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A Dry-Spot Model for the Prediction of Critical Heat Flux in Water Boiling in Bubbly Flow Regime

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Abstract

This paper presents a prediction of critical heat flux (CHF) in bubbly flow regime using dry-spot model proposed recently by authors for pool and flow boiling CHF and existing correlations for forced convective heat transfer coefficient, active site density and bubble departure diameter in nucleate boiling region. Without any empirical constants always present in earlier models, comparisons of the model predictions with experimental data for upward flow of water in vertical, uniformly-heated round tubes are performed and show a good agreement. The parametric trends of CHF have been explored with respect to variations in pressure, tube diameter and length, mass flux and inlet subcooling.

1. Introduction

Operation at heat fluxes safely below the critical remains a major design limitation for water cooled reactors. Therefore, it is necessary to have reliable design tools, such as correlations and models. The correlations can provide quick input to design and safety issues. However, the usefulness of the correlations diminishes very rapidly as parameters of interest start to fall outside the range of parameters for which the correlations were developed. As is known, models have the advantage, with respect to correlations, to characterize not only the developing database, but also to be used for the prediction of the CHF beyond the operating conditions of reference data set. Unfortunately, as pointed out by Weisman (1992) and Celata (1993), a full understanding of the basic CHF mechanisms in bubbly flow regime including subcooled or low-quality boiling has not been accomplished so far. Consequently, existing models proposed e.g. by Weisman and Ileslamlou (1988), Lee and Mudawar (1988) and Katto (1992) make use of empirical parameters deduced from a best-fit procedure through available CHF data sets. Similarly to correlations, their use outside the experimental ranges of developing data sets can not therefore be reliable. Furthermore, the empirical constants or parameters tend to cloud the mechanism of CHF. Recently Celeta et al. (1994) tried to eliminate all the empiricisms through rationalization of liquid sublayer dryout model proposed by Lee and Mudawar (1988) and Katto (1992) without any change of physical nature of the model. The liquid sublayer dryout model is based on macrolayer dryout model (Haramura and Katto, 1983) postulating the onset of CHF due to the dryout of a thin liquid layer (macrolayer) underneath a vapor blanket. In spite of rather good agreement of the macrolayer dryout model and experimental data, there are some reasons which make one to doubt the validity of the physical features of the model as pointed out by Ha and No (1997).

Meanwhile, as noted by Whalley (1987) and Katto (1990), it is widely admitted that CHF of subcooled or low quality flow boiling has strong similiarities to pool boiling CHF, both in mechanism and in behavior.

On this point, it may be of interest to note that present authors (Ha and No, 1977) have already presented a phenomenological dry-spot model of saturated pool boiling CHF and subcooled flow boiling CHF based on the common mechanism that CHF is caused by the accumulation and coalescences of dry spots formed through dryout of the microlayer under a bubble. One of important features of dry-spot model is that CHF has close relation with the boiling phenomena in nucleate boiling region. In other words, if the information on boiling parameters such as active site density and bubble departure diameter, etc. in nucleate boiling region is known, CHF can determined.

The aim of the present paper is to attempt to predict CHF in bubbly flow regime using the dry-spot model and existing correlations for forced convective heat transfer coefficient, active site density and bubble departure diameter in nucleate boiling region. The predicted CHF values will be compared with data for upward flow of water in vertical, uniformly-heated round tubes. Parametric trends will also be studied.

2. Summary of Dry-Spot Model

The model is based on the boiling phenomena in nucleate boiling region such as Poisson distribution of active nucleation sites, a dramatic increase in the active nucleation site density with an increase in wall superheat temperature and fluid flow in the thin liquid film (microlayer) under a bubble. It was hypothesized that when the number of bubbles surrounding one bubble exceeds a critical number, the surrounding bubbles restrict the feed of liquid to the microlayer under the bubble. Then an insulating dry spot of vapor will form on the heated surface. As the surface temperature is raised, more and more bubbles will have a population of surrounding active sites over critical number. Consequently, the number of the spots will increase and the size of dry areas will increase due to merger of several dry spots. If this trend continues, the number of effective sites for heat transport through the wall will diminish and CHF occurs. The overall heat flux is expressed as the following equation:

$$q = q_b \overline{N}\left(1 - P(n \geq n_c)\right), \tag{1}$$

where

$$P(n \geq n_c) = 1 - \sum_{n=0}^{n_c - 1} P(n), \tag{2}$$

$$P(n) = e^{-\overline{N}A}\left(\overline{N}A\right)^n / n!, \tag{3}$$

q_b is heat transferred by single bubble site, $\overline{N}$ active site density, $A = \pi d_{av}^2$, and n_c is critical site number to form dry spot under bubble. For water flow boiling, the calculation of the quantities $\overline{N}$, d_{av} and q_b in above equations will be presented in the following section.

