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CHF correlation development under ERVC conditions using local liquid velocity

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1. Introduction

In-vessel retention (IVR) through external reactor vessel cooling (ERVC) is a severe accident mitigation strategy that is applied in many light water reactors (LWR). Critical heat flux (CHF) is a key parameter which indicates the success of the IVR strategy.

Previous research have limitations that the CHF models were developed in terms of averaged factors. In this paper, particle image velocimetry (PIV) technique was utilized to measure the velocity field of the fluid in a test section. The test section simulated the gap between the reactor vessel outer wall and the insulation. Air injection was used to simulate the boiling and the CHF occurring conditions in the forced circulation water loop. Curved rectangular channel with 50 cm radius was devised to simulate flow path along the reactor vessel external wall. The channel was made of transparent acrylic.

To develop CHF correlation under ERVC conditions, liquid sub-layer dry out model was adopted. A CHF prediction correlation was developed based on the local liquid velocity data acquired from the experiment.

2. Experiments

2.1. Experimental apparatus

To evaluate the local velocity of the flow at the external vessel wall with CHF occurring situation under ERVC conditions, an experimental apparatus was set up. It consisted of a flow loop, a test section, and an air injection device. The details of the experimental setup was explained in the previous work [1].

The experiments were sorted with three inclination conditions assuming that the CHF occurs at the certain angular points. For 90 ° inclination case, the mass flux conditions were 100, 200, 300 and 400 kg/m^{2}s. For the 60 ° and 30 ° inclination cases, the mass flux conditions were 100 and 300 kg/m^{2}s.

The volumetric flow rate of the air injection was the same as the volumetric rate of vapor generation at the reactor vessel outer wall. The experimental CHF data from Park et al. [2] were used to calculate the vapor generation rate.

2.2. PIV measurements

A set of PIV configurations was used to measure the velocity field of the flow in the test section. Fig. 1 shows the PIV system used for the experiment.

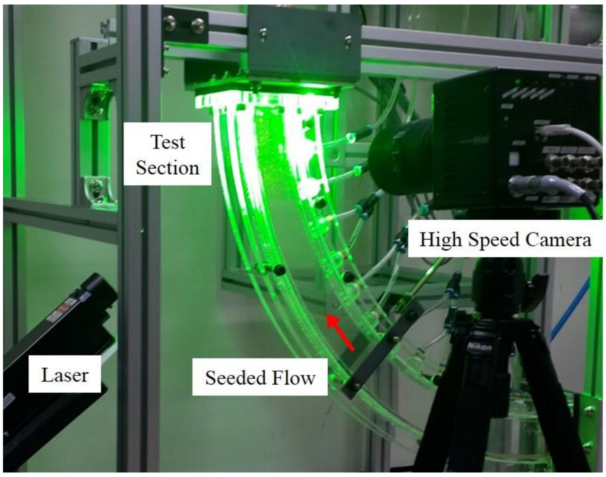

Fig. 1. PIV configurations for 90 ° case

532 nm green laser was used for the laser light source. A high speed camera was used to take images of the working fluid in a short time interval. The fluorescent red particles with 53-63 μm diameter were used as tracer particles. The density of the particles were similar with working fluid.

The PIV measurement were conducted at three different angular points. Each cases simulated the CHF occurring situation at 90°, 60° and 30° of the reactor vessel lower head. The laser sheet induced at the corresponding angular position of the test section and the high speed camera was installed perpendicular to the laser sheet. The frame speed of the camera was 2000 fps. The corresponding resolution of the image was 1280×1024 pixels.

For the PIV analysis, an open source PIV software, PIVlab was used [3]. The interrogation window size were 64 pixels for 90 ° case and 48 pixels for 60 ° and 30 ° cases, and the step size of the analysis was 50 % of the interrogation area. For the time-averaged contour analysis, 4365 pairs of images were used.

3. Results and analysis

From the PIV measurements for each inclination cases, maximum velocity and average velocity were obtained. Fig. 2 shows the velocity of the liquid at the 90 ° position of the test section. The blue circular dot indicates superficial velocity, the black triangular dot indicates the average velocity and the red rectangular dot presents the maximum velocity at 90 ° angle case. The error bar indicates the deviation of the velocity data. The maximum velocity and the average velocity increases as the inlet mass flux increases. However the increment ratio of the velocity decreased because the air injection did not linearly increased.

