3D gas-liquid interfaces and flow characteristics of two-phase flows in horizontal tubes

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Abstract. In order to investigate the characteristics of gas-liquid two-phase flows in horizontal mini circular tubes with inner diameters of 3.14 and 6.68 mm, a prism is adopted to improve the light path in the visualization experimental setup. The front and top views of air-water two-phase flow patterns in two tubes are captured synchronously based on the improved method. Three-dimensional gas-liquid interfaces, flow pattern maps, and void fraction are obtained. The experimental results show that tube diameters have significant effects on flow patterns transition lines in the flow pattern maps, but the void fractions are independent on channel sizes. The effect of gravity gradually decreases with decreasing tube diameter, while that of surface tension is enhanced. As a consequence, the proportion of annular flow in flow pattern map increases in mini tubes, while the reverse is true for the stratified flow whose proportion decreases dramatically in mini channels. The void fraction increases with increasing gas quality. Experimental void fractions obtained using the three-dimensional gas-liquid interfaces fit well with correlations in the open literature. The shape of PDF distributions varies with flow patterns, which could be used to identify flow patterns in industrial applications.

1. Introduction
Flow characteristics of two-phase flows in horizontal tubes have been widely investigated for the wide applications in industrial fields. The flow patterns and void fractions are the key parameters in these studies as they determined other characteristics such as pressure drops, heat and mass transfer coefficients. For conventional channels, bubbly, slug, stratified, annular, mist flow patterns are usually observed during the experiments. Some flow pattern maps using gas and liquid superficial velocities as coordinates were proposed based on experimental data or theoretical analysis such as Mandhane et al. [1], Barnea et al. [2], etc.

Void fraction are usually obtained using the quickly closing valves method. With the development of image processing, the imaging method has been widely adopted to measure the void fraction the advantage of non-intrusive nature and the ability to visualize the detailed two-phase interfaces. Most of previous studies using this method only captured the flow pattern images from one direction. In order to improve the accuracy of this method, the 3D reconstruction method has been developed based on the flow pattern images of two perpendicular planes. For the void fraction predictions, many correlations have been developed, such as Smith [3], Armand–Massina [4], Gregory and Scott [5], etc.

To fill the gap of three-dimensional studies of gas-liquid two-phase flows, the present work experimentally studied the 3D gas-liquid interfaces, flow pattern maps, and void fractions in 2 horizontal tubes with inner diameter of 3.14 and 6.68 mm.
2. Experimental method

The experimental setup is shown in Fig. 1, which includes the water and air circulations and data acquisition part. A prism is placed beneath the transparent tested tubes with inner diameter of 3.14 and 6.68 mm to reflect the flow pattern images from the bottom view to the front view. Thus, the two-dimensional image of flow patterns observed from the front and the bottom views are captured synchronously with a single high speed camera. These images are further processed in MATLAB to obtain the 3D interfaces and to calculate the void fractions.

![Figure 1. Schematic of the experimental setup.](image)

3. Results and discussions

Figure 2 shows the obtained 2D images and 3D reconstructed gas-liquid interfaces in the tubes. For the mass fluxes studied in the present work, the stratified flow pattern is only observed in the 6.68 mm tube. The cross-sectional shapes of bubbly, slug, and annular flow are assumed to be ellipse with semimajor and semiminor axis obtained from the front and bottom views shown in Fig. 2. For the stratified flows, the upper part above the gas-liquid interface is the gas phase, and the 3D interfaces are reconstructed based on the tube diameters and relative position of the interfaces. The gravity effect is more pronounced in the 6.68 mm tube as the bubbles and slugs are tend to flow at the upper part because of the buoyance.

| Inner diameters | 3.14 mm | 6.68 mm |
|-----------------|---------|---------|
| Bubbly          | ![Image](image) | ![Image](image) |
| Slug            | ![Image](image) | ![Image](image) |
| Annular         | ![Image](image) | ![Image](image) |
| Stratified      | ![Image](image) | ![Image](image) |

