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Influence of the Mass flux, Inclination and Void Fraction on the Flow Boiling CHF using a Hydrogen Evolution System

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1. Introduction

In-Vessel Corium Retention through External Reactor Vessel Cooling (IVR-ERVC) is known for the strategy to mitigate the severe accident in a nuclear power plant [1]. The reactor integrity can be assured when the coolant sufficiently removes the decay heat of the corium at the outer wall of the reactor vessel. The external cooling capability is an important issue [2]. The maximum coolability could be evaluated by measuring the flow boiling CHFs at the downward-facing surface.

The present study investigated the influence of mass flux, inclination and void fraction in a downward-facing flow boiling condition. These parameters are generalizing the upstream flow rate, curvature of reactor vessel lower plenum and heat flux distribution under ERVC condition, respectively. For the experiments, the mass flux varied from 250 to 1,500 kg/m^{2}s, inclination from vertical to 135° and void fraction from none to 0.3. The boiling condition was simulated by using a hydrogen evolution system to avoid difficulty of the heat transfer study such as hard thermal stress that can lead to failure of the experimental devices.

2. Background theories

2.1 Influence of mass flux and inclination on the CHF

Zhang et al. [3] measured flow boiling CHF using a rectangular channel with varying the inclination and mass flux. The saturated FC-72 was used as the working fluid. The measured CHF increased with an increasing mass flux due to the sufficient surface vapor removal in all the inclination. For the vertical upflow channel, the gravitational force helped bubble removal, which led to the high value of the CHF. When the channel was inclined to the downward-facing heated surface, the bubble was accumulated on the heated surface by the gravitational force. The measured CHF decreased with increasing inclination and was lower at the horizontal. The effect of inclination on the CHF was dampened with increasing mass flux due to the strong inertia force by the liquid.

2.2 Influence of void fraction on the CHF

Kharangate et al. [4] investigated the effect of the void fraction on the flow boiling CHF using a vertical upflow channel and saturated inlet flow condition of FC-72. The experiment performed by manipulating the mass flux and inlet quality. At the constant mass flux, the CHF increased with an increasing inlet quality. As the inlet quality increased, decreased liquid volume in the channel increased the liquid velocity on the wall region to keep the constant mass flux. Thus, the CHF increased with an increasing liquid velocity on the wall region. Konishi et al. [5] carried out a continuous research of Kharangate et al. [4] in consideration of all the inclination. The CHF showed the lowest value at the downward-facing heated surface horizontal flow. They reported that the downward-facing heated surface made decreased CHF values by pushing the generated bubble towards the heated surface. Also, the influence of the inclination diminished as the mass flux increased. The increase of the inlet quality intensified the CHF by increasing the liquid velocity at the channel wall.

3. Experimental setup

3.1 Methodology

We simulated the heat transfer flow boiling system by adopting the electrochemical hydrogen evolution system. The analogous relation between the boiling and hydrogen evolution systems has been studied [6–9]. The hydrogen gas generation reaction at the cathode in electrolysis system can be substituted for the vaporization of the boiling.

When the hydrogen gas generation rate goes over a certain upper limit, the analogous phenomenon to the CHF called critical current density (CCD) occurs at the cathode surface. Then, the voltage potential abruptly increased. The heat flux and wall superheat correspond to the current density and voltage potential, respectively. Also in this analogous relation, the curve similar to the boiling curve was obtained from the hydrogen evolution system [10].

Previously, our research group simulated the CHF at the pool boiling condition by using this experimental method [2]. The detailed methodology is introduced in the references [2, 10, 11].

3.2 Test apparatus

The schematic of the test apparatus is represented in Fig. 1. We used 1.5 Molar concentration of aqueous solution of sulfuric acid (H_2SO_4) as the working fluid. The cathode test section connected with the rectangular channel that can adjust inclination is located at the solution tank. The liquid circulates throughout the reservoir and solution tank by the pump. Hydrogen was injected into the entrance of the channel from the hydrogen gas tank. The hydrogen gas and liquid were mixed in the channel and passed the cathode surface. The liquid and gas flow rate were adjusted by using the control valve and regulator, respectively. The measured flow conditions, current, and voltage are recorded by the data acquisition (DAQ) system. The high-speed camera captured the side view of bubble behavior.

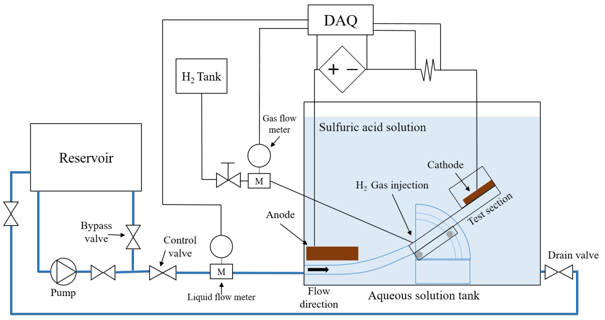


Fig. 1. The schematic of the test apparatus.

3.3 Test matrix

The range of present study is specified in Table I. The copper plate simulating downward-facing heated surface has 10 mm width and 35 mm length with 10 mm channel gap size. Experiments were conducted by changing the mass flux, void fraction and inclination.

