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Modified Hydrodynamic Instability Model in Consideration of Heater Configuration during Pool Boiling

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1. Introduction

CHF (Critical Heat Flux) indicates the safety margin of the system with boiling phenomena [1]. Therefore, various models have been proposed to predict CHF and physically analyze CHF. A representative model is the hydrodynamic instability model [2].

The hydrodynamic instability model pointed out the instability of the liquid-vapor interface as a triggering mechanism of CHF. In the hydrodynamic instability model, an infinite plate heater is assumed, and the vapor columns are assumed to be uniformly distributed (Fig. 1). The liquid and vapor are assumed to be immiscible, and the all of heat passing through the heating surface is set to be used for the phase change of the liquid (Eq. 1).

$$q'' = \frac{Q}{A_b} = \rho_g u_g \Delta h_{lg} \frac{A_g}{A_b} \quad (1)$$

As the heat flux increases, the velocity difference between liquid and vapor increases. When the velocity difference exceeds the critical value, the change of amplitude over time becomes positive and instability occurs. The critical velocity corresponds to the Kelvin-Helmholtz instability wavelength (Eq. 2).

$$u_g = \left(\frac{2\pi\sigma}{\lambda_{KH}\rho_g}\right)^{1/2} \quad (2)$$

Substituting the critical velocity, we obtain the CHF formula as Eq. 3.

$$q''_{CHF} = \Delta h_{lg} \left(\frac{2\pi^3 a^4 \sigma \rho_g}{\lambda_{KH}}\right)^{1/2} \quad (3)$$

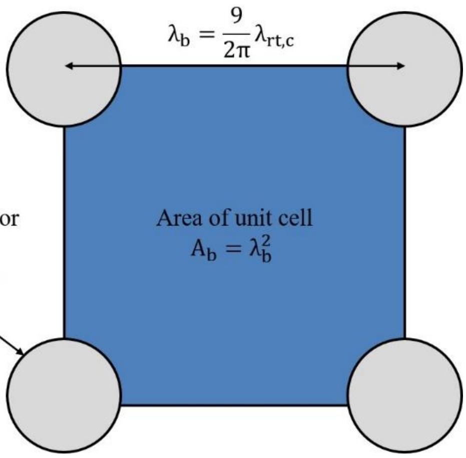

Figure 1. Top view of unit cell presented in the hydrodynamic instability model

To specify the CHF, Kelvin-Helmholtz instability wavelength should be determined. Zuber equated Kelvin-Helmholtz wavelength with Rayleigh wavelength correlated with the destabilization of the jet circumference (Eq. 4).

$$\lambda_{KH} = \lambda_R = 2\pi R_g = 2\pi a \lambda_b \quad (4)$$

The λ_b and a should be determined in the above equation. The λ_b was determined as (9/2π) $\lambda_{rt,c}$ considering the most critical and the most dangerous Rayleigh-Taylor instability wavelength. The constant (a) was determined as 1/4 for simplicity.

Based on the hydrodynamic instability model, CHF enhancement was confirmed by adding an additional liquid column in various studies [3-5] (Fig 2). In the studies, the distance between the additional liquid columns was assumed to be a modulated wavelength instead of the length of the base of the characteristic hydrodynamic cell (Eq. 5). It was experimentally confirmed that the predicted values fit well at various modulated wavelengths.

$$\frac{q''_{CHF}}{\left(\frac{\pi}{24}\right)\rho_g^{1/2}\Delta h_{lg}\left[\sigma g(\rho_l-\rho_g)\right]^{1/4}} = \left(\frac{9}{2\pi}\frac{\lambda_{rt,c}}{\lambda_m}\right)^{1/2} \quad (5)$$