3. Correlations for Boiling Parameters in Forced Convective Nucleate Boiling

Boiling parameters such as active site density and bubble departure diameter are known as key factors to predict pool and forced convective nucleate boiling heat transfer. However, in the case of forced convective boiling, there are very few experimental data providing quantitative information. Based on the concepts of the mechanistic similarity in bubble nucleation between pool boiling and forced convective boiling, Kocamustafaogullari and Ishii (1983a) correlated the nucleation site density and bubble departure diameter for water flow boiling for pressures range of 1-50 bar as

$$\overline{N}^* = \left[d_c^{*-4.4} F(\rho^*)\right]^{1/4.4}, \tag{4}$$

where

$$\overline{N}^* = \overline{N} d_{\max}^2; \quad d_c^* = d_c / d_{\max}, \tag{5}$$

$$d_{\max} = 0.0012\left(\rho^*\right)^{0.9} d_F, \tag{6}$$

$$F(\rho^*) = 2.157 \times 10^{-7} \rho^{*-3.2}\left(1 + 0.0049\rho^*\right)^{4.13}. \tag{7}$$

In the above equations, d_F is the bubble departure diameter of Fritz given as $d_F = 0.0208\phi\left(\sigma / g\Delta\rho\right)^{1/2}$ and the parameters ρ^* and d_c are defined as

$$\rho^* = \left(\rho_f - \rho_g\right)/\rho_g, \tag{8}$$

$$d_c = 4\sigma\left(1+\left(\rho_f/\rho_g\right)\right)\Big/\left(P_f\left(\exp\left(h_{fg}\left(T_g - T_{sat}\right)/R_g T_g T_{sat}\right)-1\right)\right). \tag{9}$$

The correlation for bubble departure diameter, eq. (6), can be applicable for water over a pressure range of 1-140 bar (Kocamustafaogullari and Ishii, 1983b) and contact angle ϕ in Fritz's equation represents the characteristic of the combination of liquid and surface. To evaluate the vapor temperature T_g in eq. (9), they introduced the concept of a suppression factor S proposed by Chen (1966)

$$S = \left(\Delta T_e/\Delta T_{sat}\right)^{0.99} \tag{10}$$

where $\Delta T_e = T_g - T_{sat}$. S can be calculated from fitting Chen's representation for F and S

$$S = 1/\left(1+1.5X10^{-5}\,\mathrm{Re}_{TP}\right), \tag{11}$$

$$F = 1.0 \text{ for } X_{tt} \geq 10, \tag{12}$$

$$\text{and } F = 2.35\left(0.213+1/X_{tt}\right)^{0.736} \text{ for } X_{tt} < 10, \tag{13}$$

where Re_{TP} is a two-phase flow Reynolds number and X_{tt} is the Martinelli parameter. For simplicity the power 0.99 in eq. (10) replaced by 1.0 and the effective superheat is calculated by

$$\Delta T_e = S\Delta T_{sat} \tag{14}$$

with S and ΔT_e predicted, respectively, by eqs. (11) and (14), $\overline{N}$ can be predicted using eq.(4). Time-averaged bubble diameter d_{av} can be calculated from eq. (6) assuming that the bubble diameter varies with times as $t^{1/2}$ (Han and Griffith, 1965).

Chen's heat transfer correlation has been proved to be reliable in subcooled and saturated nucleate boiling (Collier and Thome, 1994). For the subcooled boiling, the total heat flux in nucleate boiling, q_{nb}, can be represented as following equation:

$$q_{nb} = h_{NB}\left(T_w - T_{sat}\right) + h_c\left(T_w - T_f(z)\right) \tag{15}$$

where

$$h_{NB} = 0.00122\left(k_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49} / \sigma^{0.5} \mu_f^{0.29} h_{fg}^{0.24} \rho_g^{0.24}\right)\Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} S, \tag{16}$$

$$h_c = 0.023\left(G(1-x)D/\mu_f\right)^{0.8}\left(\mu c_p/k\right)_f^{0.4}\left(k_f/D\right)(F). \tag{17}$$

For the subcooled boiling, the nucleate boiling coefficient h_{NB} is evaluated from eq. (16) with the value of S obtained from the single-phase liquid Reynolds number and the convective heat transfer coefficient h_c is obtained from eq. (17) with F set equal to unity.

