A Theoretical Model of Critical Heat Flux in Flow Boiling at Low Qualities

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A new theoretical critical heat flux (CHF) model was developed for the forced convective flow boiling at high pressure, high mass velocity, and low quality. The present model for an intermittent vapor blanket was basically derived from the sublayer dryout theory without including any empirical constant. The vapor blanket velocity was estimated by an axial force balance, and the thickness of vapor blanket was determined by a radial force balance for the Marangoni force and lift force. Based on the comparison of the predicted CHF with the experimental data taken from previous studies, the present CHF model showed satisfactory results with reasonable accuracy.

Key Words : Critical Heat Flux, Flow Boiling, Sublayer Dryout Model, Theoretical Model, Pressurized Water Reactor

Nomenclature

A_g	: Cross sectional area of bubble stem
A_W	: Wall surface area
C_0	: Distribution parameter
C_L	: Lift coefficient
c_p	: Specific heat
D	: Tube diameter
D_B	: Bubble detachment diameter
F_B	: Buoyancy force
F_D	: Drag force
F_L	: Lift force
F_M	: Marangoni force
G	: Mass flux
G_m	: Liquid mass flux flowing into sublayer $(=\rho_f U_B)$
g	: Gravitational acceleration
h_{FC}	: Single-phase liquid heat transfer coefficient $\left(=0.023\frac{k_f}{D}\left(\frac{GD}{\mu_f}\right)^{0.8}\mathrm{pr}_f^{0.4}\right)$
h_{fg}	: Latent heat
j_g	: Vapor drift flux
L_m	: Vapor blanket length or sublayer length
$\dot{M}_g$	: Momentum rate
Pr	: Prandtl No.
q_{CHF}	: Critical heat flux (CHF)
r	: Radial direction
Re	: Reynolds No.
T_{SAT}	: Saturation temperature
T_w	: Wall temperature
T_b^+	: Bulk temperature where net vapor generation initiated
U_B	: Vapor blanket velocity
U_L	: Liquid velocity

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U_L^+ : Non-dimensional liquid velocity
U_m : Liquid velocity in the subalyer
U_t : Two-phase friction velocity
U_{t0} : Single-phase friction velocity
$\bar{V}_{gj}$: Drift velocity
x_e : Thermodynamic equilibrium quality
x_N : Bulk equilibrium quality where the net vapor generation initiated
x_t : True quality or flow quality
y^+ : Radial non-dimensional length
z : Axial direction

Greek symbols

α : Void fraction
δ_m : Sublayer thickness
μ : Viscosity
ρ : Density
σ : Surface tension
τ_w : Wall shear stress

Subscript

1Φ : Single-phase
2Φ : Two-phase
B : Vapor blanket
FC : Forced convection
f : Liquid
g : Vapor
L : Liquid
w : Wall

Superscript

$+$: Dimensionless quantity

1. Introduction

The CHF or boiling burnout is characterized by a sudden rise of the wall temperature and/or a sharp decrease of the heat transfer coefficient due to a change in the heat transfer mechanism (Tong 1972). The CHF for internal flow boiling at subcooled conditions or low qualities occurs at a transition from nucleate to film boiling, and it is often referred to as the departure from the nucleate boiling (DNB). At moderate to high qualities, the transition corresponds to dryout of the liquid film, and it is called dryout. The drop of the heat transfer coefficient for dryout is not as severe as that of DNB due to the high vapor velocity at dryout condition. The accurate prediction of CHF in flow boiling is of great importance in the design of a wide variety of process equipment such as boilers, evaporators and liquid cooled nuclear reactors. Especially, the estimation of CHF is a crucial parameter in the design of nuclear reactors since a sudden rise of the surface temperature of the fuel rod may result in a rupture of the rod in a short period of time.

Despite numerous investigations on CHF conditions during the last few decades, most of the proposed models on CHF prediction have been correlated based on experimental data for specific geometries due to the complexity of the CHF mechanism. The empirical correlation tends to be acceptable only within rather narrow ranges of parameter variation. The CHF mechanism or theoretical models at low qualities have not been well developed. Recently, several theoretical models (Weisman and Pei 1986; Katto 1990; Lee and Mudawar 1988) were developed based on a phenomenological approach for CHF prediction. These models that considered the basic CHF mechanism had advantages over empirical models in the development of database and prediction of CHF beyond the operating conditions of database. Celata et al. (1994) proposed an advanced model by adopting single-phase properties without including any empirical constants in the subcooled flow boiling with very high mass flux. However, a more detailed theoretical analysis of CHF in flow boiling at low qualities is required in the design of nuclear reactors that call for a high degree of reliability.

