Simulation of CHF Condition using Mass Transfer Experimental Methodology

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 boiling heat transfer, the vapor intensifies convection near the heated surface so that heat transfer coefficient is obtained through the small values of the super heat. When boiling intensified as heat flux or temperature increased, the vapor columns formed and then finally vapor film can be formed on the heated surface. In case of the heat transfer impaired by vapor film, impaired heat exchange between the surface and the bulk liquid may threat system integrity. Thus, the heat flux has a certain maximum value, called Critical Heat Flux (CHF) [1]. For this reason, many of study concerning CHF have been performed over the last half a century. So that the several CHF models have been proposed. Among them, hydrodynamic instability model and macrolayer dryout model have been accepted widely. However, understanding of the CHF mechanism is still insufficient due to the various parameters [2]. However, it is hard to conduct experiment in the vicinity of the CHF value, since the CHF phenomena occurs at high heat flux over 1,000 kW/m^2. Thus, such a high temperature condition would threat integrity of the test facility.

The authors try to develop the non-heating experimental method to simulate CHF phenomenon using mass transfer system in order to overcome exacting heat transfer experiment. Because, heat and mass transfer system can be treated as analogous system [1]. Based on this concept, the heat transfer problem can be solved through the mass transfer system as analogous governing equation and dimensionless numbers. However, the conventional mass transfer systems which substituted the heat transfer systems were limited by the single phase regime. In this paper, the authors extended conventional mass transfer system to simulate two-phase regime. Sulfuric acid (H_2SO_4) solution and copper electrodes were used for the mass transfer experiment. Hence, the authors also performed the parametric analysis to compensate the difference between heat and mass transfer system.

2. Existing studies

Many researchers have been studied for CHF phenomena in pool boiling conditions. Here are several CHF models, which have been widely accepted.

2.1 Hydrodynamic Instability Model

Kutateladze [3] proposed CHF correlation based on a dimensional analysis in an incipient study. And then, Zuber [4] established hydrodynamic instability model, which is widely accepted. Zuber [4] developed CHF correlation applying to the Rayleigh-Taylor instability and Kelvin-Helmholtz instability as expressed in Eq. (1). In this case, diameter of the vapor columns were assumed a half of Rayleigh-Taylor wavelength. At CHF condition, vapor collapse phenomenon was assumed by Kelvin-Helmholtz instability. Compared with the experimental data, *K* value was determined as 0.131 for water boiling experiment.

$$q''_{CHF} = K h_{lg} \rho_g^{1/2} [\sigma g(\rho_l - \rho_g)]^{1/4} \tag{1}$$

2.2 Macrolayer Dryout Model

Haramura and Katto [5] postulated the macrolayer dryout model. They developed Katto and Yokoya's study [6] and suggested that the heat transfer at a certain high heat flux is related with presence of macrolayer. Macrolayer is the thin liquid layer, which is located underneath of the vapor mushroom. Thus, the CHF occurs when the liquid layer is completely dried during hovering period, which is a period from generation to departure of the vapor mushroom. And they postulated thickness of the macrolayer as a forth of Kelvin-Helmholtz wavelength. Hence, CHF correlation from the heat balance equation was derived in terms of the liquid vaporization at the macrolayer.

$$\tau_d q''_{CHF} = \delta_l h_{lg} \rho_l (A_h - A_v) \tag{2}$$

τ_d, δ_l, A_h and A_v is hovering period, thickness of macrolayer, heated area, and area of the vapor stem respectively. Thus, Eq. (3) can be derived introducing Eq. (2).

$$q''_{CHF} = h_{lg} \rho_g^{0.5} [\sigma g(\rho_l - \rho_g)]^{1/4} (1+k)^{5/16} (\frac{\pi^4}{2^{11} \cdot 3^2})^{1/16} \tag{3}$$
$$(\frac{A_v}{A_w})^{5/8} (1 - \frac{A_v}{A_w})^{5/16} [(\frac{\rho_l}{\rho_g} + 1) / (\frac{11}{16} \frac{\rho_l}{\rho_g} + 1)^{3/5}]^{5/16}.$$

2.3 Other Models

Kandlikar [7] analyzed the CHF phenomena theoretically in terms of vapor receding contact angle. It means that receding contact angle between heated surface and vapor may affect the CHF. Kandlikar also suggested CHF correlation, which is well agreed with Kutateladze's correlation and existing experimental results.

