Realization of Boiling Heat Transfer Flow Regimes around a Cylinder by a Non-heating Method

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1. Introduction

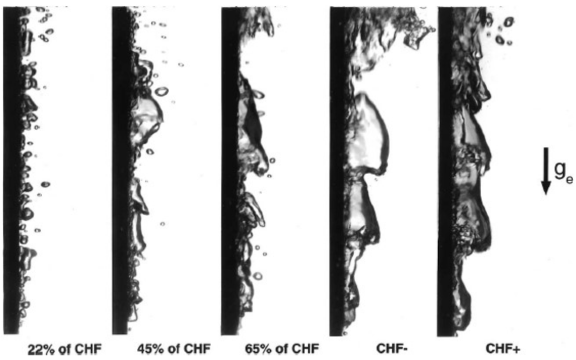
As the boiling phenomena have been applied to multiple engineering fields, such as cooling of the superconducting magnets, cryogenix system and core safety of the light water reactor, those have been studied in the variety of geometries, including plate, sphere, cylinder and wire [1-4]. Especially, the boiling phenomena that occur during the interaction process with the molten corium and the coolant are of great interest and importance in the aspect of reactor integrity [4]. In general, the quenching studies on the boiling heat transfer using the spherical metal have been highly performed. However, in the entire boiling regime, the study on the bubble behavior that is observed and analyzed is rarely conducted.

The experimental study on the boiling phenomena occurred along the circumference of horizontal cylinder was performed using a non-heating method of a mass transfer. In order to observe the two-dimensional flow, the length of cylinder was shortly fixed to 5 mm and the diameters were varied to 8.9 and 28 mm. We tried the visualization of the bubble behavior in the nucleate, transition, MHF (Minimum Heat Flux) boiling regime using the high-speed camera. The working fluid was the sulfuric acid (H_2SO_4) solution of 1.5 M.

2. Theoretical background

2.1. Flow pattern on the vertical plate

Figure 1 shows the flow pattern observed on the vertical plate in the pool boiling with increase of the heat flux. For the 22 % of CHF, the individual small vapor bubbles released from the nucleation site rise along the vertical surface. A few small vapor bubbles move toward the top of vertical plate and merge into the big bubbles as shown in Fig. 1(a). When the heat flux increases, the size and amount of generated vapor bubbles becomes large. Also, the velocity of the bubbles is more fast due to the buoyancy force. Thus, the merging phenomenon of the vapor bubbles occurs actively. In Fig. 1(b) and (c), the vapor bubbles are coalesced into the larger and longer bubbles than those of Fig. 1(a). At heat flux close to CHF (Critical Heat Flux) (Fig. 1(d)), the vapor bubbles begin to look more like a fairly continuous wavy layer. Beyond the CHF, the effect of the Kelvin-Helmholtz instability on the vertical plate due to the difference of the relative velocity between the vapor and liquid is observed (Fig. 1(e)).



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

Fig. 1. Pool boiling photographs at increasing the heat fluxes for the vertical plate [5].

2.2. Previous studies

The boiling phenomena on the outer surface of the horizontal cylinder are complex as the boiling of vertical, horizontal, and inclined plate was involved. Kim *et al.* [6] reported that it is important to investigate the boiling mechanism on the outer surface of cylinder as the tangent grade on the cylinder surface is continuously changed along the circumference. Also, the existing studies on the boiling phenomena of curved surface were insufficient. Thus, they conducted the visualization and the analysis of the bubble sliding motion on the outer surface of horizontal cylinder in the nucleate boiling regime.

I. Sher *et al.* [3] visualized the bubble behavior by changing the diameters and the materials of a sphere and proposed a classic hydraulic model considered the curvature effect.

Nishio and Ohtake [1] observed the boiling phenomena occurred along the circumference of the short horizontal cylinder in the film boiling regime. Figure 2 shows the wave pattern depending on the time proposed by Nishio and Ohtake. They envisaged that the wave pattern would be repeated periodically. It was confirmed in their experiments.

