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Quantitative characterizations of long-period fluctuations in a large-diameter bubble column based on point-wise void fraction measurements

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ABSTRACT

Quantitatively characterizing long-period fluctuations, which reflect the large-scale structure of a bubbly flow in a bubble column reactor, is essential to improving the reactor efficiency. We propose a newly developed method to extract the long-period fluctuations based on point-wise void fraction measurements. The validity of the new method is demonstrated via characterization of long-period fluctuations in a bubble column approximately 400 mm in diameter and 2000 mm in height. First, the characteristics of liquid-phase motion induced by a single bubble-swarm are described based on the results obtained via LDA measurements. The large-scale liquid-phase motion is characterized by an individual bubble cluster (i.e. a region with the same void fraction). We explain the premise of our new method based on these results. Second, we show that the bubbly flows in the bubble column can be divided into three regions (i.e. a time-spatially fluctuated region, a transition region, and a pseudo-homogenous region) based on differences in the distribution patterns of bubble diameters and velocities as well as those between time-series point-wise void fractions obtained from four-point simultaneous measurements. The spatial fluctuations fade out with height from the column bottom. Finally, analyzing the time-series point-wise void fractions measured via four-tip optical-fiber probe (F-TOP), we demonstrate that the long-period fluctuations can be extracted via waveform analysis. The characteristic spectrum pattern also fades out with height. The extracted long-period fluctuations are in good agreement with those obtained from the visualization results for the flows.

1. Introduction

Bubble column reactors and gas lift reactors are widely used in the chemical industry and other industries [1,2] due to their structural simplicity and high-mass-transfer performance. However, due to the extreme complexity of the bubbly flows, details regarding the phenomena occurring in the reactors have remained unclear. Many researchers have been investigating the mass-transfer coefficient in the reactors with regard to the average bubble diameters and average void fractions [3,4]. Furthermore, the flow regimes have been described as functions of the superficial gas velocity and the geometrical properties of bubble columns [5,6].

In order to improve the chemical reactions in bubble column reactors and to establish their similarity rule with regard to scale up, the details of the physical phenomena (i.e. turbulence specification, flow structure, axial dispersion of bubbles, and so on) have been investigated with many experimental approaches. Based on these investigations, the flows can be identified by three specific scales.

On the scale of a single bubble, local pseudo-turbulence is induced by the buoyancy current [7]. On an intermediate scale of a single bubble-swarm, the vortical structure, which is characterized by eddies of its surrounding liquid, appears with a size on the order of the bubble-swarm diameter. The vortical structure stirs the liquid phase and radially transports the bubbles. The velocity fluctuation intensity and the integral scale in the liquid phase are modulated by a single bubble-swarm [8]. On a large scale, gravity acts on non-uniformity in the spatial bubble distribution in the bubble mixture. The gravity-driven flow can form results in inhomogeneous bubble distribution, leading to a turbulent flow. Based on observation of the large-scale circulation, the buoyancy-driven bubbly flows remain relatively unstable except in a completely controlled bubble distributor, even if the superficial gas velocity is low [9].

The time-spatial fluctuation above the entrance region generates a coherent structure observed in a large-scale flow. In order to closely approach the essence of the phenomena, we should focus primarily on the fluctuation characteristics of the bubbly flows at comprehensive specific scales.

Over the last decade, several measurement techniques have been carried out to quantitatively observe the characteristics of fluctuation within the bubbly flows.

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Nomenclature

$a(t)$	time-series void fraction
A_a	area of a region in Fig. 4
D_{eq}	equivalent bubble diameter (mm)
D_{min}	chord length of minor axis (mm)
D_{maj}	chord length of major axis (mm)
f_{ai}	point-wise void fraction at $(x, y) = (x_i, y_i)$
f_{a1}	point-wise void fraction at $(x, y) = (x_1, y_1)$
F_{a1}	space-average void fraction at $(x, y) = (x_1, y_1)$
T_s	integral time of time-averaged void fraction
V_b	vertical components of bubble velocity (mm/s)
w	vertical components of liquid-phase velocity (mm/s)
φ_1	horizontal angle of bubble contact (°)
φ_2	vertical angle of bubble contact (°)

For instance, ECT (electrical capacitance tomography) has been used to describe the distribution pattern of the gas phase and the time evolution of this pattern [10,11]. Although the macroscopic flow structures and the fluctuation can be well-described based on this measurement technique, the local time-series void fraction cannot be detected at high spatial resolution. Furthermore, in order to improve the numerical schemes for gas–liquid two-phase flows, quantitative understanding of the flows based on experimental results from the small to large-scale physical phenomena is essential.