Fig. 3 and Fig. 4 shows the local liquid velocity data for the 60 ° and 30 ° inclination cases. The same as the 90 ° cases, each dots were obtained by taking average of four repeated experimental results.

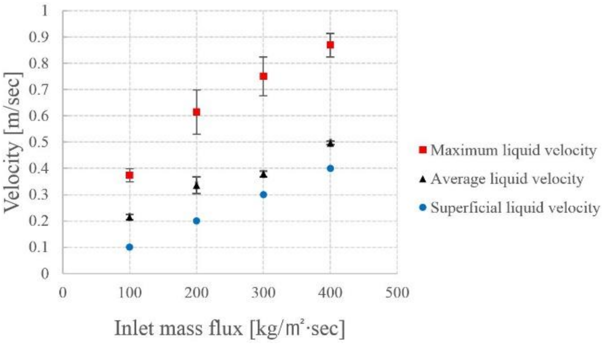

Fig. 2 Local liquid velocity in 90 ° case

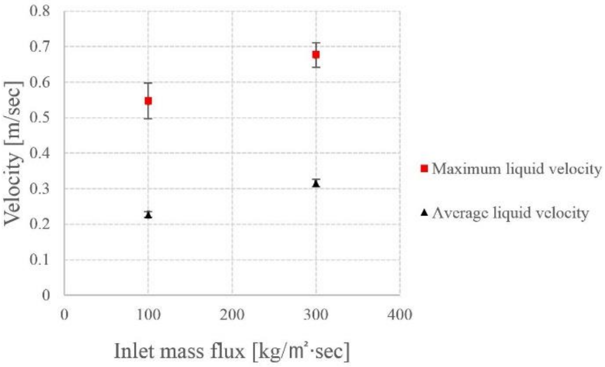

Fig. 3 Local liquid velocity in 60 ° case

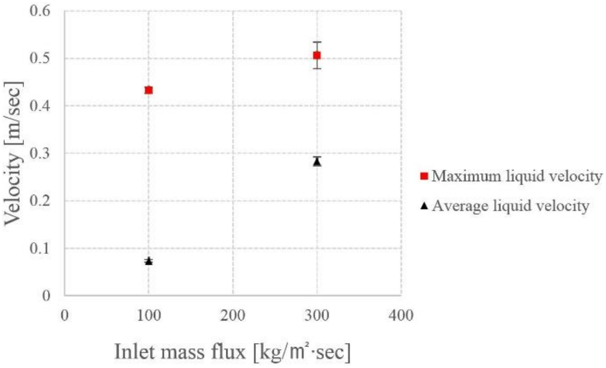

Fig. 4 Local liquid velocity in 30 ° case

4. CHF correlation development

Cheung and Haddad investigated CHF model for downward facing heating surface [4]. They developed the CHF model based on the subscale boundary layer boiling (SBLB) experiment. They investigated CHF phenomenon and two-phase boundary flow on the outer surface of a heated hemispheric vessel. The experimental condition of SBLB was pool boiling. They observed vapor slugs which were squeezed up against the downward facing curved surface by the buoyancy force passed periodically through the two-phase boundary layer. In the microscopic view of the vapor slug generation, a thin liquid film or a micro sub-layer exist under the elongated vapor slug. The small vapor produced by the nucleate boiling added to the vapor slug. Fig. 5 shows the configuration of the downward facing curved surface and the vapor slug behavior.

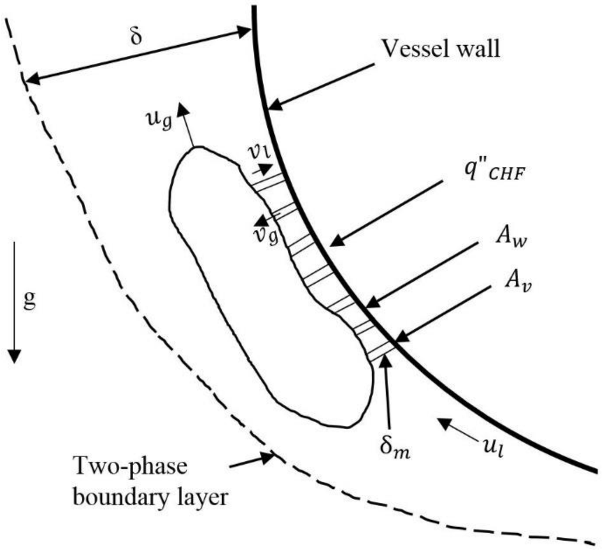

Fig. 5 Schematic of liquid sub-layer and vapor slug on downward facing curved surface

