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A dry-spot model for transition boiling heat transfer in pool boiling

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Abstract

A theoretical model for transition boiling heat transfer in pool boiling is proposed. A dry-spot model for CHF in pool and flow boiling proposed recently by the authors is extended in the analysis. The fractions of wetted area on the heating surface are estimated as a function of wall superheat. It is shown that transition boiling heat flux can be determined without any correction factor by the consideration of the influence of dry spots on active site density with the assumption that measured data of boiling parameters such as active site density and bubble diameter, etc. in nucleate boiling can be extended into transition boiling as a function of wall superheat. The predictions of boiling curve and the fraction of wetted area are in fairly good agreement with the existing data. It also turns out that the present model well explains the mechanism on how wettability affects the transition boiling. © 1998 Elsevier Science Ltd. All rights reserved.

Nomenclature

A cell area [m^2]
A_d area of a dry spot [m^2]
d_{av} time-averaged bubble diameter [m]
d_c cavity mouth diameter [m]
f_m fraction of area of dry spot overlapped by m dry spots
g gravitational acceleration [m s^{-2}]
h_{fg} latent heat of vaporization [J kg^{-1}]
k_v thermal conductivity of vapor [W m K^{-1}]
m number of dry spot sites
$\bar{N}$ average density of active sites [sites m^{-2}]
$\bar{N}_0$ average density of potential sites [sites m^{-2}]
$\bar{N}_d$ average density of dry spots [sites m^{-2}]
$\Delta\bar{N}$ increment of active site density [sites m^{-2}]
$\Delta\bar{N}_0$ increment of potential site density [sites m^{-2}]
n number of active nucleation sites
n_c critical active site number
n_{ts} number of time step
P probability function defined by equation (4)
q overall heat flux defined by equation (1) [W m^{-2}]
q_b heat transferred by single bubble site [W site^{-1}]
q_l heat flux over wetted area [W m^{-2}]
q_v heat flux over dry area [W m^{-2}]
T_{sat} saturation temperature [K]
ΔT wall superheat [K]
ΔT_{CHF} wall superheat at critical heat flux [K]
t time [s]
t_{hov} hovering time of vapor mass [s]
t_{sat} elapsed time to nucleation on whole surface [s]
Δt time step size [s]
x ratio actual to nominal dry area.

Greek symbols

Γ actual fraction of dry area
Γ_i nominal fraction of dry area
μ_v viscosity of vapor [Ns m^{-2}]
ρ_l density of liquid [kg m^{-3}]
ρ_v density of vapor [kg m^{-3}]
σ surface tension [N m^{-1}]
ϕ contact angle.

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Superscripts
j old time level
$j+1$ new time level.

1. Introduction

The transition boiling, commonly characterized by a reduction in surface heat flux with an increase in wall superheat, is important to industrial applications such as the safety analysis of nuclear reactors and quenching in material processing, as well as to the understanding of the mechanism of critical heat flux (CHF). Although continuous research efforts have been devoted to the understanding of the transition process, recent reviews by Kalinin [1], Dhir [2] and Auracher [3, 4] show that the transition boiling are not well understood. There are two main reasons to the lack of understanding: (1) Transition boiling heat transfer is very sensitive to the several parameters such as surface roughness, wettability, substrata thermal properties, and process history as to whether it is heating or cooling. Furthermore, it is generally known that transition boiling heat transfer is more sensitive to those parameters than nucleate boiling. (2) It is difficult to observe directly the physical phenomena occurring at the interface between fluid and heating surface, which may be key to a better modeling of transition boiling, due to experimental difficulties. Therefore, even though it is generally known that the heating surface is partly in contact with the bulk liquid and partly with the vapor in transition boiling, the information on characteristic of dry spots was very limited. Very recently, Nagai and Nishio [5–7] reported direct observations on dynamic behavior and patterns of dry spots on the heating surface for whole boiling regions using their novel experimental technique. Their results will be discussed in detail in the following review of works section, experimental. From the results of our review in experimental works, it is concluded that the dry spots generally found in transition boiling as well as in nucleate boiling are formed due to dryout of the microlayer under bubble and large dry areas result from the coalescence of these dry spots. In addition, the heat transfer mechanism in transition boiling has close relations with that in nucleate boiling.

