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An Improved Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling

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Abstract

Based on the bubble coalescence adjacent to the heated wall as a flow structure for CHF condition, Chang and Lee developed a mechanistic critical heat flux (CHF) model for subcooled flow boiling. In this paper, improvements of Chang-Lee model are implemented with more solid theoretical bases for subcooled and low-quality flow boiling in tubes. Nedderman-Shearer's equations for the skin friction factor and universal velocity profile models are employed. Slip effect of movable bubbly layer is implemented to improve the predictability of low mass flow. Also, mechanistic subcooled flow boiling model is used to predict the flow quality and void fraction. The performance of the present model is verified using the KAIST CHF database of water in uniformly heated tubes. It is found that the present model can give a satisfactory agreement with experimental data within less than 9% RMS error.

I. Introduction

Critical heat flux (CHF) in subcooled forced flow boiling has long been investigated mainly in relation to the design and safe operation of nuclear reactors including light water reactors and fusion reactors. Due to the difficulty in performing detailed flow visualization of the near-wall when heat flux approaches and exceeds CHF condition, many of the present models have been based on postulated mechanisms not verified through direct observation. Among many existing analytical models available today, both the bubble coalescence and the sublayer dryout models are capable of providing reasonably accurate predictions against experimental CHF data. However, neither have become generally accepted as the correct explanation for triggering CHF. Currently, there is insufficient evidence to state definitely that either the bubble coalescence or the sublayer dryout model is correctly describing the true CHF trigger mechanism. According to reviews by Celata [1] and Katto [2], the bubble coalescence model gives good results for medium-to-low subcooling or nearly saturated flow boiling. The model is the most suitable to predict the CHF with fluids other than water, especially refrigerants.

Developed in this paper is a modified Chang-Lee model [3,4], belong to the bubble coalescence model, where the CHF formula are derived form the mass, energy and momentum balance equations at the CHF conditions. The major improvements of Chang-Lee model includes the following: 1) The mechanistic subcooled flow boiling model by Lahey and Moody [5] is employed to evaluate the flow quality and void fraction. 2) Slip effect between vapor and liquid in the bubbly layer is considered. 3) Universal logarithmic velocity profile for a single phase flow is assumed to be valid in the core region, while the velocity profile in the bubbly layer is assumed to be linear. 4) CHF prediction procedure to reach converged result is modified.

II. Phenomenological model for subcooled flow boiling

A hypothetical flow structure near the wall at CHF condition is considered as shown in Fig. 1. Two-phase flow in a subcooled boiling in tube is not the separated flow but takes the form of "semi-reversal-annular" flow pattern. The outer annular layer is bubbly layer in which independent bubbles compact on the wall just prior to agglomeration and in the middle of the pipe is a mixture core consisting of liquid and bubbles. The bubble compaction or crowding occurred near the CHF location is caused by that vapor bubbles may grow and collapse whilst still attached to, or slide along the heating surface from upstream. The existence of bubbly layer plays the physical barrier of heat transfer from the wall and liquid supply from the core region.

In the Chang-Lee model, turbulent interchange between the bubbly layer and the core region is assumed to be the limiting mechanism of the onset of CHF. In the original Chang-Lee model [3], the mass and energy balances are derived based on the assumption that bubbly layer stagnates at the CHF conditions, subsequently a modified CHF formula without imposing the stagnated bubbly layer was presented in the Ref.4. From simple mass balances over the bubbly layer, Chang and Lee obtained (see Nomenclature)

$$q_b'' = G^*(x_b - x_c)h_{fg}\xi_i / \xi_w \tag{1}$$

Using Eq.(1) and an energy balance over the bubbly layer, they obtained the CHF equation with related to a boiling heat flux, q_b,

$$q_b'' = q''_{CHF}F_q = \frac{q''_{CHF}h_{fg}(x_b - x_c)}{(h_f - h_{ld}) + h_{fg}x_b - (h_g - h_l)x_c} \tag{2}$$

