

An experimental study of flow boiling on downward-facing inclined wall with various inclination angle

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1. Introduction

Effects of surface orientation on boiling heat transfer have a great importance in many engineering applications such as passive thermal-hydraulic components in nuclear power plants. In particular, the In-Vessel Retention and External Reactor Vessel Cooling (IVR-ERVC) is one of the efficient safety strategies for severe accident management of nuclear power plant. In this concept, supplied water removed the decay heat of molten corium at lower surface of a reactor vessel by boiling which is downward-facing heated surface and surface inclination angle changes along the external of a reactor vessel. Nucleate boiling heat transfer is strongly related with bubble dynamics on the heated surface, which is affected by the gravitational force. Likewise, inclination angle of a heated surface may play a role in the characteristics of nucleate boiling heat transfer.

It has been reported from photographic studies about pool boiling phenomena that bubble behavior and nucleate boiling heat transfer is strongly influenced by inclination angle [1, 2]. In downward-facing heated surface, the bubble behavior of boiling phenomenon was shown significantly different in comparison with upward-facing heated surface. Githinji and Sabersky [3] suggested that the orientation of the heated surface in respect to the direction of the gravitational force was major importance in nucleate boiling heat transfer. Chang and You [4] investigated with the bubble behavior of saturated FC-72 on a copper surface and reported that the heat transfer rate dramatically decreased from 90° (vertical) to 180° (downward-facing) in nucleate boiling heat transfer.

Konishi [5] conducted flow boiling experiments with saturated FC-72 to investigate the orientation effects of a heated surface on flow boiling heat transfer. They reported that the heat transfer coefficient was highest at 90° (vertical), but they only reported overall heat transfer results about identified boiling regimes without information of bubble dynamics. Kim and Bang [6] conducted flow boiling experiments on downward-facing inclined wall from 10° to 30° and quantitatively analyzed bubble dynamics parameters, including bubble length, velocity and frequency, and heat transfer coefficient with various mass flux, heat flux and inclination angle conditions. They proposed a reduction factor that accounts for the reduced boiling heat transfer coefficient associated with long slug bubbles formed on downward-facing surfaces.

From previous works, inclination angle plays an important role in boiling heat transfer, and necessitates the experimental study on the relationship between bubble behaviors and heat transfer coefficient on downward-facing surfaces. Objective of this study is to investigate the relation between bubble dynamics and heat transfer coefficient (HTC) during flow boiling of water at a low mass flux on a downward-facing heated surface with various inclination angles.

2. Experiment

In order to investigate the boiling characteristics and phenomena which is the effects of orientation angle on downward-facing surfaces, synchronized high-speed camera (Phantom v7.3) and infrared camera (FLIR SC6000) were used to measure the bubble parameters and wall temperature distribution simultaneously as shown in Fig. 1.

To adopt the integrated visible and infrared optical measurement techniques, the test section was fabricated with separate quartz windows and test sample. Transparent windows and test sample were formed a rectangular flow channel that dimension of cross sectional area was 10 mm in width and 20 mm in height. An entrance length was designed to fully develop the fluid flow with same cross sectional area of flow channel and 550 mm length. The test section along with a high speed camera and an infrared camera were installed on the rotatable optical table. Inclination of the optical table was altered from 0° (downward-facing) to 90° (vertical) with an interval of 15°.

The test sample of heated surface was 700 nm-thick Indium Tin Oxide (ITO) film that is deposited on a 10 mm-thick sapphire plate. Total resistance of the electroconductive ITO film was ~72 Ω, the dimension of heated surface was 8 mm in width and 130 mm in length. The DC power supply (SGA 600) applied to the ITO film and heat flux on the surface was controlled in the range of 200 - 500 kW/m². ITO film was covered with the 1.1 μm thick of Al₂O₃ thin film to protect destruction of the heated surface from electrochemical reaction with water [7] and the Pt/Ti film was deposited at the end of the sides with 150 nm/150 nm as an electrode. The static contact angle of a water on Al₂O₃ thin film was 61.6 ± 0.2°.

Flow conditions were controlled using flow loop as shown in Fig. 2. Deionized water was supplied and driven by a centrifugal pump. The mass flux was

controlled roughly by frequency inverter for the centrifugal pump and slightly set by by-pass valve in the range of 200 - 400 kg/m²s. The DI-water was heated to near saturation condition by pre-heater for degassing and it was done for 3 - 4 hours. The main experimental conditions in this study summarized in table 1.

