Quantification of the Volume and Interfacial Area of 3D Bubble for the Direct Contact Condensation in IRWST

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1. Introduction

SMART (System-integrated Modular Advenced ReacTor), being developed in South Korea, is designed with a fully passive safety system. CPRSS (Containment Pressure and Radioactivity Suppression System) [1] is a representative passive safety system for containments cooling. It has an in-containment refueling water storage tank (IRWST) that removes residual heat and radioactive material in the event of accidents such as LOCA. Direct contact condensation (DCC) from the steam injection spargers inside the IRWST is used to effectively remove decay heat from the reactor. It is important to study bubble behavior to determine condensation regimes and heat transfer in the DCC phenomenon.

Various image processing techniques have been used for the study of the bubble shape in boiling and condensation. Kim and Park [2] and Kim et al. [3] developed orthogonal two-image processing to reconstruct 3D bubble shape as an ellipsoid for the subcooled boiling condition. However, DCC bubbles in the IRWST are deformable and ununiformed shapes, so realistic visualization techniques are required.

Yang et al. [4] photographed two perpendicular images of DCC bubbles in an experiment using SISTA (SMART IRWST Separated Test Appratus). They then developed a 3D bubble reconstruction method for the DCC bubble and calculated the volume of the deformed bubbles. In this study, we improved the 3D bubble reconstruction technique and calculated and analyzed the surface area as well as the volume of the DCC bubbles from the existing image data.

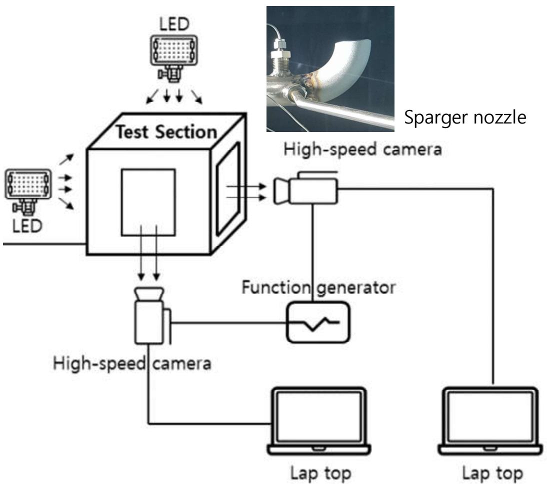

Fig. 1. Test facility and steroscopic visualization system. [4]

2. Experiments

Fig. 1 shows the IRWST simulation square tank (1 m x 1 m x 1.2 m) and 3D bubble visualization system of the SISTA [4]. The water level in the pool was 0.97 m and the initial temperature was set at 50°C. Steam was injected with a mass flux of 50 kg/m^2s through a single pipe elbow tip nozzle with an inner diameter of 18.85 mm. The vapor flow rate was measured with a Coriolis mass flow meter. The DCC test condition corresponds to the external chugging with detached bubble region in the condensation regime map [5].

Two high-speed cameras and LED lamps were used through the front (0.4 m x 0.76 m) and side window (0.4 m x 0.4 m) of IRWST. Two cameras were syncronized and recored for 5 seconds with a frame rate at 2000 fps, and a spatial resolution of image was 768 x 1024 pixels. The outer diameter of nozzle oulet was used as a reference for the actual pixel length.

3. 3D Bubble Reconstruction Method

3.1 Image Binary Morphology

Binary morphology is used to recognize the shape of the bubble [4]. The background is removed from the photographed image and binarized with Otsu algorithm, followed by the proper morphology operation such as dilation and erosion. Fig. 2 shows an example of the results of the binary morphology of the front and side images of DCC bubbles.

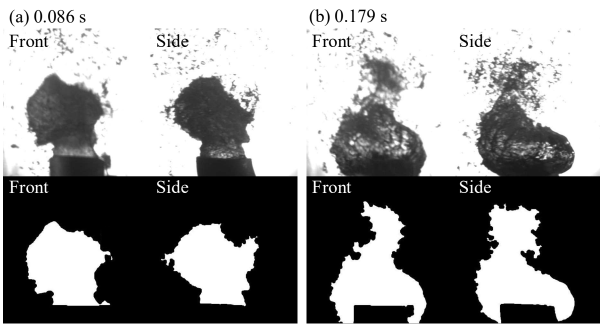

Fig. 2. Image precessing results of the binarization morpology.

