Establishment of Measurement Techniques for Sliding Bubble on a Horizontal Tube

Yu-Na 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

Accurate estimation of boiling heat transfer rate on heat exchanger in a passive safety system is of great importance as its capacity is determined by condition of heat transfer. For a better prediction of the boiling heat transfer, more and more researches are using a mechanistic wall boiling model [1] developed based on visual observation results. The mechanistic wall boiling model includes many parameters relevant with bubble behaviors, such as the bubble departure diameter, bubble lift-off diameter, bubble waiting time, etc. Although there have been a large number of studies investigating bubble behavior, the subjects of observation are almost bubbles on a plane or vertical tube. Since the bubble motion is highly influenced by the directions of gravitational force and the heating surfaces, it is expected that the bubble behavior on a horizontal tube is largely different from those on the other geometry.

The heat exchanger of APR+ [2] has horizontal U-tube configuration installed in a water pool, of which diameter is 50mm. Therefore, it is necessary to visualize the bubble behavior on a horizontal heat exchanger tube for a better understanding of the phenomena and implementation of the physical understanding into the wall boiling model.

The study aims to establish measurement techniques for sliding bubbles on a horizontal tube. The measurement parameters include the diameter, interface area, volume, and velocity of the bubble. Additionally, in order to analyze the force acting on the bubble, liquid velocity measurement method was proposed. This paper presents the procedure of the measurement; the phase separation technique, 3-D reconstruction technique, and velocity measurement techniques.

2. Experimental set-up

An air-water experimental facility designed for bubble behavior visualization has been fabricated. A schematic diagram of the facility is presented in Fig.1. The channel has 110 mm × 300 mm cross-section and a horizontal tube, of which diameter is 50mm, is installed. On the bottom of the tube, a downside air hole was installed and through it, small bubbles are generated repeatedly. The bubble motion was analyzed by the image processing technique with two synchronized high speed cameras. The cameras take pictures of bubbles from the front and side. For the liquid velocity, florescent particles were used for the PIV (Particle Image Velocimetry).

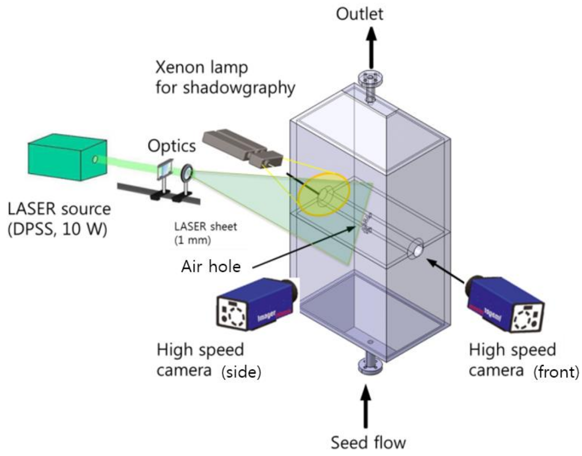

Fig. 1. Schematic diagram of air-water facility.

3. Bubble behavior measurement procedure

Using images obtained from the experiment, sliding bubble behavior measurement techniques were established. At first, phase separation technique separates bubble and liquid. Secondly, from the two images for a single bubble taken by two different cameras, one from the front and the other from the side, three-dimensional images were reconstructed. Finally, using the reconstructed 3-D images, the velocity of the bubble was measured using a PTV (Particle Tracking Velocimetry) method.

3.1 Step 1: phase separation

For measurement of bubble behavior, bubbles have to be separated from liquid phase and background images. For this, a shadowgraphy method was applied. When the lamp for the backlighting is turned on, the bubble is darker than surrounding space in the image. From the difference of image intensity, the bubble can be separated from the background. For the image processing, MATLAB image toolbox [3] was utilized. As images from the front and the side are taken on different background (for example, one from the side has the horizontal tube in the background), the phase separation processes are established to each case. The procedure of front image processing is described below and shown Fig.2.