Table. 1. Experimental conditions

Parameter	Range	Unit
Heat flux	200 - 500	kW/m ²
Mass flux	200 - 400	kg/m ² s
Inclination angle	15, 30, 45, 60, 75	°
Subcooling	Saturated	°C

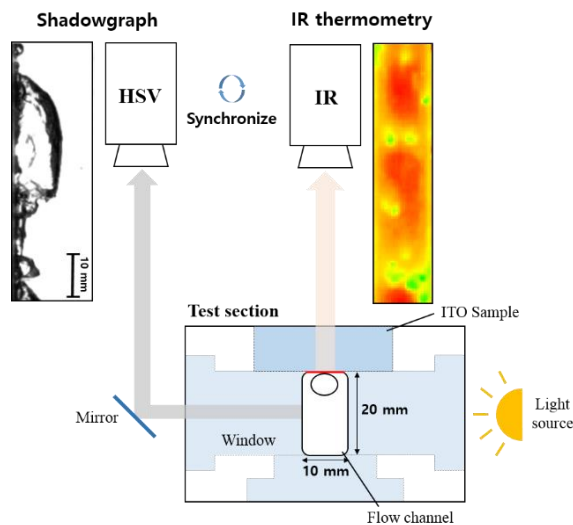


Fig. 1. Schematic diagram of experimental measurement: synchronized high-speed camera and infrared camera.

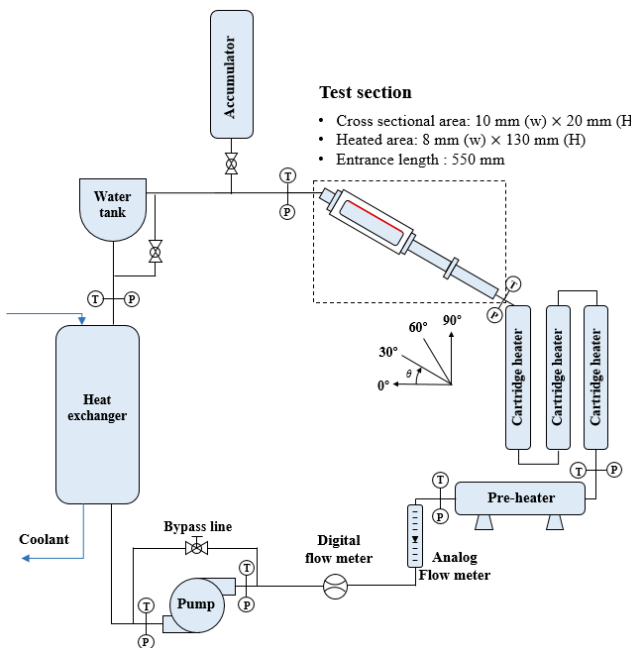


Fig. 2. Schematic diagram of flow loop to control the flow conditions.

3. Results and discussion

3.1 Effects of surface orientation on the bubble behavior

Bubble behavior was visualized using high speed camera filmed at 5,000 fps from side view with various inclination angle on downward-facing inclined wall. Fig. 3 shows the visualization results according to orientation angle on downward-facing surfaces. The applied heat flux (q'') was 296 ± 3 kW/m² and the mass flux condition (G) was 200 kg/m²s for inclination angles of 15, 30, 45, 60, 75° from horizontally downward-facing surface.

The bubble behavior was shown that generated bubble merged actively with adjacent bubbles and formed the elongated bubble without lift-off from the surface, and then slid along the heated surface. The elongated large bubble region and small bubble region were observed as periodic cycle that flow regime was slug flow. The length of slug bubble clearly increased as the inclination angle decreased and most of the heated surface was covered at lower inclination angle. In contrast, length of slug bubble was decreased as the inclination angle increased due to the difference in buoyancy and bubble coalescence.

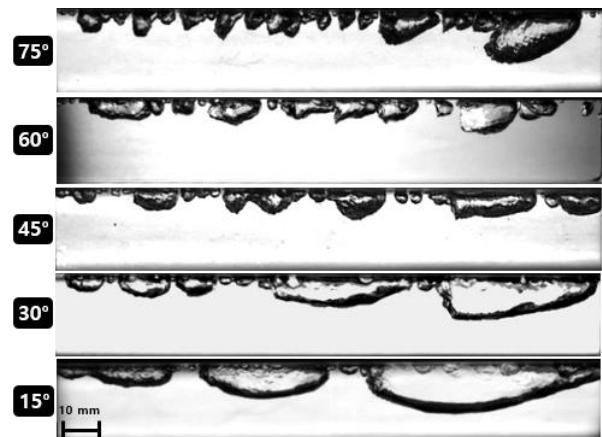


Fig. 3. Bubble behavior on downward-facing heated wall with various inclination angle.