As high speed camera recording technology improved, the scholars could observe and analyze CHF phenomena in high quality [8-9]. Ahn and Kim [8] showed presence of macrolayer and dry patch near the CHF using high speed camera. They used heater of diameter of 10 mm upward facing copper disk. In this case, CHF was increased because of the inflow at the edge of the heater. Because the inflow impeded vaporization process at the macrolayer. For this reason, the macrolayer forms as a concave shape.

3. Experiments

3.1 Methodology

The mass transfer system was introduced in order to simulate CHF phenomenon. The system is composed of anode and cathode electrodes submerged in a solution of sulfuric acid. As the applied current between anode and cathode increases, the potential increases resulting in the evolution of hydrogen. This phenomenon is similar to that of the vaporization in the boiling heat transfer.

The basic idea of this study is that the CHF phenomenon due to the film boiling can be simulated through the reduction of hydrogen ions in mass transfer system. If hydrogen generation exceeds a certain limit, hydrogen film can be formed as in the boiling system (Critical Current Density, CCD). Although it is strictly differ from the two-phase flow to the two-component flow, there are several points of similarity between two systems: general phenomenon, analysis and experimental method [10].

In the two phase flow, hydraulic behavior of vapor over the arbitrary solid surface can be similar to the two-component flow. Hence, the volume generation rate of the hydrogen can be calculated with Eq. (4).

$$\eta = V_m\left(\frac{T}{273.15}\right)\left(\frac{I}{neN_A}\right) \qquad (4)$$

Volume generation rate of hydrogen in the present work (m^3/s), η can be calculated by I, n, e and N_A, which represent current, number of the electron charge to reduction hydrogen ion, magnitude of the charge of an electron and Avogadro constant, respectively. And the volume per unit mole of the gas (m^3/mole), V_m transforms molar generation of hydrogen into volume generation, which was dependent on the temperature with respect to the Charles's law. And then the applied heat flux is simulated as follows, Eq. (5).

$$q_{CHF} = \eta h_{fg}\rho_g \qquad (5)$$

The products of η in Eq. (4) by present experiment, latent heat, h_{fg} and density of vapor, ρ_g transforms the applied current at CCD condition into the CHF condition in the heat transfer system.

3.2 Experimental Apparatus

The experimental apparatus and electric circuit are shown in Fig. 1. Copper of 10 mm diameter of horizontal upward facing disk was located in a top-opened reservoir. This cathode disk simulates heated surface. And an anode copper plate of 0.01 m × 0.05 m is placed against the cathode to supply electric charges. The power supply (SGI 100A/150V, SGI) was used for potential control and Data Acquisition system (34972A, Agilent) was used for recording the data.

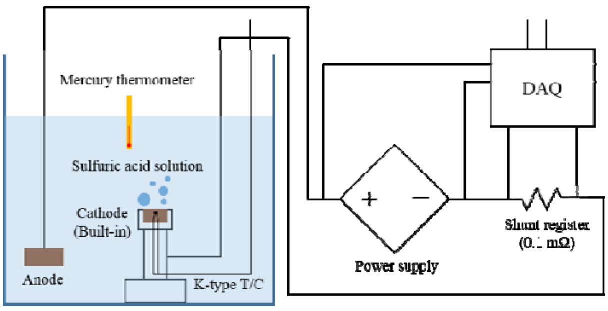
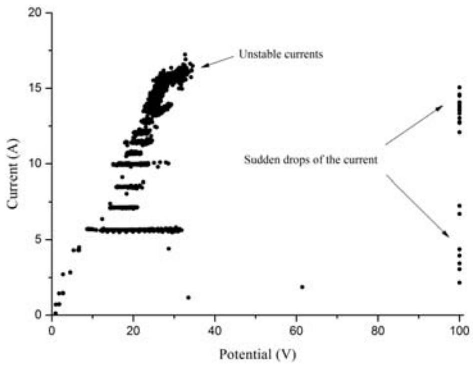


Fig. 1. Schematic design of the test electric circuit.