(1) Deleting background using the reference image (1→2)
(2) Image binarization with the threshold intensity of separation and reversal of binarized value (2→3)
(3) Fill holes which are surrounded by white cells (3→4)
(4) Deleting incomplete bubble and noise using size threshold and creating convex hull of leftmost bubble (4→5)
(5) Verification of the algorithm comparing the separated image with original one (6)

The procedure for side image processing is more complicated to separate bubble from the background due to the existence of the shadow in the air injection tube and overlap of bubbles. The procedure for the side images is described below and shown in Fig.3.

(1) Deleting background using the reference image (1→2)
(2) Image binarization using intensity threshold which varies along the bubble boundary location: The bubble at shadow region cannot be distinguished easily and therefore, the threshold has to be determined depending on the illumination condition. (2→3)
(3) Removing overlapped bubble using curvature of two bubbles (3→4)
(4) Fill holes which are surrounded by white cells (4→5)
(5) Verification of the algorithm by comparing the separated image with original (6)

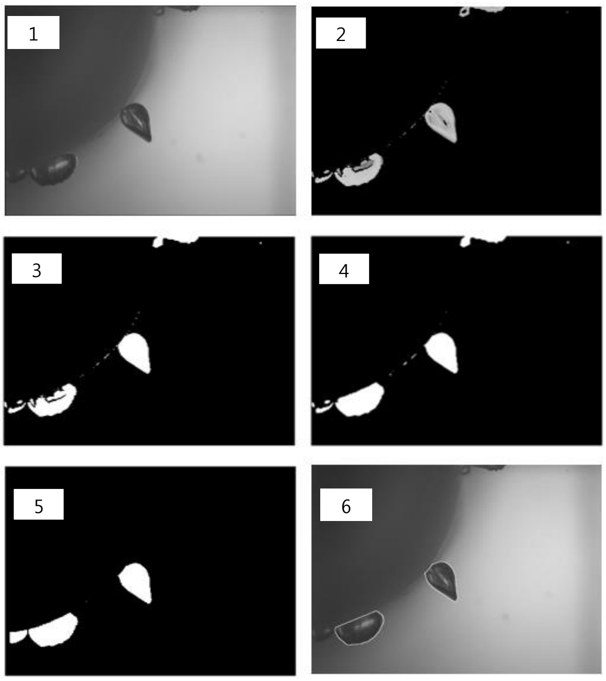

Fig. 2. Procedure for phase separation of front image.

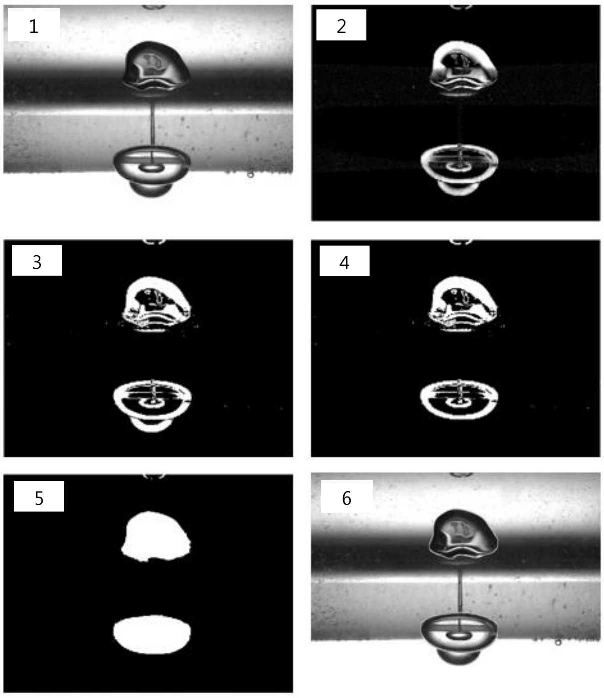

Fig. 3. Procedure for phase separation of side image.