2. Previous Studies

Theoretical CHF models for subcooled or low quality flow boiling can be classified into five groups: liquid layer superheat limit model (Tong et al. 1965), boundary layer separation model (Kutateladze and Leont'ev 1966; Tong 1968), liquid flow blockage model (Bergel'son 1980; Smogalev 1981), near-wall bubble crowding model (Weisman and Pei 1986) and liquid sublayer dryout model (Katto 1990; Lee and Mudawar 1988). The bubble crowding model and liquid sublayer dryout model are reviewed in this paper because these are generally considered to be acceptable models in the practical applications.

Bubble crowding models have focused on the liquid-vapor exchange near a heated surface. Hebel et al. (1981) investigated the CHF mechanism by considering the unbalance between the release of vapor at the heated surface and the equivalent counter-current flow of liquid. Weisman and Pei (1986) proposed a theoretical CHF model postulating the bubbly layer between the heated surface and the core flow. They assumed that the CHF condition occurred when the volume fraction of vapor in the bubbly layer exceeded 0. 82. This model can be used for the void fraction in the core flow being less than 0. 6. Ying and Weisman (1986) extended the range of void fraction in the core flow up to 0.8.

The liquid sublayer dryout model was based on the dryout of a thin liquid sublayer underneath a vapor blanket formed by bubble coalescence flowing over the wall. The CHF condition was assumed to occur when the vaporization rate exceeded the liquid flow rate in the sublayer. Lee and Mudawar (1988) proposed a sublayer dryout model, which was validated by recent experiments (Mattson et al. 1973) for high pressure and high mass velocity. Lin et al. (1989) improved the Lee and Mudawar (1988) model by introducing the assumption of homogeneous two-phase flow with the effective two-phase flow properties. Galloway (1993) considered a wave stream of vapor clots at the heated wall. Besides large dry areas, boiling took place in the wetting front between vapor clots. The CHF condition was assumed to occur when one of the wetting fronts dried out due to the radial inertia of vapor. Katto (1990) presented an alternative CHF model that differed from the Lee and Mudawar model in the aspects of estimating the thickness of sublayer and vapor blanket. More recently, Katto (1992) improved his earlier model by including a revised empirical constant to cover pressure ranges of 0.1-20.0 MPa.

Based on the same mechanism as the Lee and Mudawar model, Celata et al. (1994) developed a new model for CHF in the subcooled flow boiling with very high mass flux and liquid subcooling. This model did not include any empirical constants. The velocity of vapor blanket in vertical turbulent flow was obtained through the force balance between buoyancy and drag force as suggested by Lee and Mudawar (1988). The sublayer thickness was evaluated by using the Martinelli temperature distribution (Martinelli 1947) for turbulent flow in the tube.

The purpose of the present paper is to develop a new theoretical model of CHF in flow boiling at low qualities based on the sublayer dryout model at pressurized reactor conditions. The present model is validated with the experimental data taken from the literature for upward flow boiling at low qualities.

3. Development of Theoretical CHF Model

3.1 Basic assumptions

The assumptions of the present model are basically the same as those of the sublayer dryout models proposed by Lee and Mudawar (1988) and Katto (1990). Figure 1 shows the schematic of control volume for the present model. The

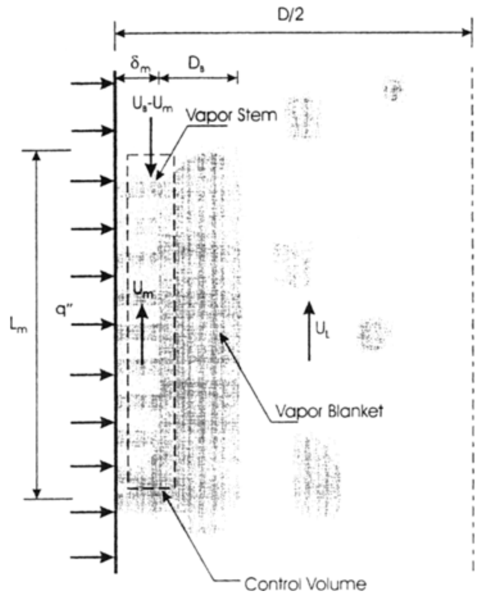

Fig. 1 Schematic of control volume for the sublayer dryout

assumptions introduced in the development of the CHF model for the subcooled and convective boiling regime in a vertical tube are as follows: (1) the length of vapor blanket is equal to the Helmholtz critical wavelength, (2) the radial thickness of vapor blanket is the same as the bubble departure diameter, (3) the velocity of vapor blanket in turbulent flow is equal to the superposition of the local liquid velocity estimated from the Karman's universal velocity profile (Arpaci and Larsen 1984), (4) the CHF condition occurs when the rate of mass loss of sublayer by evaporation exceeds the rate of the liquid mass entering into the sublayer from the liquid region, (5) the enthalpy of liquid entering the sublayer is taken as the bulk enthalpy of liquid at high heat flux and high mass flow rate, and (6) the temperature of vapor blanket at the boundary toward tube center is, at least, equal to the saturation temperature at a given pressure.

