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Characteristics of bubble-induced liquid flows in a rectangular tank

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ABSTRACT

Bubbly flows are frequently encountered in many industrial applications where multiphase contact is used to promote heat, mass and momentum transfer. These include applications where both chemical and physical processes occur, such as wastewater treatment and biological aeration systems. We investigated the behaviour of underwater-generated bubble swarms, which were produced at the bottom of a 1-m^3 square tank from a 5-mm nozzle and allowed to rise by buoyancy in still water. Instantaneous velocity fields around the bubbles were obtained using Particle Image Velocimetry (PIV) seeded with 10–15-μm poly-dispersed fluorescent particles and gas flow rates ranging from 2 to 15 L/min (1.7–12.8 m/s). A continuous laser was used to obtain the time-resolved field, and a pulse laser was used to obtain the mean velocity fields. Images were captured at up to 2000 fps. After interrogation, a post-processing validation algorithm was employed to identify and remove vectors produced by bubbles and the interface, essentially producing vector fields of the liquid phase only. Proper orthogonal decomposition analysis was carried out on 1000 realisations of each gas flow case to identify dominant flow structures, and the flow was decomposed into its constituent spatial and temporal modes. We established that induced vortices in the liquid phase more clearly manifest at far streamwise locations shown by the spatial mode at lower gas flow rates and are clearer in the temporal mode at high gas flow rates. The mean streamwise and spanwise liquid velocities increased with the gas flow rate, and the streamwise bubble velocities can be well described by a top-hat profile curve. Finally, an analysis was done to estimate the bubble entrainment coefficient using the slip velocity and the gas buoyancy flux.

1. Introduction

Bubble-driven flows occur in many industrial engineering applications, including biochemical reactors in wastewater treatment, brewing, nuclear waste treatment, and steelmaking. In many of these applications, the product quality can heavily depend on the mixing efficiency, which is affected by the heat and mass transfer rates resulting from bubble-induced turbulence [1–3]. Rising bubbles create “pseudo-turbulence”, which is defined as random velocity fields induced by the bubbles without producing turbulence [3,4]. Therefore, studying the flow characteristics is key to further understanding bubble-driven flows, especially at high Reynolds numbers where plumes or swarms are formed.

Quantities can be measured in various length and time scales using measurement techniques such as hot wire anemometry and laser Doppler velocimetry. While the former is intrusive, the latter is not but they are both able to make flow measurements at high spatial resolutions. On the other hand, they are point measurement techniques. As a result, other flow visualisation techniques have been developed such as particle image velocimetry (PIV) that make measurements where information can be extracted at any point inside the measurement region known as the “field of view”. Particle Image Velocimetry (PIV) and its sister method particle tracking velocimetry (PTV) are flow visualisation techniques that have become indispensable tools for the study and instantaneous measurement of unsteady fluid flows. Particularly for gas–liquid flows (including bubble-driven flows), PIV can provide useful insights into the wake and vortex dynamics.

Many investigators have studied gas-induced flows at low Reynolds numbers where a single or limited number of bubbles are ejected [3,5]. Bubbles have been shown to enhance the mean and turbulent kinetic energy of the liquid phase [6]. It was also reported that the mean and turbulent kinetic energy increase strongly with the gas void fraction [4]. The effect is even stronger when bubble swarms are involved, which are encountered more often in practice than single bubbles or bubble flows low Reynolds numbers and finely dispersed un-coalesced bubbles. Numerous environmental applications involve unbounded bubble swarms propagated from point sources such as nozzles or small-diameter pipes. Examples include large bubble reactors, natural gas

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bubble swarms for examining the effect of accidental underwater oil well ruptures [7,8], and deep ocean injection of CO_2 for greenhouse gas control [9,10].

Investigations of bubble swarms using PIV and PTV have faced challenges in separating the tracer particles in the continuous phase from dispersed bubbles. Hence, separate images have been used for fluorescent tracer particles and bubbles along with optical separation methods using two cameras and an optical filter [11,12]. PIV and PTV analysis were then applied to the separate images to obtain phase-discriminated velocity fields. Other variants of phase separation have been applied where a single captured image is pre-processed to identify the bubble signature and to separate the phases prior to the application of PIV/PTV [12–15]. Kiger and Pan [13] used a median filter for image analysis, while Brucker [14,15] used edge detection to discriminate bubbles. Seol et al. [16] noted that the optical methods are preferred, although they require two cameras and relatively expensive optical setups. They remarked that while single-image phase separation methods [12–15] have had high levels of success, they involve computationally expensive image processing methods or customised PIV and PTV algorithms.

In this study, we used basic vector validation to process instantaneous vector fields since bubbles edges can produce vectors with several times the magnitude of those produced by tracer particles. The aim is to produce mean velocity fields at different inlet gas flow rates and streamwise locations for an unbounded bubble swarm. We performed experiments using a planar 2-D PIV setup with sampling times of 30 min for each gas flow condition. The gas flow rates correspond to low to medium Reynolds numbers ranging from 1700 to 13,200 in a 5-mm nozzle. For each condition, experiments were conducted for three contiguous fields of view (FOV), and we examined the characteristics and evolution of the mean x- and y-liquid velocity fields induced by the rising bubble swarm.