There are only limited theoretical models in transition boiling which explain fairly well the transition boiling phenomena. The fundamental differences between theoretical models lie mainly in the divergent opinions on how dry areas form on the heating surface. And these models can be classified into time-dependent and stationary models [5]. Time dependent models assume a periodic sequence of transient conduction, nucleation and dryout for the local heat transfer history on the heating surface mainly based on the experimental observations of wall temperature fluctuation.

Kostyuk et al. [8] and Kalinin et al. [1] developed a time-dependent semi-empirical model supposing that the duration of liquid-solid contact was limited by vapor binding due to lateral coalescence of bubbles. However, these models are very specific to the data which they are based. Pan et al. [9] developed a time-dependent model based on the postulation of macrolayer dryout model [10]. However, the postulation is not consistent with actual boiling phenomena observed by Nagai and Nishio [5–7]. Nishio and Nagai [11] developed their own time-dependent model assuming that three mechanisms are involved to form dry areas ; the macrolayer dryout, the vapor binding due to lateral coalescence of bubbles, and the vapor caused by spontaneous nucleation. Dhir and Liaw [12] developed a stationary model assuming the stationary vapor stems located on a square grid and regarding the base areas of vapor stems as dry areas. However, no physical basis was given. Also, the above mentioned models cannot explain clearly why dry spots are observed even at low heat fluxes of nucleate boiling, as observed by Nagai and Nishio [5, 7]. It is not clear what the relation between the time-dependent model and the stationary model is and which type of model is appropriate. However, the concept of wetting pattern consisting of clearly separated wet and dry spots on the heating surface in the time-dependent model are not realistic. As more promising concept, Hsu and Kim [13] attempted to correlate transition boiling data by simulating the transition boiling with a Poisson distribution of bubble sites and showed that the transition boiling curve is related to the profiles of bubble activation as functions of wall superheat. The model can handle the surface effect by anchoring the bubble activation curves at either CHF or minimum heat flux (MHF) points. However, data for the quantities of these two points are required.

Based on the situations discussed above, a new model to describe the phenomena of transition boiling is required. And the model should be consistent with observed boiling phenomena in nucleate boiling as well as in transition boiling, because it is reasonable to expect that the mechanism of dry spot formation in transition boiling is the same as that in nucleate boiling. The present authors [14] have presented a dry-spot model to describe the boiling phenomena for high heat flux nucleate boiling and CHF in pool and flow boiling by introducing the new concept of dry area formation. In the model, it is assumed that a dry spot is formed when the number of bubbles surrounding one bubble exceeds a critical number. The model is well consistent with experimental observations by Nagai and Nishio [5–7]. In the present paper, the model is extended to the transition boiling. In addition, the fractions of wetted area on the heating surface are estimated as a function of wall superheat assuming that dry spots follow a Poisson distribution and the area of each dry spot is equal to the base area under the bubble. The influence of dry spots on active site density will also be discussed. The predictions of boiling curve and the fraction of wetted area in transition region are compared with the existing data.

2. A brief review of experimental works

Many experimental works dealing with studies of the transition boiling mechanism were performed to examine qualitatively and/or quantitatively the influence of parameters, temperature fluctuation on the heating surface, and visual observations on fluid behaviors and dry areas appearing on the heating surfaces, etc. Particularly, some experimental works have focused on the relations of heat transfer mechanism between nucleate boiling and transition boiling.

As noted previously, several parameters including heating surface characteristics can affect the transition boiling. And all the variables affecting nucleate boiling influence the transition boiling. Especially, the wettability of liquid to the surface is supposed to be an important factor controlling the mechanism of heat transfer in the transition boiling region. However, it is not clear yet how wettability affects the heat transfer process. A detailed discussion of parametric effects on transition boiling has been given by Dhir [2] and Auracher [3, 4].

In addition, it has been shown that transition boiling is a combination of nucleate and film boiling alternately existing at any given location on the heating surface [15–17]. On the other hand, at each instant some part of the heating surface is wetted by the liquid and the remainder is covered by a vapor film [18–20]. Also, it is confirmed by several studies [1, 5] that nucleation occurs during liquid-sold contact. Due to the difficulties in experimental study in transition boiling, photographic studies for direct observations on characteristics of dry spots, most of which are quoted by Ha and No [14], have usually been performed up to high heat flux nucleate boiling region near CHF. Some of them showed that the dry spots are formed under bubbles.