3.2 Vapor blanket length

Based on assumption (1), the vapor blanket length L_m is equal to the critical wavelength of Helmholtz instability when U_B is larger than the liquid velocity U_m in the sublayer (Lee and Mudawar 1988).

$$L_m=\frac{2\pi\sigma(\rho_g+\rho_f)}{\rho_g\rho_f U_B^2} \tag{1}$$

3.3 Liquid velocity

The liquid velocity U_L for turbulent flow in the tube is represented by the Karman 3-layer velocity distribution for a homogeneous two-phase flow (Arpaci and Larsen 1984).

$$U_L^+=y^+ \qquad 0\le y^+<5 \tag{2a}$$
$$U_L^+=5.0\ln y^+-3.05 \qquad 5\le y^+<30 \tag{2b}$$
$$U_L^+=2.5\ln y^+ +5.5 \qquad y^+\ge 30 \tag{2c}$$

where,

$$U_L^+=\frac{U_L}{U_t},\ U_t=\sqrt{\tau_w/\rho_{2\Phi}} \tag{3}$$

$$\tau_w=\frac{1}{2}(0.046\mathrm{Re}_{2\Phi}^{-0.2})\,G^2/\rho_{2\Phi} \tag{4}$$

$$y^+=y\frac{U_{t0}}{\mu_f}\rho_f \tag{5}$$

$$\mathrm{Re}_{2\Phi}=\frac{GD}{\mu_{2\Phi}} \tag{6}$$

$$\rho_{2\Phi}=\rho_f(1-\alpha)+\rho_g\alpha \tag{7}$$

$$\mu_{2\Phi}=\rho_{2\Phi}[x_t\mu_g/\rho_g+(1-x_t)\mu_f/\rho_f \tag{8}$$

The true quality x_t is determined using the correlation proposed by Levy (1967) for subcooled or low quality flow boiling.

$$x_t=x_e-x_N\exp(x_e/x_N-1) \tag{9}$$

The bulk equilibrium quality x_N at the location of initiating vapor generation downstream of the incipient nucleate boiling point is given by

$$x_N=-c_p\Delta T_N/h_{fg} \tag{10}$$

where

$$\Delta T_N=q''\left(\frac{1}{h_{1\Phi}}-\frac{T_b^+}{c_p\rho_f U_{t0}}\right) \tag{11}$$

The dimensionless bulk temperature T_b^+ at the location of initiating vapor generation is given by (Arpaci and Larsen 1984)

$$T_b^+=\mathrm{Pr}y^+ \qquad 0\le y^+<5 \tag{12a}$$

$$T_b^+=5\left\{\mathrm{Pr}+\ln\left[1+\mathrm{Pr}\left(\frac{y^+}{5}-1\right)\right]\right\} \qquad 5\le y^+<30 \tag{12b}$$

$$T_b^+=5\left[\mathrm{Pr}+\ln(1+5\mathrm{Pr})+0.5\ln\left(\frac{y^+}{30}\right)\right] \qquad y^+\ge 30 \tag{12c}$$

The void fraction α is calculated from the correlation proposed by Chexal and Lellouche (1992) based on the drift flux model:

$$\alpha=\frac{\langle j_g\rangle}{C_0\langle j\rangle+\bar{V}_{gi}} \tag{13}$$

The distribution parameter C_0 and the drift velocity $\bar{V}_{gi}$ can be found in Chexal and Lellouche (1992).

