Resemblance of critical current density to critical heat flux

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1. Introduction

The critical heat flux (CHF) is one of the prime design and safety parameters in the nuclear power plant. The measurements of the CHF are difficult due to the extreme experimental conditions, which cause the failure of the test facility. The present work proposes a possible alternative experimental method to overcome the difficulty of the CHF experiment by extending the analogy relation between heat and mass transfers. The critical current density (CCD) is an operation limit in the water electrolysis when hydrogen film is formed on the working electrode [1]. Based on the hydrodynamic similarities between the CHF and the CCD, analogous characteristics of the CCD with the CHF are explored. Dilute sulfuric acid electrolysis of 1.5 M was employed to produce hydrogen gas, which simulates vaporization in the boiling system. The present paper is based on the authors' previous studies [2-6] to show comprehensive result.

2. Comparison of nucleation characteristics

Prior to investigate upper operation limits between boiling and hydrogen evolving systems (CHF and CCD), the prime nucleation characteristics of the hydrogen evolving system are measured and compared with the boiling system; active nucleation site density, bubble departure diameter and bubble frequency.

The active nucleation site density (N_a) in the hydrogen evolving system increases with increased current density, which corresponds to the heat flux. Because the hydrogen generation takes place at the surface cavity, similar to the boiling system [6]. However, much higher N_a is measured in the hydrogen evolving system.

The bubble departure diameter (D_d) decreases with increased current density, which is inverse tendency to the boiling system. And the size of D_d is much smaller in the hydrogen evolving system due to the electrocapillarity [6].

Due to the decreasing trend of D_d, the bubble frequency (f) of the hydrogen evolving system increases as the current density increased [6].

In summary, the boiling and hydrogen evolving systems share the increasing trend of N_a, while higher N_a was measured in the hydrogen evolving system. And decreasing trend of D_d was measured in the hydrogen evolving system with smaller D_d.

3. Applicable CHF models for CCD

Some of well-accepted CHF models are borrowed to elucidate CCD mechanism. The present section shows similarities and differences between the CHF and the CCD.

3.1 Dry spot model

Ha and No [7] proposed dry spot model, which elucidated the CHF mechanism by employing bubble coalescence phenomenon on the surface. They insisted that when the number of bubbles surrounding a single bubble exceeds five, the CHF is triggered. Similar to the dry spot on the surface, the insulated spot is formed underneath a hydrogen bubble on the cathode surface in the hydrogen evolving system [2]. Park and Chung [2] calculated the critical number of bubbles (n_c) leading to the CCD using Poisson distribution, same as Ha and No's expression.

$$I'' = I_b N_a (1 - P(n \geq n_c)), \tag{1}$$

where I_b denotes the amount of current of single hydrogen bubble.

Fig. 1 shows the measured CCD and plotted CCD using Eq. (1) in case of n_c = 5, 6 and 7. Particularly, in case of the n_c = 6 shows the best agreement with the experimental result. The calculated CCD is 7.4% higher. Hence, the critical number of bubbles in the hydrogen evolving system is six, which enables to envisage the bubble configuration at the CCD as shown in the Fig. 2.

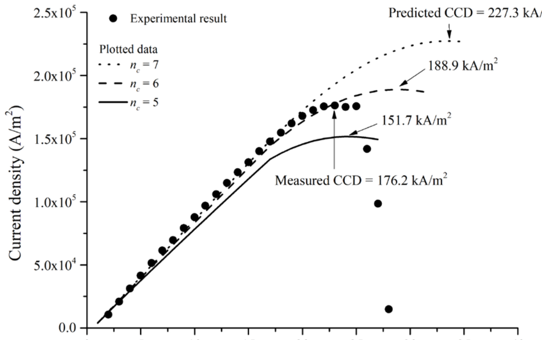

Fig. 1. Plotted curves with critical number of bubbles compared to the experimental data.

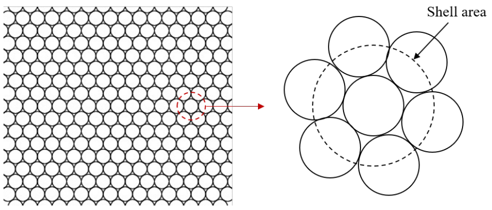

Fig. 2. Hexagonal packing structure expected for the hydrogen bubble configuration at the CCD.

