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Theoretical studies on transient pool boiling based on microlayer model

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Abstract

An analytical model for transient pool boiling heat transfer was developed in this study. The boiling curves of the transient boiling were obtained based on the microlayer model proposed by the authors and the mechanism of transition from the non-boiling regime to film boiling, i.e., direct transition was theoretically examined. Since the nucleate boiling heat flux is mainly due to the evaporation of the microlayer and its initial thickness decreases rapidly with increasing superheat, the duration of nucleate boiling is markedly decreased as the incipient boiling superheat is increased. It is found that the direct transition is closely connected to the rapid dryout of the microlayer which occupies almost the whole surface at high wall superheat.

1. Introduction

Transient boiling heat transfer is very important for many practical applications such as the metallurgical processing and the safety evaluation in a nuclear reactor, etc. However, the mechanism of transient boiling heat transfer has not been clarified, although a large number of experimental studies have been performed in the past three decades.

The experimental data on the transient boiling of water, reported by Sakurai and Shiotsu [1–3], were obtained by exponential heating with time. The first of transient process type has a maximum heat flux similar to that of the steady-state boiling curve, with the nucleate boiling region extended to the higher heat flux and higher superheat region. This type occurs for a relatively low heating rate. For a higher heating rate, on the other hand, the boiling process becomes irregular and the boiling curve never reaches that of steady-state nor its extended region.

To explain the increase of the maximum heat flux, Pasamehmetoglu et al. [4] developed an analytical model which is essentially based on the so-called macrolayer model for the CHF of steady-state pool boiling proposed by Haramura and Katto [5]. However, the analytical model seems to be invalid for predicting the CHF of the transient boiling, because macrolayer cannot be formed in the case of rapid heating. In fact, the prediction by Pasamehmetoglu et al. [4] is much higher than the experimental result by Sakurai and Shiotsu [2,3] for the case that the heating period is less than 20 ms.

Other interesting phenomena, which have been reported by Kutateladze et al. [6], Okuyama and Iida [7], and Sakurai et al. [8], are the boiling transitions for liquid nitrogen, liquids helium, and benzene. Two kinds of transitions, i.e., direct transition (DT) and semi-direct transition (SDT), have been observed by Sakurai et al. [8]. The DT is the transition phenomenon from non-boiling to film boiling without passing through the nucleate boiling region, and occurs under the relatively high heating condition. The SDT, which occurs at high system pressure, means that nucleate boiling appears in a very narrow region, compared to the general boiling

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Nomenclature

A_b	microlayer area $= \pi(d/2)^2$
A_d	the largest cross-sectional area of individual bubble
A_{ev}	evaporating area of liquid layers
c_l	change rate of surface temperature
c_D	specific heat of liquid
D_d	departure diameter of individual bubble
D_t	instantaneous diameter of individual bubble
d	diameter of individual bubble at the end of initial growth
h_{fg}	latent heat of evaporation
k_l	thermal conductivity of liquid
m	group number of nucleation
N	density of active sites per m^2
q	wall heat flux
q_{ev}	evaporation heat flux on microlayer
r	radius of individual bubble, or coordination
r_c	position where the superheat boundary layer reaches the liquid–vapor interface
$r^d_{(t)}$	radius of dryout area
t	time
t_g	period of initial growth
T	temperature
ΔT_{in}	incipient superheat of boiling $= T_0$
ΔT_s	wall superheat
α	thermal diffusivity of liquid
β	contact angle
θ	configuration angle
δ_{ma}	thickness of macrolayer
δ_{mi}	thickness of microlayer
ρ_v	density of vapor

Subscripts

i, j, k	number of bubble group

curve. However, the transition mechanisms and the heat transfer characteristics have not yet been clarified.

Recently, we have proposed a microlayer model [9,10] which focuses on individual bubbles and can be used to explain the pool boiling mechanism and to predict the heat flux in the nucleate boiling region, at high heat flux and to the minimum heat flux point. In this model, the evaporation and partial dryout of the liquid microlayer underneath the individual bubbles were considered to be important in nucleate boiling heat transfer, and the CHF has been derived as the maximum value of the heat flux. For transition boiling, in the low-superheat region, the heat flux is mainly due to the evaporation of the microlayer, and in the high-superheat region, the evaporations both of the microlayer and macrolayer (note that the macrolayer is different from that defined in the study of Haramura and Katto [5]) play important roles in heat transfer.

