Subcooled CHF model for narrow rectangular channel under downward flow condition

Huiyung Kim, Jinhoon Kang, Jae Jun Jeong and Byongjo Yun*
Department of Mechanical Engineering, Pusan National University 2, Busandaehak-ro, 63 beon-gil, Geumjeong-gu, Busan, 46241, Korea
**Corresponding author: bjyun@pusan.ac.kr*

1. Introduction

A new research reactor under construction at Kijang adopts plate-type fuel with downflow for radioisotope production. Critical heat flux (CHF) is the most important threshold of flow boiling. Therefore, it is necessary to predict accurately the CHF of a narrow rectangular channel, which is a subchannel of plate-type fuel, for the evaluation of safety of the new research reactor.

The CHF for the narrow rectangular channel has been studied by some previous researchers [1–5]. And several empirical correlations have been proposed to predict the CHF. However, applicable conditions of those are limited to flow conditions of experimental data, which is obtained from each study. Therefore, it is necessary to develop a new CHF model over a wide range of flow conditions in narrow rectangular channel. The CHF can be modeled by dividing into subcooled CHF and saturated CHF. Aim of present work is to develop subcooled CHF model based on mechanistic analysis. The development, determination of the constants, and evaluation of the CHF model are described in present study.

2. Literature review

Kandlikar [6] reported that CHF affected by surface tension, inertia, viscous and evaporation momentum forces at the contact surface of the liquid and vapor. According to diameter of channel, the channel is classified as micro (10–200 μm), mini (200 μm–3 mm) and conventional channel (> 3 mm). And dominant forces relevant to CHF mechanism are determined for each scale of channel. The narrow rectangular channel, the subject of this study, has a small gap size of 2.35 mm and a channel width of 66.6 mm, and corresponds to the mini channel.

In addition, the CHF is classified into subcooled CHF or saturated CHF according to the thermodynamic quality of CHF occurrence point. Among them, DNB type CHF models have been developed to predict subcooled CHF. Mechanistic CHF models applicable to subcooled flow boiling include liquid sublayer dryout model [7–9], and superheated layer vapor replenishment model [10].

3. Existing CHF models

3.1. Liquid sublayer dryout model

Lee and Mudawar [7] proposed a mechanistic liquid sublayer dryout model. The model is based on the dryout of thin liquid sublayer under vapor blanket or elongated bubble. This model is adopted by several researchers for prediction CHF of subcooled boiling flow [7–9]. The CHF is determined as Eq. (1) and constitutive equations of the model are length of vapor blanket, velocity of vapor blanket and thickness of liquid sublayer. Each model adopts different constitutive equations. Among the models that can be applied to the mini-channel, Celata et al. [8] and Liu et al. [9] are worth to investigate.

$$q_{\mathrm{CHF}} = \frac{\rho_{\mathrm{f}} \delta h_{\mathrm{fg}}}{L_{\mathrm{B}}} U_{\mathrm{B}} \tag{1}$$

In both Celata et al. [8] and Liu et al. [9] model, length of vapor blanket is critical wavelength of Helmholtz instability at the liquid-vapor interface. In Celata et al. model [8], the velocity of vapor blanket is determined by forces balance, i.e. drag and buoyancy forces. The calculation procedure is the same as that in Lee and Mudawar [7] except for bubble diameter and friction factor of vapor blanket. The thickness of liquid sublayer is determined as distance that local temperature is saturation temperature in Martinelli universal temperature profile [11].

In Liu et al. model [9], the velocity of vapor blanket is calculated by assumption that the critical wavelength of Helmholtz instability is the same at top and bottom of vapor blanket. The thickness of liquid sublayer is determined as distance that vapor blanket velocity in vertical turbulent flow is equal to local velocity in Karman velocity profile.