3.4 Vapor blanket velocity

The velocity of the vapor blanket U_B is estimated from an axial force balance between buoyancy force, drag force and momentum rate caused by evaporation of the liquid film under the bubble.

$$\sum F_x=F_B+F_D+\dot{M}_g=0 \tag{14}$$

where

$$F_B=\frac{\pi}{4}D_B^2L_m(\rho_f-\rho_g)g \tag{15}$$

$$F_D=\frac{1}{2}\rho_f C_D (U_m-U_B)^2\frac{\pi D_B^2}{4}$$
$$=6\pi\mu_f D_B(U_m-U_B) \tag{16}$$
$$\dot{M}_g=-\dot{m}_g U_B=-3.605\times 10^{-5}\rho_g D_B^{0.6}L_m\left(\frac{\rho_g}{\rho_f}\right)^{0.2}U_B \tag{17}$$

The term of $\dot{m}_g$ in Eq. (17) denotes the mass flow rate of vapor provided to the vapor blanket by evaporation of the thin liquid film:

$$\dot{m}_g=\rho_g V_g A_g \tag{18}$$

where V_g is the radial velocity of vapor and A_g is the area of vapor stems on the heated wall. The radial velocity of vapor can be calculated using the velocity profile of vapor bubbles suggested by Hebel and Detavernier (1982):

$$V_g=0.0024(0.8D_B)^{-0.4} \tag{19}$$

The ratio of the cross sectional area of vapor stems to the wall surface area A_g/A_W is determined using the correlation proposed by Haramura and Katto (1983).

$$A_g/A_W=0.0584\left(\frac{\rho_g}{\rho_f}\right)^{0.2} \tag{20}$$

Substituting Eqs. (15) through (17) into Eq. (14), the governing equation for U_B is given by

$$U_B^3-U_m+\frac{3.065\times 10^{-4}\sigma(\rho_f+\rho_g)gV}{3\mu_f\rho_f D_B^{0.4}}\left(\frac{\rho_g}{\rho_f}\right)^{0.2}U_B-\frac{\pi\sigma D_B g(\rho_f^2-\rho_g^2)}{12\mu_f\rho_f\rho_B}=0 \tag{21}$$

3.5 Sublayer thickness

The sublayer thickness δ_m is determined from the force balance on the vapor blanket in the radial direction. Vandervort et al. (1992) analyzed the forces on bubbles at the wall and on departed bubbles for subcooled boiling at very high heat flux. Marangoni force was generated due to the temperature gradient, which was the strongest force near the CHF condition. The dominant forces on the vapor blanket in the radial direction are the lateral lift force and Marangoni force. The equation of the force balance in the radial direction is given by (Vandervort et al. 1992)

$$\sum F_y=F_L+F_M=0 \tag{22}$$

where,

$$F_L=C_L(U_m-U_B)\frac{\partial U_m}{\partial y} \tag{23}$$

$$F_M=\pi D_B^2\left(\frac{\partial\sigma}{\partial T}\right)\left(\frac{\partial T}{\partial y}\right) \tag{24}$$

The lift coefficient C_L in Eq. (23) is represented as a function of the local void fraction (Beyerlein et al. 1985; Zun 1980):

$$C_L=0.3\cdot\exp(-\alpha) \tag{25}$$

The variation of surface tension with temperature is written as (Kestin and White 1975):

$$\frac{\partial\sigma}{\partial T}=-\frac{\sigma_0}{T_c}\left\{\mu\left(\frac{T_c-T}{T_c}\right)^{\mu-1}\left[1+b\left(\frac{T_c-T}{T_c}\right)+b\left(\frac{T_c-T}{T_c}\right)^{\mu}\right]\right\} \tag{26}$$

The temperature gradient in the radial direction is calculated by the multiple of the local void fraction to the wall superheat, T_W-T_{SAT}:

$$\frac{\partial T}{\partial y}=e^{\alpha}\cdot\frac{T_W-T_{SAT}}{\delta+D_B} \tag{27}$$

The wall temperature is obtained from the Shah correlation (Shah 1977) for the heat transfer coefficient in subcooled boiling:

$$T_W=T_L+\frac{(\Psi_0-1)(T_{SAT}-T_L)+(q/h_{FC})}{\Psi_0} \tag{28}$$

where,

$$\Psi_0=230\sqrt{q/Gh_{fg}} \tag{29}$$

Substituting Eqs. (23) through (29) into Eq. (22), the sublayer thickness δ_m is given by

$$\delta_m=\frac{\pi D_B^2}{0.3}\frac{\partial\sigma/\partial T}{(U_{BL}-U_B)}\frac{(T_W-T_{SAT})}{\partial U_{BL}/\partial y}\cdot e^{2\alpha}-D_B \tag{30}$$

3.6 Critical heat flux

From the energy conservation for the sublayer with assumption (5), the CHF is calculated from the vapor blanket length L_m, the velocity of vapor blanket U_B, and the sublayer thickness δ_m:

$$q_{CHF}=\frac{\rho_f U_B\delta_m h_{fg}}{L_m} \tag{31}$$

The CHF is proportional to the sublayer thickness, the mass flux entering into the sublayer G_m ($=\rho_f U_B$) and the latent heat h_{fg}, while it is inversely proportional to the length of the vapor blanket.