where the factor, F_q, represents the fraction of the heat flux producing vapor that enters the core region. The qualities in Eq.(2) are actual flow qualities and determined subcooled flow boiling model. The value of x_b is calculated as the quality corresponding to the void fraction of the bubbly layer to be determined later by empirical constant. The quantity, G^*, in Eq. (1) represents a limited mixing mass flux defined at the CHF condition. This mass flux is determined by one-dimensional momentum equations of separated flow model [5]. From momentum balance equations on the core region and bubbly layer, the transverse interchange of mass flux at the bubbly-core interface is obtained.

$$G^* = \left[-(\rho_c - \rho_b)g + \frac{\tau_w \xi_i}{A\beta_c(1-\beta_c)} + \Phi_{acc}\right]\frac{A\beta_c(1-\beta_c)}{(U_c - U_b)\xi_i} \tag{3}$$

In which the wall shear stress, τ_w, was assumed in downward force direction at the core and bubbly interface, because the bubbly layer is assumed to act as uniform roughness elements. Flow sees the bubbly layer as a wall roughness, therefore the friction factor depends upon the height of bubbly layer. The wall shear stress, τ_w, is calculated as follows; $\tau_w = 0.5 * f_w * \rho_c * U_c^2$. Nedderman and Shearer's [6] friction factor model was employed to determine the roughness size distribution due to the bubbly layer which projects beyond the laminar sublayer, i.e.,

$$\frac{1}{\sqrt{f_w}} = 3.48 - 4\log_{10}\left\{\frac{2\varepsilon}{D} - \frac{10\sqrt{2}}{\mathrm{Re}\sqrt{f_w}}\right\} \tag{4}$$

Also, Chang and Lee have shown that the acceleration term, Φ_{acc}, was small with respect to radial mixing flow effect and may be neglected. In the prediction of CHF using above equations, only two empirical coefficients, such as critical void fraction in the bubbly layer, α_b, and bubbly layer thickness, s, are required indirectly. The quantity, s, is empirically determined as k times the bubble detachment diameter. These coefficients were determined by fitting a large number of experimental CHF data. The values of α_b and k were found to be 0.75 and 1.5 in Ref.3, respectively.

III. Revised model

In the Chang-Lee model, the bubbly layer was assumed to be homogeneous so that the value of x_b corresponding to the critical void fraction of the bubbly layer was calculated assuming zero slip between vapor and liquid phases. As Weisman and Ying [7] pointed out, this assumption becomes invalid when the flow velocity is reduced. To account for slip effect in calculating the quality of bubbly layer, the relative velocity of the vapor in the bubbly layer is assumed to be equal to the bubble rise velocity recommended by Zuber et al [8]. Since the bubbly layer is very thin, a linear velocity profile is assumed. Therefore, average velocity of bubbly layer, U_b, is equal to one half of the velocity of core fluid adjacent to the bubbly layer. The velocity profile for turbulent flow through a tube is represented by the Nedderman-Shearer's [6] universal velocity equation as a function of distance from the wall.

$$U_l = \sqrt{\frac{\tau_w}{\rho_c}}\left[5.657\log_{10}\left(\frac{y\sqrt{\tau_w\rho_c}}{s\sqrt{\tau_w\rho_c} - 5\mu_c}\right) + 8.485\right] \tag{5}$$

The vapor velocity in the bubbly layer is assumed to be the superposition of the local liquid velocity and the relative velocity of the vapor. Compared to Chang-Lee model, the bubbly layer quality considering slip, x_b, and mean velocities of U_b and U_c can be determined in the present model