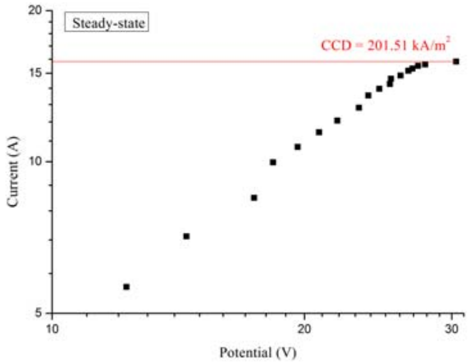
4. Results and discussion

4.1 CCD measurement

Figure 2(a) shows the measured current (I) and potential (V) during experiment. Potential increased as applied current increased at low-current regime, which is similar to the nucleate boiling regime of the conventional boiling curve. When current density exceeded about 16 A, a sudden drop was measured. It seems that the coalescence of hydrogen on the cathode surface impeded supplement of the electron charge. As in the Fig. 2(b), steady-state data, the CCD was measured at 201.51 kA/m^2. And this CCD can be transformed to CHF by using Eq. (4) and (5), 37.12 kW/m^2. Meanwhile, the correction of the result by the physical properties, such as gas density and buoyancy force, which were different between the present system and boiling system, were applied and thus CCD was reduced by 12.77 kW/m^2. This result is about 120 times smaller than that of the heat transfer results by Haramura and Katto's [5] and Ahn and Kim's [8] experiments, which were conducted identical geometry condition with present works.



(a) CCD result with applied current.



(b) CCD result at steady-state.

Fig. 2. CHF simulation results using mass transfer system.

4.2 Departure hydrogen diameters

The departure bubble diameters of hydrogen bubble at low current regime (Under 851.80 A/m^2) were measured. The high speed camera (Phantom, v7.3-4GB Mono) was used for still cuts of the departure bubble, which was not coalesced and departed independently. The average hydrogen departure diameter was 0.124 mm. However, the typical range of departure bubble diameters measured by various researchers in heat transfer system using water under 0.1 MPa were from 2 mm to 3 mm [11]. Meanwhile, the departure bubble diameter decreases as pressure increases and the similar diameter scale with present result was measured at 2 MPa condition [12]. The authors suspected that the solid surface-to-gaseous interaction such as surface tension or certain electro-chemical reaction may cause these discrepancy.

4.3 Behaviors of hydrogen mushroom

Figures 3 compares the hydrogen and vapor behavior just before the CCD and CHF trigger. Hydrogen mushroom did not observed at the present result, while large vapor mushroom was observed in the boiling experiment. Clearly, the coalescence of hydrogen occurs, while the diameter of it does not exceed the cathode boundary.

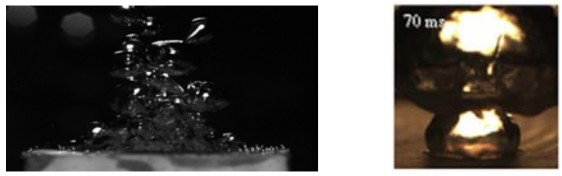
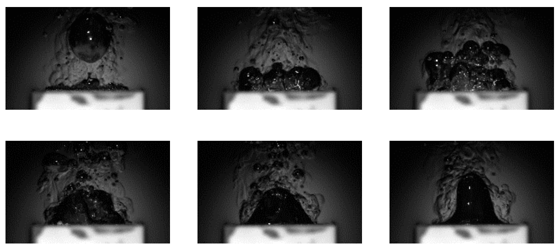
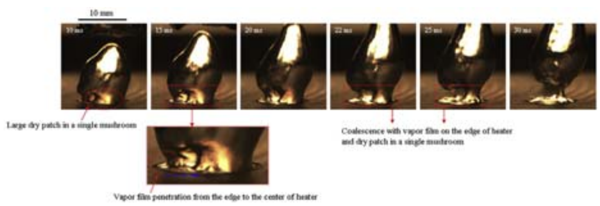


Fig. 3. Hydrogen and vapor mushroom behavior just before CCD and CHF, respectively.

Figure 4 compares the mushroom behavior between the present experiment and the boiling experiment at CCD and CHF trigger, respectively. The sphere-shaped mushroom formed in the present work as in the Fig. 4(a), while relatively oval shaped vapor mushroom formed at the heat transfer result of Ahn and Kim (2012) as in the Fig. 4(b). However, as shown in the Fig. 4(c), hydrogen mushroom behavior of the present work seems to be similar with heat transfer under hydrophobic surface condition, which vapor mushroom formed as sphere. Moreover, the CHF value at the hydrophobic surface condition was significantly decreased compare to the bare surface [13]. O'Henley *et al*. [13] measured the CHF at 20–40 kW/m^2 with hydrophobic surfaces, while the authors measured CHF at 12.77 kW/m^2. Based on the observation of mushroom behavior and the experimental results at the hydrophobic surfaces, the authors suspected that the hydrogen behavior would be similar to the vapor behavior of the hydrophobic surface condition at the boiling experiment.



