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The Measurement of the Critical Heat Flux for Annuli Submerged in a Pool of Saturated Water

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Abstract

To understand boiling phenomena and the effect of gap condition on CHF, experiments have been accomplished with various gap sizes and inclination angle at atmospheric pressure using annulus test section. Inclination angle is changed from horizontal to vertical. The annular gap size is varied from 0.5 to 3.5 mm and the channel length is 200 mm. From experimental results, CHF increases with gap size and inclination angle. One-dimensional two-phase model was derived and friction factor correlation is suggested. Correlation for inclined narrow channel is compared with other gap CHF data.

1.Introduction

Sometimes the Critical Heat Flux(CHF) means the maximum heat transfer rate without any deformation or degradation of heat transfer materials. For the research of the severe accident in nuclear power plants, it is important to predict the magnitude of CHF. In the TMI-2 accident, a significant part of the RPV lower head was overheated (one part of the RPV wall is estimated to have reached a temperature of at least 1000 °C for about 30 minutes) and then experienced a comparatively rapid cooldown. One of the mechanisms to account for that phenomena is relative movement between the wall and the heat generating material which would occur when the reactor pressure vessel wall experiences material creep. With the increase in the gap, water ingress between the debris crust and the reactor pressure vessel wall when the molten core is relocated at the lower plenum of reactor pressure vessel. The magnitude of CHF determines the possibility of cooling of the molten core and maintaining the integrity of the RPV safely. Currently there are only a few CHF data in narrow channel, which are not enough to understand phenomena in narrow channel or crevice. Some investigations were performed for a horizontal shell-and-tube heat exchanger with boiling in the shell side and flat plate. But they need more experiment in various conditions.

In present study, literature related to gap was reviewed, CHF was measured in a narrow annular geometry varying gap size and inclination angle, and semi empirical correlation was suggested.

2. Background

Some researchers investigated boiling heat transfer and CHF in small crevice. Jensen et al.(Katto et al., 1979) investigated boiling and dryout phenomena on a horizontal boiling tube with fluid flow restricted by a concentric baffle. By using a modified Reynolds number based on the vapor flow within the annular space, a scaling factor taking into account the density change for different fluids, and two dimensionless geometric groups, Jensen et al. proposed the following empirical correlation for the dryout heat flux for a restricted annular region :

$$\left[\frac{q_c\, l(D/s)}{2h_{fg}}\left(\frac{D}{s}\right)\left(\frac{\rho_f-\rho_g}{\rho_g}\right)\right]^{0.78} = 2.994\times10^{5}\left(\frac{s}{l}\right)^{-0.213} \tag{1}$$

Horizontal-Plate gap experiments were performed by Katto and his co-workers[1977, 1979]. They used parallel disks which diameter is 10, 20 mm. To obtain accurate gap size, they used micrometer. Also Katto and Kosho[1979] proposed a semi-empirical correlation:

$$\frac{q_c}{\rho_g h_{fg}}\Bigg/\sqrt[4]{\left(\frac{\sigma g(\rho_f-\rho_g)}{\rho_g^2}\right)} = 0.18\left(1+0.00918\left(\frac{\rho_g}{\rho_f}\right)^{0.14}\sqrt{\left(\frac{g(\rho_f-\rho_g)D^2}{\sigma}\right)}\left(\frac{D}{s}\right)\right)^{-1} \tag{2}$$

. The uncertainty is about ±15%.

An experimental study of the critical heat flux was carried our for natural convective boiling at atmospheric pressure in vertical rectangular channels by Monde et al[1982]. The channel length is 20, 35, 50 mm. A genralized correlation for the critical heat flux is suggested.

$$\frac{q_c}{\rho_g h_{fg}}\Bigg/\sqrt[4]{\left(\frac{\sigma g(\rho_f-\rho_g)}{\rho_g^2}\right)} = \frac{0.16}{1+6.7\times10^{-4}(\rho_f/\rho_g)^{0.6}(l/s)} \tag{3}$$

Aoki et al.[1982] carried out experiments with annular narrow gaps having the gap widths 0.2, 0.3, 0.4, 0.5, 1.0 and 1.5 mm for the open bottom case and for the closed bottom case. In the open bottom case, the heat transfer coefficient is improved as the gap size decreases. In the closed bottom case the heat transfer coefficient is not affected by the gap size or length.

