Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-19, 2017

Visualization of CHF varying the Surface Orientation using Non-heating Method

Seung-Min Ohk 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

Severe accidents have been gaining research interests since Fukushima nuclear power plant accident. In vessel retention through external reactor vessel cooling (IVR-ERVC) is one of the severe accident management strategy and has been applied in the design of nuclear power plants [1].

In a severe accident condition, the core may melt and relocate to the lower part of the reactor vessel. The reactor vessel is submerged by the coolant and cooled by it. Boiling condition may occur due to the large decay heat. The applicability of the IVR-ERVC strategy relies on whether the decay heat can be sufficiently removed by the external cooling water to maintain the integrity of the reactor vessel. As the maximum cooling can be expressed by the CHF (Critical Heat Flux), lots of researches have been devoted to measure it some have investigated the CHF considering the influence of surface orientations [2-7].

In this study, we investigated the CHF phenomena using non-heating method. We simulated the CHF using the hydrogen bubble generated from electrode as a potential is applied to the copper electrodes in aqueous solution of sulfuric acid. The width and length of cathode, which acts as the heated surface was 10 mm and 35 mm. We visualized the behavior of vapor for each state of the surface orientations. The surface orientations were varied from 0° (Downward-facing) to 180° (Upward-facing).

2. Theoretical Background

2.1 Phenomena of CHF in boiling condition

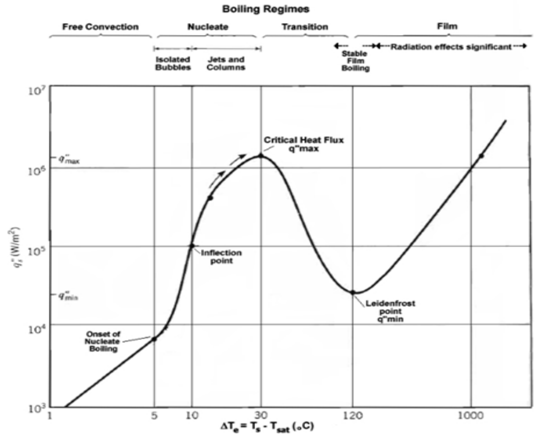

Fig. 1. Boiling curve [8].

Figure 1 shows pool boiling curve. Boiling curve can be divided into nucleate boiling, transition boiling, and film boiling as the superheat increases. Nucleate boiling starts at a relatively low superheat. In this regime, isolated bubbles formed at nucleation site and separate from the surface. most of heat exchange is through the fluid motion due to the rising bubble. More bubble generated as the superheat increased, they start interferece and coalescence with each other. And after inflection point as superheat increases, coalescence of bubble makes column and vapor escapes as this formation. when the number of these vapor column increase and more dense, the liquid flow near the surface is suppressed. So that the heat transfer gradually decreases and show the peak point, called critical heat flux.

As reach to the above the critical point, vapor behavior shows unstable film boiling. Bubble formation may oscillate between film and nucleate boiling at any point on the surface. Beyond this region as the superheat is higher that that of transition region, the film boiling is countinued. At this condition, there is no heat transfer between surface and fluid through the phase change due to the vapor film. So that the heat flux decreases no matter what the boiling surface temperature increases [8].

2.2 Effect of the surface orientation

Vishnev [2] proposed the most widely used pool boiling CHF correlation, considering the surface orientation based on the experimental data from various scholars. Correlation is derived from the data produced with a variety of fluid such as Helium, Nitrogen, Oxygen, Hydrogen, Neon and Freon.

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

El-Genk and Guo [5] measured boiling curve for each angle experimentally using a quenching method in a saturated pool boiling condition near the atmospheric pressure. They presented the CHF correlation for water, considering the influence of the angle as shown in Eq. (2)

$$\frac{q_{CHF}}{\rho_g^{0.5} h_{fg}\left[\sigma\left(\rho_f-\rho_g\right)g\right]^{0.25}} = 0.034 + 0.0037\left(180-\theta\right)^{0.656} \qquad (2)$$

Brusstar and Merte [6] measured the CHF varying the surface orientation by using a copper plate. The working fluid was R-113. They suggested an empirical CHF correlation for both pool and flow boilings as shown in Eq. (3-1) and (3-2).

