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A CHF Model in Narrow Gaps under Saturated Boiling

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1. Introduction

Many researchers have paid a great attention to the CHF in narrow gaps due to enormous industrial applications [Monde et al., 1982; Fujita et al., 1988; Kandlikar et al., 2001]. Especially, a great number of researches on the CHF have been carried out in relation to nuclear safety issues such as in-vessel retention for nuclear power plants during a severe accident [Kim et al., 2000; Kim et al., 2003; Kim et al., 2005; Wu et al., 2011]. Analytical studies to predict the CHF in narrow gaps have been also reported [Tanaka et al., 2002; Seiler, 2006; Zhang et al., 2011; Yu et al., 2012]. The models of Tanaka et al. (2002), Seiler (2006) and Zhang et al. (2011) based on counter current flow limitations (CCFL) well predict the experimental data in case of inclined and vertical channels. However, these models cannot be available for the CHF in horizontal channels. As the heater surface becomes parallel to a horizontal plane, these models predict the CHF inconsistent with the experimental data. Yu et al. (2012) developed an analytical model to predict the CHF on downward facing and inclined heaters based on the model of Kandlikar et al. (2001) for an upward facing heater.

A new theoretical model is developed to predict the CHF in narrow gaps under saturated pool boiling. This model is applicable when one side of coolant channels or both sides are heated including the effects of heater orientation. The present model is compared with the experimental CHF data obtained in narrow gaps.

2. Theoretical Model

Fig. 1 schematically shows a bubble attached on two parallel plates with a narrow gap. Small bubbles generated at the heater surfaces grow and depart during boiling heat transfer. It is supposed that the bubbles grown at the upper heater and (or) the lower heater coalesce into bigger one before departing the boiling site depending on the gap size and bubble departure diameter. Under quasi-static assumption according to the analysis of Kandlikar (2001), forces on the right half of the bubble such as surface tension, gravity, and momentum due to evaporation are balanced in the direction parallel to the heater surfaces.

The forces of F_{s1} and F_{s2} are surface tensions acting at the bubble bases. The surface tension force of F_{s3} acts at the bubble sides as shown in Fig. 1 (b). The surface tension forces in the direction parallel to the heater surfaces are given as

$$F_{s1}^{h} = \sigma D\cos\alpha \tag{1}$$

$$F_{s2}^{h} = \sigma D cos\beta \tag{2}$$

and

$$F_{s3} = 2\sigma\delta \tag{3}$$

where α and β are the contact angles, and δ, σ, and D are the gap thickness, surface tension, and bubble diameter, respectively.

As shown in Fig. 1 (a) the resultant gravity force on the bubble interface acting in the direction parallel to the heater surface is given as

$$F_{G} = \frac{1}{2}g\Delta\rho\delta D^{2}\sin\theta \tag{4}$$

where θ, g, and Δρ are the inclined angle to the horizontal plane, gravitational acceleration, density difference of saturated vapor and liquid, respectively.

The momentum force is resulted from the change in momentum due to evaporation at the interface of the bubble, which is a product of the evaporation mass flow rate and the vapor velocity relative to the interface. The component of the momentum force in the direction parallel to the heater surfaces are

$$F_{M} = \left(\frac{q_i}{h_{fg}}\right)^{2}\frac{\delta D}{\rho_g} \tag{5}$$

where q_i, h_{fg}, and ρ_g are the heat flux at the bubble interface, phase change enthalpy, and saturated vapor density, respectively.

The momentum force due to the evaporation, the surface tension forces, and the gravity force are balanced as below

$$F_{M} = F_{s1}^{h} + F_{s2}^{h} + F_{s3} + F_{G} \tag{6}$$

With assuming that the contact angles, α and β, equal each other and that the channel gap thickness is the same as

$$\delta = D \cdot cos\alpha\ , \tag{7}$$

Eq. (6) is simplified as

$$q_i = h_{fg}\rho_g^{0.5}\left(\frac{4\sigma}{D} + \frac{1}{2}g\Delta\rho_g D sin\theta\right)^{0.5} \tag{8}$$