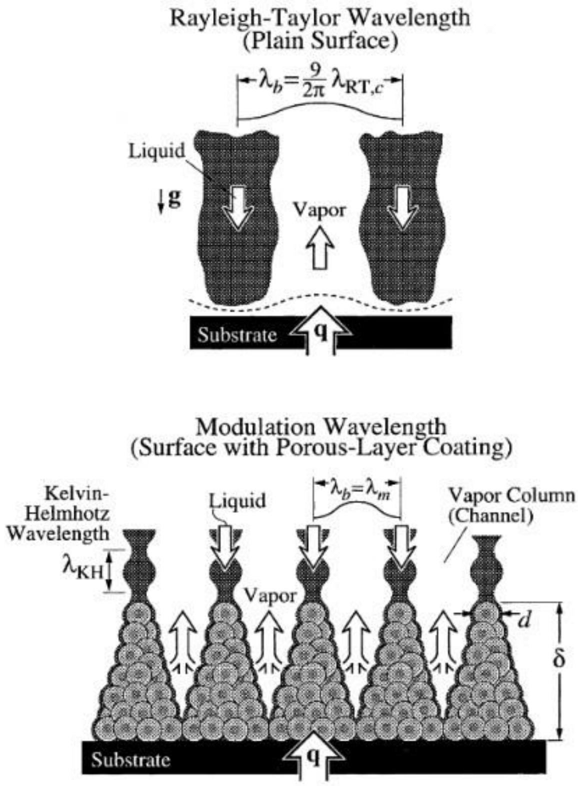

Figure 2. Schematic of modified hydrodynamic instability model with additional liquid columns [3]

However, the initial hydrodynamic instability model has limitations in that the actual heater dimension is not infinite and the characteristics of the heating surface are not considered. To solve this limitation, a modified instability model was developed in the previous study considering the heater dimension [4]. In the study, experiments with various surfaces were conducted by changing the heating length in square-type heaters. To explain the heater size effect, a modified instability model was developed. If the length of one side is less than the base wavelength, the length of one side is assumed to be the modulated wavelength. Also to include the surface characteristics (nucleate site density, wettability) the ratio of the radius of the vapor column to the length of the unit cell was used as a fitting factor.

Although the existing studies explain the CHF change and mechanism relatively well, these studies have limitations in the shape of the heater. Compared to the actual cooling channel having a rectangular shape, the experimental study was conducted only with a square or circular type heater. Considering the above, in this study, CHF on rectangular type heaters were experimentally evaluated and modified instability was developed considering the effect of heater dimension.

2. Experiments

CHF with various rectangular heaters under pool boiling conditions was experimentally evaluated (Fig. 3). To remove the effect of sub-cooling and pressure, the experiments were carried out under saturated boiling condition at atmospheric pressure.

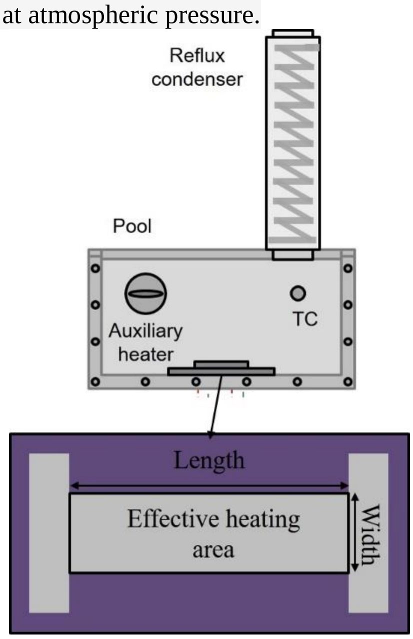

Figure 3. Schematic of pool boiling facility; Down figure indicates the bottom view of Pt heater used in this study

To make specimens of various dimensions, specimens were fabricated using the MEMS process. Using the electrode, we used the electric Joule heating method. The surface on which the phase change occurs was set as SiO_2 for all experimental cases.

Two working fluids (Water, NOVEC^{TM} 7100) were selected in consideration of dimensionless length (characteristic length / capillary length). The capillary of each fluid was 2.51 mm for water, 0.96 mm for NOVEC^{TM} 7100, respectively.

Heater dimension was set considering the heating width (the shorter one of the two side lengths) and heating length (the longer one of the two side lengths). The heating length was set to 15mm and 40mm to investigate the effect of heating length. The heating width was set to 4mm and 8mm for both working fluids. In the case of water, 3, 5, and 10 mm were additionally selected as experimental cases to investigate the trend in the relatively low normalized width region.

3. Results and discussion

A significant CHF difference according to the heater dimension was experimentally confirmed (Fig. 4).