To develop the CHF correlation under ERVC conditions in the present study, the CHF occurrence mechanism was adopted from Cheung and Haddad model [4]. This mechanism can be expressed in a balance equation between the supply rate of the liquid into the sub-layer and the evaporation rate of the liquid film. The basic form of the CHF equation was expressed in the equation (1)

$$q"_{CHF} = \rho_l h_{fg} u_l \frac{\delta_m}{l} \qquad (1)$$

where u_l is local liquid velocity and δ_m is the thickness of the micro sub-layer. For the liquid velocity term, the maximum velocity from the PIV measurement data were adopted. The maximum velocity was measured at the center of the slug pathway where the buoyancy force and the drag force of the slug were balanced. The length of the vapor l, and micro sub-layer δ_m were adopted from Park's dissertation [5].

Table 1 shows the equations for the CHF correlation. The vapor velocity term was calculated by solving the slug length equation and the force balance equation. The drag coefficient in the force balance was obtained from Harmathy's paper [6].

Table 1: Equations for the CHF correlation

	Equation
CHF occurrence	$q"_{CHF} = \rho_l h_{fg} u_l \frac{\delta_m}{l}$
Slug length	$l = \frac{2\pi\sigma(\rho_l + \rho_g)}{\rho_l \rho_g u_g^2}$
Micro sub-layer thickness	$\delta_m = C_m \sigma \rho_g (1 + \frac{\rho_g}{\rho_l})(\frac{\rho_g}{\rho_l})^{0.4}(\frac{h_{fg}}{q"_{CHF}})^2$
Force balance	$\frac{\pi}{4} D_b^2 l \, g(\rho_l - \rho_g) \, sin\theta = \frac{1}{2}\rho_l C_D (u_g - u_l)^2 \frac{\pi D_b^2}{4}$

$$C_D = \frac{2}{3}(\frac{g\Delta\rho d^2}{\sigma})^{1/2} \qquad (2)$$

By combining the equations in the Table 1, The CHF correlation can be expressed in the following equation.

$$q"_{CHF} = h_{fg}(\frac{C_m}{2\pi}\rho_l^{0.6}\rho_g^{2.4}u_l u_g^2)^{1/3} \qquad (3)$$

The constant C_m was obtained by conducting non-linear regression analysis. The constant C_m was 0.034 and the R^2 value, or the coefficient of determinant was 0.883. Fig. 6 shows the prediction ability of the CHF correlation. The experimental CHF data was compared with the predictions results of the correlation. The error bar on the graph indicates deviation of the CHF values caused by the measurement deviation of the liquid velocity. The RMS error was 2.23 %

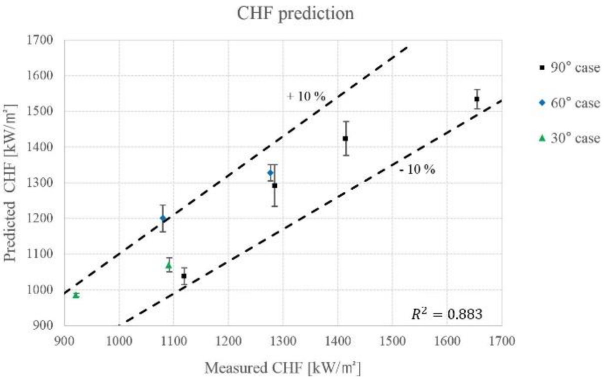

Fig. 6 Prediction of the CHF correlation.

5. Conclusions

In this study, the liquid velocity measurement was conducted for ERVC conditions by using PIV technique. The measurement was conducted for the situation that the CHF occurred at 90°, 60°, and 30° inclination angle of the external wall of the reactor vessel. For each cases the experiment were performed with 100, 200, 300, and 400 kg/m^{2}s mass flux conditions.

Based on the experimental local velocity data, the CHF correlation was developed based on the liquid sub-layer dry out model. The R^2 value of the correlation was 0.883. The prediction results of the correlation were compared with the experimental data. The RMS error was 2.23 %.

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