Chang and Yao[1983] studied pool boiling heat transfer in a confined space for vertical narrow annuli with closed bottoms. Experiments were performed for Freon-113, acetone, and water at 1 atm. for annuli with heights of 25.4 and 76.2 mm, and gap sized of 0.32, 0.80 and 2.58 mm. They found three boiling regimes, isolated deformed bobble regime, coalesced deformed bubble regime and nucleation by bond number boiling number. Hung and Yao[1985] proposed a semi-empirical analysis based on the balance between the buoyancy driving force and the viscous drag force on the two-phase crevice flow. The annuli are 76.2mm long with the gap sizes of 0.32, 0.80, and 2.58 mm respectively. The fourth annulus is 25.4 mm long with a gap size of 0.32 mm.

Fujita et al.[1988] investigated pool boiling heat transfer in a confined narrow space for saturated water at atmospheric pressure between heated and unheated parallel rectangular plates. Experiments are performed at heat flux from boiling inception to the critical heat flux on heating surfaces with a width of 30 mm, lengths of 30 and 120 mm, and gap sizes of 5, 2, 0.6 and 0.15 mm under three surface peripheral conditions. They are all edges open, closed side edges, and closed side and bottom edges. Space inclination is also changed from vertical to facing downwards nearly to the horizontal. From his experimental results, the heat transfer coefficient increases up to a certain maximum value with decrease of the gap size at moderate heat flux, while degradation occurs for a further decrease of the gap size over the whole heat flux range. For the enhanced boiling heat transfer, a predictive method is proposed based on the consideration of heat transfer mechanisms. Burnout mechanisms are also considered as the narrow spaces of two basically different periphery conditions and the predicted critical heat fluxes are compared with the measured ones.

3. Experimental Apparatus

The test section and experimental apparatus is illustrated in Fig. 1 and Fig. 2.

The inner tube of the test section is made with conventional stainless steel tube and copper tube. The diameter of the inner tube is 19.0 mm. To measure the surface temperature, three thermocouples are located under the stainless steel tube surface. The test section is heated by DC power supply and the heat flux is calculated by subdividing the supplied power by the outer surface area of the stainless steel tube. To maintain the size of gap, two supporters are used. The size of gap is 0.5, 1.5, 3.0, 3.5 mm and the heating length is 20 mm. Pyrex tubes are used to make gap and to observe the bubble behavior.

The experimental pool is made with stainless steel. The height is 0.8 m and the area is 0.6 by 0.6 m^2. During experiments water level is about 0.45 m.

The experiments are performed with saturated and distilled water at atmospheric pressure. Prior to each test run, the heating surface is finished with emery paper in an attempt to keep the same surface conditions for all test runs. Critical heat flux is defined when the heating surface temperature starts rising gradually or suddenly.

4. Results and Discussion

4.1 Bubble behavior

During experiments, flow path is established like figure 3. When the inclination angle is 30°, 60° and 90°, the flow is entered from bottom of the channel and goes out through upper side of the channel. But for the case of 0°, the flow is entered from lower region of the each side of channel and goes out through the upper region of both sides of channel. It is expected that there is flow path transition angle between 0° and 30°.

For 1.5, 3.0, 3.5 mm gap size

When the inclination angle is 30°, 60° and 90° and the heat flux is nearly CHF, flow pattern is observed as annular flow. Also, before CHF occurrence, dryout of liquid film and small bubbles are observed. Small bubbles are shown before film dryout. First, one bubble is made in the middle of channel. After that, many small bubbles are made successively. CHF is occurred at exit, but liquid film dryout is initiated in the middle of channel.