Assuming that each bubble site has uniform heat duty, the heat transfer q_b in eq. (1) can be evaluated from following equation:

$$q_b = q_{nb}/\overline{N} \tag{18}$$

4. Results and Discussions

4.1. Comparison with CHF Data

The present model is compared with the CHF data from KAIST CHF data base (Chang et al., 1996) for upward flow of water in vertical, uniformly-heated round tubes. To extract CHF data in bubbly flow regime at CHF conditions from this data base, flow regime transition criteria proposed by Mishima and Ishii (1984) was used. The range of pressure was limited within available range of eq. (6), i.e. 1-140 bar. It is assumed that the validity range of Chen correlation and active site density correlation, eq. (4), can be extended in the range of data set used in the present study. The data set consists of 2627 data points covering the following operating ranges: $1 \leq P \leq 140$ bar; $0.33 \leq D \leq 37.5$ mm; $0.002 \leq L \leq 3.66$ m; $350 \leq G \leq 90000$ kg/m^{2}s; $58 \leq \Delta h_i \leq 1460$ KJ/kg. As for the value of contact angle, Hsu and Graham (1976) reported that with most industrial metals water exhibits a contact angle of 40°-60°. Figure 1 shows a comparison of experimental vs calculated CHF with contact angle 50°. About 57% of calculated data points are predicted within ±30%, with a r.m.s. of 39.5%. Though there are slightly higher prediction error, it can be concluded that present model can predict CHF data reasonably well without any correction factors. The major contributor to prediction errors is considered as the uncertainty, ±33% averaged deviation, involved in bubble departure diameter correlation. Kocamustafaogullari and Ishii (1983b) developed the correlation assuming that bubble departure diameter depends on pressure only and ignoring effect of other boiling conditions such as flow conditions and wall superheat temperature, etc. Due to large suppression in active site density, 1110 points out of 2627 can not be calculated. The dependency of predicted CHF on contact angle are reported in Table 1. They are also compared with existing correlations developed by Bowring (1972) and Katto and Ohno (1984). The comparison is limited to the data within the applicable range of each correlation. As the contact angle increases, average prediction to measured CHF ratios (CHFR) decrease and calculated data points increase. This is due to the fact that present model largely depends on $\overline{NA}$, i.e. larger bubble diameter occurs premature CHF.

4.2. Parametric Trends

Parameters affecting the CHF in vertical tube, as given by Collier and Thome (1994), are pressure (P), diameter (D), length to diameter ratio (L/D), mass flux (G) and inlet subcooling (Δh_i). The parametric trends of CHF at subcooled or low quality conditions can be summarized as follows: (1) CHF increases with pressure, passes through a maximum, and then drops off, (2) CHF increases as tube diameter increases, (3) CHF decreases as tube length increases, (4) CHF increases as mass flux increases, (5) CHF increases with increasing degree of subcooling.

Figures 2-6 show the parametric effects on CHF predicted by present model. The figures also show a comparison with the predictions by Bowring (1972)'s correlation. Figure 2 shows that present model provides the similar trend with the predictions by the correlation for a wide range of P. Figure 3 shows CHF plotted against tube diameter. As the tube diameter is increased, the CHF increases at constant inlet subcooling. Figure 4 shows CHF plotted against tube length to diameter ratio. As the tube length is increased, CHF decreases. Figure 5 shows CHF plotted against mass flux. The CHF increase as mass flux increases. Figure 6 shows CHF plotted against inlet subcooling. CHF appears to increase linearly with inlet subcooling. Conclusively, the parametric trends from present model coincide well with those observed in experiments and correlation compared.

5. Conclusions

(1) A study has been attempted to predict CHF in bubbly flow regime using dry-spot model presented recently by the authors and existing correlations for forced convective heat transfer coefficient, active site density and bubble departure diameter in nucleate boiling.

(2) Model predictions of CHF were compared with experimental data without any correction factors and Parametric trends were studied. The results coincide well with those observed in experiments.

(3) The results of present study strongly support the validity of physical feature of dry-spot model for subcooled or low-quality boiling CHF.

(4) To improve the prediction capability and accuracy, further work on active site density and bubble departure diameter will be required.