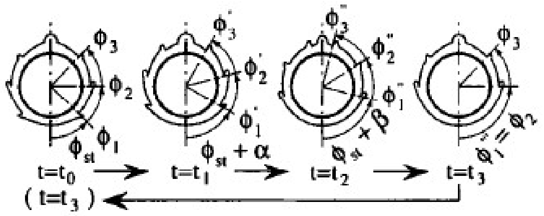


Fig. 2. The film boiling situation imagined around horizontal cylinder of a large diameter [1].

3. Experimental methodology

Heat and mass transfer systems are analogous, as the governing equations and parameters are mathematically the same [7, 8].

The copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system was generally used for analogy experiments for simulating single phase heat transfer system. As the applied potential between anode and cathode increases, the current reached to the certain value termed as plateau where a further increase in the applied potential does not affect. The current at the plateau is termed as the limiting current. Meanwhile, with a further increase in the potential beyond the plateau, hydrogen ions reduce and the current increases again. Simultaneously, the potential increases resulting in the evolution of hydrogen at the cathode. The hydrogen generated at the cathode can be simulated to the hydraulic vapor behavior. At a certain high current value, vigorous hydrogen generation forms hydrogen film on the surface as film boiling beyond the CHF value. The plot of the potential-current has similar trend to the boiling curve to the MHF point.

Therefore, in this present study, the developed experimental method of conventional mass transfer system based on the copper electroplating was used to simulate nucleate, transition, film boiling regimes phenomena.

4. Experimental setup

Figure 3 shows the electric circuit of the experimental apparatus. In order to observe the two-dimensional flow, the front of horizontal cylinder was insulated using the reinforced epoxy. The length of the horizontal cylinder was fixed to 5 mm and the diameters were 8.9 mm, 28mm. The diameter was determined by considering the critical wavelength on a horizontal plate [9, 10]. The cathode of a horizontal cylinder acts as the heated surface. The anode of 0.01 m × 0.05 m was located against to the cathode. The working fluid was the sulfuric acid (H_2SO_4) solution of 1.5 M. The power supply (N8952A, Keysight) was used for potential control and data acquisition system (34972A, Agilent) was used for recording the data. High speed camera (Phantom, Lab111 6GMono) was used to take an image of hydrogen behavior.

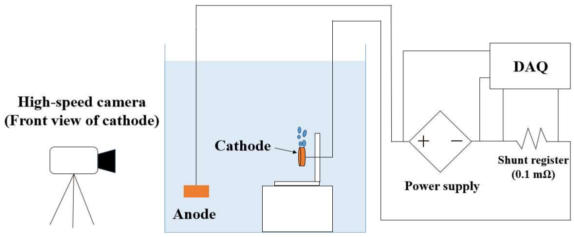
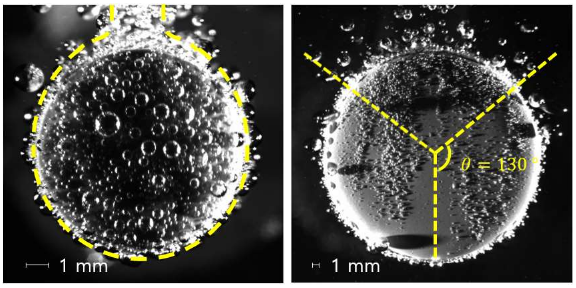


Fig. 3. Schematic design of the test electric circuit.

5. Results and discussion

Figures 4-7 show the experimental results for the horizontal cylinders with the diameters of 8.9 mm and 28 mm. The scale of the photographs was adjusted in order to confirm the bubble behavior clearly. The clung bubbles on the front of cylinder were observed in all figures due to the interaction between the reinforced epoxy and sulfuric acid solution. However, these had not an influence on the main flow observed along the circumference of the horizontal cylinder.

Figure 4 shows the visualized results of the bubble behavior less than 20 % of the CHF depending on the diameter. In cases of the diameter of 8.9 and 28 mm, as the bubbles moved from the bottom to the top, the size of the bubbles became large. For D=8.9 mm, the ascending plume is observed on the top of the cylinder in Fig. 4(a). It means that the laminar flow was formed. On the other hand, for D=28 mm, the flow separation was occurred at the angle of the 130° (Fig. 4(b)). It signifies the turbulent flow. These results are very similar to Lee and Chung [11] and Kitamura *et al.* [12].