3.2 Bubble Shape Parameters

The 3D bubble shape is approximately reconstructed from the binarized stereoscopic images, as shown in Fig. 3. The positions of r_1, r_2, w_1 and w_2 are obtained in all pixel layers from the top to the bottom of the bubble region in both images. The each horizontal cross-section of the 3D bubble was reconstructed as an ellipse based on the four endpoints. Especially the bubble area below the nozzle inlet is considered as a donut-shape subtracting the circular nozzle area, as shown in Fig. 2 (b).

The bubble volume was calculated by integrating the elliptical cross-sectional volume corresponding to each elevation layer from the top to the bottom of the bubble region, as follows.

$$V = \sum_{top}^{bottom} \left[AB\pi h_{pixel} \right] \quad (1)$$

The interfacial area of the bubble is obtained by multiplying the perimeter P and hypotenuse δ between the cross section layers and integrating them, as follows.

$$A = \sum_{top}^{bottom} \left[P\bar{\delta} \right] \quad (2)$$

The perimeter of each ellipse was calculated using the following Ramanujan's approximative formula.

$$P \approx \pi (A+B) \left[1 + \frac{3\{(A-B)/(A+B)\}^2}{10+\sqrt{4-3\{(A-B)/(A+B)\}^2}} \right] \quad (3)$$

Since the hypotenuse between cross sections at each elevation is not constant along the perimeter, it was determined as the average of the values calculated at points r_1, r_2, w_1 and w_2 as follows.

$$\bar{\delta} \approx (\delta_{r1} + \delta_{r2} + \delta_{w1} + \delta_{w2})/4 \quad (4)$$

$$\text{where } \delta_{r1} = \sqrt{(r_1 - r_1')^2 + h_{pixel}^2} \quad (5)$$

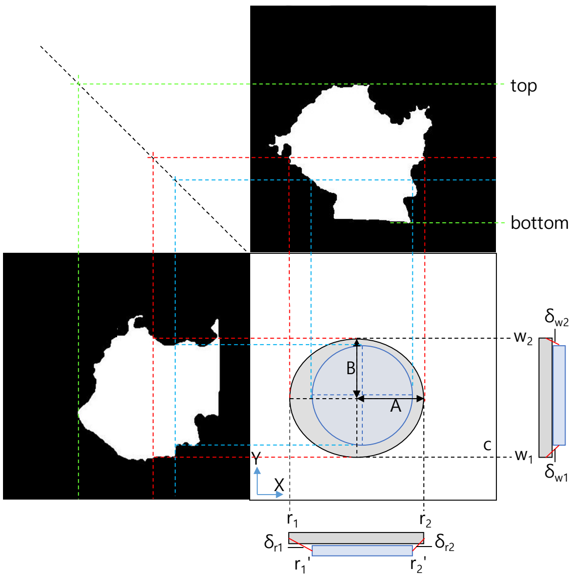

Fig. 3. 3D Reconstruction method for the DCC bubbles

4. Results and Discussion

Fig. 4 shows the volume and surface area of the DCC bubble calculated from the stereoscopic image processing for 0.5 seconds. To investigate the validity of the 3D reconstruction method, the volume and interfacial area calculated from monoscopic image were compared with the stereoscopic image method. In the monoscopic image method, the cross section of each layer was assumed to be a circle.

Figs. 5(a) and (b) show the deviation by monoscopic image method for the instantaneous volume and interface area, respectively, compared to the stereoscopic image analysis. It is notable that an error can occur more than 50% depending on the instantaneous shape of the bubble.

Table 1 shows the time averages calculated from the derived data. The results of the monoscopic image analysis showed a deviation of 10% on average compared to the streoscopic image analysis.