3.2. Superheated layer vapor replenishment model

Celata et al. [10] proposed a superheated layer vapor replenishment model, which is a CHF mechanism of much simpler nature to predict CHF in water subcooled boiling flow. It is assumed that the CHF occurs when the vapor blanket replenishes the superheated layer that fluid temperature exceeds saturation value. Therefore, the CHF is determined when thickness of superheated layer is the same as thickness of vapor blanket as Eq. (2). In model, thickness of superheated layer is calculated by the Martinelli universal temperature profile [11].

$$y^* = D_{\mathrm{B}} \tag{2}$$

4. Development of new CHF model

4.1. Assumptions of new model

The basic assumptions of newly proposed model are based on that by Lee and Mudarwar [7] (liquid sublayer dryout model) and by Celata et al. [10] (superheated layer vapor replenishment model). In micro-channel, bubbles nucleate and quickly grow to channel gap size such elongated slug bubble that confined by headwall are formed [12]. And liquid microlayer is formed by lubrication at near wall [13]. In mini and micro-channel, viscous force and surface tension have more influence on the CHF mechanism than those in macro-scale [6]. Since heated wall surface is likely to wet by surface tension effect, occurrence of CHF may be postulated to evaporation of the liquid microlayer. In addition, single-phase heat transfer occurs simultaneously between the heated walls and the liquid in the region of no bubbles. Fig. 2 shows schematic of the present model.

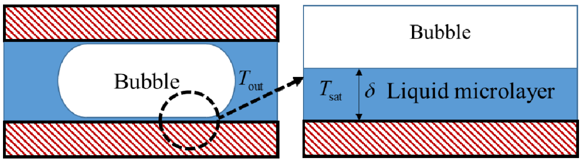

Fig. 2 schematic of new model.

4.2. Constitutive equations

The main constitutive equations of present model are for the thickness of the liquid microlayer, the velocity in the liquid microlayer, and the single-phase heat transfer coefficient. Thickness of liquid microlayer is determined by Zhang and Utaka model [12] as shown in Eq (3). The model is applicable to microchannel for maximum local velocity of bubble observed at the forefront of 19 m/s, and was developed by basis of analysis of experimental results and numerical simulation.

$$\frac{\delta}{S}=\left\{\left[0.32\mathrm{Ca}^{0.95}\mathrm{We}^{0.45}\mathrm{Bo}^{-0.5}\right]^{-3}+\left[0.44\mathrm{Ca}^{0.53}\mathrm{We}^{0.03}\mathrm{Bo}^{-0.5}\right]^{-3}\right\}^{-1/3}$$

(3)

where, $\mathrm{Ca}=\frac{\mu_f V_L}{\sigma}$ $\mathrm{We}=\frac{\rho_f S V_L^2}{\sigma}$ $\mathrm{Bo}=\frac{\rho_f S^2 \boldsymbol{a}}{\sigma}$

$$\boldsymbol{a}=\frac{V_L^2}{2D_d}\quad D_d=0.030$$

Tunc and Bayazitoglu velocity model [14] was applied for calculation of the velocity in the liquid microlayer. This model is analytically derived from the boundary conditions of the H-2 type and is applicable to rectangular channels. The local velocity can be calculated with the aspect ratio of the channel and the Knudsen number. And, single-phase heat transfer is calculated by Dittus-Boelter equation.

For a given geometry and flow conditions, the CHF can be predicted by an iterative calculation through the follow equation with above constitutive equations.

$$q_{CHF}=C_1\rho_f U_B\frac{A}{A_H}h_{fg}+C_2 H_{sp}\left(T_{sat}-T_{out}\right) \tag{4}$$

where, $C_1=0.5$ $C_2=3$

5. Results

It is necessary to evaluate applicability of the new and existing CHF models to the narrow rectangular channel. To evaluate the CHF models, experimental data are used in present study. In addition, pseudo data produced by neural network, which is trained with dataset, are used to cover a wide range of flow condition. The neural network, which is used for generation of pseudo data, is verified against experimental data, in previous study [15]. The flow conditions of data utilized in present study are summarized in Table I. Fig. 1 shows comparison of available experimental data and prediction by CHF models and error statistics of existing models are summarized in Table II. Among existing models, new model proposed in present study has the best prediction performance. Since the new model is a mechanistic CHF model based on investigation on CHF in micro, mini and conventional channel, the new model may have extra predictive capability under unevaluated flow conditions.