(a) D = 8.9 mm (b) D = 28 mm

Fig. 4. Hydrogen Bubble behavior around a cylinder in nucleate boiling regime.

Figure 5 indicates the bubble behaviors depending on time on the outer surface of the horizontal cylinder in the transition boiling regime. For the Fig. 5(a), the unstable hydrogen film was temporarily formed around the horizontal cylinder and collapsed to the numerous hydrogen bubbles immediately (t = 0-6 ms). And then the numerous hydrogen bubbles moved to the isotropic direction (t = 6 ms). In the transition boiling regime, these process are periodically repeated (t = 0-15 ms). For the Fig. 5(b), the bubble behavior was similar to Fig. 1(a) until the initially formed unstable hydrogen film collapses into the numerous hydrogen bubbles (t = 0 ms). However, hydrogen bubbles which were obstructed by the cylinder due to the difference of the relative size between the hydrogen bubble and the horizontal cylinder could not travel to bulk liquid (t = 0-16 ms). Thus, many hydrogen bubbles did not travel to the bulk liquid but looked as if a one bubble moved along the circumference of horizontal cylinder.

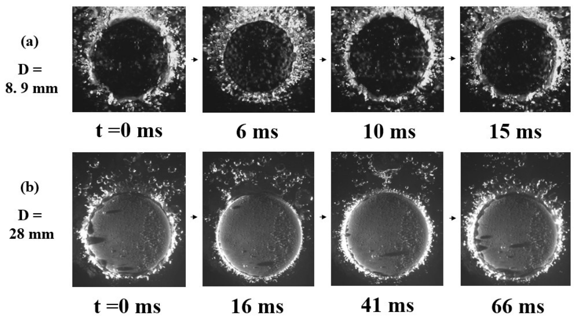
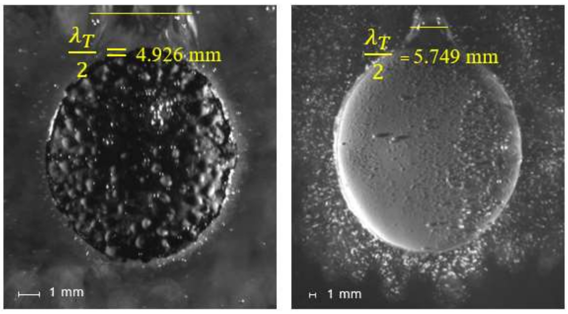


Fig. 5. Hydrogen bubble behavior around a horizontal cylinder in Transition boiling regime.

Figure 6 shows the departure bubble observed on the top of the cylinder due to the Rayleigh-Taylor instability at the MHF. The critical wavelength [8, 9] on the horizontal plate, considering the working fluid of this study, was approximately 16.56 mm. The critical wavelength on the top of the horizontal cylinder for the Fig. 6(a) and (b) were 9.85 mm and 11.49 mm, respectively. The critical wavelength on the horizontal cylinder was shorter than that of the horizontal plate due to the curvature effect.



(a) D = 8.9 mm (b) D = 28 mm

Fig. 6. Hydrogen film wave motion on the top of a horizontal cylinder at MHF.

Figure 7 presents the visualization of the wave motion occurred along the circumference of the horizontal cylinder at the MHF regime for D=28 mm. When the time was 0 ms, the waves were located at $\emptyset_1$, $\emptyset_2$ and $\emptyset_3$. After 10 ms, all of the waves moved to $\emptyset'_1$, $\emptyset'_2$, $\emptyset'_3$. Over time, if the wave moved from $\emptyset_1$ to the $\emptyset_2$, the new wave was formed at the $\emptyset_1$. As a result, the waves for t=25 mm were same as the initial arrangement. These wave motions are periodically repeated. The visualization result of this study is very similar to that of Nishio and Ohtake [1]. However, the wave motion for D = 8.9 mm was not observed, as the circumference was not long enough for the flow to grow sufficiently.