In the present study, an analytical model was developed based on the microlayer model to predict the heat transfer characteristics for transient saturated pool boiling. Also the mechanism of DT was theoretically examined.

2. Microlayer model for transient boiling

2.1. Modeling of bubble behaviors

The bubble behavior for transient saturated pool boiling on a horizontal surface is considered here in Figs. 1 and 2, where the following assumptions are made:

1. The temperature of heating surface is uniform and increases monotonically with time.
2. At each active site, a bubble is formed once throughout the rapid transient boiling period.
3. The density of the active sites is determined by the instantaneous wall superheat. For a normal heating rate, the population of individual bubbles increases with time and bubbles with different site exist on the surface, as shown in Fig. 1. In the case of ultra-rapid heating rate, higher overshoot phenomenon occurs at the initiation of boiling and the nuclei on the heated surface are activated almost at the same time. Therefore the bubbles on the surface may be in the same size and the heat transfer model can be simplified as Fig. 2.
4. Both microlayer and macrolayer are formulated in a way similar to the steady-state boiling.

In the first place, we consider the general situation in which boiling initiates at a low wall superheat. As depicted in Fig. 1, new vapor bubbles are generated continuously among the individual bubbles with increasing wall superheat. In order to calculate the population of individual bubbles, the time duration τ is divided into m steps. In each time-step a new group of bubbles with the same size are generated and grow. The time-step is Δt_j ($j = 1, 2, \dots, m$), so, $\tau = \sum_{i=1}^{m} \Delta t_i$. At the beginning of the jth time-step, the jth group of bubbles are produced at the wall temperature of T_{j-1} at the time t_{j-1} ($= \sum_{i=1}^{j-2} \Delta t_i$).

The initial area of the heating surface is A_0. The first group of bubbles begin to grow at time t_1 with the density of N_1. The evaporating area of liquid layers can

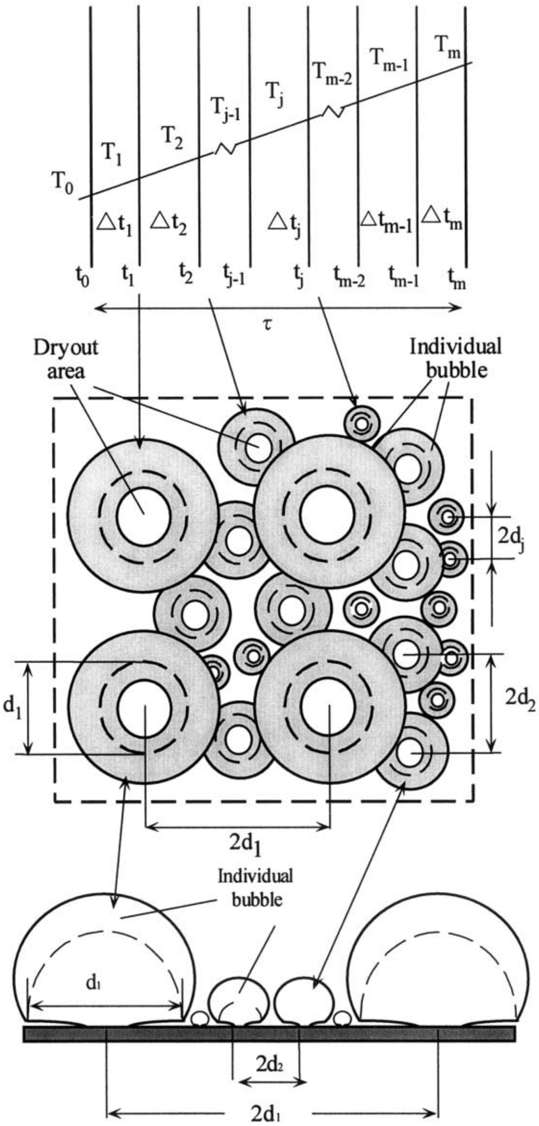

Fig. 1. Models for the case of low incipient superheat.