Very recently, Nagai and Nishio [5, 7] photographically studied the behavior of dry areas for whole boiling regions using transparent single-crystal sapphire plate as the boiling surface and using the total reflection method to distinguish the wetted areas from the dry areas on the video images. They reported the following facts: (1) contrary to conventional expectation on appearance of dry areas at the departure from nucleate boiling (DNB) point, dry spots (called "primary dry areas" in refs. 5, 7), formed under bubbles, have appeared scattered even at low heat flux nucleate boiling region; (2) the number density of dry spots increased as the wall superheat increased; (3) the formation of large dry areas results from the coalescence of neighboring dry spots and the pattern of dry areas at CHF are different from that postulated in the macrolayer dryout model proposed by Haramura and Katto [10]; and (4) the liquid–solid contact situation at low superheat transition boiling was similar to that at the CHF point. Nagai and Nishio [6] also conducted experiments of the Leidenfrost temperature on an extremely smooth surface and observed numerous dry spots in the wetted area.

In addition, Katto et al. [21] reported that fluid behavior varies continuously over nucleate and transition boiling, and no instability is found at their boundary. Kalinin et al. [1] reported that temperature fluctuations of the heating surface for transition boiling adjacent to CHF is characterized by the same temperature fluctuations as those of nucleate boiling region near CHF. They also suggested that the physical mechanism of the process in the nucleate boiling region near CHF is similar to that in the transition region near CHF.

3. The present model

In literature, three heat transfer modes contribute to the overall heat transfer: transient conduction, pure nucleate boiling and pure film boiling. Transient conduction begins at the moment that the liquid replaces the departing vapor mass and contacts the surface. In pure nucleate boiling, heat is removed from a wetted area by bubble activity. Pure film boiling occurs over a dry area on the heating surface. It is now commonly accepted that transient conduction cannot be the principle heat transfer mechanism except the transition region near the minimum heat flux point [3, 4]. In the present study, transient conduction is ignored. As the heating surface is partly in contact with the bulk liquid and partly with the vapor, the boiling surface will have non-uniform temperature distribution. However, for simplicity the boiling surface is assumed to be isothermal in the present study.

The overall heat flux is then expressed as the sum of two contributions from pure nucleate boiling and pure film boiling

$$q = (1-\Gamma)q_l + \Gamma q_v, \quad (1)$$

where q_l and q_v are pure nucleate boiling heat flux and pure film boiling heat flux respectively; Γ denotes the fraction of the heating wall in contact with vapor. According to Ha and No [14], the heat transfer over a wetted region $(1-\Gamma)q_l$ is given by

$$(1-\Gamma)q_l = q_b\bar{N}(1-P(n \geqslant n_c)), \quad (2)$$

where

$$P(n \geqslant n_c) = \sum_{n=0}^{n_c-1} p(n), \quad (3)$$

$$P(n) = \frac{e^{-\bar{N}A}(\bar{N}A)^n}{n!}, \quad (4)$$

where q_b is heat transferred by a single bubble site and can be estimated assuming that if there is no generation of dry spots on heated surface, heat flux will increase along the extension of nucleate boiling heat flux and that each bubble site has uniform heat duty, $\bar{N}$ active site density, A cell area $(=\pi d_{av}^2)$, and n_c is critical site number to form dry spots under bubbles and determined by 5 in ref. [14].

In the present study, the heat flux q_v is evaluated from the study of Bui and Dhir [22] on a vertical surface.

$$q_v = 0.37\left[\frac{k_v^3 \rho_v(\rho_l-\rho_v)gh_{fg}}{\mu_v\sqrt{\sigma/g(\rho_l-\rho_v)}}\right]^{1/4} \Delta T^{3/4}. \quad (5)$$

The main quantities remaining still unknown in the calculation of equation (1) are the fraction of dry area Γ and active site density $\bar{N}$ affected by dry area.

