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ON THE MECHANISM OF MACROLAYER FORMATION IN NUCLEATE POOL BOILING AT HIGH HEAT FLUX

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Abstract – In nucleate boiling at high heat flux, a liquid layer, known as the 'macrolayer', is trapped between the heating surface and the vapour masses. An analysis of the mechanism of formation of this macrolayer is presented. Based on the analysis, a theoretical expression has been derived for the initial thickness of the macrolayer. The agreement between the theoretical values of the initial macrolayer thickness and the experimental values published in the literature is reasonably good.

NOMENCLATURE

- c, specific heat of liquid [J kg^{-1} K^{-1}];
- D, D_d, bubble diameter; bubble departure diameter [m];
- f, bubble departure frequency, cycles/s;
- h, heat transfer coefficient [W m^{-2} K^{-1}];
- h_{fg}, latent heat of vaporization [J kg^{-1}];
- h_{nc}, heat transfer coefficient due to natural convection [W m^{-2} K^{-1}];
- h_{nuc}, heat transfer coefficient due to nucleation [W m^{-2} K^{-1}];
- k, thermal conductivity of liquid [W m^{-1} K^{-1}];
- N/A, number of active sites per m^2;
- q_w, wall heat flux [W m^{-2}];
- t, time [s];
- T, T_s, T_w, temperature; saturation temperature; wall temperature [K];
- ΔT, wall superheat, $T_w - T_s$ [K];
- u, bubble rise velocity [m s^{-1}].

Greek symbols

- α, thermal diffusivity of liquid [m^2 s^{-1}];
- β, coefficient of thermal expansion of liquid [K^{-1}];
- δ, δ_0, macrolayer thickness; initial macrolayer thickness [m];
- θ_0, average superheat [K];
- μ, dynamic viscosity of liquid [N s m^{-2}];
- ρ, ρ_v, density of liquid; density of vapour [kg m^{-3}].

INTRODUCTION

IT HAS been generally agreed that a single nucleate boiling mechanism does not explain the heat transfer process in the whole regime of nucleate boiling. Various attempts have been made to divide the nucleate boiling regime into different regions, each region being characterized by a particular heat transfer mechanism. Gaertner [1] proposed the following regions: (i) isolated bubble region, (ii) first transition region, (iii) vapour mushroom region, (iv) second transition region.

The last of these (second transition region) lies between 0.6 q_c and q_c.

It has been reported [2] that a thin liquid layer, called the 'macrolayer', exists on the heating surface beneath a growing vapour mass at high heat flux near the critical value, as shown in Fig. 1. The bubbles emitted from an active site at high frequency coalesce and form vertical vapour stems in the macrolayer that feed vapour to the overlying vapour mass [3]. Gaertner, in a study on saturated pool boiling of water on a horizontal copper surface at atmospheric pressure [1], made measurements of this macrolayer thickness, and gave the following relationship for the initial macrolayer thickness:

$$\delta_0 = 0.6\,D_d \qquad (1)$$

where D_d is the average diameter of vapour stems or the average bubble departure diameter. The best fit to the experimental data of Gaertner and Westwater [4] on D_d in saturated pool boiling of water at atmospheric pressure has been found to be

$$D_d = 0.809 \times 10^5\, q_w^{-1.4225}. \qquad (2)$$

Iida and Kobayasi [5] also made measurements of the macrolayer thickness in the high heat flux region for the saturated pool boiling of water at atmospheric pressure on a horizontal copper surface. The best fit to their experimental data has been found to be

$$\delta_0 = 3.2296 \times 10^5\, q_w^{-1.5148}. \qquad (3)$$

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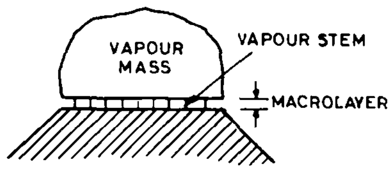

FIG. 1. Nucleate boiling at high heat flux.

Equations (1), (2) and (3) show that the macrolayer thickness decreases with increasing heat flux.

The macrolayer, when initially formed, decreases in thickness due to the consumption of its liquid by vapour generation during the growth period of the vapour mass [3].

In the present work, the mechanism of formation of the macrolayer in the high heat flux region (above $0.6\,q_c$) has been investigated and an expression for the macrolayer thickness derived.