Table I: comparison between stereoscopic and monoscopic analysis for the time average volume and interface area

Parameters	Methods	Time average	Deviation
Volume	Stereoscopic	19598 mm^3 (D = 16.7mm)*	-
	Monoscopic (front image)	19438 mm^3 (D = 16.7mm)*	-0.8% (-0.3%)*
	Monoscopic (side image)	21955 mm^3 (D = 17.4 mm)*	12.0% (+3.9%)*
Interfacial area	Stereoscopic	6472 mm^2	-
	Monoscopic (front image)	5813 mm^2	-10.2%
	Monoscopic (side image)	7082 mm^2	9.4%

* Volume equivalent diameter assuming shepere

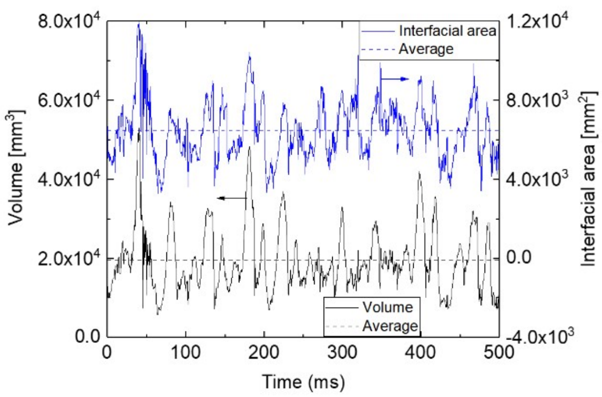

Fig. 4. Volume and interface area of the DCC bubbles

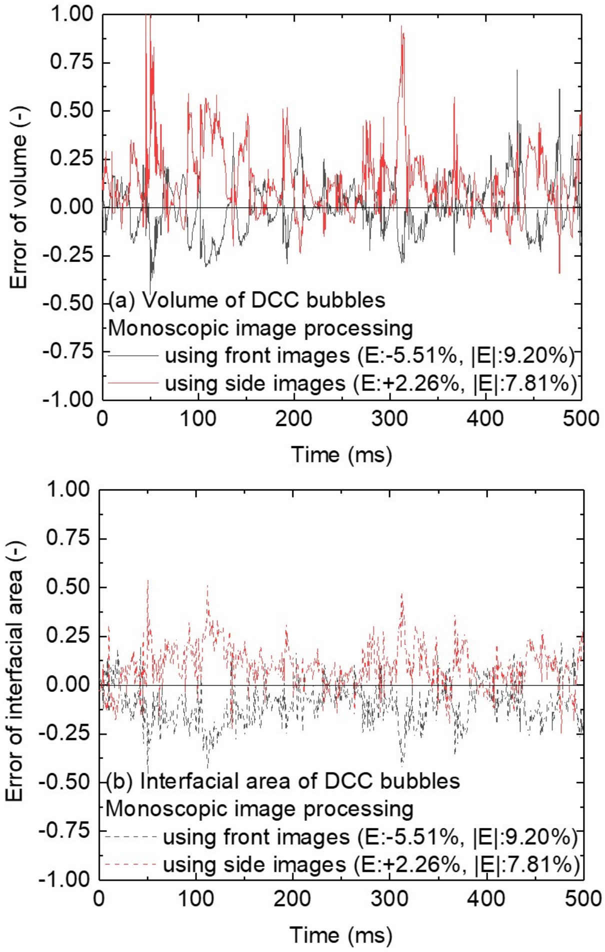

Fig. 5. Comparison between stereoscopic and monoscopic analysis for the instantaneous (a) volume and (b) interface area

5. Conclusions

Volume and interface area of the DCC bubbles was determined from the stereoscopic images perpendicularly taken from the front and side. The horizontal layers of the bubble are assumed to be ellipses and stacked to reconstruct the 3D bubble and calculate bubble parameters. The DCC bubble data were obtained under external chugging with detached bubble conditions at 50°C of subcooling temperature and 50 kg/m^{2}s of steam mass flux. It was confirmed that the 3D bubble reconstruction method using the stereoscopic image could be more accurate compared to the monoscopic image method, showing more than 50% of deviation depending on the instantaneous bubble shape and about 10% deviation in the time-averaged data. the image analysis methodologies can be useful for the further studies on the DCC bubble, such as frequency analysis, interfacial area density, and interfacial heat transfer coefficient.

ACKNOWLEDGMENTS

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