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Statistical Model to Describe Boiling Phenomena for High Heat Flux Nucleate Boiling and Critical Heat Flux

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Abstract

The new concept of dry area formation based on Poisson distribution of active nucleation sites and the concept of the critical active site density is presented. A simple statistical model is developed to predict the change of slope of the boiling curve up to critical heat flux (CHF) quantitatively. The predictions by the present model are in good agreement with the experimental data. Also it turns out that the present model well explains the mechanism on how the surface wettability influences CHF.

1. Introduction

The advent of high power systems such as nuclear reactors and spacecraft gave a great impetus to research into boiling heat transfer over last several decades. A number of efforts have been made to study and predict heat transfer during boiling.

Of the three boiling heat transfer regimes (nucleate, transition, and film boiling), nucleate boiling is the most important regime for industrial applications. The nucleate boiling on a classical boiling curve of heat flux versus wall superheat starts with incipient boiling and extends until the first boiling crisis, CHF takes place. The typical regions of nucleate boiling classified by Gaertner (1965) from his experimental study are (a) incipient boiling, (b) discrete bubble region, (c) first transition region, (d) vapor mushroom region, (e) second transition region, and (f) CHF.

Studies of the CHF phenomena mainly fall into three categories (Hsu and Graham, 1976): empirical correlation (Kutateladze, 1951), bubble interactions (Rohsenow, 1956), and hydrodynamic instability models (Zuber, 1961). For the empirical models, the CHF is expressed in terms of dimensionless groups. Bubble interaction considers the CHF to be limited by the removal rate of bubbles, which carry away the heat in the form of evaporation. This theory was based on critical bubble spacing near the heated surface. The hydrodynamic model is based on the instability of a wave at the liquid/vapor interface. However, these models exclude any existing influences of the heating surface conditions such as wettability and the thermal properties of the surface material on CHF, which have been known to have very large influences on nucleate boiling crisis.

There are two main reasons to the lack of overall mechanistic description of CHF. Firstly, the onset of burnout is very sensitive to the several parameters such as a kind of liquids, the bulk temperature of liquid, system pressure, heater type, size, and configuration, gravity (acceleration or deceleration), heating surface inclination, side wall and immersion depth, heater material and thickness, surface condition, confined space, heater vibration and fluid vibration, electric field, magnetic field, heating method, etc. Secondly, the instability that leads to CHF has not been observed directly. Only the gross CHF process has been observed.

The purpose of the study is to develop a model for CHF based on the mechanism of dry spot formation on heating surface. We also consider the mechanism of surface wettability effects on CHF.

2. Boiling Phenomena

2.1 Poisson Distribution of Active Nucleation Sites

Poisson distribution is a form of statistical distribution to describe the distribution of members of a random sample in cells. The mathematical form is

$$P(NA)=\frac{(\overline{N}A)^{NA}e^{-\overline{N}A}}{(NA)!}. \tag{1}$$

where A is sub-area, N local nucleation density and $\overline{N}$ average nucleation density.

Gaertner et al.(1960) first discovered that the bubble sites on a boiling surface are randomly distributed and can be represented by Poisson distribution. Furthermore, Gaertner (1965) reported that with increasing heat flux and bubble population, the bubble configuration transits from discrete bubbles regime to that of multi-stem bubbles feeding into hovering vapor mass. Hsu (1964) studied the multi-bubble distribution and found that the area fraction covered by the multi-bubble can be approximately represented by the probability $P(NA\geq 2)$. Del Valle and Kenning (1985) reported that although the bubble site distribution can be represented by Poisson distribution, the nearest distance between bubbles cannot be represented by Poisson distribution. Hsu and Kim (1988) proposed a statistical approach to treat transition boiling. The transition boiling curve is simulated by a Poisson distribution model. Given the location of a maximum or minimum point, the model can basically handle the surface effect, with the exception of surfaces having very large or very small contact angles. Wang and Dhir (1993) reported that the distribution of local cavity population densities is described by the Poisson distribution and the distribution of nearest-neighbor distance by the modified Poisson distribution, respectively.

Kang et al. (1994) proposed a probability model using Poisson distribution to predict the transition points on the boiling curve. Unfortunately, they did not predict the curve quantitatively.

2.2 Reviews of Boiling Phenomena near CHF

In the nucleate boiling region, a distinctive feature is the generation of bubbles from preferential sites randomly located on the heating surface. Increasing superheat activates more nucleation sites, resulting in a rapid increase in heat flux and leading to a decrease in natural convection. With a further increase in surface superheat, bubbles interfere with each other and begin to coalesce. The former causes the formation of vapor columns and the latter causes the formation of dry patches under vapor mass. The dry patches on the heating surface yield much poorer heat transfer coefficients which are same as those in film boiling. The occurrence of the dry patches was believed to be the reason causing a change in slope of the nucleate boiling curve by Gaertner and Westwater (1960).