3.1. The fraction of dry area

Suppose that all dry spots follow a Poisson distribution [7, 23] and the area of each dry spot is equal to base area under bubble [5–7] and let Γ_i be the fraction of dry spots when all of the dry spots are isolated among them. Γ_i can be calculated as the following equation:

$$\Gamma_i = \bar{N}_d A_d, \quad (6)$$

where A_d is the area of a dry spot $(=\pi d_{av}^2/4)$ and $\bar{N}_d$ is the average number density of dry spots and can be estimated by means of the concept of critical site number [14].

$$\bar{N}_d = \bar{N} P(n \geqslant n_c). \quad (7)$$

When the dry spots become numerous, their areas overlap and the dry areas are reduced. Suppose that the fraction of dry areas is reduced by overlap from Γ_i to $x\Gamma_i$ i.e. Γ in equation (1). Dividing each area of dry spot into fraction f_m, where m is the number of dry spot sites ($m = 1$ denoting no overlap), then

$$\sum_{m=1}^{\infty} f_m = 1, \quad (8)$$

and averaged over all areas of dry spot

$$x = \sum_{m=1}^{\infty} f_m/m. \quad (9)$$

To calculate the overlap variables f_m, let us consider the simple configuration of dry spots as shown in Fig. 1. The probability that any element da of an area of dry spot A_d forms part of the fraction f_m is the probability that it is overlapped by $(m-1)$ other area of dry spot, i.e. that $(m-1)$ dry spot sites lie within a circle of area A_d centered on da. The expected number of dry spot, sites in A_d is $A_d\bar{N}_d$. Therefore, the Poisson distribution the probability of having $(m-1)$ dry spot sites is

$$P(m-1) \equiv f_m = \frac{e^{-\Gamma_i}\Gamma_i^{m-1}}{(m-1)!}. \quad (10)$$

Substituting the above eq (9) and since $x\Gamma_i$ is equal to

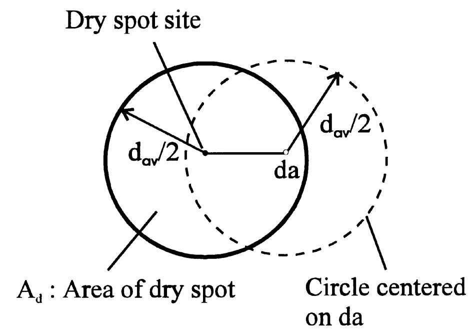

Fig. 1. Configuration of dry spot for calculation of overlap.

Γ in eq (1), the fraction of dry area affected by overlap is given by

$$\Gamma = 1 - e^{-\Gamma_i}. \quad (11)$$

3.2. Active site density

For nucleate boiling at high heat fluxes as well as transition boiling under pool boiling, fluid behavior is characterized by the periodic growth and departure of vapor mass formed due to the coalescence of small vapor generated at nucleation sites [21, 24, 25]. A lot of small vapor are supplying vapor to an overlying vapor mass, resulting in growth and subsequent departure of the vapor mass. After the departure of the vapor mass, bulk liquid replace it.

In the present study, according to Ha and No's hypothesis [14], it is assumed that a dry spot is formed when the number of bubbles surrounding one bubble exceeds a critical number. Consequently, dry spots are formed on local areas having dense active sites. In addition, it is assumed that after the departure of the vapor mass, all dry spots generated partly on the heating surface are rewetted because of the inertia of bulk liquid. This rewetting has been confirmed by several investigators [3]. After the rewetting, nucleation occurs scattered on the heating surface at the start, and spreads to the whole surface sooner or later [25]. Progressive spreading of nucleation on the heating surface plays a very important role in active site density because the dry spots formed previously inhibit the activation of nucleation sites which will be activated in the absence of dry spots. Consequently, true active site density will deviate from the extension of active site density measured in nucleate boiling into transition boiling as a function of wall superheat, because the fraction of dry area rapidly increases with an increase in wall superheat in transition boiling.

