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Distributions of void fraction and liquid velocity in air–water bubble column

Shimpei Ojima, Kosuke Hayashi, Shigeo Hosokawa, Akio Tomiyama *

Graduate School of Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe 657-8501, Japan

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It is our great pleasure to dedicate this paper to Professor Geoffrey Hewitt on the occasion of his 80th birthday, recognizing his outstanding long-term contributions to multiphase flow research and technology. From the very beginning of our research activity on multiphase flows, we have learned and been inspired a lot from Geoff's excellent instrumentations, models and ways to gain physical essence from flow visualization, experimental data and so on. His continuous encouragement has been also one of the important driving forces on our multiphase research. We heartily wish Geoff further happy, healthy and productive years!

Keywords:
Bubble column
Heterogeneous regime
LDV
Velocity fluctuation
Multi-fluid model

A B S T R A C T

Multi-fluid simulations of heterogeneous bubbly flows in an air–water bubble column were carried out to verify the speculation that a heterogeneous bubbly flow is predictable without turbulence models such as k–ε and LES models, provided that the velocity fluctuation caused by large-scale vortical flow structures prevails over the bubble-induced and shear-induced turbulences. Experiments on the heterogeneous air–water bubbly flows in a rectangular bubble column were also carried out to obtain experimental data of the mean velocity, fluctuation velocity and void fraction for validation of the numerical method. A small LDV probe developed in our previous study was utilized to measure the liquid velocity in the column at high spatial and high temporal resolutions. The distribution of void fraction was measured using an electrical conductivity probe. The conclusions obtained under the present experimental conditions are as follows: (1) the small LDV probe is of great use in measuring the distributions of mean and fluctuation velocities of the liquid phase at high spatial and high temporal resolutions, (2) the velocity fluctuation in the heterogeneous regime in the bubble column is mainly due to large-scale vortical structures, and (3) the multi-fluid model can give good predictions of a heterogeneous bubbly flow without using the turbulence models, provided that large-scale vortical structures in the flow prevail over the bubble-induced and shear-induced turbulences.

1. Introduction

Bubble column reactors have been utilized in various engineering fields such as petrochemical and biochemical industries. The shape, diameter and height of a column and the operating condition depend on the chemical process, so that various bubble columns with a wide range of physical parameters have been investigated, e.g. the order of the gas volume flux, J_G, ranges from 10^{-2} to 10^{-1} m/s (Maretto and Krishna, 1999; Judd and Judd, 2006; Shimada et al., 2012). Bubbly flows in bubble columns are classified into homogeneous and heterogeneous flow regimes. Ruzicka et al. (2001) pointed out that the flow regime map strongly depends on the inlet condition: bubbly flows with small gas inlet holes are apt to be heterogeneous at high J_G, whereas those with larger inlet holes can be heterogeneous at any J_G. The heterogeneous regime is characterized by the presence of large-scale vortical structures and a wide range of bubble sizes resulting from bubble coalescence and breakup (Chen et al., 1994; Zahradník et al., 1997). Hence good numerical predictions for heterogeneous bubbly flows cannot be performed without accounting for those characteristics.

Judging from a huge number of bubbles in a bubble column, neither interface tracking methods nor Euler–Lagrange methods are appropriate for predicting heterogeneous bubbly flows in the column. Numerical methods based on a multi-fluid model may have a potential to deal with heterogeneous flows with a huge number of poly-dispersed bubbles (Lehr et al., 2002; Laborde-Boutet et al., 2009; Tanaka et al., 2009; Ojima et al., 2014). A population balance model (PBM) has been often implemented into the multi-fluid model to account for bubble coalescence and breakup. Tanaka et al. (2009) examined the applicability of a

* Corresponding author. Tel./fax: +81 78 803 6131.
E-mail address: tomiyama@mech.kobe-u.ac.jp (A. Tomiyama).

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combination of bubble coalescence models proposed by Prince and Blanch (1990) and Wang et al. (2005) and a breakup model proposed by Luo and Svendsen (1996) to various bubbly flows, i.e. coalescence-dominating flows, breakup-dominating flows, flows in-between and flows with low coalescence-breakup frequencies. They confirmed that this combination gave accurate predictions for distributions of void fraction and bubble diameter.

The large-scale vortical structures, bubble-induced pseudo turbulence and shear-induced turbulence would be the main sources of velocity fluctuation and mixing in a bubble column. Most of multi-fluid simulations for heterogeneous bubbly flows have utilized turbulence models to account for the turbulent momentum transfer (Lehr et al., 2002; Laborde-Boutet et al., 2009). Lehr et al. (2002) carried out multi-fluid simulations of heterogeneous bubbly flows using a standard k–ε model. Predictions of time-averaged local void fraction and mean liquid velocity agreed with experimental data (Hills, 1974; Grienburger and Hofmann, 1992). Though the large-scale vortical structure was also predicted, the predicted velocity fluctuation did not quantitatively agree with the experiments. Laborde-Boutet et al. (2009) investigated effects of k–ε models on prediction of heterogeneous flows and confirmed that the standard and realizable k–ε models (Shih et al., 1994) gave inaccurate predictions, whereas the RNG k–ε model was in better agreement with the experimental data by Chen (2004). On the other hand, we speculated that good predictions could be obtained without using those turbulence models if the velocity fluctuation caused by large-scale vortical structures prevails over the bubble-induced and shear-induced turbulences and carried out multi-fluid simulations of heterogeneous bubbly flows in a slurry bubble column without using the turbulence models (Tanaka et al., 2009; Ojima et al., 2014). Though good agreement between measured and predicted distributions of void fraction has supported our speculation, it is still insufficient for verifying the speculation because the validation of the method against velocity data has not been carried out yet due to the lack of reliable experimental data on liquid velocity in a heterogeneous flow.