For 0.5 mm gap size

Bubble is squeezed and bubble shape is deformed. It is hard to recognize the flow pattern. Flow path is similar with other gap sizes.

4.2 The effect of gap size and inclination angle

CHF data obtained from experiments are shown at figure 4 and 5. For the gap sizes more than 1.5 mm CHF linearly increased with gap size. But CHF sharply decreased as the gap size is changed from 1.5 mm to 0.5 mm when inclination angle is larger than 30°. Also CHF sharply decreased as the inclination angle is changed from 30° to horizontal angle. There is no big difference in CHF when the gap sizes are more than 3.0 mm and the inclination angles are more than 60°. At figure 4, solid line and dashed line mean Monde correlation and Chyu correlation. Monde correlation can be applied for vertical narrow channel and Chyu correlation can be applied for horizontal annulus. Above correlation underpredict experimental data.

4.3 Comparison with other CHF data

To compare experimental results with other CHF data, some CHF data are collected from literature. Those data are shown at Figure 6. Collected data are consisted with the results of Monde et al.' s and Fujita' s experiments which were conducted using vertical rectangular channel at atmospheric pressure. Those data form a thick band. When the length to gap size ratio(L/s) increase, data approach Monde correlation. But for small L/s, error increases. Presents experimental data show same tendency.

5. Derivation of Correlation

5.1 One-dimensional homogeneous model

Chyu[1988] suggested one-dimensional two-phase flow model in a narrow vertical channel. In his model, inclination angle was not considered. In this study, his model is modified to show the effect of the inclination angle(30° ~ 90°) (Fig. 7). Saturated liquid enters the channel at the bottom, and is vaporized by the heating wall while ascending due to buoyancy. Saturated vapor vents from the top at a much higher velocity because of the low vapor density compared with liquid. If considering mass, momentum and energy balances in this model like Chyu, following correlation can be obtained;

$$q_c = \rho_g h_{fg} \left\{ \left(\frac{s}{l} \right) \left[\frac{g l \sin\theta \left[\left(\rho_f / \rho_g \right) - 2 \right]}{1 + f l / 2s} \right] \right\}^{1/2} \tag{4}$$

where f is friction factor. Chyu obtained friction factor, f from his experimental data.

$$f = 0.13 \left(\frac{\rho_f - \rho_g}{\rho_g} \right)^{0.5} Bo^{1.3} \tag{5}$$

$$\text{where } Bo = s \left\{ \left[\frac{g}{\sigma} \right] \left(\rho_f - \rho_g \right) \right\}^{0.5}$$

Eq. (5) is not adequate in current experiments. Because horizontal annulus data were used to make friction factor correlation. For the case of vertical and inclined channels, new friction factor is needed. If eq. (4) is rearranged using f, then that is changed as

$$.\ f = \left\{ \left[\frac{g l \sin\theta \left[\rho_f / \rho_g - 2 \right]}{\left\{ \frac{q_c}{\rho_g h_{fg}} \frac{l}{s} \right\}^2} \right] - 1 \right\}^{1/2} \times \frac{2s}{l} \tag{6}$$

Figure 8 shows the results applying CHF data at above equation. From the graph

$$f = 0.0041 \cdot s^{(3.66 \log s - 0.94)} \tag{7}$$

is obtained. RMS error is 5.87 % (Fig. 9).

5.2 Comparison correlation with CHF data

Some CHF data in narrow vertical rectangular channel are obtained from literature. The results of comparison eq. (4) and (7) with CHF data shows at figure 10. When gap size is larger than 0.25 mm and smaller than 3 mm, and width is 30 mm, CHF correlation shows good agreement. However other data (i.e. very small or large gap size) cannot predict well. This is the limit of homogeneous model and friction factor. Considering the circumference of test section (19 x π mm), CHF correlation applicable range is $30 < w < 60$ mm and $0.5 < s < 3$ mm.