![Figure 2. Typical flow patterns obtained from captured images and 3D reconstruction.](image)
Figure 3 shows the flow pattern maps and flow pattern transitional lines in the present work and those in Barnea et al. [2] with inner diameter of 12.7 mm and in Mandhane et al. [1] with inner diameters ranging from 12.7 to 165 mm. Compared with conventional tubes, bubbly flows are obtained at lower liquid superficial velocities. The transitions from slug flow the annular flow occurs at a lower gas superficial velocity for mini tubes compared with the conventional ones. As the gravity effect gradually decreases with decreasing tube diameters, the surface tension tends to dominate the two-phase flow patterns in mini tubes. The stratified flow pattern is hard to be formed in mini tubes as the upper part of the tube is easier to be occupied by the liquid film. These leads to the higher proportion of annular flow in the flow pattern maps shown in Fig. 3 (c).

The void fraction is calculated using the volume ratio of the gas phase to the flow domain obtained from the 3D images. As shown in Fig. 4 (a), the void fraction $\alpha$ increases with increasing volumetric quality $\beta$. For cases with $\beta$ lower than 0.6, the values of $\alpha$ and $\beta$ are nearly the same, which indicates that the homogenous models are suitable for these cases. With increasing $\beta$ further, $\alpha$ is lower than $\beta$ because of the velocity difference between the liquid and gas phases. Though the tube diameter has significant influence on flow pattern maps, no significant difference of void fraction is obtained for cases with different tube diameters. Figs. 4 (b) and (c) show the comparisons of experimental data and predicted values with three classical correlations. Nearly all experimental data locate within the $\pm$ 20% error bands of these correlations, which indicates the 3D reconstruction and void fraction calculating processes are suitable for the studies of two-phase flows.

Fig. 5 shows the profiles of Probability Density Functions (PDF) of cross-sectional void fractions at the middle of flow domain for different flow regimes. As shown in Fig. 5, shapes of PDF profiles changes for different flow patterns. Two peaks are observed in the PDF profiles for intermittent flows, while only one peak exists for the annular flow. For the bubbly flow with low $\beta$, the highest PDF is obtained when $\alpha$ is around zero. This means that the cross section is occupied by the liquid phase for most time. With increasing $\beta$, another peak is obtained at a relatively high $\alpha$. This crest corresponds to
cases when gas slugs pass through the cross section. For the slug flows, the changes of PDF shapes are relatively smaller compared with the bubbly flow. The second peak of PDF is obtained when the middle part of the slug passing the cross section with a constant liquid film. For the separated annular flow, the gas phase exists along the flow domain, resulting in the disappearance of the first peak of PDF profiles. The shape of PDF is an efficient way to distinguish intermittent flows from separated flows.

![PDF Distributions for different flow patterns](image)

**Figure 5.** PDF distributions for different flow patterns.

4. Conclusions

Flow characteristics of gas-liquid two-phase flows in horizontal tubes with inner diameter of 3.14 and 6.68 mm have been studied experimentally. A virtual multi-vision method is adopted to capture the images of flow patterns from two orthogonal views with the help of a prism. 3D gas-liquid interfaces are reconstructed in MATLAB. The following conclusions can be drawn from the present work.

1. 3D gas-liquid interfaces are reconstructed assuming an elliptical cross section for the bubbly, slug and annular flows. The gravity effect is more pronounced in the 6.68 mm tube as the bubbles and slugs tend to flow at the upper part because of the buoyance.

2. The stratified flow is not observed in the mini tube with 3.14 mm inner diameter for the low gravity effect, while the bubbly, slug, and annular flow patterns are observed for both tubes. The proportion of annular flow in the flow pattern maps is high for the mini tubes because of the lower gravity and higher surface tension effects at smaller tube sizes. However, the effect of tube diameter on void fraction is relatively small. Void fraction increases with increasing volumetric quality. Experimental results fit well with correlations.

3. Shapes of PDF profiles changes for different flow patterns. Two peaks are observed in the PDF profiles for the bubbly and slug flows, while only one peak exists for the annular flow.

References

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