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Visualization Experiment for Sliding Bubble Behaviors on a Horizontal Tube Heater

Yu-Na Kim [a], Jae-Soon Kim [a], Goon-Cherl Park [a], Hyoung Kyu Cho [a*]
[a]*Department of Nuclear Engineering, Seoul National University 1 Gwanak-ro, Gwanak-gu, Seoul 151-744*
[*]Corresponding author: *chohk@snu.ac.kr*

1. Introduction

The boiling heat transfer mechanism is relevant with bubble motions, such as the bubble departure diameter, bubble lift-off diameter, bubble frequency, etc. Even though the widely accepted boiling heat transfer model, named heat partitioning model, considers the effect of these parameters, it was developed based on the experimental observation on horizontal and vertical heating plates[1]. Thus, its application on a horizontal heat exchanger tube, such as the passive condensation heat exchanger adopted by PAFS (Passive Auxiliary Feedwater System) of APR+[2], can be restricted because it cannot consider the sliding motion of a bubble on the bottom of the curved surface.

The sliding bubble on a horizontal tube has characteristic behaviors different from those on plates, in particular, longer sliding length on downward heating face due to the gravity effect, which forces the lifted off bubble to reattach on the surface and retain it on the heater. The heat transfer rate of the sliding bubble is associated with parameters of bubble behaviors including the volume, departure, lift-off, sliding length etc. Therefore, the observation of bubble behaviors on a horizontal tube is of great importance for the development of heat transfer model applicable to that geometry.

In the present study, an experimental technique was proposed for the visualization of the sliding bubble on a curved heating surface using the stereoscopic observation with two synchronized high speed cameras and the parameters regarding bubble motions were measured.

2. Experimental Setup

The objective of this experiment is to measure the behaviors of bubble generated and sliding on the horizontal tube heater. For this, a horizontal tube heater with 50mm diameter composed of flexible printed circuit board is equipped. If all the surface of a tube is heated as a regular heater, a number of bubbles can be generated on the heater and the images taken along the observation line parallel to the horizontal tube may include overlapped bubbles. These overlapped bubbles cannot be separated accurately and consequently, experimental condition is constricted to a low heat flux condition where the bubble overlapping can be minimized. In order to overcome this drawback, a flexible band heater was devised for a better visualization of bubble behaviors as shown in Fig. 1. Its particular features are that heating area has narrow band shape with the width of 1mm and that nucleation site can be controlled. From these features, we were able to visualize bubble behaviors distinctly and discriminate bubble shapes much accurately as shown in right image of Fig. 1.

For quantification of bubble behaviors in various conditions, heat flux and velocity of liquid conditions are controlled in the experimental loop. The test section of the loop is made of transparent square channel as presented in Fig.2. A horizontal tube heater is installed in the test section and the visualization systems are employed around the test section.

The visualization systems consist of two high speed cameras, three lamps and a function generator. Two cameras synchronized by the function generator are equipped along the parallel and perpendicular directions to the tube for the stereoscopic observation. Two lamps are installed on opposite side of each camera for shadowgraphy, and the other lights specific spot of the tube to support the determination of the bubble departure and lift-off. A schematic diagram of visualization systems setup is shown in Fig.3.

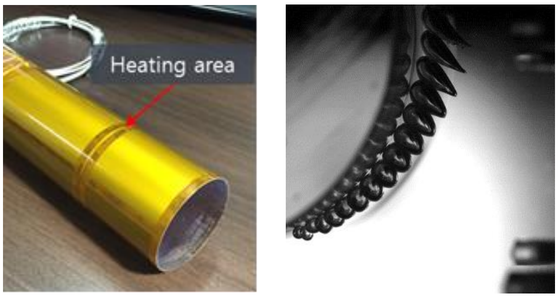

Fig.1. Film heater and visualization of sliding bubbles on it.

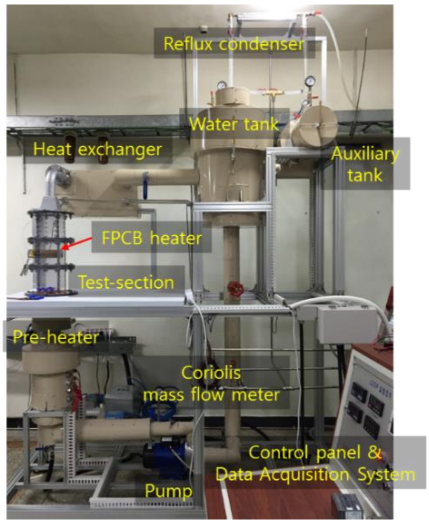

Fig.2. Experimental loop.