Based on the above situations, for simple calculation of active site density in the presence of dry spots, let the potential site density reach a saturation value $\bar{N}_0$ within a limited time t_{sat} and increase linearly as a function of

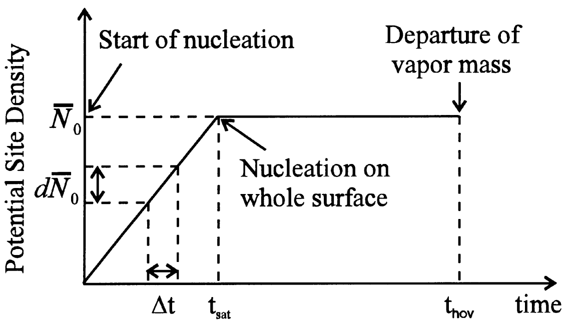

Fig. 2. The postulated variation of potential site density as a function of time.

time for $0 \leqslant t \leqslant t_{sat}$ as shown in Fig. 2. In this paper, a potential site is one which would be active in the absence of dry spots. Even though there is limited quantitative information on t_{sat} in transition boiling at present, it is expected that t_{sat} is very short compared to vapor mass hovering period t_{hov} based on the observations at near CHF made by Katto and Yokoya [24]. The point of view may also be true that the higher a heating surface temperature is, the more rapidly the vaporization takes place. Therefore, the effect of the variation of heat flux with time on overall heat flux during t_{sat} was ignored and heat flux during hovering time of vapor mass was assumed to be uniform in the derivation of eq (1).

In Fig. 2, dividing time t_{sat} into a series of finite time steps and eliminating the increment of potential sites in dry area formed at old time level j, the finite increase in active site density and active site density at new time level $(j+1)$ can be calculated as follows:

$$\mathrm{d}\bar{N}^{j+1} = \mathrm{d}\bar{N}_0(1-\Gamma^j), \tag{12}$$

$$\bar{N}^{j+1} = \bar{N}^j + \mathrm{d}\bar{N}^{j+1}, \tag{13}$$

where $\mathrm{d}\bar{N}_0 = \bar{N}_0/n_{ts}$, n_{ts} number of time steps $(=t_{sat}/\Delta t)$ and Γ^j is the fraction of dry area at time level j and can be obtained by substituting eqs (4), (6) and (7) in eq (11) with $\bar{N}$ replaced by $\bar{N}^j$. By iterating the above equations for n_{ts} time steps, saturated values for $\bar{N}$ and Γ are computed; and the resulting values will depend on n_{ts} selected. This will be discussed in the following section.

4. Results

To evaluate the model presented in the last section, the information of boiling parameters such as potential site density and bubble diameter in transition boiling is required. Several parameters, including heater surface characteristics such as surface wettability have been experimentally found influencing the nucleate and transition boiling. Also, it is well known that these parameters affect boiling parameters [2]. However, there is very limited information on such boiling parameters for given boiling conditions, particularly in transition boiling. Thus, in the present study, it is assumed that data of boiling parameters measured in nucleate boiling could be extended into transition boiling as a function of wall superheat. Furthermore, the active site density measured in nucleate boiling is assumed as potential site density by assuming that the fraction of dry area is negligible in nucleate boiling. Recently, Wang and Dhir [26] have studied systematically the effect of wettability on the active nucleation site density in nucleate boiling. They correlated their data for active site density as a function of the wall superheat and contact angle as follows:

$$\bar{N}_0 = 5\times10^{-27}(1-\cos\phi)/d_c^6, \tag{14}$$

where the cavity mouth diameter d_c is a function of the local superheating,

$$d_c = \frac{4\sigma T_{sat}}{\rho_v h_{fg}\Delta T} \tag{15}$$

In addition, Dhir and Liaw [12] (see also Liaw [27]) conducted experiments on the pool of saturated water at 1 atm on a vertical rectangular copper surface with several contact angles. They measured time- and space-averaged wall void faction by means of a γ-beam traversing parallel to the heating surface and data of heat flux in transition boiling under transient conditions and data of heat flux in nucleate boiling under steady state condition. The time-averaged bubble diameters with contact angles were obtained using the Poisson distribution of active site density and analyzing the geometry of the overlapping area between bubbles. The bubble diameters were estimated to vary with wall superheat as $\Delta T^{-1.5}$ by comparing with wall void fraction data. The predicted wall void fractions at CHF for contact angles were compared with experimental data in ref. [14]. The obtained functional dependence of bubble diameter as a function of wall superheat is similar to predictions from Lay and Dhir [28]. They showed that the vapor stem diameter varies with wall superheat as $\Delta T^{-1.7}$.