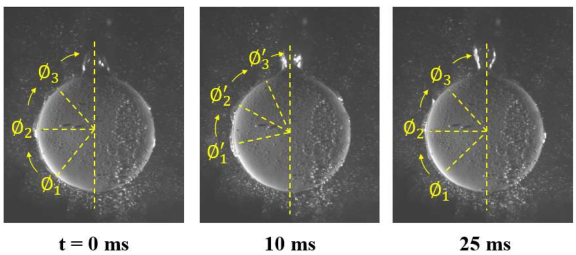


Fig. 7. Time-dependent wave motion of hydrogen film occurred along the circumference of the cylinder at MHF.

6. Conclusions

In this study, the boiling phenomena occurred along the circumference of the horizontal cylinder was visualized using a non-heating method. This experimental method was developed the conventional mass transfer system based on the copper electroplating. In the nucleate boiling regime, the laminar and turbulent flow were observed for the diameters of 8.9 and 28 mm, respectively. For the transition boiling regime, we confirmed the bubbles for the small diameter escaped from the surface with the isotropic motion, whereas that for the large diameter moved along the outer surface of cylinder. We confirmed the Rayleigh-Taylor instability at the MHF point as the departure bubble on the top of cylinder. The critical wavelength of the departure bubble was shorter than that of the horizontal plate due to the curvature effect. The wave motion of this study is very similar to Nishio and Ohtake [1].

The further works are undertaken such as the literature survey of the boiling phenomena, typical issues and design of the extended experiment to investigate the influence of the diameter of horizontal cylinder on the bubble behavior in detail.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. Nishio and H. Ohtake, Vapor-film-unit model and heat transfer correlation for natural-convection film boiling with wave motion under subcooled conditions, International Journal of Heat and Mass Transfer 36 (10) (1993)

[2] J.H. Lienhard and P.T.Y. Wong, The dominant unstable wavelength and minimum heat flux during film boiling on a horizontal cylinder, ASME. Journal of Heat transfer 86 (2) (1964) 220-225

[3] I. Sher, R. Harari, R. Reshef and E. Sher, Film boiling collapse in solid spheres immersed in a sub-cooled liquid, Applied Thermal Engineering 36 (2012) 219-226.

[4] M.L. Corradini *et al.*, Vapor explosions in light water reactors: A review of theory and modeling, Progress in Nuclear Engerg 22 (1) (1988) 1-117.

[5] A.H. Howard and I. Mudawar, Orientation effect on pool boiling critical heat flux(CHF)and modeling of CHF for near-vertical surface, International Journal of Heat and Mass Transfer 42 (1999) 1665-1688.

[6] Y.N. Kim, J.S. Kim, G.C. Park and H.K. Cho, Mesurement of sliding bubble behavior on a horizontal heated tube using a stereoscopic image processing technique, International Journal of Multiphase Flow 94 (2017) 156-172.

[7] Bejan, Convection Heat transfer. Fourth ed. Wiley & Sons. New Jersey (2003).

[8] F.P. Incropera, D.P. Dewitt, T.L. Bergmen, A.S. Lavine, Principle of heat and mass transfer, 7^{th}ed. John Wiley & Sons, INC., New York (2013)

[9] N. Zuber, Hydrodynamics aspects of boiling heat transfer, Atomic Energy Commission Report no. AECU-4439, Phys. Math (1959).

[10] N. Zuber, The hydrodynamic crisis in pool boiling of saturated and subcooled liquids, International Developments in Heat Transfer 27 (1964)

[11] D.Y. Lee, Visualization of natural convection heat transfer on a sphere, Heat Mass Transfer DOI 10 (2017).

[12] K. Kitamura, A. Mitsuishim, T. Suzuki, Misumi-T, Fluid flow and heat transfer of high-Rayleigh-number natural convection around heated spheres, International of Heat and Mass Transfer 86 (2015) 149-157. 230-236.