Investigation of CHF for IVR-ERVC Condition using a Hydrogen Evolving System

Jeong-Won Han, Dong-Young Lee, Hae-Kyun Park and Bum-Jin Chung*
Department of Nuclear Engineering, Kyung Hee University
#1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea
**Corresponding author: bjchung@khu.ac.kr*

1. Introduction

In-Vessel Retention through External Reactor Vessel Cooling (IVR-ERVC) is the widely adopted strategy to mitigate a severe accident, maintaining the integrity of the nuclear reactor vessel. The heat removal capability by the external cooling is an important issue [1]. The maximum heat removal capability could be estimated by the CHFs at the outer wall of the reactor vessel.

This study simulated the CHF according to the curvature of the reactor vessel lower plenum. Experiments were performed for the downward-facing plate varying the inclination from vertical to near horizontal, void fraction from none to 0.5, and mass flux from 250 to 1500 kg/m^{2}s, respectively. The boiling condition was simulated by the electrochemical hydrogen evolving system.

2. Background theories

2.1 Influence of mass flux on the CHF

Sudo et al. [2] investigated the CHF at the forced convection boiling conditions of saturated water in vertical rectangular channel. The CHF values were measured for both up-flow and down-flow, respectively. The mass flux was varied from 0 to 600 kg/m^{2}s. They proposed a correlation (2.1) based on the experimental results.

$$q_c'' = 0.005 h_{fg} G^{0.611} \times \left[\rho_g (\rho_f - \rho_g) g \sqrt{\frac{\sigma}{(\rho_f - \rho_g) g}} \right]^{0.1945} \tag{2.1}$$

Oh and Englert [3] investigated the CHF in a uniformly heated vertical rectangular channel. The mass flux was varied from 30 to 80 kg/m^{2}s with subcooled temperature range of 5–72 °C. They reported that when the subcooled temperature was below 40 °C, the results well agreed with the existing studies. But, when subcooled temperature was over 50 °C, the CHF increased more than 15% as the subcooled water condensed the bubble and increased the flow rate at the heating surface. Based on the results, they proposed a correlation (2.2) as below:

$$q_c'' = \frac{A_c}{A_h} h_{fg} \times \left[0.458 \left(1 + \frac{\Delta h_{sub,i}}{h_{fg}}\right) G + 2.412 \sqrt{\rho_g \{\sigma g (\rho_f - \rho_g)\}^{0.5}} \right] \tag{2.2}$$

The existing studies show that the increased mass flux delays the CHF and hence increases the CHF values.

2.2 Influence of void fraction on the CHF

The CHF strongly depends on the void fraction. Weisman and Pei [4] reported that there was a critical void fraction for the CHF and that the CHF decreased as the void fraction increased when the bubble layer formed near the heating surface.

Kharangate et al. [5] measured the flow boiling CHF varying the inlet quality and the mass flux of FC-72 in a vertical rectangular channel. The inlet quality was varied from 0.06 to 0.3, which corresponds to the slug and annular flow. As a result, the CHF increased as the quality increased. The increased void fraction in the tube caused the increased velocity of the liquid film to maintain constant mass flux.

2.3 Influence of inclination on the CHF

Zhang et al. [6] investigated the influence of the inclination on the flow boiling CHF of FC-72 using a rectangular channel. For the horizontal downward-facing plate, as the vapor accumulated easily beneath the heating surface, the CHF value decreased significantly as the heating surface became horizontal at low inlet velocity. However, this trend became weaker as inlet velocity increased.

Konishi et al. [7] improved the study of Zhang et al. [6] varying inlet quality and mass velocity to investigate the influence of the inclination on the CHF using FC-72. As inclination became horizontal for downward-facing surface, the clear stratification of the flow occurred, which started from channel inlet. Thus, the CHFs for these inclinations were very small.

3. Experiments

3.1 Methodology

In this study, the electrochemical hydrogen evolving system was adopted to simulate the boiling system. The hydrogen reduction reaction at the cathode surface when the potential is applied, simulated the vaporization phenomenon of the boiling system because the gas generation mechanisms of both systems are dominated by the heterogeneous nucleation [8].

The basic idea of this methodology is that the CHF depends largely on the hydrodynamics and that the bubble behavior can be simulated through the evolution of hydrogen. It assumed that if hydrogen generation rate exceeds a certain limit, the similar phenomenon with the CHF can be expected to occur at the cathode surface (Critical Current Density, CCD). The current density and potential difference in the hydrogen evolving system is analogous to the heat flux and wall superheat, respectively. And the analogous curve to the boiling curve can be obtained using the hydrogen evolving system [9]. 1.5 M of sulfuric acid (H_2SO_4) solution was used as the working fluid and the copper cathode was used to simulate heating surface. The authors' research group previously performed the similar experiments introducing this experimental methodology and a more detailed information can be found in the references [1,9,10].