Kirby and Westwater (1965) and Van Ouwerkerk (1972) conducted pool boiling on a horizontal glass surface plated with an extremely thin conducting material. They observed that the dry spots sometimes grew in size, and neighboring ones would merge. Near the CHF, the dry spots were frequently generated and the coalescences of dry spots were common also. And Kirby et al. showed that the average diameter of a dry spot before they grew to large dry patches was about 0.25mm which size was almost the same as the maximum diameter of a bubble. If the heat flux was sufficiently high, at some point on the heated surface a dry area was not wetted and started growing, leading to burnout.

However, none of models we have discussed above consider the dry spots in the second transition region leading up to the CHF point.

2.3 New Model for Dry Spot Formation

As mentioned above, the local population distributions of active sites play an important part in boiling heat transfer. It has been suggested that the CHF corresponds to a situation where the number of sites is so great that every bubble coalesces with its neighbor, and together they form a continuous blank of vapor.

Gaertner (1965) hypothesized that the stems of the vapor mushrooms become hydrodynamically unstable in the local surface areas which have a certain critical active site population. Haramura and Katto (1983) proposed a macrolayer dryout model based on Gaertner's hypothesis, which a liquid sublayer (macrolayer) formed under hovering vapor mass is evaporated away during a hovering period and this sublayer is replenished only after each large bubble departs. However, these model exclude any existing influences of the heating surface conditions as mentioned previously. Lienhard (1988) pointed out that the sublayer could be replenished continuously.

In the present work, it is hypothesized that there will be a certain random local area on the surface that will achieve such a critical active site density that prevents the liquid supply to the microlayer formed under the bubble. Then an insulating dry spot of vapor will form on the surface. As the surface temperature is raised, more and more local areas of the surface will have a critical population of active sites. Both the number and size of the patches will increase, and the number of effective sites for latent heat transport through the wall will diminish. If this trend continues, the surface temperature of some parts of dry region will be reached to the temperature that dry surface cannot be rewetted and boiling crisis occurs. Such a model is compatible with the experimental observations.

3. Statistical Model of Boiling Heat Transfer

3.1 Basic Assumptions

(1) The nucleation site distribution obeys the Poisson distribution law, and the average site-to-site distance L is related to the site density as $L = \overline{N}^{-0.5}$ (Wang and Dhir, 1993).
(2) The statistical variations in bubble size and frequency are ignored.
(3) The heater surface temperature does not vary spatially.
(4) The effect of overlap between bubbles on heat transfer is not large.
(5) The boiling parameters measured in fully developed nucleate boiling can be applicable up to CHF.

3.2 Proposed Model

The proposed model used here can be easily extended to transition boiling region. However, the analysis is restricted within nucleate boiling region because of the lack of some boiling parameters at high wall superheat temperature.

In saturated pool boiling, the total heat flux q can be expressed as the sum of a nucleate boiling component, a single phase convective flux on the heating surface completely void of active sites, and a film boiling on dry area. The heat flux fractions due to single phase convective heat flux and due to film boiling are ignored in predicting the boiling curve up to CHF.

If an arbitrarily selected active site is chosen as the center of a circle having an average diameter of bubble d_{av} (shell area $A = \pi d_{av}^2$), the probability that no active site will be found in this circle other than the selected site, which is located in the center (probability equals 1), is given by Poisson equation

$$P(1\_0) = e^{-\overline{N}A} \ . \tag{2}$$

Similarly, the probability that n active sites will be found in a shell area A other than the selected site is

$$P(1\_n) = \frac{e^{-\overline{N}A}\left(\overline{N}A\right)^n}{n!}. \tag{3}$$

Then the probability that the number of active site is greater than or equal to the critical active site density, n_c, will be found in a shell area A is

$$P(1\_n \geq 1\_n_c) = 1 - \sum_{n=0}^{n_c-1} P(1\_n). \tag{4}$$

Therefore, the heat flux contributing to nucleate boiling is obtained as the following equation:

$$q = q_b\overline{N}\left(1 - P(1\_n \geq 1\_n_c)\right). \tag{5}$$

where q_b is heat flux transferred by single bubble activity. The heat flux, $q_b\overline{N}$, means physically the quantity of heat transfer by all bubbles activated without dry spot formation, and can be estimated by fitting the nucleate boiling data linearly on a logarithmic scale of boiling curve as a function of wall superheat temperature. Equation (5) is completely different from the conventional approach for generating complete boiling curves based on the area fraction of wetted region.

4. Results and Discussions

To demonstrate the appropriateness of the present model based on the mechanism of dry spot formation and the statistical model, a comparison of the predictions by Eq.(5) with the experimental data reported by Liaw (1988), Wang and Dhir (1993) is done. The experiments were performed for atmospheric pool boiling of water and include the effect of surface wettability. Though there exist some deviations, the transition on the boiling curve can be reasonably predicted by the model as shown in Fig.1. And it is shown that the present model explains the surface condition effects on CHF very well. With the comparison to the experimental data, it is concluded that the critical site density is five. For more accurate prediction of the boiling curve including transition region, one of key issues is the knowledge of boiling parameters such as the active nucleation site density and the bubble departure diameter as a function of surface conditions and wall superheat temperature.