Following the assumption made by Han et al. (1965), an influence area of the heater surface by the bubble growth and departure is a circle with a diameter of two times D as shown in Fig. 1 (b). Additionally the influence area of the heat removal is also assumed to be proportional to the ratio of the heater length (L) to the channel gap thickness (δ) according to the Monde et al. (1982) model to account for the effect of the channel gap and heater sizes on the CHF in narrow gap channels (Yu et al., 2012). The heat removal of the heater is expressed as

$$Q_w = q \cdot \frac{\pi}{4}(2D)^2 \cdot \mathrm{N} \cdot \mathrm{A} \tag{9}$$

and

$$A = 1 + 6.7 \times 10^{-4} \left(\frac{\rho_l}{\rho_g}\right)^{0.6} \left(\frac{L}{\delta}\right) \tag{10}$$

where q, N, and ρ_l are the average heat flux at the heater surfaces, number of heaters, and saturated liquid density, respectively.

According to the analysis of Kandlikar (2001), the heat removed from the bubble growth since its inception is given as

$$Q_i = q_i \cdot \frac{\pi D_a}{2} \cdot \delta_a \tag{11}$$

where q_i is the average heat flux at the bubble interface between the liquid and vapor. D_a and δ_a are the average bubble diameter and bubble height, respectively.

From the heat balance between the heater surfaces and bubble interface, the heat flux at the heaters becomes

$$q = q_i \cdot \frac{cos\alpha}{8 \cdot N} \cdot \frac{1}{A} \tag{12}$$

At a critical heat flux the bubble diameter is assumed to be a half of the critical wave length (λ_T) of the Taylor instability of a vapor film over the heater surfaces based on the analysis of Kandlikar (2001). The critical wave length for initiating this instability is given by Zuber

$$\lambda_T = C_1 \cdot 2\pi(\frac{\sigma}{g\Delta\rho_g})^{0.5} \tag{13}$$

The constant (C_1) ranging from 1 to $\sqrt{3}$ is assumed to be $\sqrt{3}$ and the critical wave length is substituted for the bubble diameter in Eq. (8). And then Eq. (12) predicts the critical heat flux as follows:

$$q_c = h_{fg}\rho_g^{0.5}(\sigma g \Delta\rho)^{0.25} \cdot \frac{B}{A} \cdot \frac{1}{\mathrm{N}} \tag{14}$$

where

$$B = \frac{cos\alpha}{8}\{\frac{4}{\sqrt{3}\pi} + \frac{\sqrt{3}\pi}{2}sin\theta\}^{0.5}$$

The analytical CHF model for saturated boiling includes the effects of hydrodynamics, contact angle, and heater surface orientation as well as the effects of coolant channel gaps and heater sizes in narrow channels. Since the liquid would start to recede at the onset of CHF, the dynamic receding contact angle is used.

3. Results

Kim et al. (2003) carried out a series of CHF experiments in rectangular channels with various gap sizes and heater orientations. The coolant channel is the length of 35 mm and the width of 15 mm. The CHF data obtained in various gap thicknesses of 1, 2, 5, and 10 mm. The heater orientation ranges from a horizontal and downward facing surface to a vertical surface. The heater is a copper block and the working fluid is saturated water at atmospheric pressure. One side of the channels is only heated.

Fig. 2 shows a comparison of the predictions of the present model with the experimental data. In these predictions the receding contact angle is assumed to be 45 degrees according to the Kandlikar's analysis (2001). The present model generally under-predicts the experimental data except the data obtained in the gap thickness of 10 mm and the horizontal downward facing heater. The experiment of Kim et al. (2003) reported that the CHF for the horizontal downward facing heater decreased with the increase of the gap size. However, this is different with the experiment of Wu et al. (2011) carried out in a horizontal downward facing disk with a diameter of 300 mm.

Kim et al. (2000) performed CHF experiments in annular tubes with an inner tube diameter of 19 mm. The gap sizes of the annular tube are 0.5, 1.5, 3, and 3.5 mm and the length is 200 mm. The heater is a stainless steel and the working fluid is saturated water at atmospheric pressure. The inner tube is only heated.

Fig. 3 shows a comparison of the present predictions with the experimental data. The receding angle is assumed to be 45 degrees. The present model shows a good agreement with the experimental data obtained in the horizontal annular tubes. The CHF increases with the increase of gap size. Fig. 3 also shows a good prediction of the CHFs with the orientation angle of annular tube in case of the gap size of 0.5 mm. In other gap sizes the present model considerably under-predicts the experimental data. The difference increases with the increase of the heater orientation angle and the gap size. The parameter of Eq. (10) accounting for the effect of the heater length and channel gap size on CHF is developed from the rectangular channels (Monde et al., 1982). Thus it is supposed that the difference between the present predictions and the experimental data is resulted from the different channel geometry. Kim et al. (2000) also showed the difference between their experimental data and the correlation of Monde et al. (1982) for a vertical channel. In the comparison the difference also increases as the gap size increases.