3.2 Test apparatus

Figure 1 shows a schematic of the experimental apparatus. 1.5 M of aqueous solution of sulfuric acid is pumped from the reservoir and hydrogen gas is injected from the tank into the square tube mixing chamber through the flow meters. The liquid flow rate and the gas flow rate were controlled with the control valve, and the gas governor, respectively. The cathode was embedded at the test section which varies the inclination. Voltage, current, gas flow rate, liquid flow rate, and surface temperature of the cathode were measured by data acquisition (DAQ) system. The bubble behavior was recorded using high-speed camera in the perpendicular direction to the flow direction.

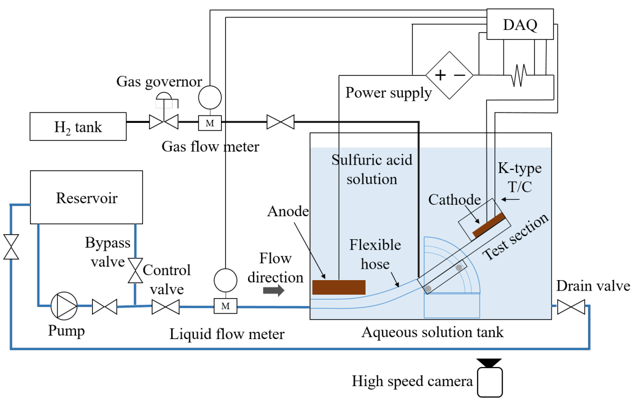


Fig. 1. The schematic circuit of the experimental apparatus.

3.3 Test matrix

Table I shows the test matrix of the present study. The cathode surface is 35 mm long and 10 mm wide with 10 mm gap size. The range of mass flux and void fraction were 250–1500 kg/m^{2}s and 0.0–0.5, respectively. The inclination of cathode was varied from 90º to 172º, which corresponds to vertical to near horizontal.

Table I: Test matrix

Copper plate W × L (mm)	Gap size (mm)	Mass flux (kg/m^{2}s)	Void fraction	Inclination (degree)
10 × 35	10	250–1500	0.0–0.5	90, 120, 135, 152, 172

4. Results and discussion

4.1 Influence of mass flux on the CCD

Figure 2 compares the CCD values measured in this study with the existing CHF values. Both the CHF and the CCD increased with the mass flux. As the mass flux increased, formation of the gaseous film was interrupted by the inertia of the bulk fluid. The coherent tendencies between the CHF and the CCD experiments appeared regardless of the void fraction.

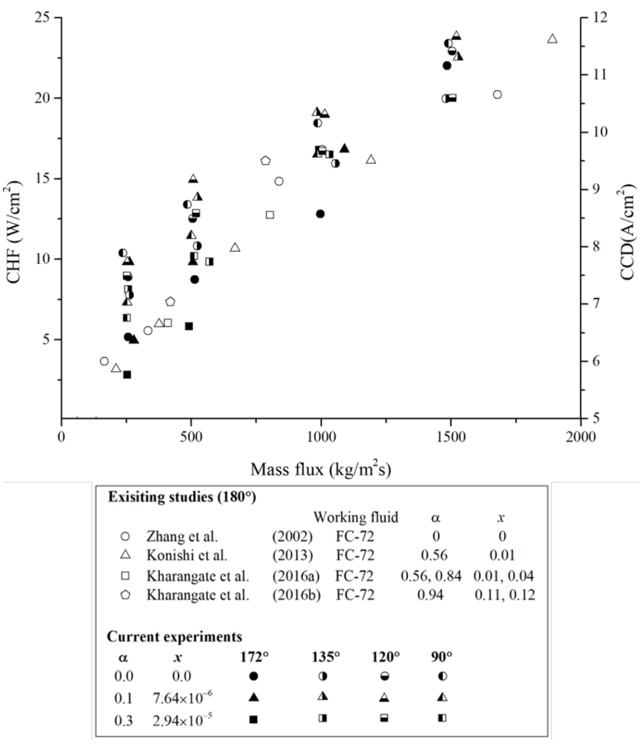


Fig. 2. Influence of mass flux on CHF and CCD.

4.2 Influence of void fraction on the CCD

Figure 3 shows the CCD at vertical according to the void fraction (α). The CCD decreased as the void fraction increased for all cases. Bubbles from upstream, flow along the center of the channel as shown in Fig. 4(b). In this case, as the centerline velocity is enhanced due to the bubbles, the velocity of liquid near the wall decreased compared with the void free condition, Fig. 4(a). And thus, the decreased local velocity at the wall expedites the CCD condition. Moreover, with further increase of the void fraction, the CCD decreased further as upstream bubble developed to a slug flow regime due to the increased contact area between the bubble and the cathode surface.