5. Conclusions

(1) Based on the physical structure mentioned above, a statistical model has been developed. The model has been validated with existing data.

(2) The contributing mechanism for dry spot formation is that when a number of bubbles surrounding one bubble exceed the critical number, then these bubbles restricts the feed of liquid to the thin liquid film (microlayer) under the bubble located at center.

(3) Both the number and size of the dry spots will increase with increasing the wall superheat temperature, and as a result, the number of effective nucleation sites will diminish and the rate of heat transfer decreases.

(4) For the better prediction of boiling curve, the concept of the fraction of effective nucleation sites rather than the fraction of the effective area of the wetted region should be used.

(5) The suggested model well predicts the effects of the wettability on CHF.

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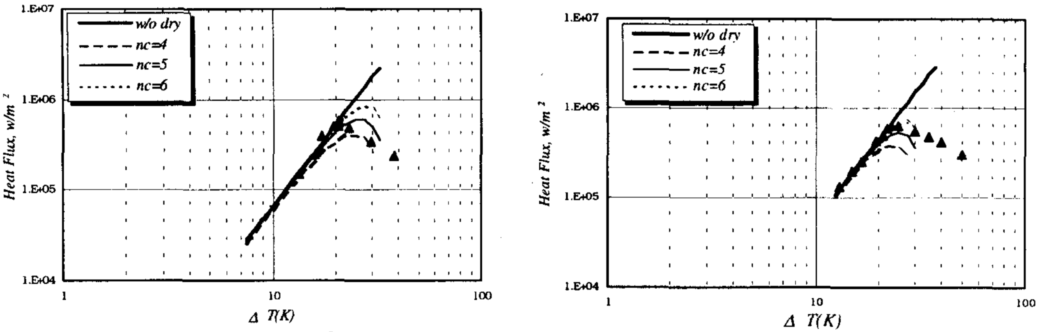
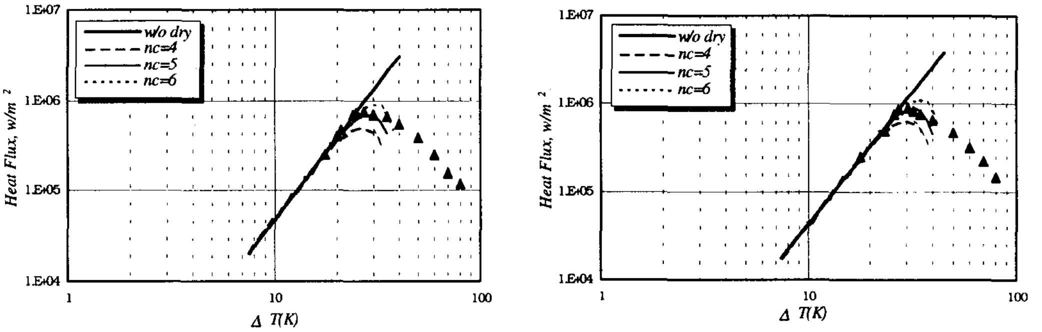


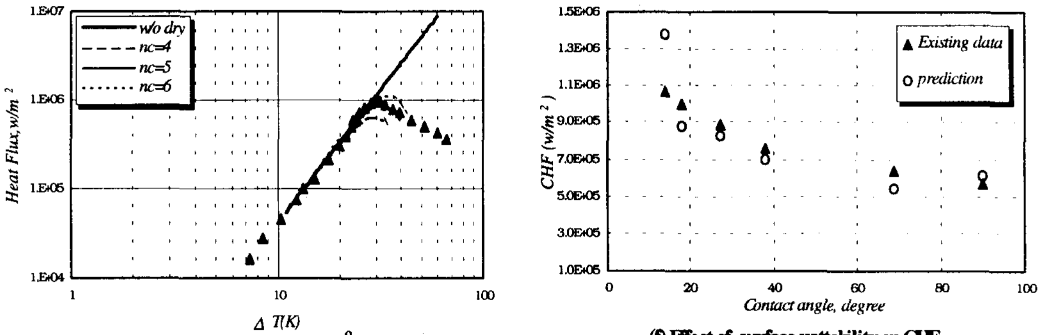
(a) Contact Angle : 90°

(b) Contact Angle : 69°



(c) Contact Angle : 38°

(d) Contact Angle : 27°



(e) Contact Angle : 18°

(f) Effect of surface wettability on CHF

Figure 1. Comparison of predictions and experimental data; (a)-(d) : Liaw (1988); (e) : Wang et al. (1993);(f) : CHF with n_c=5; symbol (▲) : Experimental data