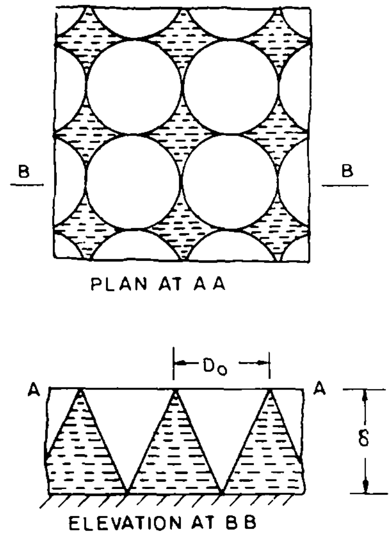

FIG. 3. Macrolayer cross-section.

ANALYSIS

As mentioned above, the vapour mass is formed on top of the macrolayer, the vapour mass and the heating surface being connected through vapour stems. At the departure of the vapour mass, bulk liquid impinges on the macrolayer, thus destroying its identity. It is assumed that due to this impinging action of the relatively cold bulk liquid, the vapour stems are also disturbed.

In the waiting period of the vapour mass, bubbles emitted from an active site form a vapour stem. The diameter of the vapour stems at a height $D_d/2$ above the heating surface is D_d, as shown in Fig. 2. But above this height, the diameter of the stem increases due to two factors (i) the vertical coalescence of the bubbles and (ii) the heat transfer from the superheated macrolayer to the vapour–liquid interface of the vapour stem which causes vaporization at the interface. It is suggested here that the macrolayer is formed due to the lateral coalescence of the vapour stems at the top of the macrolayer, as shown in Fig. 3. This lateral coalescence can take place if the diameter of the vapour stems at the top of the macrolayer becomes D_0, where

$$D_0 = \left(\frac{1}{N/A}\right)^{1/2}. \tag{4}$$

The lateral coalescence of the vapour stems and consequent formation of the macrolayer marks the end of the waiting period and the beginning of the growth of the next vapour mass.

As may be seen in Fig. 2, the bubble is initiated on an active site of radius r_c (shown exaggerated) where r_c is the effective cavity radius. The bubble grows to the departure diameter and then departs and merges into the vapour stem. In each cycle of bubble formation, the shape of the vapour stem changes slightly due to the variation in the bubble size from zero in its waiting period to D_d at departure. Tolubinsky *et al.*, in their study on nucleate boiling in thin liquid films [6], proposed a model of vapour nuclei generation in thin liquid films as shown in Fig. 4. As the bubble is nearing departure, the neck connecting the bubble with the heating surface narrows until at departure the liquid film joins at the centre, thus separating the nucleus from the departing vapour bubble. This model explains, in the present study, the merging of the departed bubble into the vapour stem and the growth of the new bubble from the same active site.

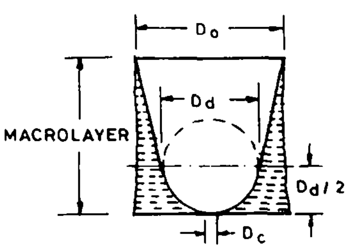

FIG. 2. Macrolayer thickness.

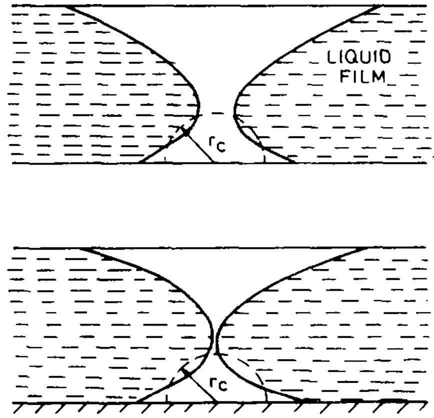

FIG. 4. The scheme of vapour volume capture by a thin liquid film.

The effects of (i) the vertical coalescence of bubbles and (ii) the heat transfer to the vapour–liquid interface of the vapour stem, on macrolayer formation will now be analysed separately. Later an analysis of their combined effect will be presented.

Macrolayer formation due to vertical coalescence of bubbles

After departure, bubbles rise with a velocity which, for $D < 1$ mm, may be taken as [7]

$$u = CD \tag{5}$$

where $C = 143$ for bubbles rising in water. If $fD_d > u$, as is the case in the high heat flux region, then bubbles emitted at an active site will coalesce vertically with the preceding bubbles, thus increasing their volume and, therefore, their diameter.