4. Comparison of the Model with Experimental Data

General trends of the predicted CHF using the present model are shown in Figs. 2, 3 and 4 with a variation of mass flux, pressure and inlet subcooling, respectively, at the specified conditions. As shown in Fig. 2, the CHF increases as the mass flux increases. The effects of the mass flux on CHF are increased with a decrease in pressure. Figure 3 shows that the CHF decreases with an increase of the pressure. The effect of the pressure on CHF becomes larger as the mass flux increases. As shown in Fig. 4, the predicted CHF is linearly proportional to the inlet subcooling, and the effect of the inlet subcooling increases with an increase of the mass flux. General trends observed from the present model were consistent with the experimental data obtained from the literature (Becker et al. 1965; Debortoli et al. 1958; Hood and Isakoff 1962; Lee and Obertelli 1963; Matzner 1964) for pressurized water reactors (PWR) at the conditions of high pressure, high mass flux, subcooled or low quality.

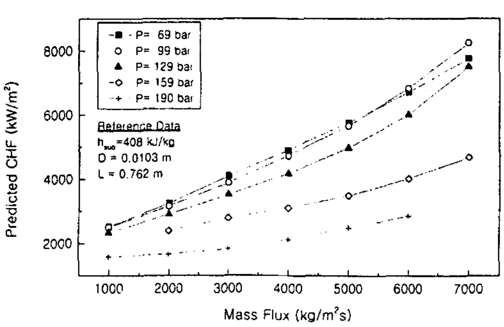

Fig. 2 Effect of mass flux on CHF

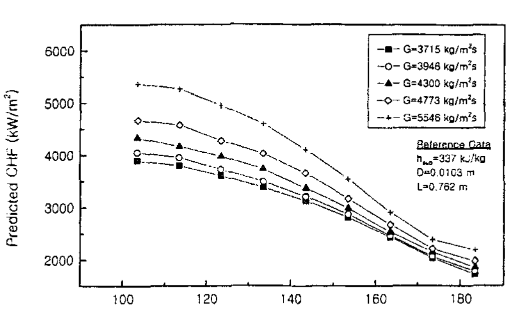

Fig. 3 Effect of pressure on CHF

To validate the proposed theoretical model, the experimental data for CHF were collected from the literature (Becker et al. 1965; De Bortoli et al. 1958; Hood and Isakoff 1962; KAIST 1990; Lee and Obertelli 1963; Matzner 1964; Thompson and Macbeth 1964; Weatherhead 1963) under the test conditions listed in Table 1. The negative qualities in Table 1 indicate the subcooled range. Flow regimes for these data corresponded to bubbly and dispersed bubbly flows for qualities lower than 0.2 in the two-phase upward flow map of McQuillan and Whalley (1980). The total number of data points used in the present study was 1132. The accuracy of the predicted CHF was represented using an estimator parameter (P/M),

$$(P/M)=\frac{Predicted\ CHF}{Measured\ CHF} \tag{32}$$

Figure 5 shows the comparison of the predicted CHF from the present model with the experimental data (1132 data points). Generally, the predicted CHFs were consistent with the experimental data. For the present model, the average of (P/M) was 1.0139, and the standard deviation of (P/M) was 12.88%. The accuracy of the present

Table 1 Ranges of the experimental data for CHF

Parameter	Range
Tube diameter (m)	0.004-0.0375
Tube length (m)	0.035-2.0
Pressure (MPa)	3-19
Mass flux (kg/m^2s)	1000-18000
Inlet subcooling (kJ/kg)	59.8-1534
Exit quality	−0.477-0.114

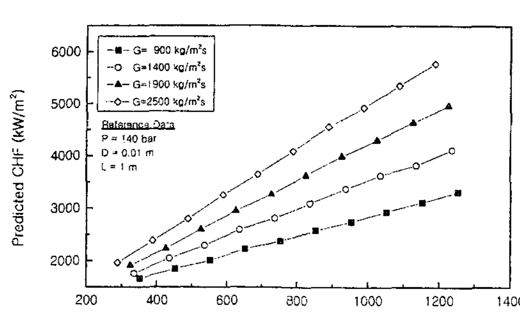

Fig. 4 Effect of inlet subcooling on CHF

model was compared to that of the various models in the literature, and the results are given in Table 2. The CHFs for the various models in Table 2 were estimated with the same data set, however some of the data was excluded due to the restriction of the models. The models of Lee and Mudawar (1988), and Ying and Weisman (1986) overpredicted CHF, while the Celata et al. (1994) model underpredicted CHF compared to the database. The models of Lee and Mudawar (1988), and Katto (1992) showed a higher standard deviation of (P/M). The Lin et al. (1989) model showed the most accurate prediction results with an average (P/M) of 1.002 and standard deviation of 6.85%. However, it should be noted that the Lin et al. (1989) model was not a purely theoretical model because it contained experimental constants to enhance the prediction capability. The present model without containing any empirical constants showed satisfactory results compared to the semi-empirical models.