$$\frac{q_{CHF}}{q_{CHF,0}} = 1.0\,,\ 0^\circ < \theta \le 90^\circ \qquad (3\text{-}1)$$

$$\frac{q_{CHF}}{q_{CHF,0}} = \sin\theta^{0.5}\,,\ 90^\circ \le \theta \le 180^\circ \qquad (3\text{-}2)$$

3. Experiments

3.1 Methodology

The copper electroplating was employed to the simulate CHF phenomena. This system is composed of anode and cathode electrodes which are submerged in a sulfuric acid solution. When the potential applied, hydrogen is reduced at the surface of the cathode. The current and the amount of hydrogen increase with the applied potential between electrodes.

The basic idea of this study is that the behavior of the vapor generation at the heated surface and the resulting nucleate and film boiling can be simulated by the hydrogen gas generated at the cathode surface under the assumption that hydraulic behaviors of both vapor and the hydrogen are the same although there are differences material properties and the difference between two-phase flow and two-component flow [9].

For the two phase flow, hydraulic behaviors of vapor on the arbitrary solid surface might be similar to the two-component flow under the identical gaseous volume condition. Thus, the volume generation rate of the hydrogen can be calculated with Eq. (4) and it can be transformed to the corresponding heat flux using Eq. (5).

$$\eta = V_R\left(\frac{T}{273.15}\right)\left(\frac{I_{CMF}}{neN_A}\right) \qquad (4)$$

Volume generation rate of the 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, which represent 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 gaseous (m^3/mole), V_R transforms molar generation of hydrogen into volume generation, which was dependent on the temperature regarding to the Charles's law. And then the applied heat flux is simulated as follows

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

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

3.2 Test matrix and apparatus

Table 1 shows the test matrix. Experiments were conducted in a pool boiling condition at the atmospheric pressure. The length of boiling surface is 35 mm, which was determined to be longer than the Taylor instability wavelength of water (22 mm). Surface orientations are varied from 0° (Downward) to 180° (Upward).

Table 1. Test matrix for experiments.

Boiling surface ***w* × *L* (mm)**	**Orientation** **(°)**
Copper, 10 × 35	180, 175, 170, 65, 160, 150, 135, 120, 90, 0

Figure 2 depicts the test apparatus and the schematic diagram. A flat copper plate is located in a top-opened glass tank. This plate of 10 mm × 35 mm acts as cathode and generates hydrogen bubbles at the surface. It is connected to the supporting assembly to set the surface orientation. An anode, 50mm square copper plate is placed against the cathode to supply the cupric ions. The copper anode was used to prevent the oxygen generation at the anode. The power supply was used for applying the potential and data acquisition system (34972A, Agilent) was used for recording the data. The surface temperature was measured by using a thermocouple (K-type).

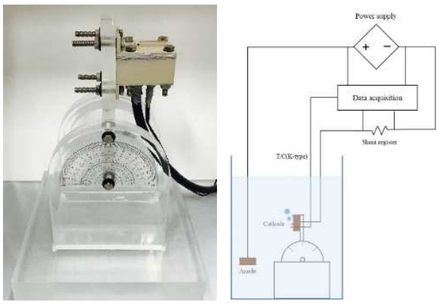

Fig. 2. Test apparatus and schematic diagram.

4. Results and discussion

4.1 Visualization

Figure 3 − 7 show the vapor behavior on the surface according to the 0°, 90°, 120°, 150°, 175° orientations. The photos were taken 1000 frames per second by using high speed camera (phantom, v7.3 4-GB mono)

Figure 3 shows vapor behavior on upward-facing flat plate. When applied potential increases, increase of current lead small bubble to large volume of vapor as bubble merging mechanism. When the large vapor leave from the surface, new bubbles are formed and grow as shown in Fig. 3 − (a), (b). Further increase of current result in the film of hydrogen bubble on the surface as shown in Fig. 3 − (c), (d). Also Taylor instability wavelength can be observed on the surface of films when film boiling occurred, whose length was approximately 17mm for Fig. 3 − (c) and 21mm for Fig.3 − (d). Those are close to that of water (22mm).