In the calculation of CHF, a subcooled flow boiling model is required to predict the flow quality and void fraction. The subcooling at the bubble detachment position is a very important parameter in determining the bubble detachment or initial point of significant void generation. All existing subcooled boiling models, basically, fall into two categories: profile-fit models and mechanistic models. Profile fit models are fully empirical, while the mechanistic models satisfy some conservation laws but use some degree of empiricism for closure. A profile-fit model suggested by Levy [9] was used in the Chang-Lee model. It is known that the profile-fit method is normally easier to use than a mechanistic model and is as accurate for steady-state calculation. However, since this simple model is based on a fit to uniform axial heat flux data, it is unconfirmed in the case of nonuniform axial heat flux. Furthermore, the profile-fit method is inadequate for cases where condensation of detached bubbles is significant. In the present CHF model, Lahey and Moody's [5] mechanistic model is employed to evaluate the flow parameters in the subcooled flow boiling.

In order to close the equations for CHF prediction, additional relationships are needed regarding parameters such as bubble diameter at departure, friction factor model and quality-void relationship, etc. The same models as used in Chang-Lee model are utilized in the present CHF model. It should be noted that the predictive scheme of the Chang-Lee model was modified to improve a predictability, so that all the experimental CHF data could be reproduced by the present model.

IV. Comparison of revised theory with experimental data

Prediction using the present theoretical CHF model are compared with the experimental CHF data by examining the statistical results of CHFR, defined as the predicted CHF to measured CHF. A perfect CHF correlation will give CHFR value of 1.0 for every data point. The same data base used in the improved Chang-Lee model [4] was utilized to evaluate the performance of the present model. A total of 736 water CHF data points for uniformly heated vertical round tubes were collected from KAIST CHF data base. The parametric ranges of the CHF data base are length-to-diameter ratios from 20 to 700, mass fluxes from 374 to 7485 kg/m^{2}s, pressures from 6.7 to 20 MPa, outlet qualities from -0.5 to 0.01, and critical heat fluxes from 643 to 14,764 kW/m^2.

The values of α_b and k are varied so as to obtain an average CHFR of ~1.0 while minimizing a r.m.s of CHFR. The best constant value of α_b was found to be 0.54 and k to be 2.5. The present model predicts all data points within 8.7 % standard deviation with a r.m.s. of 8.71%, while the original Chang-Lee model [3] predicted within about 12% standard deviation of CHFR. The improved Chang-Lee model[4] predicted within 11% standard deviation, although the predictability increased against Ref.3. Fig.2 shows that that most of the experimental data are successfully predicted within 20% error bounds. Few points in the outside of error bounds belong to the prediction at low mass fluxes. To show the visual comparison of the predicted and measured CHF and the dependences of the prediction accuracy on major parameters, Fig.3 through Fig.5 are presented.

V. Conclusions

An improved theoretical CHF model has been implemented for subcooled flow boiling in tubes. The improved model is constructed on more solid theoretical bases and is considered to be reasonable from the physical standpoint. The comparison of the predictions with the experimental CHF data shows that the prediction can be performed within 20% error bounds with two empirical constants. The overall mean ratio of predicted to measured CHF values is 0.998 with a standard deviation of 8.7% and a r.m.s. error of 8.71%

Nomenclature

A	cross-section area,
D	diameters of tube,
G^*	limited mixing mass flux,
f	skin friction factor,
g	acceleration due to gravity,
h	enthalpy,
q''	heat flux,
U	mean velocity,
x	flow quality,
y	distance from the heated wall,
α	void fraction,
β	*fraction of cross-section,*
ε	roughness height,
ρ	density,
μ	viscosity
τ	shear stress,
ξ	perimeter..

subscripts

b	bubbly layer,
c	core,
CHF	at CHF condition,
eq	thermodynamic equilibrium,
f	saturated liquid,
g	vapor phase,
i	at the interface of bubbly layer and core,
l	subcooled liquid,
ld	at the bubble detached point
w	at the heated wall.