5. Conclusions

A new analytical CHF model is proposed to predict CHF for narrow gaps under saturated pool boiling. This model can be applied to one-side or two-sides heating surface and also consider the effects of heater orientation on CHF. The present model is compared with the experimental data obtained in narrow gaps with one heater. The comparisons indicate that the present model shows a good agreement with the experimental CHF data in the horizontal annular tubes. However, it generally under-predicts the experimental data in the narrow rectangular gaps except the data obtained in the gap thickness of 10 mm and the horizontal downward facing heater.

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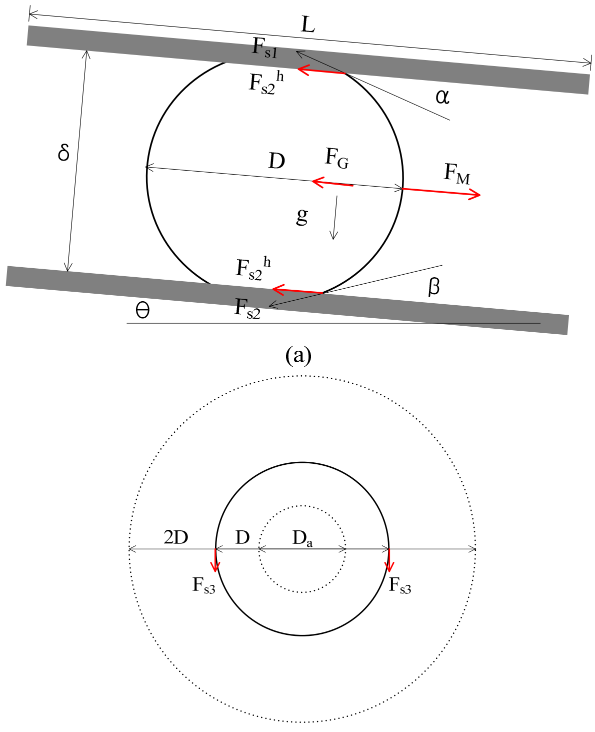
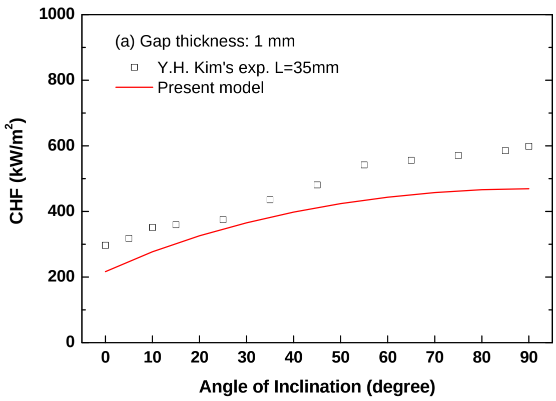
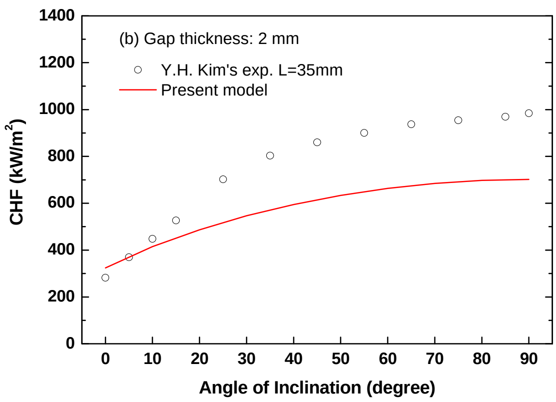


Fig. 1. Schematic diagram of forces acting on a bubble and influence region of boiling heat transfer