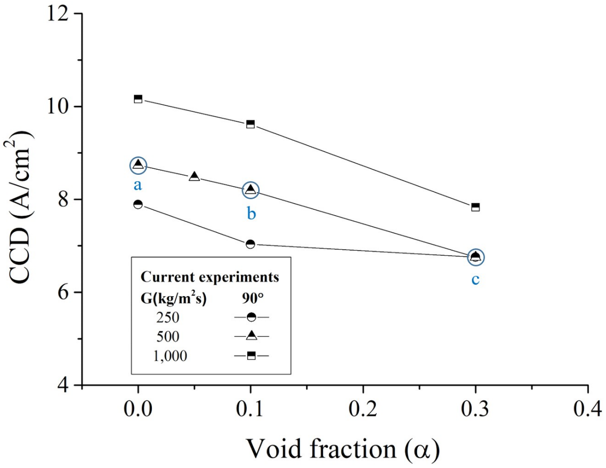


Fig. 3. CCD varying by void fraction for 90º.

(a) α = 0.0 (b) α = 0.1 (c) α = 0.3

Fig. 4. Hydrogen bubble behavior for CCD varying void fraction at 90º.

Figure 5 shows the CCD at 120º inclination with respect to the void fraction. As the void fraction increased, the CCD showed peak values for all cases. Bubbly flow was observed at the upstream until the peak CCD was measured as shown in the Fig. 6(b). In this case, the local velocity near the cathode surface increased due to the buoyancy force of the upstream bubble, which interrupted the formation of gaseous film on the cathode and thus the CCD increased. Therefore, it seems that the contribution of upstream bubble to the CCD phenomenon of the intermediate inclination was different from that of the vertical case. On the other hand, further increase of void fraction generated a plug flow at upstream. The plug flow enhanced contacting of bubbles at the cathode surface so that the CCD condition was easily attained, which decreased the CCD. This peaks were also measured in case of 135º and 152º as well.

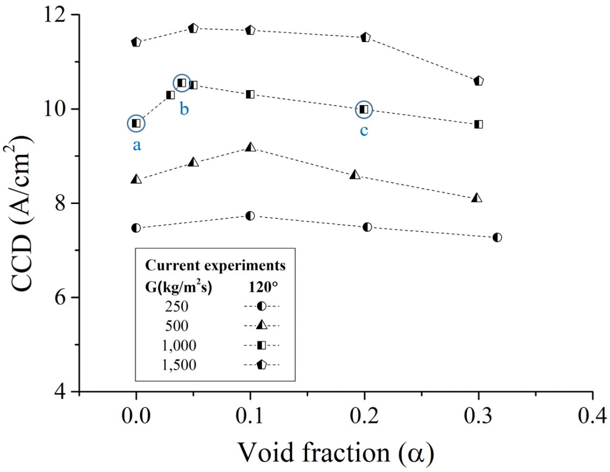
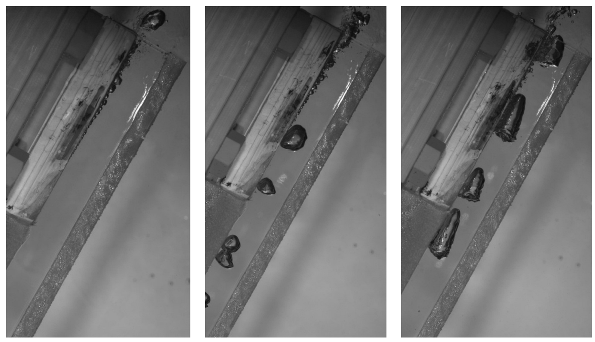


Fig. 5. CCD varying by void fraction for 120º.



(a) α = 0.0 (b) α = 0.05 (c) α = 0.2

Fig. 6. Hydrogen bubble behavior for CCD varying void fraction at 120º.

Figure 7 shows the CCD with respect to the void fraction at near horizontal inclination. As the void fraction increased, the CCD decreased. In this case, the buoyancy direction of bubbles is nearly perpendicular to the channel. The squeezed bubbles had large contacting area with the cathode surface compared to the Fig. 6(c). Thus, as the void fraction increased, the CCD decreased.