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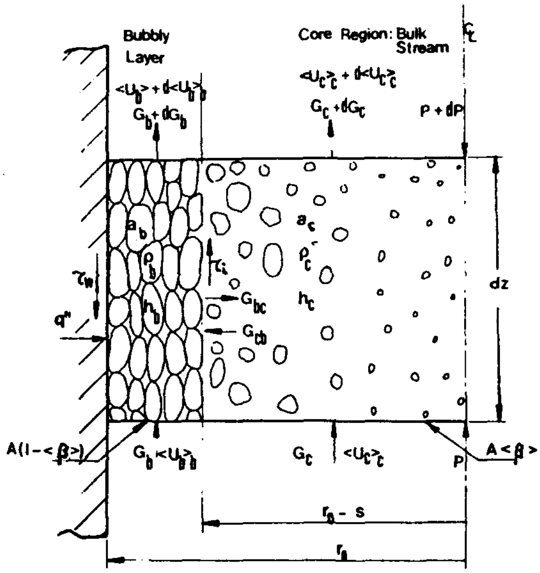

Fig.1 Schematic diagram for the physical model

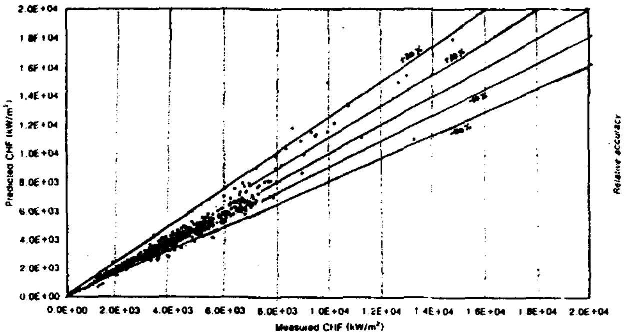

Fig.2 Comparison of predicted and measured CHFs

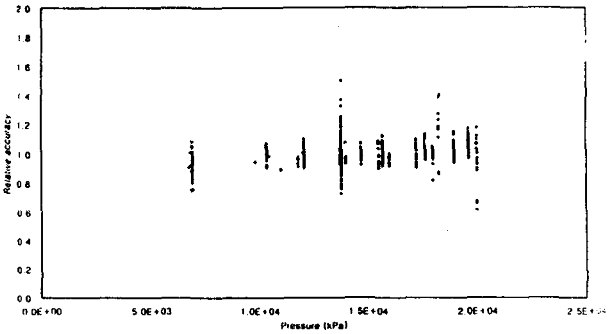

Fig.3 Dependency of prediction accuracy on pressure

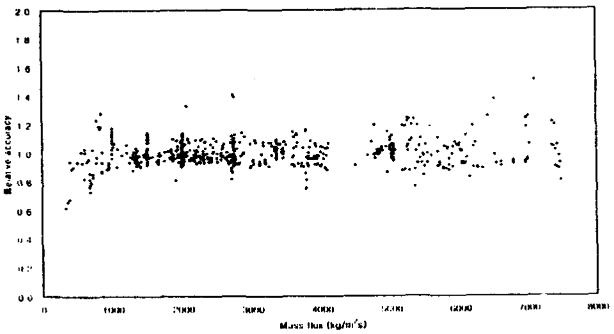

Fig.4 Dependency of prediction accuracy on mass flux

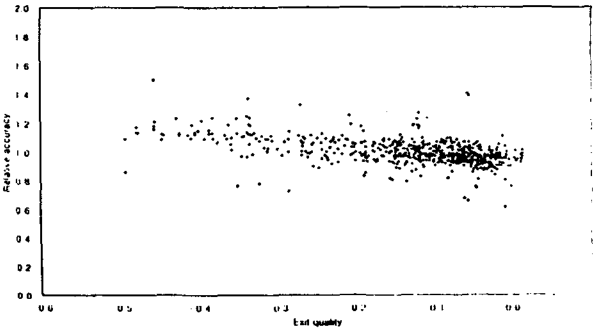

Fig.5 Dependency of prediction accuracy on exit qualit