If it is assumed that the bubble grows to a diameter D_0 during its movement through a distance H after departure (Fig. 5) then the thickness of initial macrolayer, δ_0, is given by

$$\delta_0 = \frac{D_d}{2} + H. \tag{6}$$

Consider the movement of a bubble (Fig. 5) through a differential height $dh(=\bar{u}\,dt)$ in time dt during which the bubble increases in diameter by dD, due to a volume increase of dV given by

$$dV = (fD_d\,dt - \bar{u}\,dt)\frac{\pi}{4}D^2. \tag{7}$$

The consequent increase in bubble diameter dD is given by

$$dV = 1/2\pi D^2\,dD. \tag{8}$$

Equations (7) and (8) give

$$dD = 1/2(fD_d/\bar{u} - 1)\,dh. \tag{9}$$

Assuming a linear relation between D and h, it can be shown that the average velocity $\bar{u}$ is given by

$$\bar{u} = C\frac{D_d + D_0}{2}. \tag{10}$$

Integrating equation (9) and making use of equation (6) gives

$$\delta_0 = \frac{D_d}{2} + 2(D_0 - D_d)/(fD_d/\bar{u} - 1). \tag{11}$$

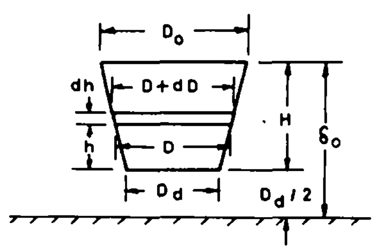

FIG. 5. Differential element of macrolayer.

Macrolayer formation due to heat transfer from superheated liquid

The temperature distribution in the macrolayer may be taken as [9]

$$\theta = T - T_s = \Delta T(1 - y/\delta_0).$$

The average superheat could be obtained as

$$\theta_0 = (1/\delta_0)\int_0^{\delta_0} \theta\,dy = \Delta T/2. \tag{12}$$

Using the bubble growth rate equation given by Han and Griffith [10] for a uniformly superheated liquid,

$$\frac{dD}{dt} = \frac{2M\theta_0}{t^{1/2}} \tag{13}$$

where

$$M = \frac{1}{\pi^{1/2}}\frac{\rho c \alpha^{1/2}}{\rho_v h_{fg}},$$

the bubble diameter after departure can be written as

$$D = D_d + 4M\theta_0(t^{1/2} - t_d^{1/2}). \tag{14}$$

The departure period t_d is related to the frequency and waiting period by

$$t_d = \frac{1}{f} - t_w. \tag{15}$$

The distance moved by the bubble during the period in which it grows in diameter from D_d to D_0 is a measure of the macrolayer thickness δ_0, given as

$$\delta_0 = \frac{D_d}{2} + \bar{u}(t_0 - t_d). \tag{16}$$

The time interval $t_0 - t_d$, during which the bubble diameter increases from D_d to D_0, is given by

$$t_0 = \left(\frac{D_0 - D_d}{4M\theta_0} + t_d^{1/2}\right)^2.$$

The average velocity, $\bar{u}$, could be found to be

$$\bar{u} = C\left\{D_d + 4M\theta_0\left[\frac{t_0^{3/2} - t_d^{3/2}}{\frac{3}{2}(t_0 - t_d)} - t_d^{1/2}\right]\right\}. \tag{17}$$

Results of equations (10) and (17) showed that values of $\bar{u}$ obtained from the two equations differ by 0.9–1.6% in the heat flux range of 0.6 q_c to q_c.

Superposition of bubble coalescence and heat transfer effects

Consider the differential height dh across the vapour stem as shown in Fig. 5. The increase in volume dV comprises two components,

$$dV = dV|_c + dV|_{HT}. \tag{18}$$

The component of increase in volume due to coalescence $dV|_c$ is given by equation (7), and using equations (8) and (13) the component due to heat transfer $dV|_{HT}$ can be written as

$$dV|_{HT} = \pi D^2 M\theta_0\,dt/t^{1/2}. \tag{19}$$

Using equations (7), (18) and (19) and writing $dh = \bar{u}\,dt$ and $t = t_d + h/\bar{u}$, we obtain

$$dV = \pi D^2/4\{(fD_d/\bar{u}-1) + 4M\theta_0/[\bar{u}(t_d+h/\bar{u})^{1/2}]\}\,dh. \quad (20)$$