be given by $N_1 A^1_{ev}$, where A^1_{ev} represents the evaporation area under one bubble of the first group. So the non-dimensional non-evaporation area A/A_0 is

$$\frac{A_1}{A_0} = 1 - N_1 A^1_{ev}$$

New bubbles of the second group are formed within the area A_1. The non-dimensional non-evaporation areas after the second, and the jth group of bubbles should be

$$\frac{A_2}{A_0} = (1 - N_1 A^1_{ev})(1 - N_2 A^2_{ev})$$

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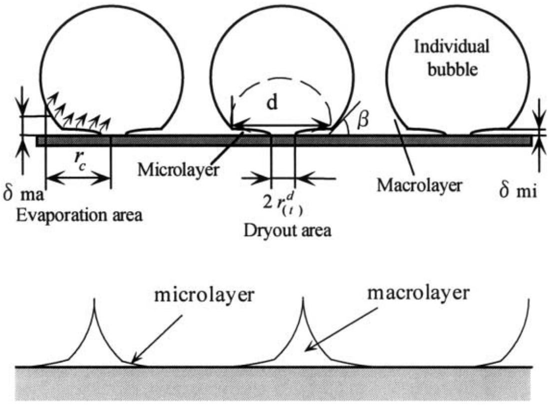

Fig. 2. Models for the case of high incipient superheat.

$$\frac{A_j}{A_0} = \prod_{k=1}^{j} (1 - N_k A^k_{ev}) \quad j = 1, \ldots, m \tag{1}$$

where N_k is the kth active site density at the time t_k. Therefore, the instantaneous surface-averaged heat flux at time $t(t_{j-1} < t < t_j)$ is given by

$$\bar{q}(t) = \sum_{k=1}^{j} \frac{A_{k-1}}{A_0} N_k A^k_{ev} q^k_{ev} + \frac{A_j}{A_0} q_{cd}(t) \tag{2}$$

where q^k_{ev} is the heat flux due to evaporation for one of the kth group of bubbles. $q_{cd}(t)$ is the heat flux due to the transient heat conduction within the liquid layer.

For boiling at very high incipient wall superheat, all bubbles are formed almost at the same time and occupy the whole heated surface. In this case, the surface-averaged heat flux can be expressed as follow:

$$\bar{q}(t) = N_1 A^1_{ev} q_{ev} + (1 - N_1 A^1_{ev}) q_{cd}(t) \tag{3}$$

2.2. Microlayer model

For steady-state pool boiling, the microlayer model has been proposed to explain the boiling mechanism and to predict the heat flux in nucleate boiling. In this model we focused on the behavior of the individual bubbles and the micro- and macrolayer.

In the microlayer model proposed, the growth of individual bubbles can be divided into two periods, the initial growth period ($t \leqslant t_g$) and the final growth period ($t > t_g$). During the initial growth period, the bubble grows in a semi-spherical shape and the microlayer is formed underneath it. The microlayer does not expand during the final growth period and the shape of bubble changes from the semi-spherical to the spherical segment geometry due to the evaporation of the microlayer. In the final growth period, a thicker liquid layer than the microlayer is formed under the bubble and among the adjacent individual bubbles as shown in Figs. 1 and 2, which is termed a macrolayer in this paper. Heat transfer is dominant in the growth of bubbles in the initial growth period and both dynamics and heat transfer are important in the final growth period.

The formation mechanism of the microlayer has been studied theoretically and experimentally by Cooper and co-workers [11,12] and its thickness can be expressed as

$$\delta_{mi} = 0.8\sqrt{\nu_l t} = \sqrt{c\alpha t} \tag{4}$$

where $c = 0.64Pr$. Here the effect of surface tension can be neglected because the duration of initial growth is usually very short.

