l}\right]^{1/3}. \tag{14}$$

From equation (14), the value of ε can be calculated for any y, and the temperature distribution in the liquid can be determined from equation (13).

The heat transfer rate by transient conduction is given by [28]

$$Q_{\text{trans}} = \frac{k_l A(\Delta T)_m}{\sqrt{(\pi \alpha t)}}, \tag{15}$$

where

$$A = \frac{1}{2}\left[2\pi a^2 + \frac{\pi b^2}{\varepsilon}\ln\frac{1+\varepsilon}{1-\varepsilon}\right].$$

and

$$\varepsilon = \frac{a^2 - b^2}{a}.$$

Therefore, the total rate of heat transfer to the growing bubble at any time is given by

$$Q_{\text{total}} = \frac{k_l \pi (x_2^2 - x_1^2)}{\bar{y}} (\Delta T)_l + 0.2\pi \left[\frac{g(\Delta T)_l \rho_l^2 C_l k_l^3 \beta}{\mu_l} \right]^{1/4} \frac{(y_3^{3/4} - y_2^{3/4})}{(y_3 - y_2)} \times (x_3^2 - x_2^2)(\Delta T)_l + \frac{kA(\Delta T)_m}{\sqrt{(\pi \alpha t)}}. \quad (16)$$

The above equation can yield the rate of growth of the bubble at any time but does not give its departure volume. Hence a model is proposed to find out the bubble departure volume.

MODEL FOR DETERMINING THE BUBBLE DEPARTURE VOLUME

The bubble departure volume and the duration of the bubble remaining attached to the cavity mouth are of importance. These factors are determined on the basis of the modified model of Khurana and Kumar [29]. In this analysis bubble formation is assumed to occur in two stages. The first stage is assumed to be identical with that of Khurana and Kumar [29].

First stage

$$V_t(\rho_l - \rho_v) g = \frac{(\rho_v + (11/16)\rho_l)(3V_t(\mathrm{d}Q_t/\mathrm{d}t) + Q_t^2)}{12\pi(3/4\pi)^{2/3} V_t^{2/3}} + \pi D \gamma \cos\theta, \quad (17)$$

where

$$Q_t = \frac{Q_{\text{total}}}{\lambda \rho_v}.$$

For completely wetting liquids, the contact angle is taken as zero.

Second stage

The basic equation for this stage is the same as proposed by Khurana and Kumar [29]. The second stage equation is given as

$$\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{vQ_t}{V_t} + \frac{(3V_t(\mathrm{d}Q_t/\mathrm{d}t) + Q_t^2)}{12\pi(3/4\pi)^{2/3} V_t^{5/3}} = \frac{(\rho_l - \rho_v) g}{(\rho_v + (11/16)\rho_l)} + \frac{\pi D \gamma \cos\theta}{V_t(\rho_v + (11/16)\rho_l)}. \quad (18)$$

It is assumed that the bubble detaches from the cavity as soon as v equals $\mathrm{d}r/\mathrm{d}t$. The time required for the departure is the growth time.

VERIFICATION OF THE MODEL

The results obtained through the model are compared with the ones obtained experimentally. Figure 5 shows the comparison of bubble growth time predicted by equation (18) and the experimental data of Howell and Siegel [30]. Figure 6 shows the comparison of the present and other theories with the experimental data available in the literature and that collected during this work. It can be observed from Fig. 6, that there is considerable deviation between the present data and theoretical equations of Fritz [1], Roll and Meyers [21] and Zuber [17]. This may be due to the fact that Fritz [1] and Roll and Meyers [21] did not consider the liquid superheat and cavity radius. On the other hand Zuber [17], though he considered the cavity radius, did

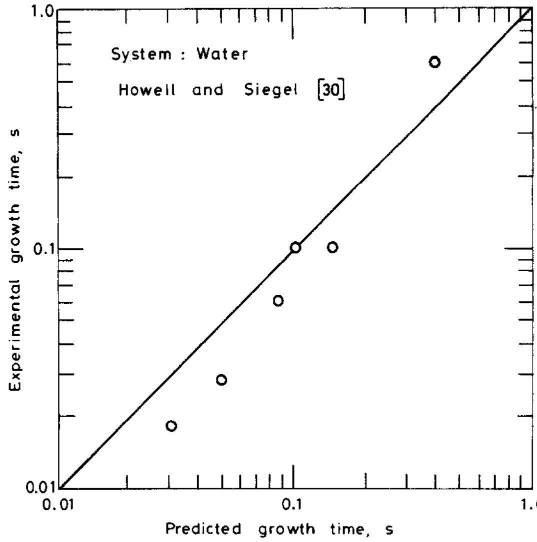

FIG. 5. Comparison of experimental and predicted growth time.

