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Experimental study of bubbly flow using image processing techniques

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ABSTRACT

This paper presents an experimental study of bubbly flows at relatively high void fractions using an advanced image processing method. Bubble overlapping is a common problem in such flows and the past studies often treat the overlapping bubbles as a whole, which introduces considerable measurement uncertainties. In this study, a hybrid method combining intersection point detection and watershed segmentation is used to separate the overlapping bubbles. In order to reconstruct bubbles from separated segments, a systematic procedure is developed which can preserve more features captured in the raw image compared to the simple ellipse fitting method. The distributions of void fraction, interfacial area concentration, number density and velocity are obtained from the extracted bubble information. High-speed images of air-water bubbly flows are acquired and processed for eight test runs conducted in a 30 mm × 10 mm rectangular channel. The developed image processing scheme can effectively separate overlapping bubbles and the results compare well with the measurements by the gas flow meter and double-sensor conductivity probe. The development of flows in transverse and mainstream directions are analyzed and compared with the prediction made by the one-dimensional interfacial area transport equation (IATE) and the bubble number density transport equation.

1. Introduction

The objective of this research is to measure the two-phase flow parameters that are necessary for the validation of advanced models such as the interfacial area transport equation (IATE), in air-water bubbly flows in a rectangular channel. Bubbly flow plays a critical role in many industrial applications including chemical processing, petroleum extraction, and nuclear power generation. The interfacial structures in bubbly flow are very complicated due to the interaction of various hydrodynamic forces and bubble coalescence and breakup mechanisms, which makes the modeling and prediction very difficult. One example is in the co-current upflows. It has been known that bubbles tend to aggregate in the near wall region due to the lift force effect under certain conditions (Drew and Lahey, 1982). However, the wall peak may transition into center peak as void fraction and bubble size increases. To date, the lift force effect has not been fully understood and an accurate prediction of the transition boundary under different conditions remains to be a challenging task.

To measure and study different phenomena in bubbly flows, both intrusive methods such as conductivity probe (Kim et al., 2000), fiber optic probe (De Lasa et al., 1984), sampling probe (Alves et al., 2002), and wire-mesh sensors (Prasser et al., 1998), and non-intrusive methods such as X-ray computed tomography (Bieberle et al., 2008), image processing technique (Honkanen et al., 2005) and laser Doppler anemometer (Kulkarni et al., 2001), have been used in the literature. Compared with the intrusive methods, the non-intrusive methods do not place the measurement device in the flow field, which eliminates the measurement uncertainty due to the disturbance of the flow. With the rapid development of the high-speed digital camera technology, image processing method has become an effective non-intrusive technique for obtaining high-speed, high-resolution data in bubbly flows. The most challenging aspect for this method is to accurately quantify the geometrical parameters of individual bubbles captured by the camera, given that bubbles overlap with one another in acquired images when void fraction is higher than 1–2%. The quantitative studies performed in recent years using image processing techniques are summarized in Table 1. To separate the overlapped bubbles, one way is to utilize the geometry information of bubbles for segmentation (Honkanen, 2009; Honkanen et al., 2005; Karn et al., 2015; Lau et al., 2013). Based on the intensity gradient difference along the edge of overlapped bubbles (Bröder and Sommerfeld, 2007), the focused bubbles can also be distinguished from the defocused bubbles in the cluster. In some cases, only solitary bubbles are considered and the overlapped bubbles are excluded according to the shape of the identified object (Ferreira

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Table 1
Summary of related image processing works on bubbly flow.

References	Void fraction	Test section geometry	Processing algorithm
Honkanen (2009), Honkanen et al. (2005)	Up to 2%	Round: $D = 105$ mm	Breakpoint; Ellipse fitting; Breakline
Bröder and Sommerfeld (2007)	0.5–5%	Rectugular: 300 mm × 100 mm	Edge intensity gradient
Yu et al. (2009)	N/A	Round: $D = 9$ mm	Hough transform; Ellipse fitting
Ferreira et al. (2012)	Up to 11%	Rectugular: 140 mm × 20 mm	Shape complexity
Lau et al. (2013)	6.8%	Rectugular: 200 mm × 30 mm	Watershed
Karn et al. (2015)	N/A	Rectangular: 1 m × 0.19 m	Watershed; Morphological characters

et al., 2012). This treatment may introduce large uncertainty at higher void fractions since bubble overlapping will become more severe. After segmentation, separated image objects are either considered as solitary bubbles or are fitted by ellipses for further analysis. Without bubble reconstruction, the information of the overlapped parts will be missing. The ellipse fitting method may introduce large uncertainties as the actual bubble shape could be quite different from circular or elliptical depending on flow conditions and fluid properties. Thus, a reconstruction algorithm is necessary to complete the separated bubbles while preserving the original non-overlapping outline. Because of these challenges, the existing studies are limited to void fraction up to 11% as shown in Table 1.