It follows from equation (20) that the change in diameter across the height dh is

$$dD = \{1/2(fD_d/\bar{u}-1) + 2M\theta_0/[\bar{u}(t_d+h/\bar{u})^{1/2}]\}\,dh. \quad (21)$$

After integration and rearrangement, we obtain

$$X^2 + X/K_1 - K_2 = 0 \quad (22)$$

where

$$X = (H/\bar{u}+t_d)^{1/2}, \quad (23)$$

$$K_1 = \frac{u}{8M\theta_0}(fD_d/\bar{u}-1)$$

and

$$K_2 = \frac{1}{K_1}\left[\frac{D_0-D_d}{4M\theta_0} + t_d^{1/2} + \frac{\bar{u}t_d}{8M\theta_0}(fD_d/\bar{u}-1)\right].$$

So, from equations (6) and (23) we get

$$\delta_0 = D_d/2 + \bar{u}(X^2 - t_d) \quad (24)$$

and equation (22) gives

$$X = \tfrac{1}{2}[-1/K_1 \pm (1/K_1^2 + 4K_2)^{1/2}]. \quad (25)$$

RESULTS AND DISCUSSION

In the present work, the results of the above analysis have been applied to the case of saturated pool boiling of water on a horizontal copper surface at atmospheric pressure, in the high heat flux region between 0.6 q_c and q_c. Equation (2) and the following relations have been used:

[8] $fD_d = 0.111\ \mathrm{m\ s^{-1}}$

[11] $N/A = \frac{1}{\pi D_d^2}(h-h_{nc})/(h_{nuc}-h_{nc})$,

[11] $h_{nc} = 0.15[g\beta c(\rho k)^2/\mu]^{1/3}\Delta T^{1/3}$,

[11] $h_{nuc} = \left(\frac{2}{\pi^{1/2}}\right)(\rho c k)^{1/2}(f)^{1/2}$,

[1] $h = 1.57 \times 10^5(\Delta T)^{-0.4}$.

In the absence of any detailed data in the high heat flux region about its duration, the waiting period, t_w, has been assumed to be equal to the growth period, t_d, in equation (15). Results obtained from equations (11), (16) and (24) are plotted in Fig. 6. The value for X in equation (24) is taken from equation (25) with positive sign of the discriminant. The measured values of δ as given by equations (1) and (3) are also plotted in Fig. 6. It is seen that the values of the macrolayer thickness obtained from equation (24), which is the result of combined effects of coalescence and heat transfer, are close to those obtained by Gaertner [1]. Gaertner has made the measurements of the macrolayer thickness by