3.2 Step 2: 3-D reconstruction

For the 3-D reconstruction of the bubbles, a reconstruction method proposed by Kim et al. [4] was applied. This reconstruction step uses images taken by two synchronized high speed cameras. The bubble cross section was assumed as an oval shape described by front and side images. As shown in Fig.4, the center of each cylindroid is determined by diagonal line which connects the upper and lower boundaries (blue lines in Fig. 4). Then, at each cross section, four different pieces of an ellipse are created, one in each quadrant separated by two orthogonal lines which cross the center of the cylindroid. Each piece of ellipse includes information of two images. For example, when the top-right ellipse line in the top view figure of Fig. 4 is determined, the values of the major and minor axis lengths of the ellipse are determined by right radius (red line) in the front image and right radius (magenta line) of the side image. With this method, an asymmetrical cylindroid is constructed at a single cross section.

Afterwards, the same procedure is repeated for all elevation from the top of the bubble to the bottom and finally, a 3-D image of a single bubble can be generated. Fig. 5 shows the reconstructed image of bubbles together with the horizontal pipe.

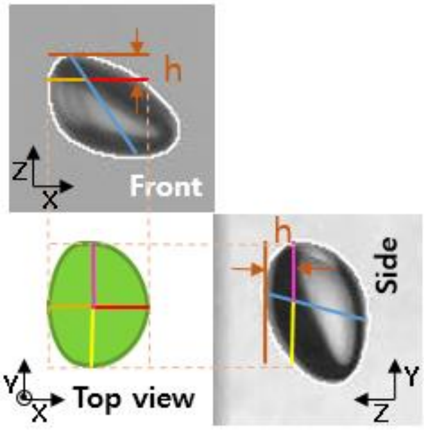

Fig. 4. Schematic representation of the asymmetric oval cross section.

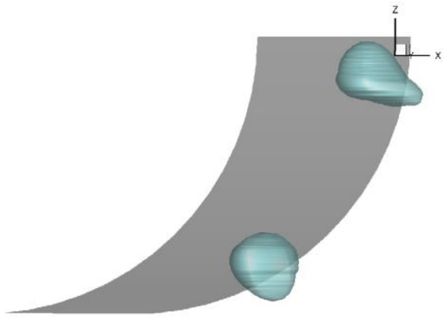

Fig. 5. Result of 3-D construction.

3.3 Step 3: bubble velocity measurement

Bubble velocity is obtained from the reconstructed image and PTV (Particle Tracking Velocimetry) method. Displacement of the center of a bubble in a certain time interval is used to calculate the bubble instantaneous velocity. Fig. 6 shows an example of the bubble velocity measurement result along the angle from the bubble injection point. The velocity of bubble increases gradually and the acceleration of the bubble by the gravitational force can be clearly seen as it slides along the wall.

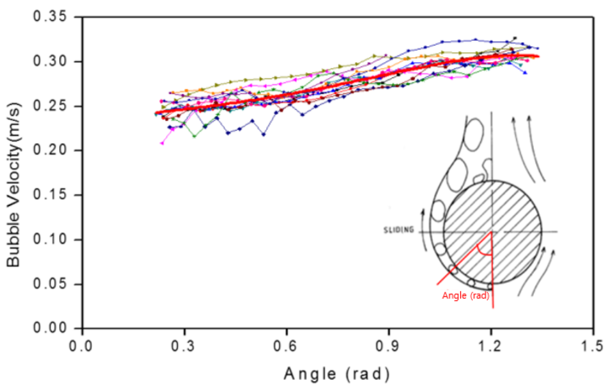

Fig. 6. Result of bubble velocity by angle.