Figure 3 shows the comparison between predictions for various given time step numbers n_{ts} and measured data from Dhir and Liaw [12] for contact angle 27°. The predictions by equation (1) show smooth transition of boiling curve before and after CHF. Also it is shown that the heat transfer rate decreases with an increase in wall superheat in transition boiling independent of the number of time steps n_{ts} selected. The involved mechanism is that in nucleate boiling, increasing wall superheat activates more nucleation sites, resulting in a rapid increase in heat flux. However, a further increase in wall superheat causes higher density of active sites; then more bubbles have a population of surrounding active sites over the critical number, resulting in an increase in the number of dry spots and fraction of dry area. Thus, the number of effective active sites which transport heat through the wall

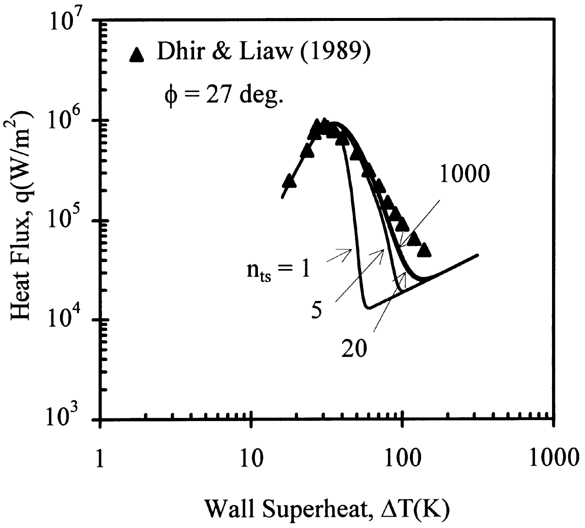

Fig. 3. Comparison of predictions for various numbers of time steps.

effectively, decreases. Consequently, the heat transfer rate decreases with increasing wall superheat in transition boiling region. As n_{ts} increases, the overall heat flux for given superheat increases and later reaches a converged value, because active site density decreases and attains to the converged value with an increase in n_{ts} as shown in Fig. 4. At low wall superheats, the active site densities even for $n_{ts} > 1$ almost equal the potential site density ($\bar{N} = \bar{N}_0$ when $n_{ts} = 1$) because the fraction of dry area on the heating surface is very small. When the fraction of dry area becomes dominant with an increase in wall superheat, the active site density decreases because potential nucleation sites in dry spots cannot be activated. Good agreement between predictions and measured data is obtained for n_{ts} as large as 20 in Fig. 3.

A comparison of the model predictions with the data for contact angles of 38° and 69° is made in Fig. 5 (a) and (b), respectively. The predictions appear to be in good agreement with the data. The heat transfer over the wetted area and the dry area are also plotted. As wall superheat changes, the proportion between the contributions of pure film and pure nucleate boiling to overall heat transfer varies gradually. The pure nucleate boiling over the wetted region is the major contributor to

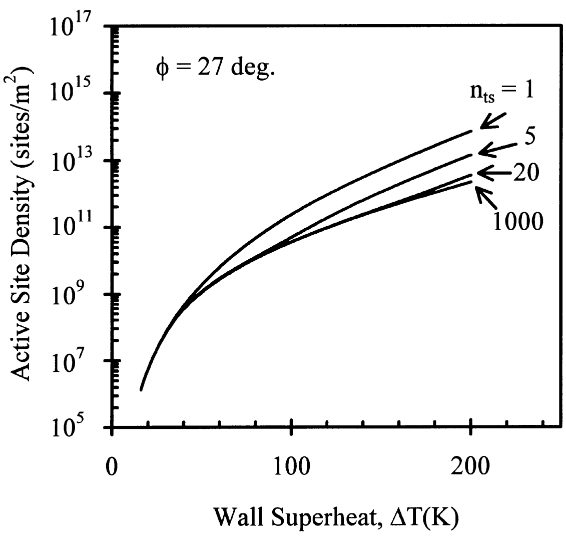

Fig. 4. Variation of active site density as a function of wall superheat for various numbers of time steps.

