Investigation of CHF in Channel Boiling varying the Surface Inclination using a Non-heating Experimental Method

Seung-Min Ohk, 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

High heat transfer rate can be obtained even with small superheat in boiling heat transfer. Beyond a certain point termed Critical Heat Flux (CHF), Heat transfer between heated surface and liquids become drastically reduced, as the generated vapors on the heated surface form the vapor films [1]. For this reason, prediction of CHF is important for the cooling devices as CHF can be a criterion of maximum cooling capacity.

For the nuclear power plant, in normal operating condition, coolant circulating reactor core performs the nuclear fuel cooling. But, the core may melt and relocated to the lower part of the reactor vessel if the inadequate cooling performed due to the severe accident such as Loss of Coolant Accident (LOCA). In addition, CHF can be occurred on the outer surface of reactor vessel, as the boiling intensified due to the decay heat from the core melts about 20–30MWth [2]. In fact, the structure near the reactor wall such as shear key can affect CHF [3]. Hence, the research of CHF should be conducted for the outer wall of reactor vessel to predict the CHF which was the criteria of the maximum cooling capacity. Thus, it is necessary to carry out basic experiment for phenomenological understanding.

In this study, the authors investigated for the CHF phenomena using a non-heating experimental method extended conventional mass transfer experiment based on the copper electroplating system [4,5]. CHF was simulated through generated hydrogen vapor as applying the potential between electrodes. The width and length of boiling surface was 10 mm and 35 mm respectively. The surface inclinations were varied from vertical (90°) to near totally downward-facing (177.5°).

2. Existing studies

2.1 Influence of surface inclination

Vishnev [6] suggested the most widely accepted pool boiling CHF correlation considering the surface inclination based on a various research data.

$$\frac{q_{CHF}}{q_{CHF,0}} = \frac{(190-\theta)^{0.5}}{190^{0.5}} \quad (1)$$

El-Genk and Guo [7] measured overall heat flux from film boiling to nucleate boiling using a quenching method. They suggested a pool boiling CHF correlation varying a fluid conditions for the water, liquid nitrogen, and liquid helium.

$$\begin{aligned} q_{CHF} &= C_f(\theta)\rho_g h_{lg}\left[\frac{\sigma(\rho_l-\rho_g)}{\rho_g^2}\right]^{0.25} \text{ where} \\ C_{water}(\theta) &= 0.034 + 0.0037(180-\theta)^{0.656} \\ C_{liq.nitrogen}(\theta) &= 0.033 + 0.0096(180-\theta)^{0.479} \\ C_{liq.helium}(\theta) &= 0.002 + 0.0051(180-\theta)^{0.633} \end{aligned} \quad (2)$$

Chang and You measured [8] CHF varying the surface inclinations for three different surface conditions. They reported that the region where CHF decreased drastically as the inclination increased.

$$\frac{q_{CHF}}{q_{CHF,0}} = 1.0 - 0.000120\theta tan(0.414\theta) - 0.122 sin(0.318\theta) \quad (3)$$

While almost the whole correlations were developed in the manner of measuring CHF, Howard and Mudawar [9] suggested the CHF correlation through the analysis of the vapor behavior model for just before CHF at near vertical region. They asserted that CHF triggered when the boiling surface covered fully with vapor as the wetting front lift off the surface due to the intensified pressure in high heat flux condition.

$$q_{CHF} = 0.25\rho_g h_{lg}\left(1+\frac{C_{p,l}\Delta T_{sub}}{h_{lg}}\right)\left[2\sqrt{2\pi}\frac{\sigma}{\rho_g\lambda_c^2}\right]^{0.5} \quad (4)$$

2.2 Influence of gap size

Monde et al. [10] investigated for the CHF according to the gap size for a vertical channel. CHF decreased with increasing the length-to-spacing ratio, *l/s*. They suggested a fitted correlation based on the experimental data of various fluids.

$$\frac{q_{CHF}}{\rho_g h_{lg}}\left[\frac{\sigma g(\rho_l-\rho_g)}{\rho_g^2}\right]^{-0.25} = \frac{0.16}{1+6.7\times10^{-4}\left(\frac{\rho_l}{\rho_g}\right)^{0.6}\left(\frac{l}{s}\right)} \quad (5)$$

Bonjour and Lallemand [11] developed the channel boiling correlation modifying the correlation of monde with considering the influence of pressure. The pressure varied from 1 bar to 3 bar. CHF decreased with decreasing gap size for any pressure.

$$\frac{q_{CHF}}{\rho_g h_{fg}}\left[\frac{\sigma g(\rho_l-\rho_g)}{\rho_g^2}\right]^{-0.25}=\frac{0.18}{1+6.39\times10^{-5}\left(\frac{\rho_g}{\rho_l}\right)^{1.343P^{0.252}}\left(\frac{d}{s}\right)^{1.517}} \quad (6)$$

3. Experiments

3.1. Methodology

The developed experimental method of convectional mass transfer system based on the copper electroplating was used to the simulate CHF phenomena.