Table I: Range of present study

Copper plate W × L (mm)	Gap size (mm)	Mass flux (kg/m^2s)	Void fraction	Inclination (°)
10 × 35	10	250–1500	0.0–0.3	90, 135

4. Results and discussion

4.1 Influence of mass flux and void fraction on the CCD at the vertical channel

Figure 2 shows the influence of mass flux and void fraction (α) on the CCD at the vertical channel. The CCD decreased with an increasing void fraction. For vertical channel, the vapor injected from the channel entrance moves toward center of the channel. The moving vapor attracts the surrounding liquid and increases the liquid velocity at the center. As a result, the liquid velocity near the wall region reduced to keep the constant mass flux. The reduced liquid velocity near the wall region affects the decreasing of the CCD. Fig. 3 shows the photographic appearance of the vapor according to the void fraction. The grown sized bubble by increased void fraction attracts more surrounding liquid and the liquid velocity at the wall region decreases further.

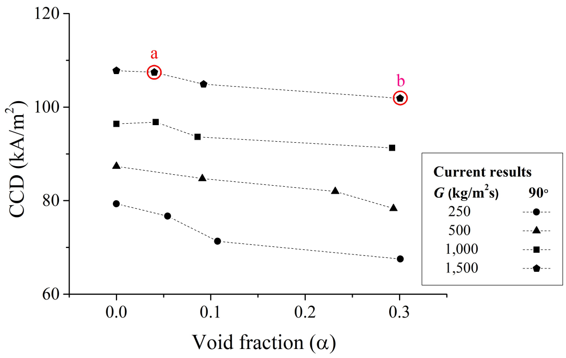


Fig. 2. CCD variation according to the mass flux and void fraction at the vertical channel.

(a) $\alpha = 0.05$ (b) $\alpha = 0.30$

Fig. 3. Bubble appearances according to the void fraction at the vertical channel.

4.2 Influence of mass flux and void fraction on the CCD at the inclined channel

Figure 4 and 5 show the CCD results and photographic images at the inclined channel, 135°. For inclined channel, the bubble showed biased toward downward-facing cathode because of the gravitational force affect directly with the generated bubble at the cathode surface. The CCD increased as the void fraction increased. And, after a certain void fraction, the CCD decreased as the void fraction increased at all the mass flux. At the lower void fraction, the inlet bubble helped the generated bubble detachment by sweeping at the cathode surface. The bubble removal by the inlet bubble led to the increasing CCD values. Fig. 5(a) shows the captured image of the bubble sweeping moment at the low void fraction condition. By contrast, as the void fraction increased, the grown sized bubble coalesced with the generated bubble forming a film at the cathode surface. The inlet bubble aided film on the cathode surface expedites the CCD as shown in Fig. 5(b).

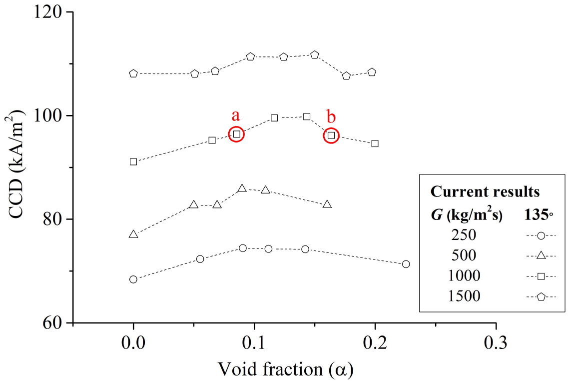
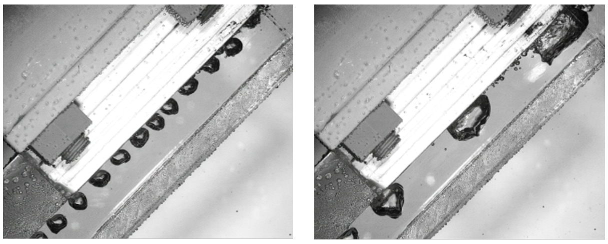


Fig. 4. CCD variation according to the mass flux and void fraction at the inclined channel.



(a) $\alpha = 0.09$ (b) $\alpha = 0.16$

Fig. 5. Bubble appearances according to the void fraction at the inclined channel.

5. Conclusions

The downward-facing flow boiling CHF condition was simulated through the hydrogen evolution system. The influences of mass flux, void fraction and inclination on the CCD were explored to investigate the analogous relation between the CHF and CCD.

The mass flux retarded the CCD, which is analogous to the mass flux influence on the CHF. However, void fraction influence on the CCD was different according to the inclination. For the vertical channel, The CCD reduced with an increasing void fraction due to the decreased liquid velocity at the wall region. In case of the inclined channel, The CCD showed a peak according to the bubble shape. The photographic evidences supported the condition of increasing or decreasing CCD.

Based on the present work, the authors expected that the complex CHF research condition such as IVR-ERVC can be substituted by the hydrogen evolution system, which can achieve a critical point (CCD) readily than that of the boiling system.

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