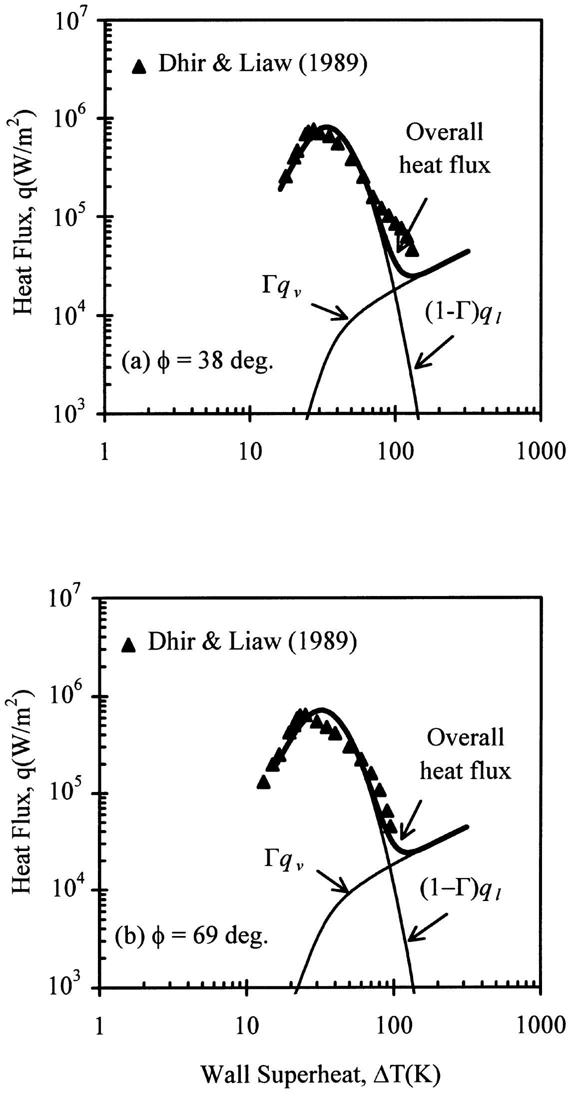

Fig. 5. Comparison of the predictions of boiling curves with experimental data for two contact angles.

overall heat flux in low superheat transition region. At lower wall superheats, as expected, the pure film boiling over the dry region is not significant. As wall superheat increases, pure film boiling becomes increasingly important due to an increase in the fraction of dry area and an increase in wall superheat, and it is dominant at high wall superheats near MHF point. In high superheat transition region, the model generally tends to underpredict the data as shown in Figs 3 and 4. The reason leading to underprediction of the data comes from neglect of transient conduction heat transfer in the present model. Kalinin et al. [1] noted that the contribution of transition conduction to overall heat transfer is dominant in high wall superheat transition boiling.

The effect of surface wettability on the boiling curve predicted in the present study is shown in Fig. 6(a). It is seen that for given wall superheat the heat flux throughout the transition boiling region increases with better wetting, i.e., lower contact angle, while in nucleate boiling, the heat transfer is higher with higher contact angle. Also both CHF and MHF points are moved upward and to the right by decreasing the contact angle. Also, the figure shows that transition boiling heat transfer is more sensitive to the wettability of the boiling surface than nucleate boiling heat transfer. These trends predicted by the model are the same as those reported in the literature by experiments [27, 29]. The present model shows clearly the mechanism how wettability affects heat transfer process. As we know, boiling parameters such as active site density are affected by the surface wettability. At a given wall superheat, the heating surface with higher contact angle has the higher density of active sites; then the number of dry spots increases and the number of effective sites for heat transport through the wall decreases relatively. Consequently, the heat transfer rate of the surface with higher contact angle is smaller than that of lower contact angle surface in transition boiling. Figure 6(b) shows the predicted fraction of wetted area as a function of wall superheat for various contact angles. It can be seen that at a given superheat, surfaces with small contact angles have much larger fractions of wetted area.