For transient boiling, the structures of the liquid layers (microlayer and macrolayer) are assumed to be the same as that of the steady-state boiling. Then the local surface heat flux during the growth of the ith group of individual bubbles can be given as

$$q_{(r,t)} = \begin{cases} 0, & r \leqslant r^{d}_{(t)} \\ -\rho_l h_{fg}\frac{d\delta_{mi}}{dt}, & r^{d}_{(t)} < r \leqslant d/2 \\ -\rho_l h_{fg}\frac{d\delta_{ma}}{dt}, & d/2 < r \leqslant r_c \\ q_{cd}, & r \geqslant r_c \end{cases} \tag{5}$$

$$\sum_{j=1}^{i-1}\Delta t_j \leqslant t \leqslant \sum_{j=1}^{i}\Delta t_j, \quad \Delta t_i \geqslant t_g$$

where $r^{d}_{(t)}$ is the radius of dryout area. δ_{mi} and δ_{ma} are the thickness of microlayer and the thickness of macrolayer, respectively. The heat transfer in the dryout area has been neglected.

Until the superheated boundary layer reaches the interface of liquid–vapor, the heat flux q_{cd} can be determined by transient heat conduction within the liquid layer, i.e.,

$$q_{cd} = \frac{k_l}{\sqrt{\pi\alpha}}\left[\frac{\Delta T_s(t)}{\sqrt{t}} + \frac{1}{2}\int_0^t \frac{\Delta T_s(t) - \Delta T_s(\mu)}{(t-\mu)^{3/2}}\,d\mu\right] \tag{6}$$

The heat flux due to evaporation is expressed by

$$q_{ev} = \frac{1}{A_{ev}}\left[\int_{A_b}\left(-\rho_l h_{fg}\frac{d\delta_{mi}}{dt}\right)dA + \int_{\pi r_c^2 - A_b}\left(-\rho_l h_{fg}\frac{d\delta_{ma}}{dt}\right)dA\right] \tag{7}$$

Substituting Eqs. (6) and (7) into Eq. (2), the instantaneous wall heat flux can be found.

In order to carry out the analytical calculation of the heat flux, the thickness of liquid layers and the radius of the dryout area are necessary and will be shown in the next sections.

2.3. Thickness of liquid layers and dryout area

The growth rate of individual bubble, the thickness of liquid layer and the radius of dryout area can be obtained by the same methods which are used in steady-state boiling. In the present study, the linear increase of wall temperature with time is considered, for simplicity.

$$\Delta T_s = T_0 + c_1 t \tag{8}$$

where T_0 is the incipient boiling wall temperature and c_1 is a constant and represents the rate of change of the wall temperature.

2.4. Growth of individual bubble

During the initial growth of an individual bubble, the semi-spherical bubbles grow from active nuclei. The growth equation of individual bubbles can be derived by the heat balance between the latent heat of evaporation of the microlayer and conduction heat through the microlayer.

$$\frac{d}{dt}\left(\frac{2}{3}\pi r^3 \rho_v h_{fg}\right) = 2\pi k_l \int_0^t \frac{\Delta T_s}{\delta_{mi}} r\dot{r}\,dt \quad t \leqslant t_g \tag{9}$$

So, the equation of bubble growth is obtained in the initial growth period, as

$$r = \frac{2k_l(T_0 + c_1 t/7)t^{1/2}}{\rho_v h_{fg}\sqrt{c\alpha}} \quad t \leqslant t_g \tag{10}$$

From Eq. (10), the time required for the microlayer to reach the r position, can be represented by

$$\tau_g = f(r), \quad t \leqslant t_g \tag{11}$$

At radius r, the initial thickness of the microlayer is

$$\delta_0 = \sqrt{c\alpha f(r)} \tag{12}$$

At the end of the initial growth of individual bubble i.e. at $t = t_g$, the bubble diameter d can be given as

$$d = \frac{4k_l(T_0 + c_1 t_g/7)t_g^{1/2}}{\rho_v h_{fg}\sqrt{c\alpha}} \tag{13}$$

After the microlayer is formed, the bubble growth goes into its final period. In this period, the microlayers evaporate and partial areas of microlayers are dried out.