The basic idea of this study start from the assumption that hydraulic behavior of both vapor and hydrogen are the same though the difference between two-phase flow and two component flow [12]. In the mass transfer system, the hydrogen vapor was generated through the reduction of hydrogen ions as the high potential applied between electrodes.

For the two phase flow, hydraulic behavior of vapor on the arbitrary surface may be similar to the two-component flow under the identical gaseous volume condition. Thus, the volume generation rate of hydrogen can be calculated through Eq. (7)

$$\eta=V_R\left(\frac{T}{273.15}\right)\left(\frac{I}{neN_A}\right) \quad (7)$$

Volume generation rate of hydrogen in the mass transfer system (m^3/s), η can be calculated by the applied current, I over products between n, e, and N_A that represent number of the elector charges 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 convers molar generation of hydrogen into volume generation regarding to the Charles's law. Thus the applied heat flux is represented as follows.

$$q_{CHF}=\eta h_{fg}\rho_g \quad (8)$$

3.2 Test matrix and diagram

Table 1 showed the experimental test matrix. Experiments were carried out pool boiling condition under the atmospheric pressure. The length of boiling surface was 35 mm. It determined to be longer than instability wave length of water. Surface inclination was varied from vertical (90°) to downward-facing (177.5°)

Table I: Test matrix for experiments.

Boiling surface, $w \times L$	**Inclination (θ)**
Copper plate, 10 × 35	90°, 120°, 135°, 150°, 160°, 170°, 175°,177.5°

Figure 1 shows the illustration of test diagram. Test apparatus designed to adjust surface inclination was submerged into top-opened glass tank. The tank was filled with a 1.5 M aqueous sulfuric. The surface of cathode generating hydrogen vapor was polished with 1000 mesh of sandpaper. The anode was located against to the cathode. The power supply (N8952A, Keysight) was used to applying potential between electrodes. Data was acquired 10 times per second using DAQ (34972A, Keysight). The boiling surface and bulk temperature was measured by using K-type thermocouple and mercury thermometer respectively. High speed camera (Phantom, Lab111 6GMono) was used to take an image of vapor behavior.

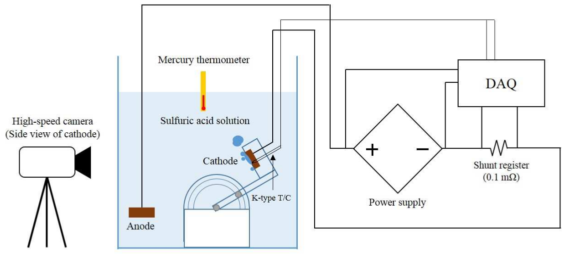


Fig. 1. Illustration of test diagram.

4. Results and discussion

4.1. Justification of this study

Figure 2 showed CHF with regard to the surface inclinations which was calculated by Eq. (8). CHF decreased with increasing the inclination. The trend showed half-parabolic shape. The calculated CHF about 100 times lower than that of heat transfer for water. Even though the calculated CHF was low, CHF near downward was 1/3 compared to the vertical one. The present heat transfer correlations noticed a similar trend. So, we performed a scale analysis to investigate the effect of the vapor behavior on the CHF even if the system is different.

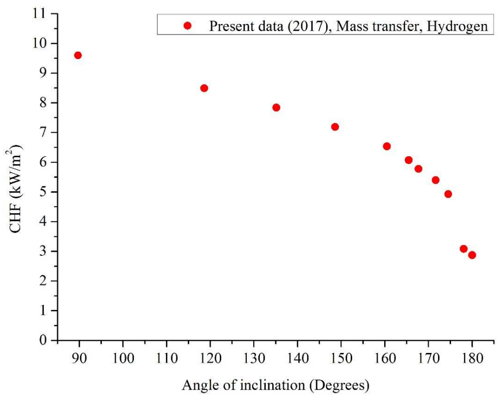


Fig. 2. Absolute CHF value of mass transfer according to the angle of inclination.