To investigate the characteristics of the present model, the variations of the vapor blanket length, vapor blanket velocity, and sublayer thickness were compared to those of the various models in the literature (Lee and Mudawar 1988; Celata et al. 1994; Lin et al. 1989; Katto 1992). Figure 6 shows the vapor blanket length for the various models as a function of the mass flux. As the mass flux increased, the vapor blanket velocity increased and the vapor blanket length gradually decreased. The trends of the vapor blanket length predicted from the present model were similar to those of the Lin et al. (1989) model. However, the Katto (1992) model showed significantly higher vapor blanket length than the others compared in the present study.

Figure 7 shows the ratio of the vapor blanket velocity to the liquid velocity as a function of the mass flux. Mattson (1973) observed that for bubbly flow the vapor blanket velocity was lower than the liquid velocity near the wall at the CHF

Table 2 Comparison of the present model with the models in literature

Model	No. of data	DOC*	Avg. (P/M)	Std. deviation of (P/M)
Katto	810	71.6%	1.0385	16.93%
Lee and Mudawar	1126	99.5%	1.1355	27.06%
Celata et al.	1110	98.1%	0.7483	14.95%
Lin et al.	1122	99.1%	1.002	6.85%
Present model	1097	97.0%	1.0139	12.88%

* DOC (Degree of convergence) $= \dfrac{\textit{No. of calculated data}}{\textit{Total measured data}} \times 100$

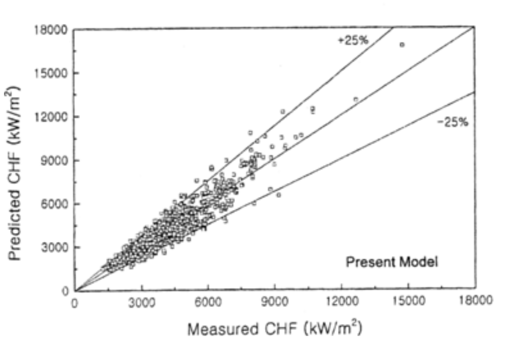

Fig. 5 Comparison of the predicted CHF using the present model with the experimental data

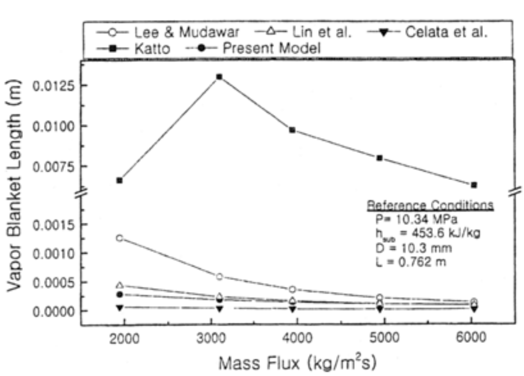

Fig. 6 Vapor blanket length as a function of mass flux

Table 3 Mean values of the parameters predicted by the various models

Model	$L_m(m)$	U_B/U_{BL}	$\delta_m(m)$	δ/L_m
Katto	0.01311	0.0663	$2.15\times^{-4}$	0.02093
Lee and mudawar	6.70×10^{-4}	1.0175	$2.31\times^{-6}$	0.00393
Lin et al.	2.71×10^{-4}	1.0043	$8.47\times^{-7}$	0.00271
Present model	1.93×10^{-4}	0.8811	$4.56\times^{-7}$	0.00239

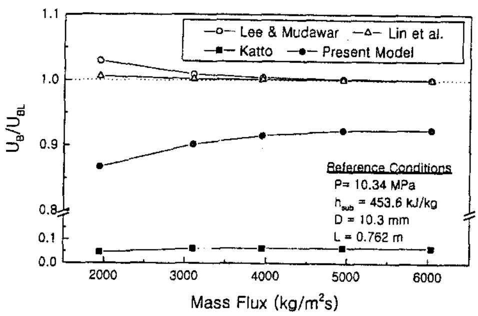

Fig. 7 Ratio of vapor blanket velocity to liquid velocity as a function of mass flux