3.2 Macrolayer dryout model

Haramura and Katto [8] proposed macrolayer dryout model based on the existence of macrolayer underneath the vapor mushroom. They predicted the CHF using thickness of the macrolayer (δ_c) and hovering time (τ) of the vapor mushroom using Eq. (2).

$$q''_{CHF} A_h \tau = h_{fg} \rho_l \delta_c (A_h - A_g). \qquad (2)$$

Park and Chung [3] firstly observed the macrolayer of the hydrogen evolving system as shown in the Fig. 3. They derived Eq. (3) as the analogous relation to the Eq. (2) to predict CCD value using δ_c and τ at the hydrogen evolving system.

$$I''_{CCD} = \frac{F}{m_{H+}} \rho_l m_f \frac{\delta_e}{\tau}. \qquad (3)$$

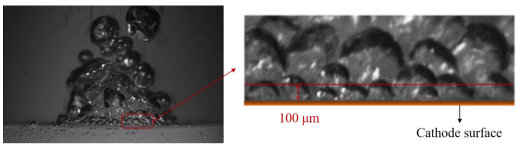

Fig. 3. Existence of macrolayer in hydrogen evolving system.

As a result, the CCD by applying the macrolayer dryout model was predicted using Eq. (3). The measured CCD and predicted CCD are 179.32 kA/m^2 and 171.48 kA/m^2, respectively; relative error of 4.37%. Thus, the prediction is well agreed with the experimental data. Based on the result, the macrolayer dryout model of CHF phenomenon also can envisage the CCD phenomenon.

4. Applications of CCD to various conditions

Based on the similar triggering mechanism of the CCD to the CHF, the influences of hydrodynamic parameters on the CCD are presented in this section.

4.1 Influence of mass flux and inclination

The CHF increases as the mass flux increases due to the enhanced bubble elimination on the heating surface [9,10]. Similarly, the CCD increases with the increased mass flux as shown in the Fig. 4 [4]. And the CCD decreases as the surface inclination becomes horizontal, which is again similar to the CHF.

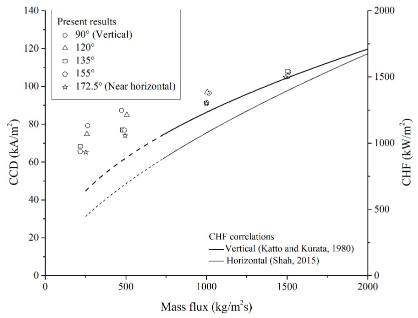

Fig. 4. Influences of mass flux and inclination on the CHF and the CCD.

Fig. 5 shows hydrogen bubble behavior around the CCD. Just before the CCD, the nucleate bubbles were observed. However, a partial hydrogen film is formed at the trailing edge of the cathode surface when the CCD is triggered, which is similar to the vapor behavior around the CHF [11].

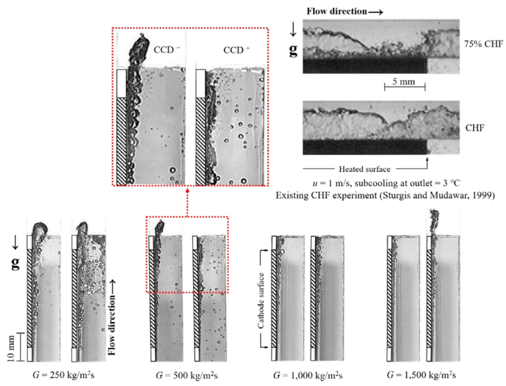

Fig. 5. Hydrogen bubble behavior just before and at the CCD.

4.2 Influence of inlet void fraction

Fig. 6 shows the influence of the void fraction (α) at the vertical inclination [5]. The CCD decreases as α increases due to the increased channel center velocity, which reduces the velocity near the cathode wall. Fig. 7 shows the voids from upstream, which flow along the channel center.

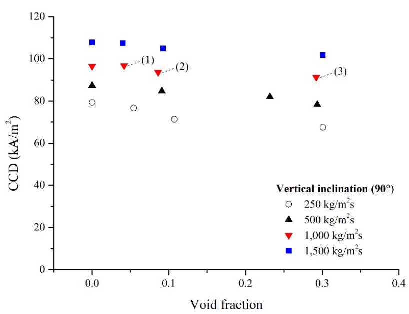

Fig. 6. Variation of the CCD according to α; vertical.

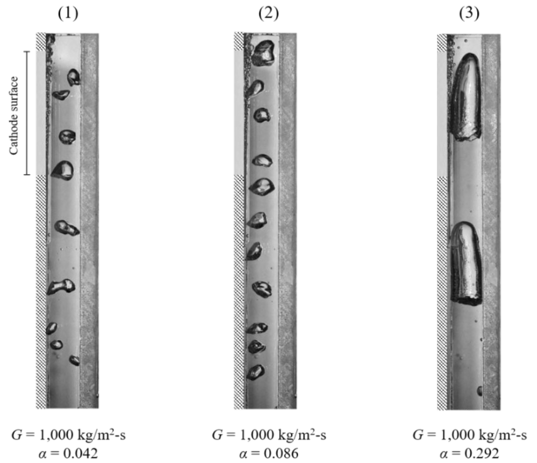

Fig. 7. Upstream flow regime according to α; vertical.