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Table 1. The Dependency of prediction accuracy on contact angle and comparison with existing correlations

reference	Bowring (1972)	Katto and Ohno (1984)	present model				
contact angle (deg.)			90	70	60	50	40
CHFR	0.85	1.22	0.78	0.85	0.87	0.91	0.97
r.m.s. (%)	29.7	37.4	38.7	39.0	38.5	39.5	41.3
calculated data points	1465	2389	2394	2111	1811	1517	1172

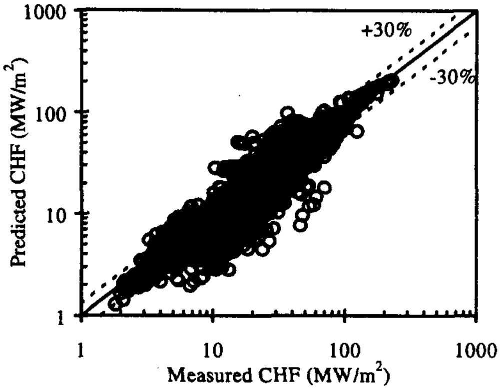

Fig. 1. Experimental vs calculated CHF using the data set in bubbly flow regime.

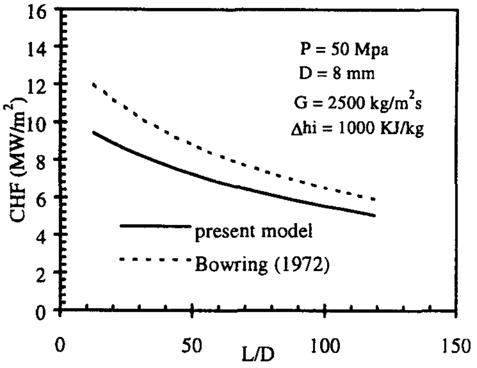

Fig. 4. Tube length to diameter effect on CHF

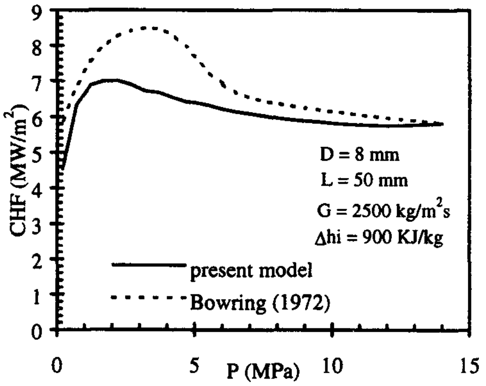

Fig. 2. Pressure effect on CHF

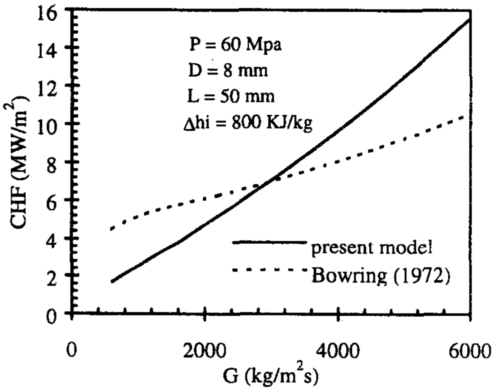

Fig. 5. Mass flux effect on CHF

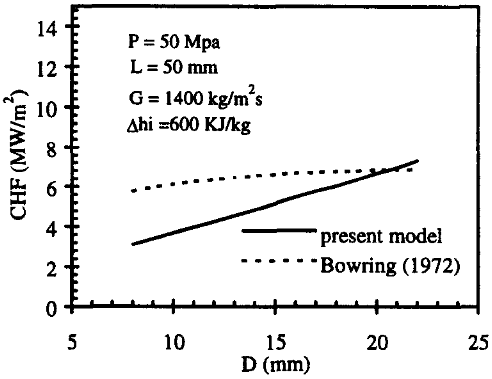

Fig. 3. Tube diameter effect on CHF

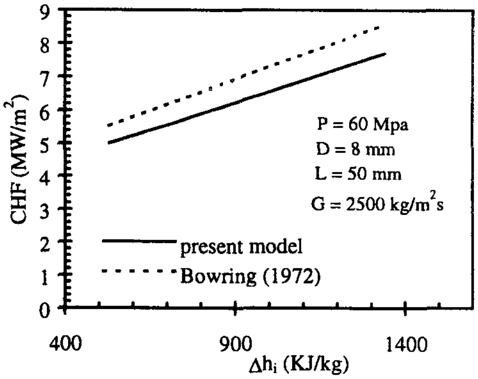

Fig. 6. Inlet subcooling effect on CHF