Fig. 4 shows the bubble parameters characterizing slug behavior corresponding to inclination angle on downward-facing surfaces. L is the length of merged bubbles, V is the velocity of slug bubble at front head, and f is the frequency which is periodic cycle of passing slug bubbles. All the visualization images were post-processed using an image analysis software (ImageJ) [8] and re-scaled based on a reference length scale. Bubble parameters of interest were quantitatively measured as shown in Fig. 5. The mean value of measured bubble parameters were plotted and the error bars indicate the scattering range of experimental measurement data.

Fig. 5 (a) shows the length of slug bubble respect to inclination angle. It was measured the interface from front to rear of slug bubbles at the end of the heated wall.

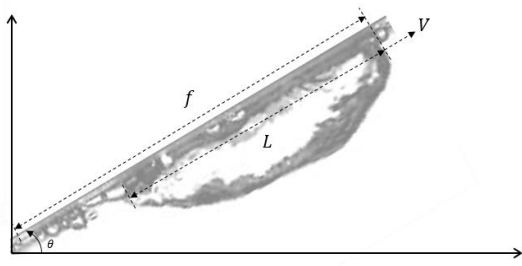


Fig. 4. Bubble parameters characterizing slug behavior on downward-facing surfaces.

The length of slug bubble was exponentially increased as the inclination angle decreased due to the relatively strong coalescence of bubble. The trend seems that augmentation of bubble length is higher when the heat flux is increased.

Fig. 5 (b) shows the bubble velocity at front interface of slug bubbles. It was calculated with moving distance of the slug bubble and frame rate of images. The bubble velocity has increased as the heat flux increased, but there was no significant variation with inclination angle. In general, the bubble velocity can be maximum when the buoyancy force acts parallel and co-current to the flow. However, buoyancy force is different to sliding bubble with inclination angle changed, the contribution of buoyancy relatively weak compared to bubble velocity by Stokes' law.

Fig. 5 (c) shows the frequency of bubble flow that periodic cycle of passing slug bubbles. The average number of passing bubbles were counted in a second. The frequency of slug bubble slightly increased as the inclination angle increased and length of slug bubble was observed shorter as shown in Fig. 3 (a). In this study, the experiment was not investigated on 15° and 75° to avoid the critical heat flux (CHF) and captured image error, respectively.

3.2 Effects of surface orientation on the boiling heat transfer coefficient

In present study, the temperature distribution on boiling surface was measured using infrared thermometry technique with 500 frame rate. The heat transfer coefficient was measured that spatial and temporal distribution were averaged on the heated surface. The average heat transfer coefficient was exponentially decreased as the inclination angle decreased on downward-facing surfaces as shown in Fig. 5. The trend corresponded to bubble dynamics in Fig. 4 (a) which is length of slug bubble. The obtained results show quite similar trend with the experimental results of previous experiment [9].

Elongated slug bubble covered most of heated surface, it could disturb the heat transfer on the surface. Apparent evidence that elongated bubble disturbed the heat transfer could be indicated with quantitative local tempe-