However, the CCD shows peak value at the inclined surface as in the Fig. 8 [5]. It is due to the different upstream flow regime of inlet void, which disturbs or helps the hydrogen film formation on the cathode surface. As shown in the Fig. 9, the bubbly flow appeared at (1) and (3), while the slug flow appeared at (2) and (4). The former and the latter disturbs and helps the formation of hydrogen film, respectively.

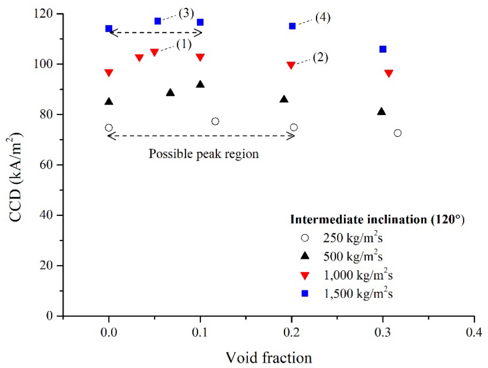

Fig. 8. Variation of the CCD according to α; inclined surface.

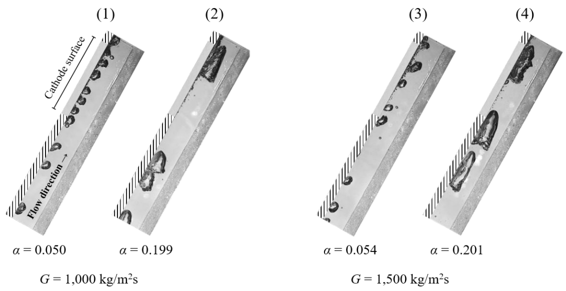

Fig. 9. Upstream flow regime according to α; inclined surface.

3. Conclusions

Analogous characteristics of the CCD with the CHF are investigated based on the hydrodynamic similarities. Experimental investigations were performed together with the phenomenological analysis based on the visualization of two-phase flow using high-speed camera. An electrolysis of dilute sulfuric acid is employed to generate hydrogen gas, which simulates the vaporization of the boiling system.

The CCD phenomenon is envisaged by utilizing the CHF models. Existing CHF models are borrowed and customized to understand CCD mechanism. Both dry spot model and macrolayer dryout model not only interpret the CCD triggering mechanism but also predicts the CCD with hydrodynamic aspects.

Similar influences of the hydrodynamic parameters to the CHF are confirmed to extend the analogy. The influence of mass flux and inclination on the CCD showed similar trend to those of the CHF.

The study proposes possible alternative experimental method for CHF by utilizing the water electrolysis.

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REFERENCES

[1] H. Vogt, Heat transfer in boiling and mass transfer in gas evolution at electrodes – The analogy and its limits, International Journal of Heat and Mass Transfer, Vol.59 pp.191–197, 2013.

[2] H. K. Park, and B. J. Chung, Estimation of critical number of hydrogen bubbles for critical current density using the dry spot model, Chemical Engineering Science, Vol.249, 117344, 2022.

[3] H. K. Park, and B. J. Chung, Application of macrolayer dryout model for the critical current density of water electrolysis, International Communications in Heat and Mass Transfer, Vol.130, 105759, 2022.

[4] J. W. Han, D. Y. Lee, H. K. Park, and B. J. Chung, Experimental investigation on the flow CCD by analogically utilizing the CHF correlation, International Journal of Heat and Mass Transfer, Vol.183, 122242, 2022.

[5] H. K. Park, J. W. Han, and B. J. Chung, Influence of hydrodynamic parameters on the critical current density at water electrolysis: Mass flux, channel inclination and inlet void fraction, International Journal of Hydrogen Energy, Vol. 47, pp.7535–7546, 2022.

[6] H. K. Park, and B. J. Chung, Comparison of bubble parameters between boiling and hydrogen evolving systems, Experimental Thermal and Fluid Science, Vol.122, 110316, 2021.

[7] S. J. Ha, and H. C. No, A dry-spot model of critical heat flux in pool and forced convection boiling, International Journal of Heat and Mass Transfer, Vol.41, pp.303–311, 1998.

[8] Y. Haramura, and Y. Katto, A new hydrodynamic model of critical heat flux, applicable widely to both pool and forced convective boiling on submerged bodies in saturated liquids, International Journal of Heat and Mass Transfer, Vol.26 pp.389–399, 1983.

[9] Y. Katto, and C. Kurata, Critical heat flux of saturated convective boiling on uniformly heated plates in a parallel flow, International Journal of Multiphase Flow, Vol.6 pp.575–582, 1980.
[10] M. M. Shah, A general correlation for critical heat flux in horizontal channels, International Journal of Refrigeration, Vol.59, pp.37–52, 2015.
[11] J. C. Sturgis, and I. Mudawar, Critical heat flux in a long, rectangular channel subjected to one-sided heating–I. flow visualization, International Journal of Heat and Mass Transfer, Vol.42, pp.1835–1847, 1999.