4. Liquid velocity measurement

For the liquid velocity measurement, PIV (Particle Image Velocimetry) method was applied. A DPSS LASER (continuous LASER), which illuminated the test section from the side, and the front high speed camera in Fig. 1 were used in order to measure it together with the bubble velocity. In the present experimental condition, the liquid velocity near the horizontal pipe (Region 1 in Fig. 7) where bubbles flow has much faster liquid velocity than the other region (Region 2). For this reason, if the time duration of two consecutive images optimized for the velocity measurement in Region 1 is applied for the analysis of Region 2 velocity, a large error was caused because the displacement of the particles in Region 2 was too small. For this reason, a new method was proposed, which uses different time durations for the two regions. For example, if we have five consecutive images taken by high speed camera, the first and second images were used for the velocity measurement in Region 1 and the first and fifth images were used for that in Region 2. After that, the two velocity measurement results were merged with proper mask images. Fig. 8 shows an example of the liquid velocity measurement results and high liquid velocity near the bubble could be observed.

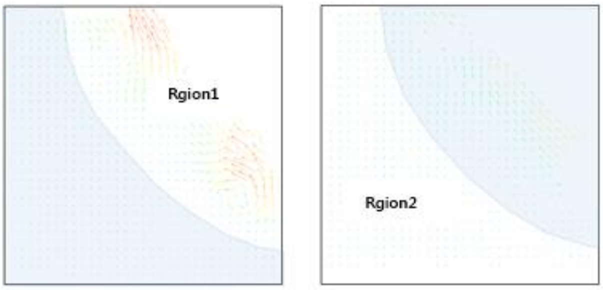

Fig. 7. Separated regions for PIV method.

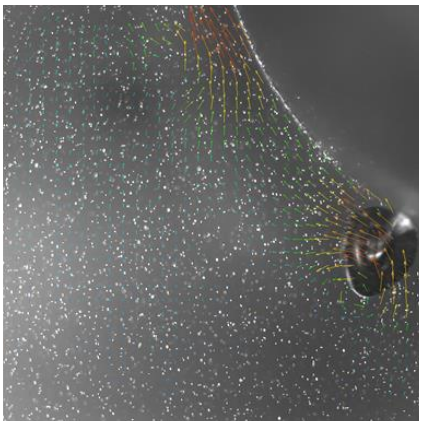

Fig. 8. Result of liquid velocity measurement.

As shown in Fig.9, the result which compares bubble velocity and liquid velocity at specific point shows that the liquid velocity increases when a bubble approaches the point and the velocity reaches a maximum, almost same value with the bubble velocity, immediately after passage of the bubble. Then it decreases gradually until a new bubble approaches the point.

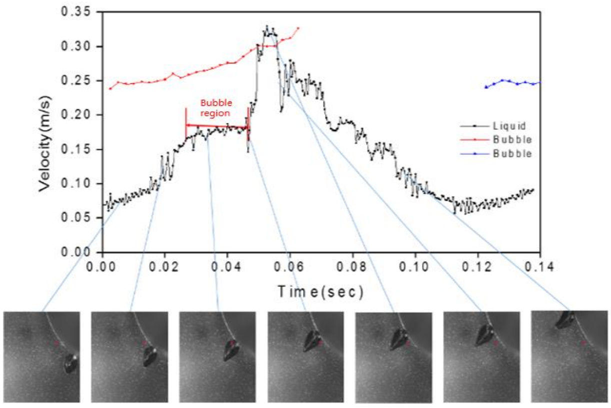

Fig. 9. Comparison of bubble and liquid velocities.

4. Conclusions

For visualization of the sliding bubble behavior, bubble and liquid velocity measurement methods were established which use two high speed cameras and a continuous LASER for the PTV and PIV. Three steps for the bubble shape and velocity measurement (the phase separation, 3-D reconstruction, and velocity calculation), were successfully set up and verified. A PIV technique which uses two different time duration for two regions where the velocity difference is huge was proposed and tested. Using these methods, various information regarding a sliding bubble can be obtained such as bubble and liquid velocities, shape, volume, surface area etc.

In the future, a series of experiments will be conducted with various liquid and gas flow rates and the measured data will be used for the force balance analysis of a sliding bubble, which is one of the important sub-models of the mechanistic wall boiling model.

Acknowledgement

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