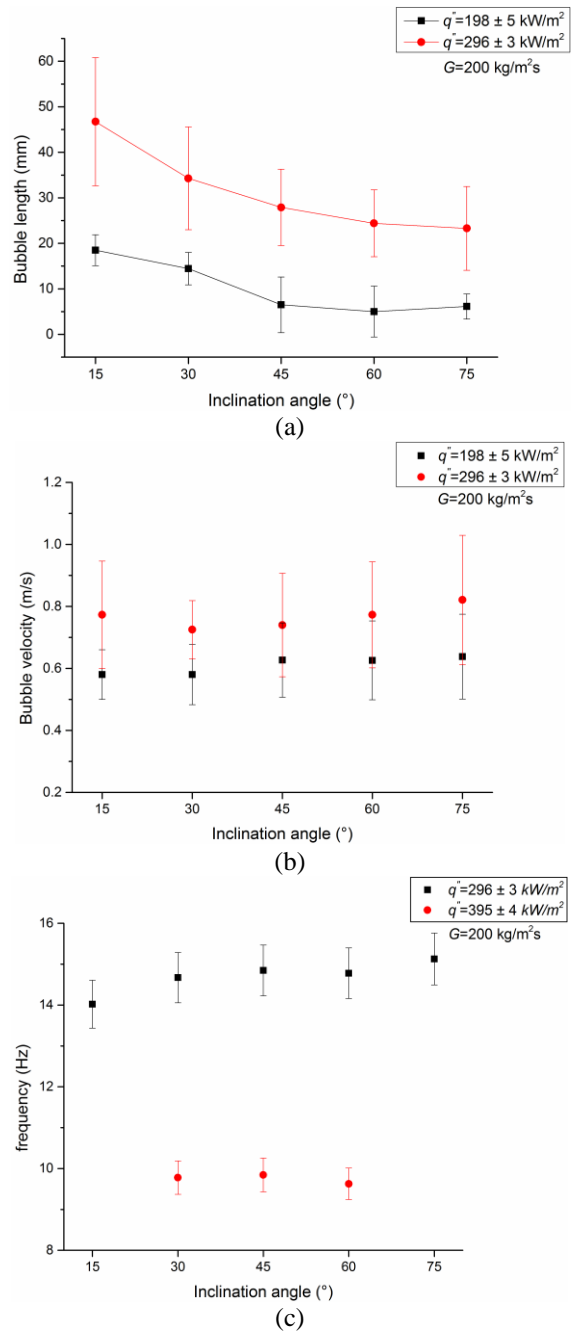


Fig. 5. Boiling parameters of slug behavior with inclination angle: (a) slug bubble length, (b) bubble velocity, (c) frequency.

perature variation on the surface by IR thermometry technique. The heat transfer coefficient on the surface was increased as the heat flux increased and exponentially decreased further at higher heat flux condition.

Fig. 6 shows the effect of mass flux to heat transfer coefficient on downward-facing surface for 30° and 60° inclination angle. When the mass flux increased, the average heat transfer coefficient slightly increased. It could be identified from the visualization results that bubble behavior revealed a significant difference in

bubble behaviors when the mass flux conditions were changed. The effect of mass flux trend has different results with previous research by Kim and Bang [6], they reported no difference in the heat transfer coefficients for all inclination angles.

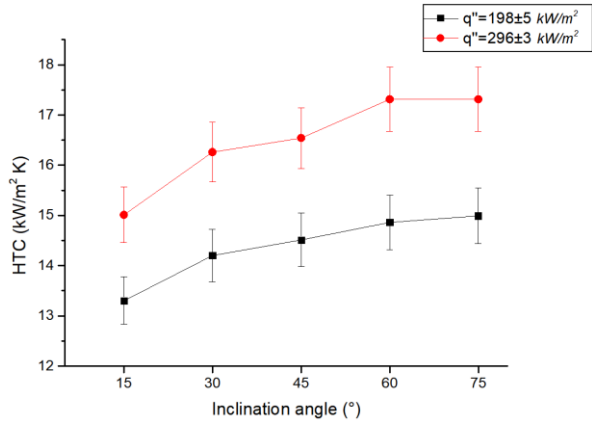


Fig. 5. Heat transfer coefficient with various inclination angle on downward-facing surface.

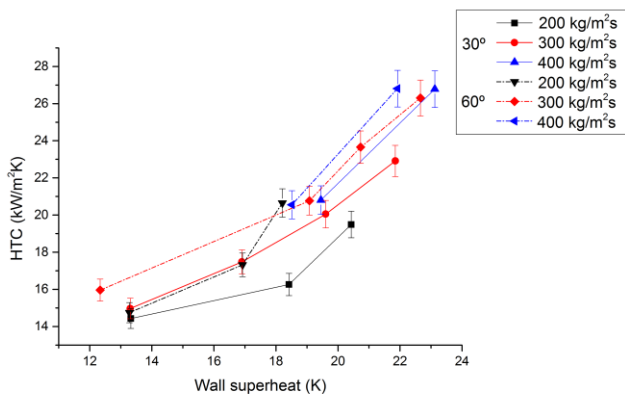


Fig. 6. Heat transfer coefficient with various mass flux conditions on 30° and 60° inclination angle.

4. Conclusion

Flow boiling experiment was performed to understand the effects of surface orientation on downward-facing surface with an interval of 15°. The experiment was conducted with saturated water under atmospheric pressure and investigated the bubble dynamics and heat transfer coefficient using synchronized high speed camera and infrared camera.

- The bubble behavior was observed that generated bubble merged actively and slid along the surface without lift-off from the surface. Merged bubbles formed elongated and showed large bubble region and small bubble region with periodic cycle as slug flow in nucleate boiling.
- The quantitative analysis of bubble dynamics was

performed. From the obtained visualization results, bubble parameters were measured as a function of inclination angle which are length of slug bubble, bubble velocity, and frequency.

- The heat transfer coefficient was measured with averaged spatial and temporal distribution on the surface. It was shown that the trend corresponds to bubble dynamics, and bubble behavior clearly affects to boiling heat transfer on the surface.

The measurement data of bubble dynamics and boiling heat transfer in the present study can be utilized for assessment of existing wall boiling models for computational simulation and development of physically reasonable wall boiling models for downward-facing surfaces with various inclination angles. It may contribute to the accuracy and reliability improvement of thermal-hydraulic analysis of IVR-ERVC, including wall boiling heat transfer phenomenon on the downward-facing half-spherical dome of a reactor vessel.

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