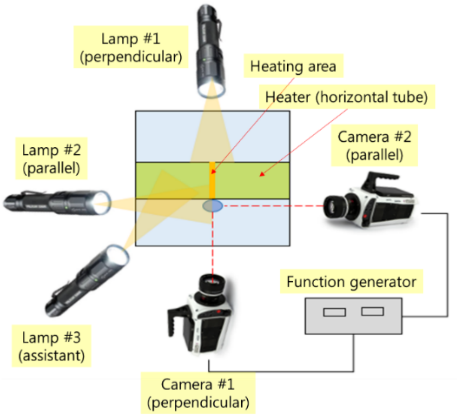

Fig.3. Visualization systems setup.

3. Bubble behavior measurement procedure

Two images of a bubble from the parallel and perpendicular views have different measurable variables. So the phase separation procedures using MATLAB image toolbox [3] were established differently depending on the observation direction. Afterwards, a 3-D reconstruction was conducted to measure the volume of bubble accurately and investigate bubble behaviors quantitatively. Finally, an algorithm deriving variables of bubble behaviors is established using the separated bubble phases.

3.1. Phase separation technique

For measurement of bubble behaviors, the bubble phase has to be separated from the background image. For this, a shadowgraphy method incorporated with the backlighting that recognizes the shape of an object on the basis of brightness level is applied.

Two synchronized images have different purposes in image processing by the observation angle and different lighting conditions. In parallel images, not only axial shape but also important variables of bubbles can be obtained such as the bubble departure and lift-off. Thus, they were used to make phase separation in the region near the heating surface sensitively. For this, the original image was divided by a mask image, with which the boundary between the heating surface and bubble could be distinguished.

On the other hand, the perpendicular image is used to provide the shape information of a bubble in the side view solely. As the backlight to the perpendicular direction is interfered by the bubbles and heater, the lighting condition is not as favorable as the parallel one and therefore, the phase separation is more complicated. The image processing procedure is as follows as Fig.4.

(1) Deleting background using the reference image and complementing it (1→2)
(2) Binarization and filling holes or heater region which are surrounded by white pixels (2→3)
(3) Verification of algorithm comparing the phase discriminated image and original one (3→4)

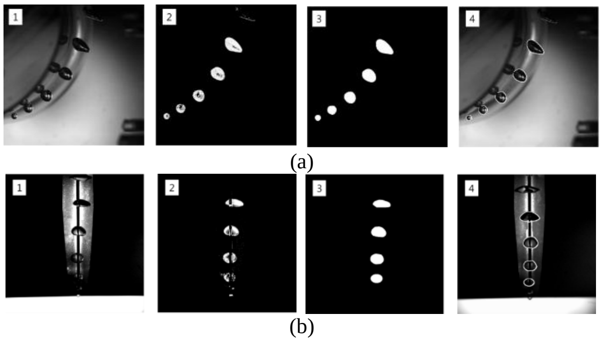

Fig.4. Procedure for phase separation (a) Parallel image and (b) Perpendicular image.

3.2. 3-D reconstruction technique

For the 3-D reconstruction of the bubbles, a reconstruction method proposed by Kim et al [4]. was applied. The method accumulates extracted solids of which cross section is obtained from the combination of the parallel and perpendicular images. Therefore, the most crucial procedure in the bubble reconstruction is to determine the configuration of the cross section at a certain elevation from the two synchronized images.

In this work, the cross-section is determined as shown in Fig.5 to estimate the bubble shape realistically. A postulated origin of each extracted solid at an elevation is determined by the diagonal line which connects the upper and lower boundaries (black lines in Fig. 5). Then, at the cross section, four different pieces of ellipses are created, one in each quadrant separated by two orthogonal lines which cross the origin. As this method is able to assign different curvature to each quadrant, the anisotropic bubble shape can be reconstructed suitably. The result of 3-D reconstruction is shown in Fig.5.