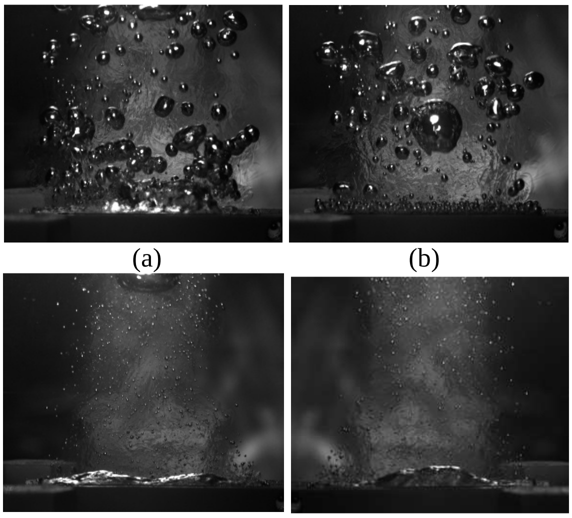
(a) (b)
(c) (d)

Fig. 3 shows vapor behavior on vertical flat plate.

Figure 4 presents the vapor behavior on the vertical surface and Fig. 5 − 7 presents that on an inclined surfaces. Unlike horizontal condition, adsorption appears between the vapor and the surface, which is adhesion from molecules to a surface. Thus the flow is subject to the balance between the driving buoyancy force and the adsorption. As inclination of the angle increased (near downward), the rate of vapor motion decreased. This is because the driving force of the vapor is weakened as the adsorption to the wall increases. This also results in early CHF at the near downward-facing surface because the large bubble (vapor mushroom) is easily formed as a gently sloping surface helps the bubble trapping on the surface.

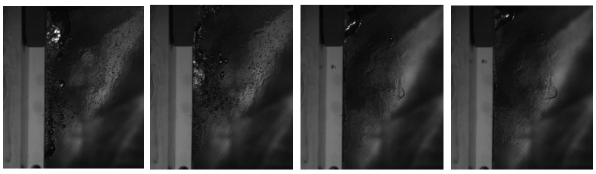
(a) (b) (c) (d)

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

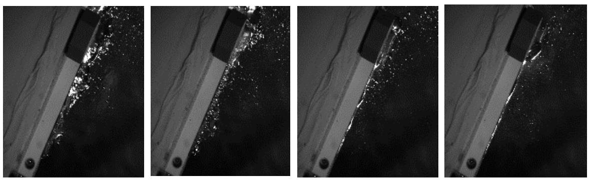
(a) (b) (c) (d)

Fig. 5. Vapor behaviors on an inclined surface (120°).

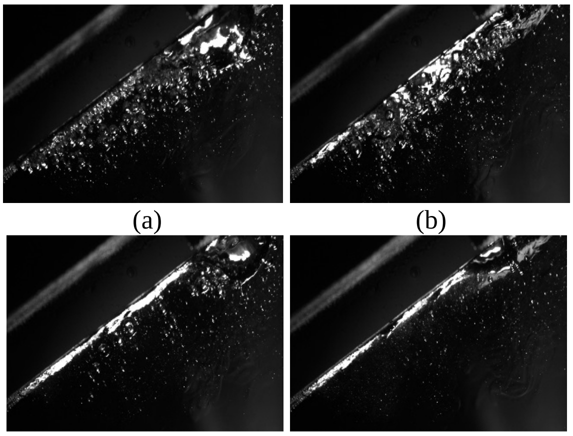
(a) (b)
(c) (d)

Fig. 6 Vapor behaviors on an inclined surface (150°).

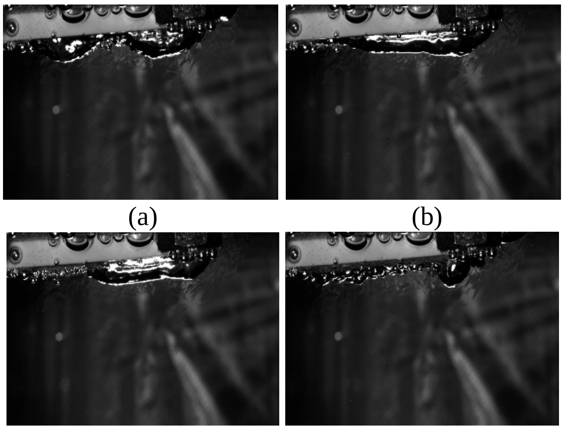
(a) (b)
(c) (d)

Fig. 7 Vapor behaviors on an inclined surface (150°).