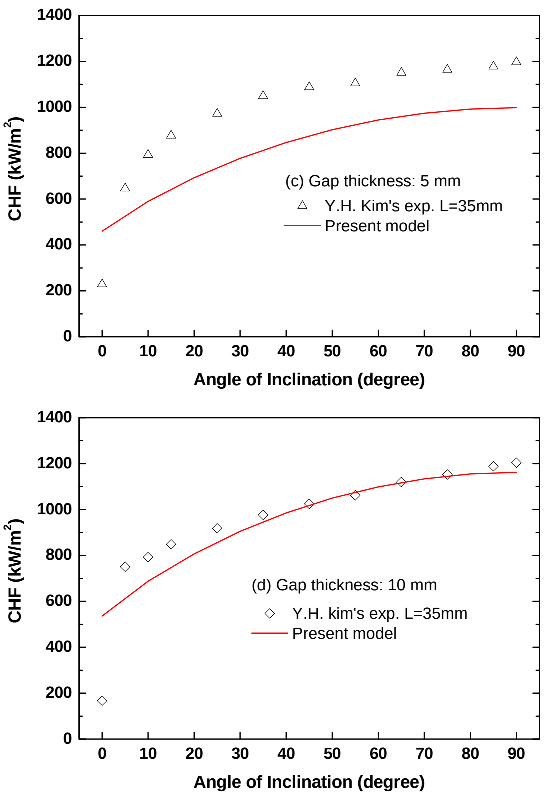
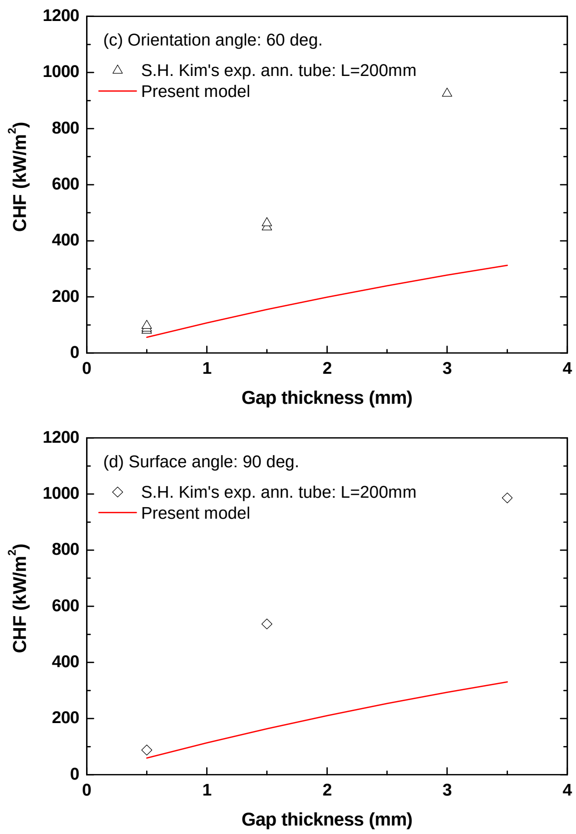


Fig. 2. Comparisons of the present model with Kim's experimental data (2003)



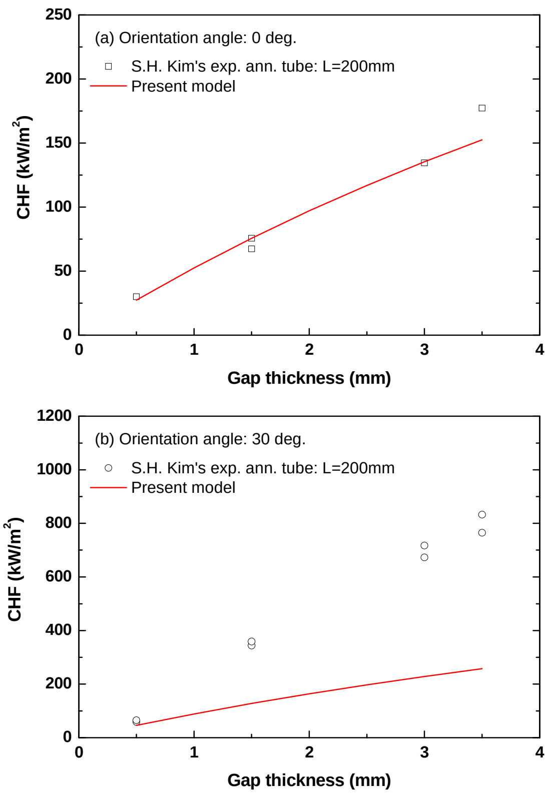


Fig. 3. Comparisons of the present model with Kim's experimental data (2000)