Fig.6 is the comparison among bubble volumes measured in the single angle observations and stereoscopic observation. When a bubble is first generated, its shape is not spherical but rather hemi-spherical. Then, the difference between the single angle observations and stereoscopic method is significant. After that, the bubble grows and it becomes a nearly spherical bubble. The bubble retains the spherical shape after the lift-off before the bubble is accelerated to a certain extent. In this period, the difference between single observations and the present method is insignificant. However, afterwards, the difference increases with the deformation of bubble while it slides. In general, the perpendicular angle observation to the horizontal heater overestimates the bubble volume and on the other hand, parallel one underestimates. It is because bubbles are pressed in the vertical direction by the drag force in sliding and oval-shaped horizontally.

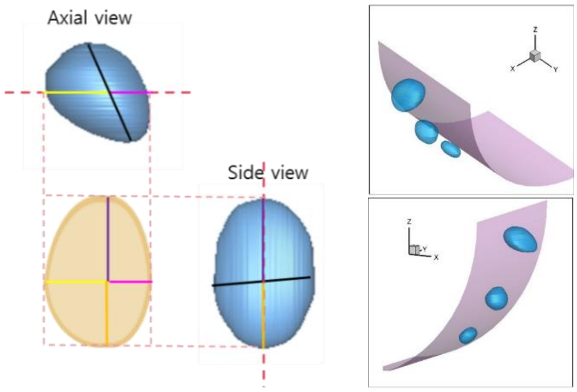

Fig.5. Schematic representation of the asymmetric oval cross section and reconstructed image.

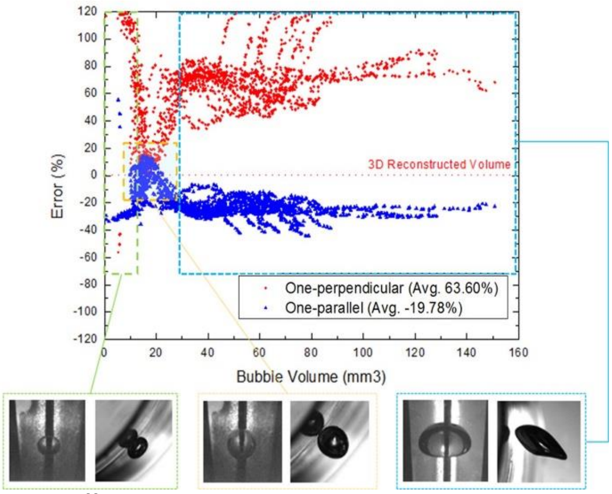

Fig.6. Difference between measurement in single and stereoscopic observations.

3.3. Measurement techniques of bubble behavior parameters

From the reconstructed images, the following parameters that describe bubble behaviors can be deduced by monitoring the surface-bubble interaction. The procedures are as follows and represented by Fig.7.

- Velocity and the location angle

The velocity is calculated by the displacement of the volume centroid (green line in Fig.7) during the time duration. For the location angle, a line which connects centers of the tube and the bubble and its inclination are used (red line in Fig.7).

- Contact length

The region where bubbles contact with the surface of the tube is considered as the contact area and the start and end points of the region (blue line in Fig.7) were used. The contact diameter is defined as the lineal distance between the two points.

- Bubble departure

The instant when the start and end points of the contact region start to move in the same upward direction is defined as the departure moment. If a bubble grows before the departure, the start and points move in the opposite directions as shown in the blue and yellow lines of Fig.8.

- Lift-off

If the contact area becomes zero, the instant is considered as the lift-off moment. In this study, two lift-offs occur in most of cases. The first occurs right after the departure and then the bubble reattaches in a short time. The second lift-off occurs after sliding and the bubble moves farther from the heating surface. The two pink points in Fig.7 indicate the location of the two lift-offs.

- Sliding length

The sliding length is calculated with the angle change between the reattachment location and the 2nd lift-off location and by multiplying it with the diameter of the tube.

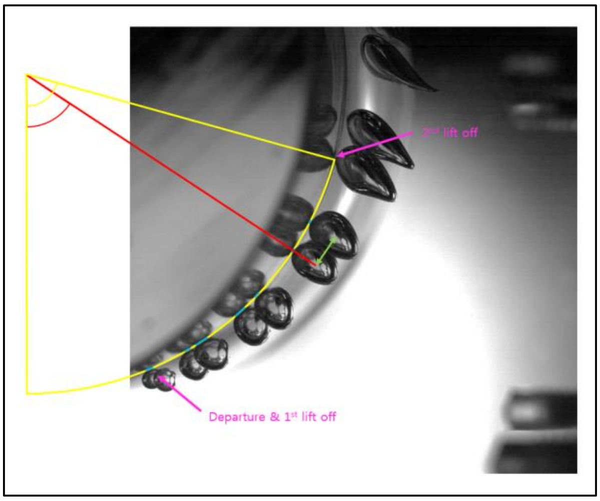

Fig.7. Procedure to deduce variables of bubble behavior.