Since the vapors rise along the surface in the longitudinal direction, the vapor flow can be assumed one-direction flow. The buoyancy affect on the vapor dominantly as the position of surface was downward-facing. Thus, the forces acting on the vapor underneath the surface can be expressed as,

$$F_{\text{Buoy, x}} \sim F_{\text{Drag}} \tag{9}$$

The length of boiling surface use as characteristic length, and Eq. (9) written as,

$$g\sin\theta(\rho_l - \rho_g)L^3 \sim \rho_l U_g^2 L^2 \tag{10}$$

As the properties were constant, the vapor velocity, $\underline{U}_g$ can be expressed in function of inclination.

$$U_g \sim C(\sin\theta)^{0.5} \tag{11}$$

Through the Eq. (12) presented heat balance equation suggested by Zuber [13], CHF depends on U_g, CHF is related to the function of inclination of the boiling surface as shown in Eq. (13).

$$q_{CHF}''(A_g/A_h) = U_g h_{lg} \rho_g \text{ (Zuber, 1959)}, \tag{12}$$

$$q_{CHF} \sim (\sin\theta)^{0.5} \tag{13}$$

Hence, the inclination of the boiling surface can be a factor that predominantly affects CHF. CHF showed a half-parabolic decreasing tendency as the inclination increased which is the same for the existing correlations (1–3). Thus, even if the absolute CHF value is different, it is considered meaningful to compare between inclinations through the normalized CHF value.

4.2. Comparison the test results to existing correlations

Figure 3 presented the normalized CHF according to the surface inclination. The normalized CHF was compared with existing heat transfer correlations. CHF values were normalized based on the CHF value of 90°. The correlations also renormalized based on the value of 90°. The angle of inclinations were varied from vertical (90°) to near totally downward-facing (180°).

The both normalized CHF and correlations decreased as the surface inclination increased. This is because the buoyancy acting on the vapor become impaired as the inclination increased. As the inclination of the surface become to the downward-facing, the vapors stay well on the surface. For these reason, early CHF appeared as the inclination increased due to the vapor covers the boiling surface easy.

For the degree of angle from 90° to 135°, the results were similar to the correlation of Chang and You [8]. For the degree of angle from 150° to 180°, the results positioned higher than all correlations except for the 177.5°. It might be the error from the renormalization process and/or due to the surface condition difference in this system.

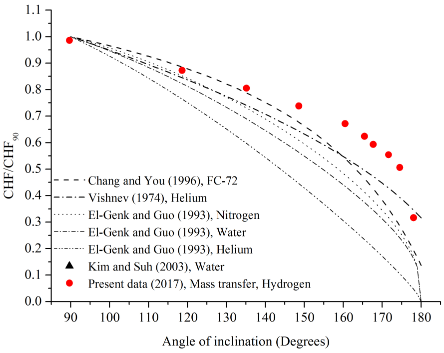


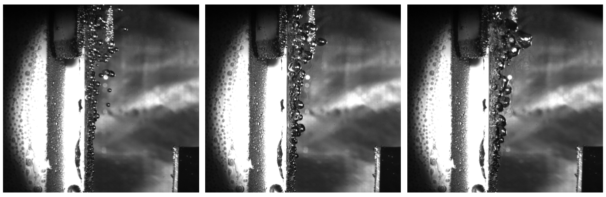
Fig. 3. Normalized CHF according to the angle of inclinations.

4.3. Visualization

Figure 4–6 showed the vapor behavior according to the representative inclination in the mass transfer experiment. The vapor behavior was observed by changing the fraction of CCD (30, 60, 99%).

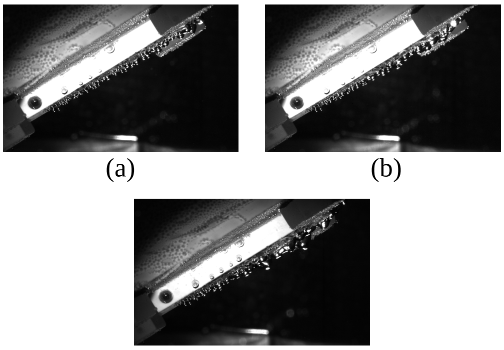
Figure 4 showed the vapor behavior according to the fraction of CCD at 90°. As the boiling condition become intensified, the ascending vapors grew through interaction with surrounding vapors. Fig. 5 showed the vapor behavior according to fraction of CCD at 150°. Vapor behaviors were similar to that of 90°. On the other hand, for the surface inclination of 175° shown in Fig. 6, the elongated vapors traveled along the surface slowly. However, For all inclination, discrete vapors formed and rised.

In heat transfer exepreiment, Kim et al. [14] showed that the vapor behavior presents a Kelvin-Helmholtz instability wave, as the boiling condition become intensified. In addition, Howard and Mudawar [9] reported that Kelvin-Helmholtz instability wavelength of the merged vapor become longer as the inclination increased. However, in this study, Kelvin-Helmholtz wave was not appeared although the boiling condition become intensified. it seems that in the mass transfer experiments, smaller vapors were generated on the surface due to the surface condition.