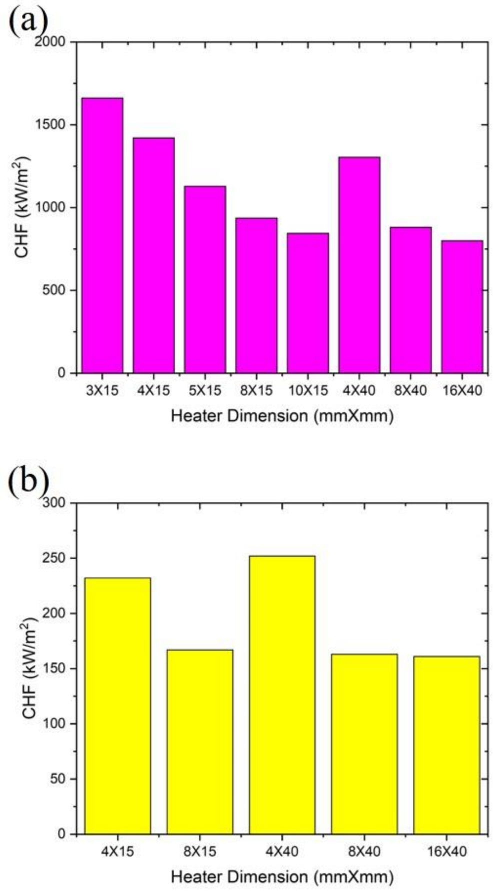

Figure 4. CHF results depending on heater dimension at (a) water, (b) NOVEC^{TM} 7100

Based on previous studies, a modified instability model was developed considering the influence of the heater dimension. We assumed that the heating situation was two-dimensional, and calculated vapor escaping velocity according to the heat flux based on the energy conservation.

In order to predict CHF, the definition of the critical wavelength for the critical escaping velocity is important. Considering the given heater dimension, the width, which is the shortest distance between vapor columns, was assumed to be the wavelength if the width is smaller than the wavelength. Else if the width is longer than the wavelength, the base wavelength was used (Eq. 6).

$$\lambda_{modulated} = \begin{cases} Width, if\ \lambda_b > width \\ \lambda_b, else\ if\ \lambda_b \le width \end{cases} \quad (6)$$

Based on the assumptions, we derived final form of the CHF prediction equation (Eq. 7).

$$\frac{q''_{CHF}}{q''_{CHF-infinite}} = \left(\frac{9}{2\pi}\frac{\lambda_{rt,c}}{\lambda_{modulated}}\right)^{1/2} \quad (7)$$

We confirmed that the original instability model over predict the CHF value at a relatively large heating dimension which can be considered as infinite heater. Therefore, we calculated the CHF of infinite heating size using the experimental results at the largest cases at each working fluid. Through this assumption, equation 6 indicates the final CHF form reflecting the heater dimension. The equation indicates that the CHF is inversely proportional to the width$^{1/2}$ (Fig. 5).

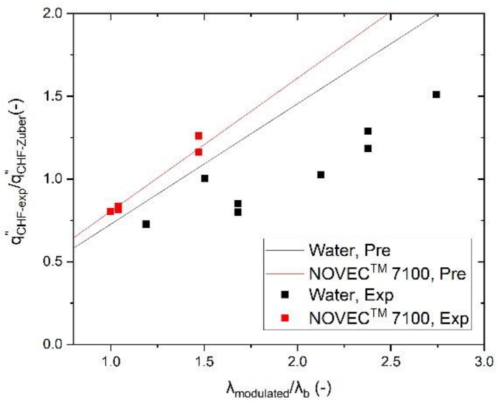

Figure 5. Evaluation of Modified hydrodynamic instability model

As predicted by the equation, it was confirmed that CHF was inversely proportional to width$^{1/2}$ in each working fluid. However, we could observe that the slope between the normalized width$^{1/2}$ and CHF show 53% difference at each working fluid This is considered to be a surface characteristic difference according to the working fluid. Although the same surface (SiO_2) is used, the contact angle for each working fluid is 63° (Water), 10° (NOVEC^{TM} 7100) respectively. Also, the nucleate site density significantly differs depending on the working fluid.

4. Conclusion

CHF change according to heater configuration at two different working fluids was experimentally evaluated in a rectangular shape heater. To consider the heating dimension for CHF, a modified instability model was developed based on the previous studies. It was confirmed that the CHF according to the width was predicted relatively well in the two working fluids, and the slope difference due to the surface characteristics was confirmed. Through the development of the model, the factors that mainly affect CHF in the rectangular shape, which is the actual shape of the cooling channel, were identified. Based on the results, accurate CHF prediction for actual cooling channels would be possible.

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