The consumption of the liquid microlayer, by evaporation, is due to heat conduction from the heated surface through the microlayer. So the energy balance is

$$-\rho_l h_{fg}\frac{d\delta_{mi}}{dt} = \frac{k_l \Delta T_s}{\delta_{mi}}, \quad t \geqslant \tau_g \tag{14}$$

With the initial condition of $\delta_{mi} = \delta_0$ for $t = \tau_g$, the thickness of the microlayer can be obtained from the above equation.

$$\frac{\delta_{\text{mi}}}{\sqrt{c\alpha f(r)}} = \left\{1 - \frac{2k_l[T_0(t-\tau_g) + c_1(t-\tau_g)^2/2]}{\rho_l h_{\text{fg}} c\alpha f(r)}\right\}^{1/2}$$
$$t \geqslant \tau_g \tag{15}$$

The radius of dryout area $r^{\text{d}}_{(t)}$, determined by the condition of $\delta_{\text{mi}} = 0$, satisfies the following equation,

$$\left(\frac{ch_{\text{fg}}}{2c_{\text{pl}}} + T_0\right) f(r^{\text{d}}_{(t)}) = T_0 t + c_1(t - f(r^{\text{d}}_{(t)}))^2/2 \tag{16}$$

Usually, for nucleate boiling $ch_{\text{fg}} \gg 2c_{\text{pl}}\Delta T_s$, so,

$$\frac{ch_{\text{fg}}}{2c_{\text{pl}}} f(r^{\text{d}}_{(t)}) = T_0 t + c_1(t - f(r^{\text{d}}_{(t)}))^2/2 \tag{17}$$

2.5. Macrolayer

The macrolayer is formed in the final growth of an individual bubble. When the surface temperature is high enough, the evaporation on the macrolayer is also significant. The initial thickness of macrolayer is given by [9,10]

$$\delta^0_{\text{ma}} = \begin{cases} \sqrt{R^2 - (d/2)^2} + \delta^{\text{d}}_{\text{mi}} - \sqrt{R^2 - r^2} & \beta \leqslant \theta \\ R\cos\beta + \delta^{\text{d}}_{\text{mi}} - \sqrt{R^2 - r^2} & \beta > \theta \end{cases} \tag{18}$$

Similar to the microlayer, the macrolayer thickness δ_{ma} can be obtained with the initial condition $\delta_{\text{ma}} = \delta^{\text{d}}_{\text{mi}}$, at $t = t^*_{\text{mg}}$. For $\beta \leqslant \theta$, δ_{ma} is given by

$$\delta_{\text{ma}} = \left\{(\sqrt{R^2 - (d/2)^2} + \delta^{\text{d}}_{\text{mi}} - \sqrt{R^2 - r^2})^2 - \frac{2k_l[T_0(t - t^*_{\text{mg}}) + c_1(t - t^*_{\text{mg}})^2/2]}{\rho_l h_{\text{fg}}}\right\}^{1/2} \tag{19}$$

where t^*_{mg} is the time at which the superheat boundary layer reaches the liquid–vapor interface. The radius of the dryout area of the macrolayer is determined by the condition of $\delta_{\text{ma}} = 0$.

$$r^{\text{d}}_{(t)} = \left\{R^2 - \left[\sqrt{R^2 - (d/2)^2} - \left(\frac{2k_l}{\rho_l h_{\text{fg}}}\right)^{1/2} \left[T_0(t - t^*_{\text{mg}}) + c_1(t - t^*_{\text{mg}})^2/2\right]^{1/2} + \delta^{\text{d}}_{\text{mi}}\right]^2\right\}^{1/2} \tag{20}$$

where t^*_{mg} is given by

$$\sqrt{\pi\alpha t^*_{\text{mg}}} = \left[\frac{2k_l[T_0(t - t^*_{\text{mg}}) + c_1(t - t^*_{\text{mg}})^2/2]}{\rho_l h_{\text{fg}}}\right]^{1/2} \tag{21}$$

Eqs. (19) and (20) are valid for the case of $\beta \leqslant \theta$. For the case of $\beta > \theta$, $r^{\text{d}}_{(t)}$ and the thickness of macrolayer can be also determined by the Eqs. (19) and (20) if $2R\sin\beta$ is used instead of d in the two equations.