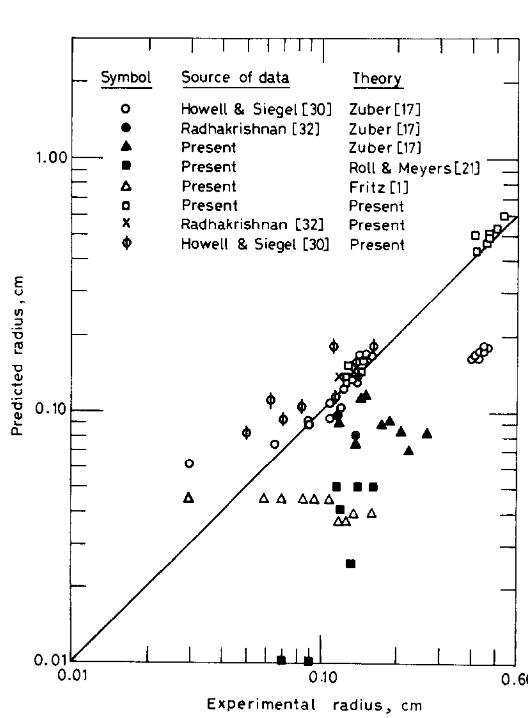

FIG. 6. Comparison of present theory and experimental data with the literature data and theory.

not include the liquid inertial forces and liquid superheat in his theory. The present model predicts the experimental values reasonably well. It has been observed that the amount of heat transferred during the first stage is roughly twice that in the second stage, which agrees with the findings of Forster and Zuber [31]. For one of the runs, the contribution of each mechanism was calculated as a function of time. The Q_{cond} contribution varied between 42 and 84%, the Q_{conv} between 4 and 14% and Q_{trans} between 12 and 54%.

CONCLUSIONS

The bubbles have non-spherical shapes during their growth and the heat transport mechanism to any growing bubble on heating surfaces comprises conduction, convection and transient conduction, all taking place simultaneously in the prescribed region of influence. Further the bubble departs from the surface only after satisfying the equilibrium forces acting over the bubble during its growth. Maximum amount of heat transfer takes place during the initial bubble growth period only.

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CALCUL DES CROISSANCES DE BULLES ET DES VOLUMES A LA SEPARATION DANS L'EBULLITION NUCLEEE EN DES SITES ISOLES

Résumé—Un modèle prédit les flux thermiques transférés et les tailles de bulles formées pendant l'ébullition nucléée en réservoir. Ce modèle suppose un mécanisme de conduction et de convection naturelle à travers la couche liquide sous la bulle et la conduction variable dans la masse liquide. La température du liquide au voisinage de la bulle est obtenue en supposant un mécanisme de convection turbulente naturelle de la plaque chaude vers le coeur liquide. La forme de la bulle est obtenue par une analyse d'équilibre. La condition de détachement de la bulle est calculée à partir d'une équation de bilan des forces. Un bon accord a été trouvé entre les rayons de bulle calculés par la théorie et ceux obtenus expérimentalement.

BERECHNUNG DER BLASENWACHSTUMSGESCHWINDIGKEITEN UND ABLÖSEVOLUMINA BEIM BLASENSIEDEN AN EINZELNEN KEIMSTELLEN

Zusammenfassung—Zur Berechung des Wärmetransports und der Größe von Blasen, die beim Behälterblasensieden entstehen, wurde ein Modell entwickelt. Als Wärmetransport-Mechanismen werden in diesem Modell Leitung und freie Konvektion in der Flüssigkeitsschicht unter der Blasse und instationäre Leitung aus der Flüssigkeit der Umgebung angenommen. Die Temperatur der Flüssigkeit in der Umgebung der Blase wird mittels der Annahme bestimmt, daß Wärme von der heißen Platte an die Flüssigkeit durch turbulente freie Konvektion übertragen wird. Die Blasengestalt wird durch Gleichgewichtsbetrachtungen bestimmt. Die Ablösebedingung der Blasen wird über eine Kräftebilanz ermittelt. Die nach der hier vorgestellten Theorie berechneten Blasenradien zeigen gute Übereinstimmung mit experimentell beobachteten Werten.

РАСЧЕТ СКОРОСТЕЙ РОСТА ПУЗЫРЬКОВ И ДИАМЕТРОВ ОТРЫВА ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ НА ОТДЕЛЬНЫХ ЦЕНТРАХ ПАРООБРАЗОВАНИЯ

Аннотация—Разработана модель для расчета плотностей теплового потока и размеров пузырьков, образующихся при пузырьковом кипении в открытом объеме. Предполагается, что перенос тепла через слой жидкости между пузырьком и нагретой пластиной осуществляется теплопроводностью и естественной конвекцией, а в объеме жидкости—неустановившейся теплопроводностью. Температура жидкости вблизи пузырька определяется исходя из предположения, что процесс теплопереноса от нагретой пластины в объем жидкости происходит с помощью турбулентной естественной конвекции. Форма пузырька находится из условия равновесия, а условие отрыва пузырька рассчитывается по уравнению баланса сил. Получено хорошее соответствие между значениями радиусов пузырьков, рассчитанными по предложенной модели, с экспериментально полученными данными.