6. Conclusion

In this study, CHF experiments was conducted with various gap sizes and inclination angle at atmospheric pressure using annulus test section. Important findings are as follow :

1) CHF increases with gap size and inclination angle.
2) Flow path transition angle exists between horizontal and 30°.
3) In the case of 0.5 mm gap size or 0° inclination angle, CHF is considerably smaller than those for other gap size or other inclination angle.
4) To estimate the CHF for vertical and horizontal condition, Monde correlation (vertical plate) and Chyu correlation (horizontal plate) have been applied. However, they cannot predict well due to the difference of heater geometry.
5) Based on experimental results, semi-empirical correlation has been developed. However applicable range is limited.

Nomenclature

Bo	bond number,		
D	inner tube outer diameter,		
f	friction factor,	*Greek*	
g	acceleration of gravity,	$\boldsymbol{r}_{\mathrm{f}}$	water density,
h_{fg}	latent heat of vaporization,	$\boldsymbol{r}_{\mathrm{g}}$	steam density,
l	gap length,	$\boldsymbol{s}$	surface tension,
q_c	critical heat flux,	$\boldsymbol{q}$(°)	inclination angle.
s	gap width.		

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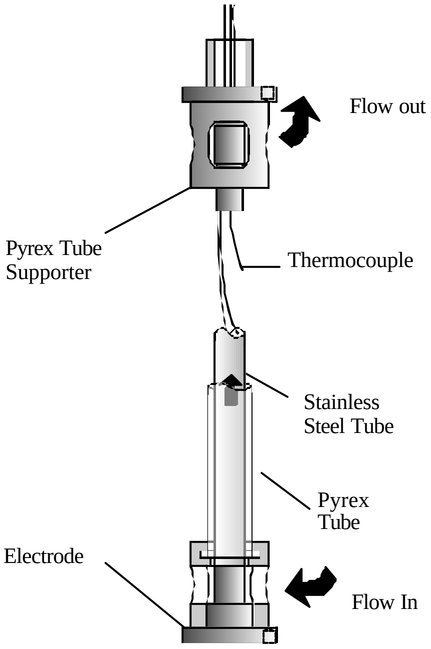