3. Results and discussion

For the relatively fast heating rate, the individual bubble formed and grows, only one time at one active site, then the boiling changes from nucleate boiling to film boiling. The heat flux q^k_{ev} in Eqs. (2) and (3) is

$$q^k_{\text{ev}} = q_{\text{ev}}(t - t_{k-1}), \quad t_{k-1} \leqslant t \leqslant t_{\text{m}} \tag{22}$$

where $q_{\text{ev}}(t)$ is given by Eq. (7).

Usually, the area of the macrolayer underneath the individual bubble is small compared with that of the microlayer and can be neglected for the estimation of the evaporating area. Then

$$A^k_{\text{ev}} \cong A_{\text{b}} = \frac{\pi d_k^2}{4}, \quad N_k = \frac{1}{\pi d_k^2}, \quad \frac{A_i}{A_0} = \left(\frac{3}{4}\right)^i \tag{23}$$

The density of active sites is a difficult parameter to be determined, theoretically or experimentally. Up to now, there are no perfect relationships for it. Some empirical relationships have been reported in the literature. In this study, the experimental result obtained by Gaertner [13] for water is used. That is

$$\bar{q} = 117.1 N_k^{2/3}, \quad d_k = 17.8\bar{q}^{-0.75} \tag{24}$$

Furthermore, the relation between the wall heat flux and the wall superheat is

$$\bar{q} = \begin{cases} 5.225 \times 10^{-2}\Delta T_s^{5.5}, & \Delta T_s \leqslant 20\ \text{K} \\ 1.509 \times 10^5 \Delta T_s^{0.6}, & \Delta T_s > 20\ \text{K} \end{cases} \tag{25}$$

Therefore, the density of active sites can be given as a function of the wall superheat.

$$N_k = \begin{cases} 9.425 \times 10^{-6}\Delta T_s^{8.25}, & \Delta T_s \leqslant 20\ \text{K} \\ 4.626 \times 10^4 \Delta T_s^{0.9}, & \Delta T_s > 20\ \text{K} \end{cases} \tag{26}$$

For boiling with high incipient superheat, the heat flux can be solved from Eq. (3). The calculation results are shown in Fig. 3. The line from a to b(b′) represents the non-boiling region which is determined by transient heat conduction. The nucleate boiling region from b(b′) to c(c′) shows a rapid increasing heat flux, due to the evaporation of microlayer. From c(c′) to d(d′), the heat transfer is sharply decreased because of the fast dryout of microlayer. The gradually decreasing curve from d(d′) to e(e′) represents the transition boiling. In this region after the dryout of microlayer, the evaporation of macrolayer is dominant.

It is known that higher superheat results in the thinner microlayer (e.g. the thickness of the microlayer is $\delta_0 = 0.32\mu_l\rho_v h_{\text{fg}} r/(\rho_l k_l \Delta T_s)$ for steady-state boiling and

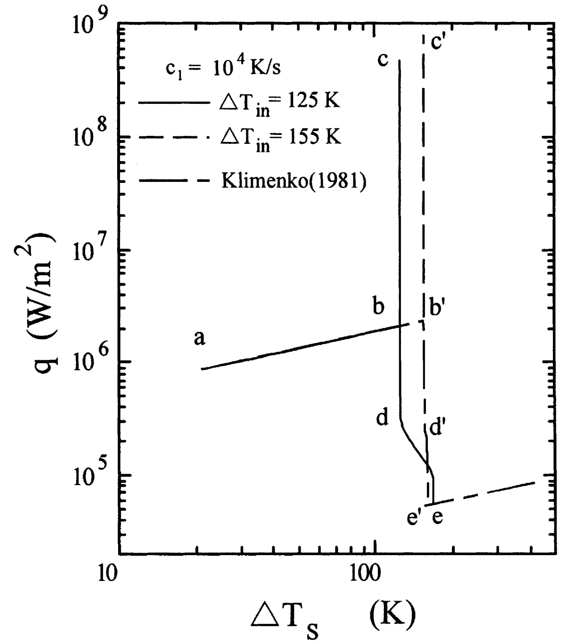

Fig. 3. Boiling curve at high incipient superheat.