(a) Hydrogen mushroom behavior at CCD trigger.



(b) Vapor mushroom behavior at CHF trigger [8].

(c) Vapor mushroom behavior of the heat transfer experiment with hydrophobic surface condition at CHF trigger [15].

Fig. 4. Photographs at CHF or CCD trigger.

3. Conclusion

The CHF phenomenon was simulated by the mass transfer system. Sulfuric acid solution and the copper electrodes were employed in order to generate hydrogen at the cathode, which simulated vaporization of the boiling system. The authors hypothesized that the CHF phenomenon can be simulated when hydrogen was identical to the rate of vapor. Based on this motivation, CHF can be transformed by measuring CCD.

The comparison of the results between heat and mass transfer were performed such as departure bubble diameter, mushroom behavior and CHF. As a result, CCD was measured which had similar trend with boiling curve. The CCD was transformed to CHF and corrected by the gas density and buoyancy force. The transformed CHF measured by CCD was only 0.83% of the CHF value. Regardless of the large discrepancies, the comparable boiling conditions exist such as pressure and surface condition. The boiling experiment under the 2 MPa condition, the similar departure bubble diameter was measured with the present result. Moreover, the CHF value and vapor mushroom shape of the boiling experiments, which employed hydrophobic surface were similar to the present work.

The authors hypothesized that there are similarity between the boiling system and the present system when the high pressure or hydrophobic surface condition were established. Clearly, the further studies such as influence of the pressure and surface treatment must be conducted in order to get closer to the boiling system.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT: Ministry of Science and ICT) (Grant code: 2017M2A8A4015283).

REFERENCES

[1] F.P. Incropera, Foundation of Heat Transfer, John Wiley & Sons, New Yotk, pp. 622-638, 2012.

[2] P. Lloveras, F. Salvat-Pujol, L. Truskinovsky, E. Vives, Boiling crisis as a critical phenomenon, Physical Review Letters, Vol.108, 215701, 2012.

[3] S.S. Kutateladze, A hydrodynamic model of the critical heat transfer in boiling liquids with free convection, Zhurn. Tekhc., Fiz., Vol.20, pp. 1389-1392, 1950.

[4] N. Zuber, Hydrodynamic aspects of boiling heat transfer, AEC Report No. AECU-4439, Physics and Mathematics, 1959.

[5] 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.

[6] Y. Katto and S. Yokoya, Principal mechanism of boiling crisis in pool boiling, International Journal of Heat and Mass Transfer, Vol.11, pp. 993-1002, 1968.

[7] S.G. Kandlikar, A theoretical model to predict pool boiling CHF incorporating effects of contact angle and orientation, Journal of Heat Transfer, Vol.123, pp. 1071-1079, 2001.

[8] H.S. Ahn, M. H. Kim, Visualization study of critical heat flux mechanism on a small and horizontal copper heater, International Journal of Multiphase Flow, Vol.41, pp. 1-12, 2012.

[9] I.C. Bang, S. H. Chang, W. P. Beak, Visualization of a principle mechanism of critical heat flux in pool boiling, International Journal of Heat and Mass Transfer, Vol.48, pp. 5371-5385, 2005.

[10] G.B. Wallis, One-dimensional two-phase flow, McGraw-Hill, 1969.

[11] N.I. Kolev, Multiphase Flow Dynamics 2, Springer Berlin Heidelberg, pp. 417-438, 2007.

[12] H. Sakashita, A. Ono, Boiling behaviors and critical heat flux on a horizontal plate in saturated pool boiling of water at high pressures, International Journal of Heat and Mass Transfer. Vol.52, pp. 744–750, 2009.

[13] H. O'Hanley, C. Coyle, J. Buongiorno, T. McKrell, L.W. Hu, M. Rubner, R. Cohen, Separate effects of surface roughness, wettability and porosity on the boiling critical heat flux, Applied Physics Letters, Vol.103(2), 024102, 2013.

[14] https://www.youtube.com/watch?v=hrvB1-dDqrA