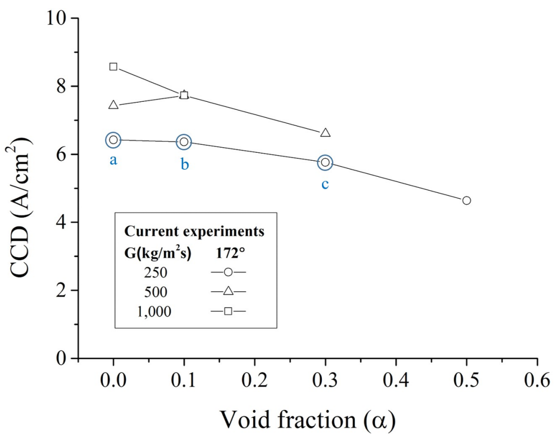
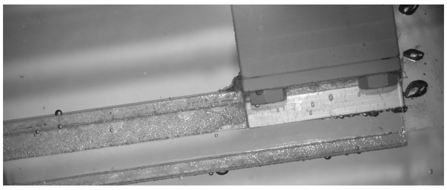
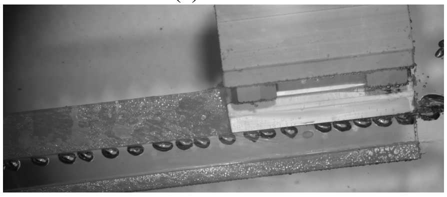


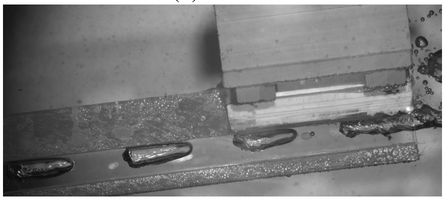
Fig. 7. CCD varying by void fraction for 172º.



(a) α = 0.0



(b) α = 0.1



(c) α = 0.3

Fig. 8. Hydrogen bubble behavior for CCD varying void fraction at 172º.

5. Conclusions

This study simulated flow boiling CHF through the electrochemical hydrogen evolving. The CCD, which is analogous to the CHF phenomenon was measured varying the inclination, void fraction, and mass flux.

It was confirmed that increasing of the mass flux delayed the CCD. However, the influence of the void fraction varied depending on the inclination. In case of vertical and near horizontal inclination, the CCD decreased as the void fraction increased. Meanwhile in case of intermediate inclination, the CCD showed peaks according to the void fraction, which means the void fraction may help or interrupt the development of the CCD condition.

ACKNOWLEDEGEMENT

This study was sponsored by the Ministry of Science and ICT and was supported by Nuclear Research & Development program grant funded by the National Research Foundation (NRF) (Grant code: 2017M2A8A4015283).

This work was also supported by “Human Resources Program in Energy Technology” of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20184030202170).

REFERENCES

[1] S. M. Ohk, H. K. Park, B. J. Chung, CHF experiments on the influence of inclination and gap size, International Journal of Heat and Mass Transfer, Vol. 132, pp. 929–938, 2019.

[2] Y. Sudo, K. Miyata, H. Ikawa, M. Kaminaga and M. Ohkawara, Experimental study of differences in DNB heat flux between upflow and downflow in vertical rectangular channel, Journal of Nuclear Science and Technology, Vol. 22, pp. 604–618, 1985.

[3] C. H. Oh and S. B. Englert, Critical heat flux for low flow boiling in vertical uniformly heated thin rectangular channels, International Journal of Heat and Mass Transfer, Vol. 36, pp. 325–335, 1993.

[4] J. Weisman and B. S. Pei, Prediction of critical heat flux in flow boiling at low qualities, International Journal of Heat and Mass Transfer, Vol. 26, pp. 1463–1477, 1983.

[5] C. R. Kharangate, I. A. Mudawar and M. M. Hassan, Exprimental and theoretical study of critical heat flux in vertical upflow with inlet vapor void, International Journal of Heat and Mass Transfer, Vol. 55, pp. 360–374, 2012.

[6] H. Zhang, I. A. Mudawar, M. M. Hassan, Experimental assessment of the effects of body force, surface tension force and inertia on flow boiling CHF, International Journal of Heat and Mass Transfer, Vol. 45, pp. 4079–4095, 2002.

[7] C. Konishi, I. A. Mudawar and M. M. Hasan, Investigation of the influence of orientation on critical heat flux for flow boiling with two-phase inlet, International Journal of Heat and Mass Transfer, Vol. 61, pp. 176–190, 2013.

[8] H. Vogt, Ö. Aras, R.J. Balzer, The limits of the analogy between boiling and gas evolution at electrodes, International Journal of Heat and Mass Transfer, Vol. 47, pp. 787– 795, 2004.

[9] H. K. Park, B. J. Chung, Simulation of critical heat flux phenomenon using a non-heating hydrogen evolving system, Frontiers in Energy Research, Vol. 7, Article 139, 2019.

[10] J. Y. Moon, B. J. Chung, Simulation of pool boiling regime for a sphere using a hydrogen evolving system, International Journal of Heat and Mass Transfer, Vol. 151, 119441, 2020.