Fig.1 Test Section

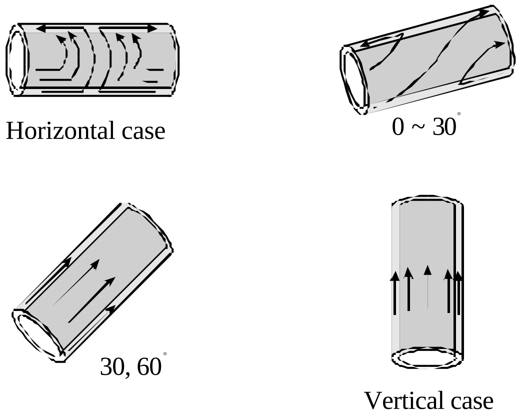

Fig. 3 Flow path

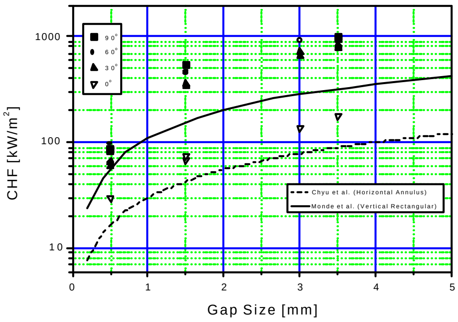

Fig.4 Gap Size and CHF in Gap

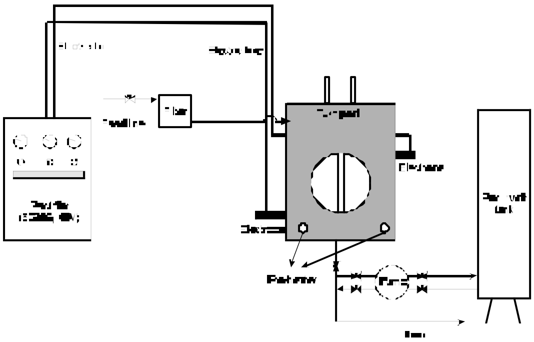

Fig.2 Test Loop

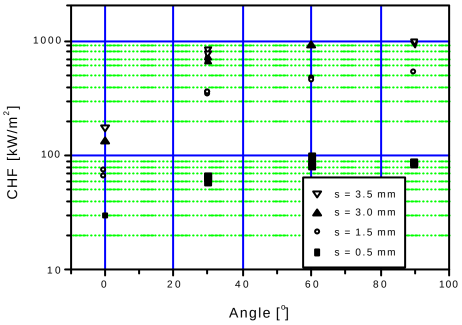

Fig.5 Inclination angle and CHF in Gap

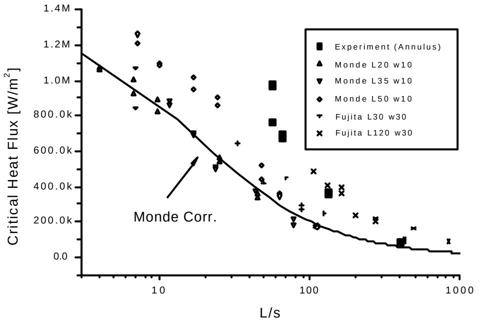

Fig.6 Comparison with other CHF data

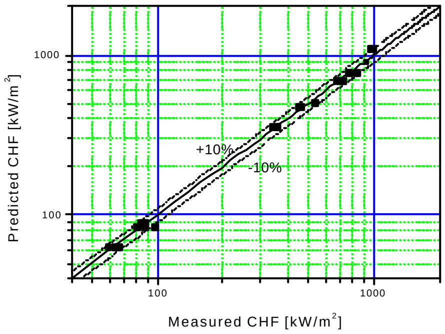

Fig.9 Prediction results

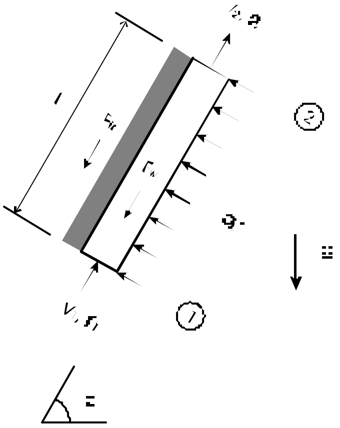

Fig.7 One-dimensional homogeneous flow model

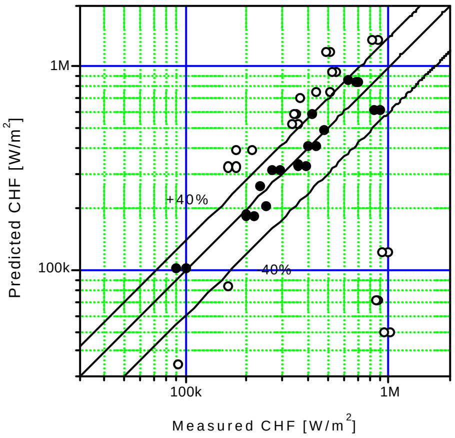

Fig. 10 Comparison correlation (4) with other data

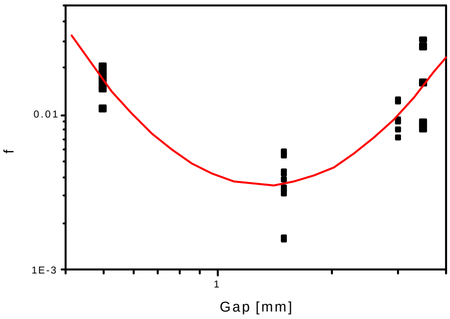

Fig.8 Relationship with gap and friction factor