In order to extend the image processing method to higher void fraction bubbly flows, an advanced processing scheme has been developed to overcome the overlapping issues and reconstruction difficulties (Fu and Liu, 2014). The scheme combines the break point detection method (Teh and Chin, 1989) and watershed segmentation technique (Bleau and Leon, 2000) to separate the overlapping bubbles, which ensures the accuracy and robustness while processing different flow conditions. The bubble reconstruction algorithm accounts for both the outline and inner edge information instead of using a direct ellipse fitting. This preserves most of the geometrical information captured in the raw images. From the information extracted for individual bubbles, the spatially and temporally averaged parameters such as bubble number density, void fraction, interfacial area concentration, velocity, and Sauter mean diameter, can be obtained by applying proper averaging schemes.

In this study, high-speed images are taken for eight air-water bubbly flow conditions in a 30 mm × 10 mm rectangular channel. The images are processed by the developed image processing scheme to obtain a high-resolution database consisting of various bubbly flow parameters at three axial locations. The effect of different hydrodynamic forces and interfacial structure development are analyzed from the measured data. The data are also used to perform a benchmarking study of the one-dimensional IATE model proposed by Sun et al. (2004).

2. Experiment

Fig. 1 shows the schematic of the experimental facility, where the major components and measurement devices are identified. The facility is designed for air-water upflows at room temperature and near atmospheric pressure conditions. The two-phase flow test section has a 3 m tall flow channel with a 30 mm × 10 mm rectangular cross section. In the present study, high speed images are taken at the three visualization ports located at $z/D_h = 8.8$, 72.4 and 136. The hydraulic diameter $D_h = 15$ mm for the test channel. The inlet water flow rate is measured by two magnetic flow meters. Four gas flow meters based on the laminar differential pressure flow technology are used to measure the air flow rate. Both the air and water flows are measured before they enter the two-phase injector and the flow rate data have accuracy of about ±1% of the readings.

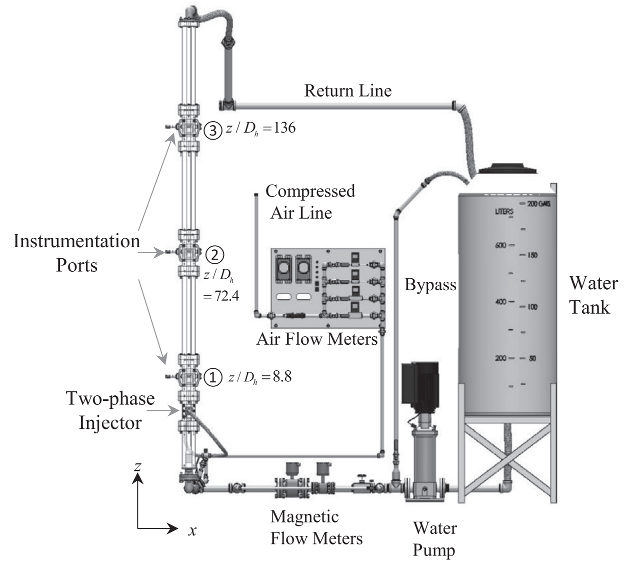

Fig. 1. Schematic of the test facility and measurement locations.

The design of the two-phase injector is shown in Fig. 2. Two opposite facing aluminum plates are installed flush with the 30 mm wide walls. On each plate, there are five 200 μm holes from where air is injected into the flow channel. The five holes are arranged in two 10-mm-apart vertical rows, with one row consisting of three holes, and the other consisting of two. The hole spacing is uniform in the 30 mm wide direction such that each could cover a similar width of the flow channel. The rows on the opposite plate are reversed upside down to avoid bubble merging at the injector, yet maintaining a symmetric inlet condition in both width (x) and depth (y) directions. Bubbles that fall in the spherical and distorted bubble regimes could be generated at the plate surface under the shear force imposed by the upward flowing water.

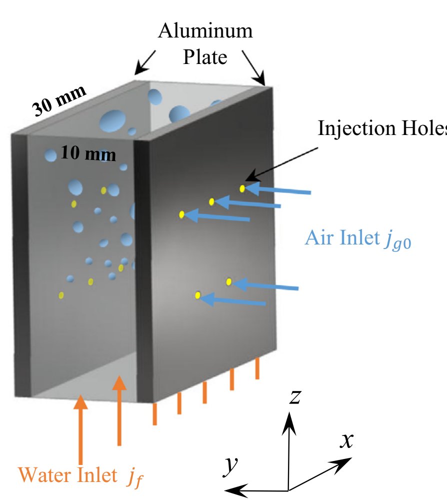

Fig. 2. Schematic of the two-phase injector.

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