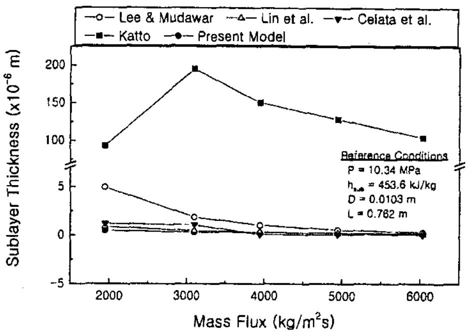

Fig. 8 Sublayer thickness as a function of mass flux

condition, while it was higher than the liquid velocity near the center of the tube. In the present study, the ratio was less than 1.0, while the ratio predicted by the Lin et al. (1989) model was nearly maintained constant at 1.0 regardless of the mass flux. The ratio from the present model gradually increased and approached to 1.0 as the mass flux increased. Figure 8 shows the variations of the sublayer thickness as a function of the mass flux. The models except the Katto (1992) model showed a gradual decrease of the sublayer thickness with the mass flux. The predicted sublayer thickness from the present model was very similar to that of the Lin et al. (1989) model. The average values of the major parameters for the various models are provided in Table 3.

5. Conclusions

The theoretical model for CHF was proposed for subcooled and low quality flow boiling at high pressure and high mass flux in tubes. The present model was based on the dryout mechanism of the thin liquid sublayer under intermittent vapor blanket due to Helmholtz instability between the interface of liquid sublayer and vapor blanket. The predicted results using the present model were compared with the experimental data as well as those from the models in the literature. The present theoretical model showed good accuracy with an average (P/M) of 1.0139 and standard deviation of 12.88 %. The variations of the vapor blanket length and sublayer thickness with the mass flux observed in the present model were similar to those of the Lin et al. model.

References

Arpaci, V.S. and Larsen, P.S., 1984, *Convection Heat Transfer*, Prentice-Hall, Edgewood Cliffs, N. J.

Becker, K. M., Hernborg, G., Mbode and Eriksson, O., 1965, "Burnout Data for Flow of Boiling Water in Vertical Round Ducts, Annuli and Rod Clusters," AE-177, Heating Engineering Laboratory of ABB Atomenergi in Sweden.

Bergel'son, B. R., 1980, "Burnout under Conditions of Subcooled Boiling and Forced Convection," *Thermal Eng.*, Vol. 27, No. 1, pp. 48~50.

Beyerlein, S.W., Cossmann, R.K., and Richter, H.J., 1985, "Prediction of Bubble Concentration Profiles in Vertical Turbulent Two-phase Flow," *Int. J. Multiphase Flow*, Vol. 11, No. 55, pp. 629~641.

Celata, G. P., Cumo, M., Marini, A., Simoncini and Zummo, M., 1994, "Rationalization of Existing Mechanistic Models for the Prediction of Water Subcooled Flow Boiling Critical Heat Flux," *Int. J. Heat Mass Transfer*, Vol. 37, pp. 347~360.

Chexal, B., Lellouche, G., Horowitz, J. and Healzer, J., 1992, "A Void Fraction Correlation for Generalized Applications," *Prog. Nucl. Energy*, Vol. 27, No. 8, pp. 255-295.

De Bortoli, R. A. et al., 1958, "Forced Convection Heat Transfer Burnout Studies for Water in Rectangular Channels and Round Tubes at Pressure above 500 psia," WAPD-188.

Galloway, J. E. and Mudawar I., 1993, "CHF Mechanism in Flow Boiling from a Short Heated Wall-Examination of Near-wall Conditions with the Aid of Photomicrography and High Speed Video Imaging," *Int. J. Heat Mass Transfer*, Vol. 36, No. 10, pp. 2511~2526.

Haramura, Y. and Katto, Y., 1983, "A New Hydrodynamic Model of Critical Heat Flux, Applicable Widely to Both Pool and Forced Convection Boiling on Submerged Bodies in Saturated Liquid," *Int. J. Heat Mass Transfer*, Vol. 26, pp. 389-399.

Hebel, W. and Detavernier, W., 1982, "On the Velocity Profile of Vapor Bubbles at Critical Heat Flux," *Nucl. Eng. and Des.*, Vol. 74, pp. 253~257.

Hebel, W., Detavernier, W. and Decreton, 1981, "A Contribution to the Hydrodynamics of Boiling Crisis in a Forced Flow of Water," M., *Nucl. Eng. Des.*, Vol. 64, pp. 433-445.