Table I: Flow conditions of each data

	Experimental data	Pseudo data
Mass flux (kg/m^2s)	-172 to -6,697	-200 to -6,000
Pressure (kPa)	112–290	100–300
Inlet subcooling (K)	16.8–95.4	12–103
Gap size (mm)	2.35, 2.58	1.5–2.5
Wetted width (mm)	20, 44.6, 66.6	20–70
Heated width (mm)	20, 40, 62	20–70
Length (mm)	182, 640	200–700

Table II: Error statistics of new and existing CHF models

Model	Experimental data		Pseudo data	
	Avg. error	RMS error	Avg. error	RMS error
Celata et al. (1994)	3.7	34.8	14.0	27.0
Liu et al. (2000)	34.8	55.6	40.1	48.3
Celata et al. (1999)	19.0	32.7	25.1	32.8
Present	**-6.9**	**16.4**	**13.4**	**20.4**

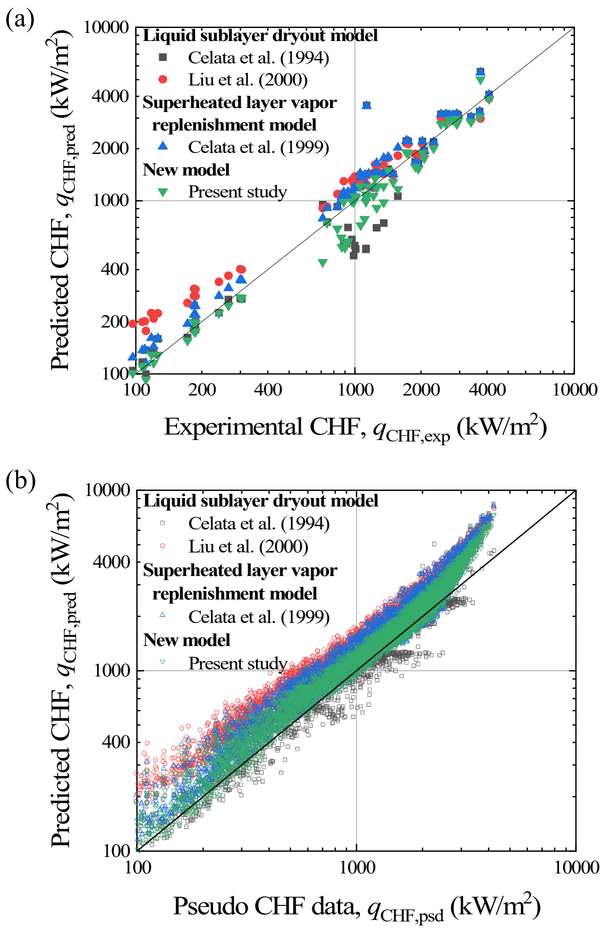

Fig. 1. Comparison of available data and predicted CHF by new and existing models: (a) experimental data, (b) pseudo data

6. Conclusions

In present study, the new model was proposed to predict subcooled CHF. The new model is applicable to the conditions for mass flux between 172 to 6,697 kg/m^{2}s, inlet subcooling between 12 to 103 K, the outlet pressure 100 to 300 kPa, the channel gap size between 1.5 to 2.58 mm and length between 200 to 700. In addition, new and existing models were evaluated against available experimental data. Among the models, the new model has the best prediction performance against experimental and pseudo data. Since the new model is applicable only to the subcooled condition, further studies will be conducted on models to predict saturated CHF.

NOMENCLATURE

- A : Flow area (m^2)
- A_H : Heated area (m^2)
- $\boldsymbol{a}$: Acceleration (m/s^2)
- Bo : Bond number (–)
- Ca : Capillary number (–)
- D_B : Bubble departure diameter (m)
- G : Mass flux (kg/m^{2}s)
- h_{fg} : Latent heat (kJ/kg)
- L_B : Length of vapor blanket (m)
- q_{CHF} : Critical heat flux (kW/m^2)
- S : Gap size (m)
- T_{out} : Outlet temperature (K)
- T_{sat} : Saturation temperature (K)
- U_B : Velocity of vapor blanket (m/s)
- V_L : Local bubble forefront velocity (m/s)
- W : Channel width of rectangular channel (m)
- We : Weber number (–)
- y^* : Thickness of superheated layer (m)
- δ : Thickness of liquid microlayer (m)
- μ_f : Dynamic viscosity liquid (kg/m^3)
- ρ_g, ρ_f : Density of gas and liquid (kg/m^3)
- σ : Surface tension (N/m)

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