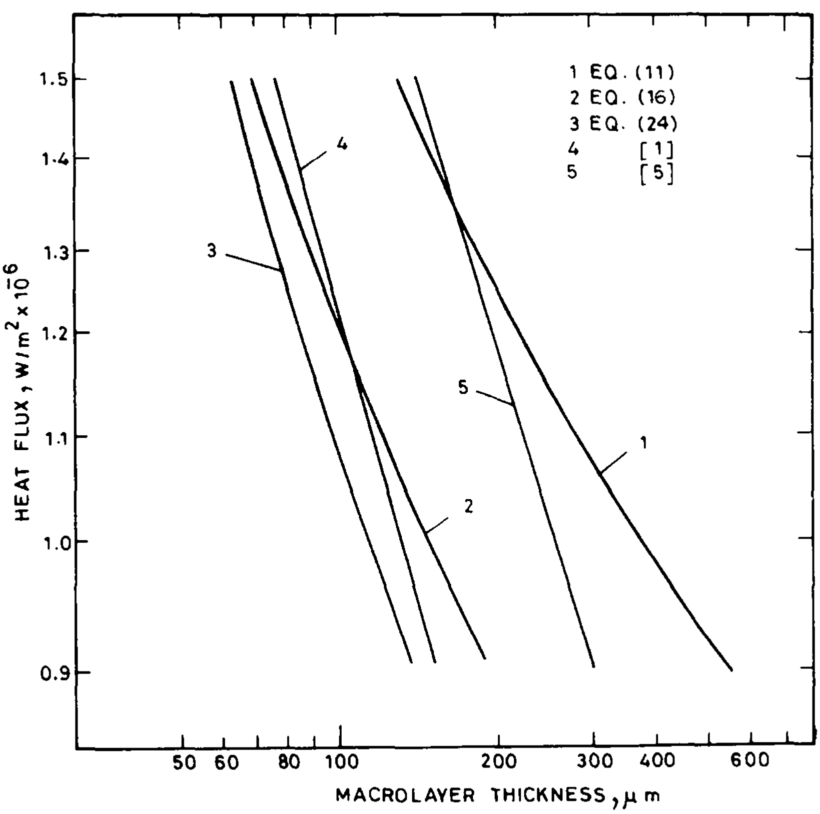

FIG. 6. Theoretical and experimental macrolayer thickness.

taking side view photographs of the vapour stems in the macrolayer. He took the height of the vapour stems on the periphery of the heating surface equal to the initial macrolayer thickness. Iida and Kobayasi [5] made the measurements of the initial macrolayer thickness through an indirect method by making use of their measurements on the void fraction in the macrolayer and above the macrolayer. The measurements of Gaertner appear to be more accurate.

Curves 1 and 2 of Fig. 6 show that both coalescence and heat transfer effects play a significant role in macrolayer formation. The effect of heat transfer from the superheated liquid is, however, more predominant throughout the high heat flux region and its contribution increases with the increase in heat flux.

Comparison of equation (24) with other experimental results could not be made as no published data is available in the literature on the measurements of the macrolayer thickness for other parameters.

CONCLUSIONS

(1) A theoretical expression [equation (24)] for predicting the macrolayer thickness in nucleate pool boiling at high heat flux is proposed.

(2) Based on the above study, the following mechanism of macrolayer formation in the high heat flux region (above 0.6 q_c) is proposed.

(i) The macrolayer is formed due to lateral coalescence of vapour stems on top of the macrolayer, as shown in Fig. 3.

(ii) The diameter of vapour stems increases from D_d at the point of bubble departure to D_0 [equation (4)] at the point of lateral coalescence due to (a) vertical coalescence of the bubbles emitted at an active site and (b) heat transfer from the superheated macrolayer to, and consequent vaporization at, the vapour liquid interface of the vapour stem.

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SUR LE MECANISME DE FORMATION DE LA MACROCOUCHE DANS L'EBULLITION NUCLEE EN RESERVOIR AUX GRANDS FLUX THERMIQUES

Résumé – Dans l'ébullition nucléée aux grands flux thermiques, une couche liquide appelée "macrocouche" est emprisonnée entre la surface chauffante et les masses de vapeur. Dans cet article est présentée une analyse du mécanisme de formation de cette macrocouche. Basée sur l'analyse, une expression théorique est obtenue pour l'épaisseur initiale de la macrocouche. L'accord entre les valeurs théoriques et celles expérimentales déjà publiées est raisonnablement bon.

ÜBER DEN ENTSTEHUNGSMECHANISMUS DER MAKROSCHICHT BEIM BEHÄLTERSIEDEN UND HOHEN WÄRMESTRÖMEN

Zusammenfassung – Beim Blasensieden bildet sich bei hohen Wärmeströmen eine als "Makroschicht" bekannte Flüssigkeitsschicht zwischen der Heizfläche und den Dampfmassen aus. In dieser Arbeit wird der Entstehungsmechanismus dieser Makroschicht untersucht. Auf analytischer Grundlage wurde ein theoretischer Ausdruck für die Dicke der Makroschicht hergeleitet. Die Übereinstimmung zwischen den theoretischen Werten der Anfangsdicke der Makroschicht und den in der Literatur veröffentlichten experimentellen Werten ist gut.

О МЕХАНИЗМЕ ОБРАЗОВАНИЯ МАКРОСЛОЯ ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ В БОЛЬШОМ ОБЪЕМЕ ЖИДКОСТИ С ИНТЕНСИВНЫМ ПОДВОДОМ ТЕПЛА

Аннотация— При пузырьковом кипении с интенсивным подводом тепла между поверхностью нагрева и объемом пара остается слой жидкости, обычно называемый "макрослоем". В данной работе представлен анализ механизма образования такого слоя и выведено теоретическое выражение для определения начальной его толщины. Получено довольно хорошее совпадение между теоретическими значениями начальной толщины макрослоя и опубликованными экспериментальными данными.