The estimated fraction of wetted area for contact angle of 27° is presented in Fig. 7. On the abscissa, the ratio $\Delta T/\Delta T_{CHF}$ is plotted. The figure also shows comparison among the measured data by several investigators [7, 11, 16–19], analytical results from Pan et al. [30] for contact angle 30° and Kalinin et al.'s correlation [1]. To plot Kalinin et al.'s correlation, data of temperature difference at CHF and MHF points for contact angle 27° from Liaw and Dhir [12] were used. The measured data show

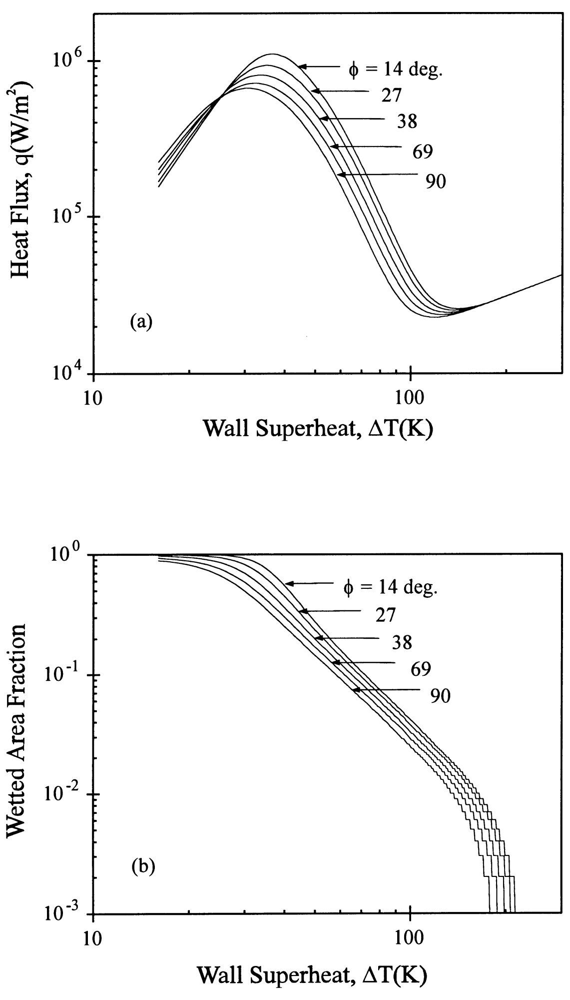

Fig. 6. Effect of surface wettability: (a) boiling curve; (b) the fraction of wetted area.

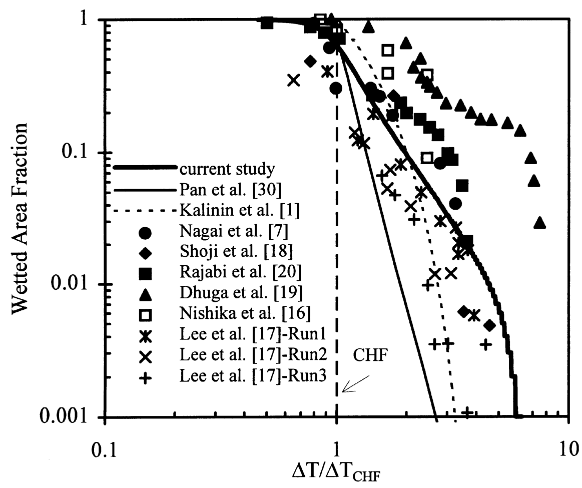

Fig. 7. Fraction of wetted area as a function of wall superheat (●: time- and space-averaged; ◆■▲: space-averaged; other symbols: time-averaged).

large scattering and the scattering may be due to the difference of test conditions and measuring techniques of each experimental facility. The prediction from current study shows that the fraction of wetted area rapidly decreases with increasing wall superheat and that the fraction of wetted area is far below unity at CHF. The predictions are in qualitative agreement with the trends of experimental data.

5. Conclusions

(1) A theoretical model of transition boiling has been proposed. When measured data of boiling parameters in nucleate boiling and extension of the data into transition boiling as a function of wall superheat are used as input to the model, the model predictions of the transition boiling heat flux and the fraction of the wetted area compare quite well with the existing data.
(2) The principal mechanism of heat transfer is pure nucleate boiling which occurs over the wetted area in transition region except near the MHF point.
(3) The fraction of wetted area rapidly decreases with an increase in wall superheat and the fraction is far below unity at CHF.
(4) By means of the model, the effect of the surface wettability on transition boiling can be reasonably explained.
(5) The results suggest that heat transfer mechanism in transition boiling has close relation with that in nucleate boiling. Boiling parameters such as active site density and bubble departure diameter, etc., which are known as key factors in predicting heat flux in nucleate boiling, is also important to predict heat flux in transition boiling.

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