4.2 Comparison test results to existing correlations

Figure 8 shows comparison of experimental results with the CHF correlations presented by several researchers. It represents normalized CHF values according to the surface orientations. CHF values were normalized that based on the value of 90 degree. CHF decreases as the surface goes to near downward-facing surface. The results of orientation degree from 120° to 10° were agree with well El-Genk and Guo [5] and orientation degree of 5° was agree with Chang and you [7].

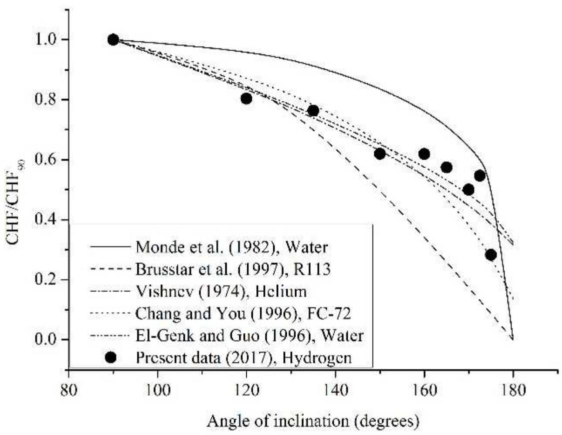

Fig. 8. CHF data comparison to correlations.

5. Conclusions

In this study, we simulated the CHF condition by using non-heating method using the hydrogen gas generated in copper electroplating.

Visualization was made for the vapor behavior varying the surface orientation by using high speed camera. For horizontal surface, Taylor instability wavelength on the film, generated by hydrogen gas is similar to that of water. For inclined surface, the bubble removal is subject to the force balance between driving buoyant force and the adsorption. Bubbles on the surface were easily trapped as inclination of angle increased.

Test results were compared with existing heat transfer correlations. They agreed well within range of heat transfer correlations.

ACKNOWLEDGMENT

This study was sponsored by the Ministry of Science, ICT and Future Planning (MSIP) and was supported by Nuclear Research and Development program grant funded by the National Research Foundation (NRF) (Grant Code: 2014M2A8A1030777).

REFERENCES

[1] J. L. Rempe, K. Y. Shu, F. B. Cheung, S. B. Kim, In-vessel retention of molten corium: lessons learned and outstanding issues, Nuclear technology Vol. 161, pp. 210-267, 2008.

[2] I. P. Vshinev, Effect of orientating the hot surface with respect to the gravitational field on the critical nucleate boiling of a liquid,

[3] K. Nishikawa, Y. Fujita, S. Uchida, H. Ohta, Effect of surface configuration on nucleate boiling heat transfer, International Journal of Heat Mass Transfer, Vol. 27, pp. 1559-1571.

[4] A. H. Howard, I. Mudawar, Orientation effects on pool boiling critical heat flux and modeling of CHF for near-vertical surfaces, International Journal of Heat Mass Transfer, Vol. 42, pp. 1665-1688.

[5] M. S. El-Genk, Z. Guo, Transient boiling from inclined and downward-facing surfaces in a saturated pool, International Journal of Refrigeration, Vol 6, pp. 424-432.

[6] M. J. Brusstar, H. Merte, R. B. Keller, B. J. Kirby Effects of heater surface orientation on the critical heat flux – I. An experimental evaluation of models for subcooled pool boiling, International Journal of Heat Mass Transfer, Vol. 40, pp. 4007-4019.

[7] J. Y. Chang, S. M. You, Heater orientation effects on pool boiling of micro-porous-enhanced surface in saturated FC-72, Journal of Heat Transfer, Vol. 118, pp. 937-943.

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

[9] G. B. Wallis, One-dimensional two-phase flow, McFraw-Hill, 1969.