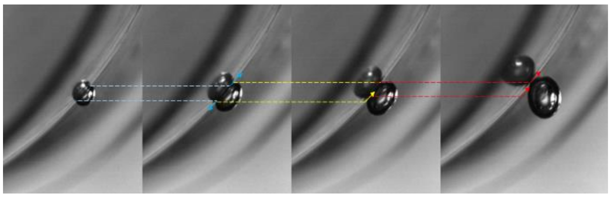

Fig.8. Identification of departure.

4. Experimental results

Fig.9 displays volumes of bubbles measured in the preliminary experiments with two heat fluxes and two fluid velocities. As the graph shows, the volumes increase due to evaporation while bubbles slide on the surface. Right after the bubble lift-off indicated with the dotted line, the volumes plateau because the heat transfer from the surface is impeded while floating. When the bubble is reattached, its volume grows again and the inclination is proportional to contact area. So the variation of volume is almost zero after 2nd lift-off. The lower heat flux cases show faster increase in volume and larger 2nd lift-off diameter as shown in Fig. 10. This is due to the higher bubble frequency in the higher heat flux conditions. Since bubble agitates the thermal boundary layer on the heating surface, the superheated liquid layer is disturbed more frequently and therefore, the volume increase rate for a single bubble decreases with the heat flux.

Fig.11 is the 3-D image indicating the time averaged void fraction and these data will be used to evaluate the boiling heat transfer prediction capability of CFD codes.

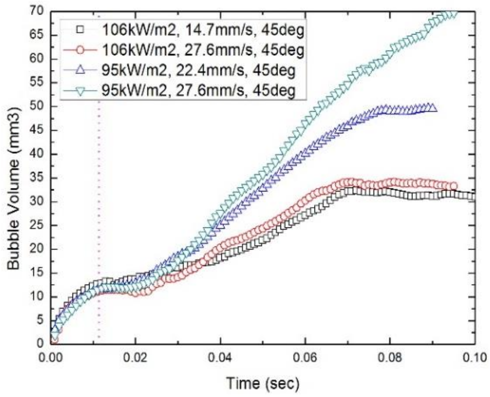

Fig.9. Bubble volume in 45degree cases.

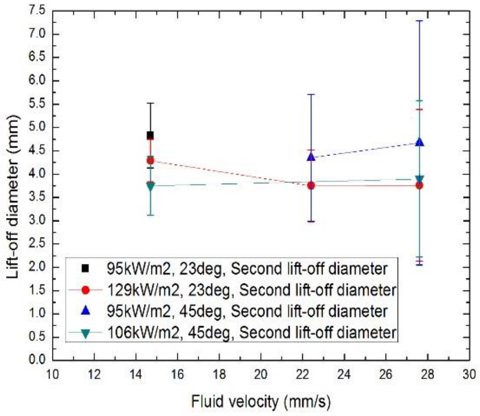

Fig.10. Lift-off diameter.

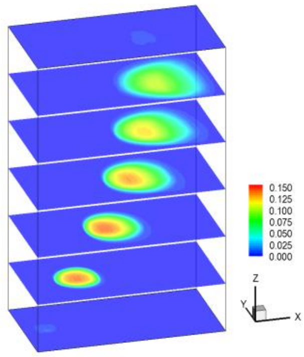

Fig.11. Time averaged void fraction.

5. Conclusions

In this study, to observe boiling bubble behaviors on a horizontal tube, the stereoscopic image processing method is proposed with parallel and perpendicular observation directions to the heater. As a result, when volume of bubbles is calculated, the proposed method is expected to be more realistic than single angle observation since it can reflect disparity between axial and side shapes of a bubble on the horizontal tube. Through the techniques established in this research, various parameters of bubble behavior are measured such as volume, angle, velocity, contact area, departure diameter, lift-off diameter, sliding length, time averaged void fraction, etc. In the future, the experimental results will be used to verify bubble behavior models and improve the heat partitioning model for the horizontal tube heater.

Acknowledgement

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