Several experimental data on liquid velocities in heterogeneous bubbly flows have been obtained by using a Pitot tube (Hills, 1974), hot film anemometry (Menzel et al., 1990) and the computer automated radioactive particle tracking (Chen et al., 1999). These experimental data on time-averaged velocity have been utilized for validation of numerical methods (Lehr et al., 2002; Chen et al., 2005a,b; Tabib et al., 2008). Experimental data of liquid velocity with high spatial and high temporal resolutions, which can be used for comparisons of mean and fluctuation velocities, are however still unavailable. Laser Doppler velocimetry (LDV) has a potential to yield velocity data for bubbly flows at high spatial and high temporal resolutions. However laser beams are more and more suffered from the interception by bubble interfaces as the void fraction increases, and therefore it becomes difficult to measure velocities under the conditions of relatively high void fractions in the heterogeneous regime. One of the remedies for this is to introduce a LDV probe inside the column. Hosokawa et al. (2013) developed a small fiber LDV probe and measured the liquid velocity in subchannels of a rod bundle by inserting the probe in a rod. The short optical path of the inserted probe reduced the frequency of beam interception due to bubbles, and facilitated liquid velocity measurement in a bubbly flow in the rod bundle.

In this study, numerical simulations of heterogeneous bubbly flows in an air–water bubble column were carried out without using turbulence models such as k–ε and LES models and the predictions of flow structure, mean and fluctuation velocities of the liquid phase and local void fraction were compared with experimental data to confirm the speculation: heterogeneous bubbly flows are predictable using the multi-fluid model without turbulence models if the large-scale vortical structures are dominant. For this purpose, distributions of mean and fluctuation velocities of the liquid phase and void fraction were measured using the small LDV probe and an electrical conductivity probe, respectively.

2. Experiments

2.1. Experimental setup

Fig. 1 shows the experimental setup. The column was made of acrylic resin. Zahradník et al. (1997) and Su et al. (2006) pointed out that the effects of column diameter on the total void fraction of air–water heterogeneous bubbly flows are small if the column diameter is larger than 150 mm. The column width and depth of 200 mm were therefore used. The column height was 1200 mm. Air was supplied from the oil-free compressor (Hitachi, Ltd., SRL-2) to the column through the oil filter and the air chamber. An air diffuser plate was placed at the bottom of the column. 49 stainless tubes of 1.4 mm diameter and 300 mm long were flush mounted on the plate to make the flow rate from each hole the same by a large pressure drop in the tubes (Garnier et al., 2002). The tube diameter is close to that used in the experiment in Ruzicka et al. (2001), who pointed out that bubbly flows with the large inlet holes can be in heterogeneous regime at any gas volume fluxes. The air flow rate was measured using a flowmeter (Nippon flow cell, STO-4, full-scale accuracy ±3%). Tap water was filled in the column. The initial liquid level was 800 mm above the diffuser plate. The gas volume flux, J_G, was set at 0.020 and 0.034 m/s. The temperature of water was measured using a thermometer (Netsuken Ltd., SN3000, accuracy ±0.5 °C) and was kept at room temperature (20 ± 2 °C). The experiments were carried out at atmospheric pressure. Horizontal distributions of void fraction and liquid velocity were measured along the x axis at z = 600 mm and y = 0 mm, where z is the elevation from the diffuser plate and y the distance from the column center in the depth direction as shown in Fig. 1.

2.2. Measurement methods

Local time-averaged void fractions were measured using an electrical conductivity probe (Ojima et al., 2014). The voltage

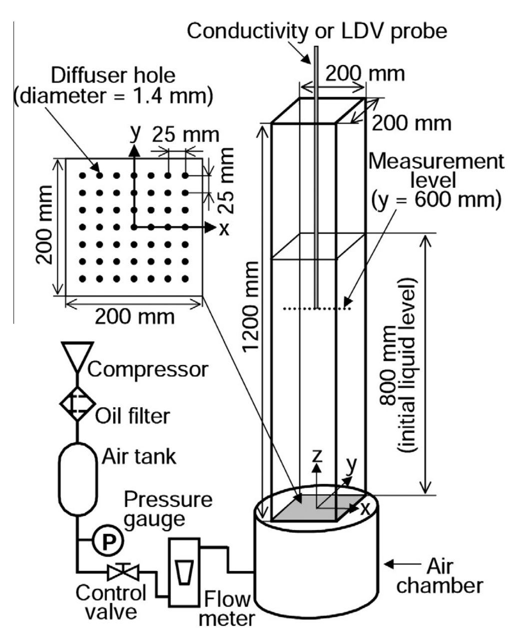

Fig. 1. Experimental setup.