Hood, R. R. and Isakoff, L., 1962, "Heavy Water Moderate Power Reactors Progress Report," RP-755.

KAIST, 1990, "Construction of Thermo-hydraulic Database for the Evaluation of ECCS in Korea," KISNS/GR-011.

Katto, Y., 1990, "A Physical Approach to Critical Heat Flux of Subcooled Flow Boiling in Round Tube," *Int. J. Heat Mass Transfer*, Vol. 33, No. 4, pp. 611~620.

Katto, Y., 1992, "A Prediction Model of Subcooled Water Flow Boiling CHF for Pressure in the Range 0. 1 - 20. 0 MPa," *Int. J. Heat Mass Transfer*, Vol. 35, No. 5, pp. 1115~1123.

Kestin, J. and White Jr, H. J., 1975, The International Association for the Properties of Steam Release on Surface Tension of Water Substance, *ASME*.

Kutateladze, S. S. and Leont'ev, A. I., 1966. "Some Applications of the Asymptotic Theory of the Turbulent Boundary Layer," Proc. *3rd Int. Heat Transfer Conf.*, pp. 9.1~9.6.

Lee, C. H. and Mudawar, I., 1988, "A Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling," *Int. J. Multiphase Flow*, Vol. 14, pp. 711-728.

Lee, D. H. and Obertelli, J. D., 1963, "An Experimental Investigation of Forced Convection Burnout in High Pressure Water: Part 1 Round Tubes with Uniform Flux Distribution," AEEW-R213.

Levy, S., 1967, "Forced Convection Subcooled Boiling Prediction of Vapor Volumetric Fraction," *Int. J. Heat Mass Transfer*, Vol. 10, pp. 951~965.

Lin, W. S., Lee, C. H. and Pei, B. S., 1989, "An Improved Theoretical Critical Heat Flux Model for Low Quality Flow," *Nucl. Technology*, Vol. 88, pp. 294~306.

Martinelli, R. C., 1947, "Heat Transfer to Molten Metals," Trans. *ASME* , Vol. 69, pp. 947~951.

Mattson, R. J., Hammitt, F. G. and Tong, L. S., 1973, "A Photographic Study of Subcooled Flow Boiling and Boiling Crisis in Freon-113," *ASME Paper*, 73-HT-39.

Matzner, B., 1964, "Basic Experimental Studies of Boiling Fluid Flow and Heat Transfer at Elevated Pressure," TID18978.

Shah, M. M., 1977, "A General Correlation for Heat Transfer during Subcooled Boiling in Pipes and Annuli," *ASHRAE Trans.*, Vo. 83, pp. 202~217.

Smogalev, I. P., 1981, "Calculation of Critical Heat Fluxes with Flow of Subcooled Water at Low Velocity," *Thermal Eng.*, Vol. 28, No. 4, pp. 208~211.

Thompson, R. V. and Macbeth, 1964, "Boiling Water Heat Transfer Burnout in Uniformly Heat Round Tube: A Compilation of World Data with

Accurate Correlations," AEEW-R356.

Tong, L. S., 1968, "Boundary Layer Analysis of the Flow Boiling Crisis," *Int. J. Heat Mass Transfer*, Vol. 11, pp. 1208~1211.

Tong, L. S., 1972, "Boiling Crisis and Critical Heat Flux," USAEC Critical Review Series, TID -25887.

Tong, L. S., Currin, H. B., Larsen and Smith, O, G., 1965, "Influence of Axially Non-uniform Heat Flux on DNB," *Chem. Eng. Prog. Symp.*, Vol. 62, pp. 35~40.

Vandervort, C. L., Bergles, A. E. and Jensen, M. K., 1992, "Heat Transfer Mechanisms in very High Heat Flux Subcooled Boiling," *ASME* HTD217, pp. 1-9.

Weatherhead, R. J., 1963, "Heat Transfer Flow Instability and Critical Heat Flux for in a Small Tube at 200 psia," ANL-6715.

Weisman, J. and Pei, B. S., 1986, "Prediction of the Critical Heat Flux in Flow Boiling at Intermediate Qualities," *Int. J. Heat Mass Transfer*, Vol. 26, No. 11, pp. 1639~1648.

Ying, S. H. and Weisman, J., 1986, "Prediction of Critical Heat Flux in Flow Boiling at Intermediate Quality," *Int. J. Heat Mass Transfer*, Vol. 29, No. 11, pp. 1639~1648.

Zun, I., 1980, "Transverse Migration of Bubbles Influenced by Walls in Vertically Bubbly Channel," *Int. J. Multiphase Flow*, Vol. 6, pp. 583~588.