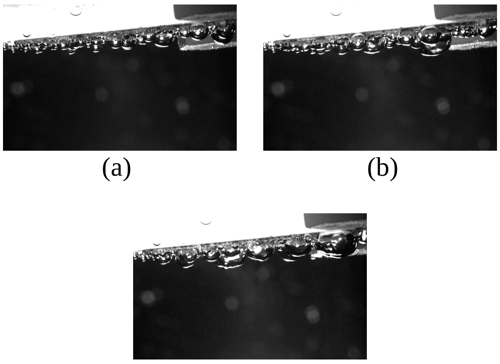
(a) (b) (c)

Fig. 4. Vapor behaviors on a vertical surface (90°).



(a) (b) (c)

Fig. 5. Vapor behaviors on an inclined surface (150°).



(a) (b) (c)

Fig. 6. Vapor behaviors on an inclined surface (175°).

5. Conclusion

CHF on the inclined downward-facing surface was simulated using non-heating experimental method and measured through the extended method of mass transfer system.

CHF converted through the mass transfer experiment was much smaller than that of heat transfer. However, through the scale analysis, the author asserted that it is reasonable to compare CHF value as the normalized CHF including influence of inclination.

The normalized CHF was compared with the heat transfer correlations. The tendency of the results were similar to the correlations.

Visualization also conducted to the each inclination of surface varying the fraction of CCD. However, in the mass transfer system, the results showed that a large number of discrete vapors were formed unlike vapor behavior in the heat transfer.

6. Further work

The influence of channel on the CHF will be verified varying the gap size (1–10 mm). We anticipate that the transition angle appears early as the gap size become small due to the increase in void faction at confined area. The normalized CHF correlation can be suggested. CHF mechanism for this system will be confirmed based on surface condition as O'Hanley [15] referred that CHF can be decreased about 97% on hydrophilic surface.

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) (No. NRF-2017M2A8A4015283).

REFERENCES

[1] F. P. Incropera, Fundation of Heat Transfer, John Wiley & Sons, New York, pp. 622–638, 2012.
[2] J. W. Park, Analytical evaluation of two-phase natural circulation flow characteristic under external reactor vessel cooling, Annals of Nuclear Energy, Vol. 36, pp. 1668–1675, 2009.
[3] K. S. Ha, F. B. Cheung, R. J. Park, S. B. Kim, Evaluation of two-phase natural circulation flow induced in the reactor vessel anuular gap under ERVC conditions, Nuclear Engineering and Design, Vol. 253, pp. 114–124, 2012.
[4] J. Y. Moon, B. J. Chung, Time-dependent Rayleigh-Bernard convection: Cell formation and Nusselt number, Nuclear Engineering and Design, Vol. 274, pp. 146-153, 2014.
[5] H. K. Park, S. H. Kim, B. J. Chung, Variation in the angular hear flux of the oxide pool with Rayleigh number, Annals of Nuclear Energy, Vol. 107, pp. 128-135, 2017.
[6] I. P. Vishnev, Effect of orientating the hot surface with respect to the gravitational field on the critical nucleate boiling of a liquid, International Journal of Engineering and Physics, Vol. 24, pp. 43–48, 1974.
[7] El-Genk, S. Mohamed, and Z. Guo, Transient boiling from inclined and downward-facing surface in a saturated pool, International Journal of Refrigeration Vol. 16, pp. 414–422, 1993.
[8] J. Y. Chang, S. M. You, Heater orientation effects on pool boiling of micro-porous enhanced surfaces in saturated FC-72, Journal of Heat Transfer, Vol. 118, pp. 937–943, 1996.
[9] A. H. Howard, I. Mudawar, Orientation effects on pool boiling critical heat flux and modeling of CHF for near-vertical surface, International Journal of Heat and Mass Transfer Vol. 42, pp. 1665–1688, 1999.
[10] M. Monde, H. Kusuda, H. Uehara, Critical heat flux during natural convective boiling in vertical rectangular channels submerged in saturated liquid, Journal of Heat Transfer, Vol. 104, pp. 300–303, 1982.
[11] J. Bonjour, M. Lallemand, Effects of confinement and pressure on critical heat flux during natural convective boiling in vertical channels, International Communications in Heat and Mass Transfer, Vol. 24, pp. 191–200, 1997.
[12] G. B. Wallis, One-dimensional two-phas flow, McFraw-Hill, 1969.
[13] N. Zuber, Hydrodynamic aspect of boiling heat transfer, AEC Report No. AECU-4439, Physics and Mathematics, 1959.
[14] Y. H. Kim, S. J. Kim, J. J. Kim, S. W. Noh, K. Y. Suh, J. L. Rempe, F. B. Cheung, S. B. Kim, Visualization of boiling phenomena in inclined rectangular gap, International Journal of Multiphase Flow, Vol. 31, pp. 618–642, 2005.
[15] H. O'Hanley, C. Coyle, J. Buongiorno, T. McKrell, L.W. Hu, M. Rubner, and R. Cohen, Separate effects of surface roughness, wettability, and porosity on the boiling critical heat flux, Applied Physics Letters, Vol. 103, 024102, 2013.