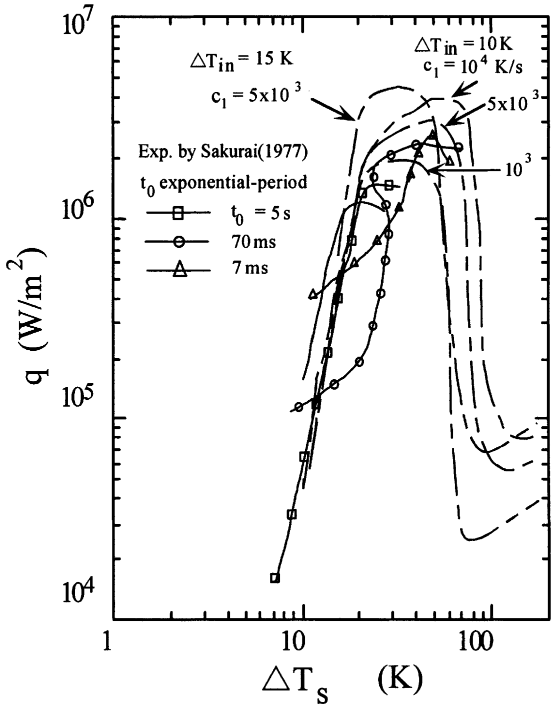

Fig. 4. Boiling curve at low incipient superheat.

is determined by Eq. (12) for transient boiling). So the maximum heat flux increases with the incipient boiling superheat (the heat flux of c′ is higher than that of c). Since both the evaporation and the dryout speed becomes faster as the microlayer becomes thinner, dramatic changes in heat flux occur. As the incipient boiling wall temperature approaches the temperature of minimum heat flux (about the temperature of the homogeneous nucleation), the area of the macrolayer becomes very small and the region of the transition boiling also becomes very narrow (d′ → e′). In the limit, the macrolayer cannot be formed at the temperature of minimum heat flux and the transition boiling will disappear. In the actual situation, the rapid increase of heat flux due to the evaporation of microlayer cannot be observed for high incipient superheat because of the effect of the heat capacity of heating body. Consequently, the boiling curve results in the type of the so-called DT, i.e., boiling transition from non-boiling directly to film boiling. The film boiling curve by Klimento [14] is also shown in Fig. 3.

For the general case of low incipient superheat, the heat flux is calculated from Eq. (2). The results are presented in Fig. 4. In this calculation, continuous nucleation is assumed with increasing surface temperature ($\Delta t_i = t_g$). The maximum heat flux increases and the nucleate boiling curve is extended along with that of steady boiling, as the heating speed of the heater surface increases. The main mechanism of the increase of the maximum heat flux is the new bubbles and new microlayers generated within the macrolayer, i.e. the macrolayer is replaced by new microlayers.

The experimental data by Sakurai and Shiotsu [2,3] are also shown in Fig. 4. Although the exact comparison cannot be made because of the exponential heat input ($Q = Q_0 e^{t/t_0}$) by Sakurai and Shiotsu [2,3], we can see the same tendencies between the present analytical results and the experimental data, i.e., the maximum heat flux increases and the nucleate boiling curve for transient boiling is extended along with that of the steady-state boiling.

4. Conclusions

For transient saturated pool boiling heat transfer on a horizontal surface, an analytical model has been developed based on the proposed microlayer model. The boiling curves of transient boiling for low incipient superheat are obtained as continuous curves. The maximum heat flux increases and the nucleate boiling region is extended along with the curve of the steady-state boiling with the increase in the heating speed. The mechanisms of DT for high incipient superheat is also clarified. Since the nucleate boiling heat flux is mainly due to the evaporation of the microlayer and the initial thickness of the microlayer decreases rapidly with increasing superheat, the duration of nucleate boiling is markedly decreased as the incipient boiling superheat is increased. Therefore the DT is closely connected to the rapid dryout of the microlayer which occupies almost the whole surface at high wall superheat.

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