2. Experiments

We set up the experimental apparatus shown in Fig. 1 to visualize bubble-induced flow in a quiescent liquid and obtain instantaneous flow velocity fields. The system consists of a 1-m^3 tank filled with tap water and an upward-facing nozzle with an internal diameter of 5 mm that is affixed to the bottom of the tank and connected to an air compressor (maximum capacity 137.3 bar; DongSeung). Air is metered into the water tank via manual valves V-1 and V-2 connected to rotameters F-1 (0–25 lit/min) and F-2 (0–50 lit/min), respectively. These correspond to gas velocity ranges of 0–21.2 m/s and 0–63.7 m/s in the nozzle.

Poly-dispersed fluorescent Rhodamine B particles (diameter 10–20 μm) were used as tracing particles. The particles have excitation and emission wavelengths of 555 nm and 580 nm, respectively. A 50-mJ Dantec Dynamics dual-pulse Nd:YAG laser was used to provide illumination at a wavelength of 532 nm. The laser emits a pair of collocated pulses, which were converted into 0.5-mm-wide laser sheet pulses using a series of optics. The light sheet was aligned vertically along the centreline of the bubble swarm to investigate the axisymmetric cross section above the nozzle exit. A 1.3-megapixel charge-coupled diode (CCD) camera was focused normal to the laser sheet to acquire images of the seeded flow field. The camera was fitted with a Micro-Nikkor 105 mm f/2.8D AF lens from Nikon and a 545-nm long-pass optical filter.

A synchronizer unit generates the required laser pulses and controls the camera, thus enabling the capture of image pairs at adjustable frequencies. A Windows 7 PC was used to run the image capture software and for storage, which was equipped with a Core i5-2500 central processing unit (3.3 GHz), 3.5 GB of RAM, and an NVIDIA GeForce GT440 graphics-processing unit. Table 1 summarises the details of the experimental setup, equipment, and conditions.

The camera distance was chosen to allow the FOVs to capture the largest bubbles and surrounding water. Three overlapping FOVs were used with dimensions of 13.0 cm × 10.4 cm in the vertical plane with the nozzle at the centre position $X/2$. A 3-mm overlap was maintained between the FOVs, which were located at the vertical centre of the tank to minimise the free surface interference and maximise the bubble flow development upon exiting the nozzle. The FOV arrangement is shown in Fig. 1(b).

Before recording images, the camera was calibrated at a certain distance from the tank. This was achieved using a calibration target next to the nozzle and a recorded image. The camera position remained unchanged for the experiments. For the bubble-induced flow experiments, images were recorded in TIFF format for each condition. For each gas flow rate, two kinds of PIV measurements were obtained. First, time-resolved measurements were obtained at 750–1000 fps (depending on the gas flow rate) using a continuous laser for studying the temporal dynamics of the flow. Second, experiments were carried out with a double-pulsed laser to record image pairs (2000 ms apart) for each capture. Successive captures are recorded over 30 min at 1.2 Hz and are considered randomly sampled and uncorrelated with respect to time. Randomly sampled snapshots provide the representative ensemble means of the flow, and turbulent statistics can be calculated since realisations are obtained over longer durations than time-resolved measurements.

3. Results and discussion

3.1. Data processing

Interrogation of the acquired PIV images was performed using a window size of 32 × 32-pixel, as well as a 32 × 32-pixel FFT window pixels with 50% window overlap. The bubble motion across the laser sheet is three dimensional, and between image frames, bubble distortion occurs and contributes to the production of spurious vectors. We used a magnitude difference method for validation where these vectors are identified and removed using PDFs of all x- and y-vectors to decide the range of vector magnitudes to be screened. An illustration is given in Fig. 2, where the excluded vectors correspond to the flattened parts of the PDF, we take the vectors that are within the horizontal section of the PDF to be erroneous and hence excluded. These excluded vectors physically correspond to those produced by the bubble outlines created at the intersection of the bubbles with the laser sheet. Additionally, we implemented a method to clean up the velocity field to clarify the bubble boundaries since residual error vectors can be produced at a few more pixels away from the boundary. Therefore, a macro was written and called in Tecplot to apply the following subroutine to remove surrounding vectors:

$$\begin{aligned}&\textit{if}\ \ U(i,j)=0,\\&\textit{then make}U(i-1,j)=U(i+1,j)=U(i,j-1)=U(i,j+1)=0\end{aligned}\qquad(1)$$

This subroutine applies to both vector components U and V. The phase discrimination technique resulted in acceptable accuracy when the processed vector fields were compared with raw PIV images. While Eq. (1) can result to error in the up to 50% error in instantaneous velocity vectors at the interface, but we note that our phase discrimination method is not intended to be better than optical phase separation techniques where multiple cameras and dichoric mirrors are employed and these entirely remove bubble signature before PIV interrogation. An alternative, we propose a simpler method that works well for mean flow characteristics in the liquid phase without resorting to additional equipment. Fig. 3(d) shows that our method provides mean velocity profile that is in close agreement with that of Seol et al.'s [16] PIV data at 1.5 L/min. This gas flow rate is the closest available condition we can compare our results with. For the PIV measurements, Seol et al. [16] adopted a phase discrimination methodology similar as ours in their study of bubble plumes [16]. However, they used a median non-linear