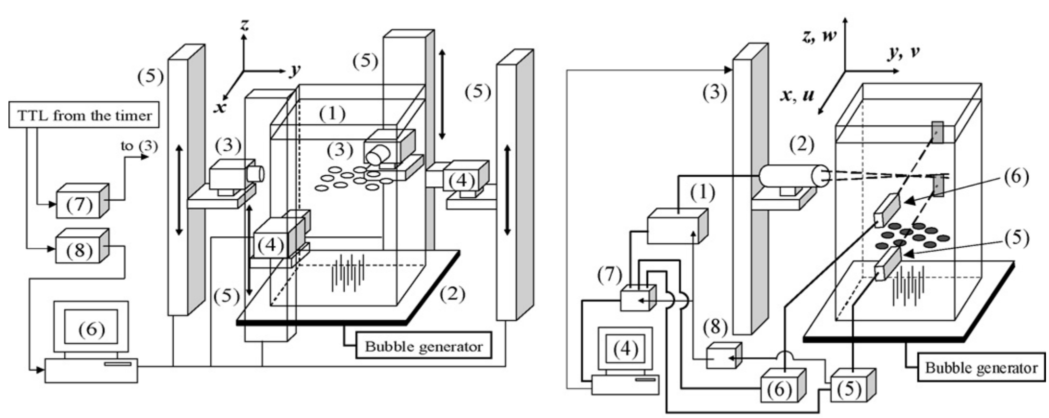
From these results, we observed the fluctuations of bubbly flow from the perspective of the comprehensive scales by using a point-wise time-series void fraction.

We discuss herein how to extract the long-period fluctuations, which correspond to the large-scale structure of the buoyancy-driven flows, based on point-wise time-series void fractions in the bubble column. Furthermore, using the newly developed method, we characterize long-period fluctuations in a bubble column 400 mm in diameter and 2000 mm in height. First, we consider the relationship between the time-average void fraction and the spatial-average void fraction. Second, characteristics of the liquid-phase motion induced by a single bubble-swarm (i.e. a controlled region with a uniform void fraction) are described based on the results obtained via LDA measurement. The large-scale liquid-phase motion is characterized by the individual bubble cluster (i.e. a region with a uniform void fraction). We explain the premise of our method based on these results. Third, we measured the void fractions, bubble diameters, and velocities in the bubble column using a four-tip optical-fiber probe (F-TOP) [12,13]. We found that the bubbly flows in the bubble column are calcified into three regions (i.e. a time-spatially fluctuated region, a transition region, and a pseudo-homogenous region) based on the distribution patterns of the bubble diameters and velocities. Furthermore, the spatial fluctuations of the void fraction fade out with height from the column bottom. Finally, analyzing time-series point-wise void fractions measured via F-TOP, we demonstrate that long-period fluctuations are well-extracted by applying the newly proposed method. The extracted long-period fluctuations are in good agreement with those obtained from the flow visualization.

2. Experiment

2.1. Buoyancy-driven flows induced by a single bubble-swarm.

The bubble-swarm examined in the present study was generated using a device diagrammed in Fig. 1(a). Nineteen needles (1) (0.32 mm in inner diameter; 0.09 mm in thickness) were arrayed at the bottom of an acrylic water vessel (2) in a lattice-like arrangement, as shown in Fig. 1(b). Two lines supplied pure air from a cylinder (10) to the needle groups of A and B. The flow rate in each line was controlled by micro-control valves (6), respectively. Each line was equipped with a pair of electromagnetic valves, (4), (4′), (5), and (5′), tripped by a digital timer (8). The valve-opening period was 1 ms (i.e. the pure air was injected in this period), and the opening interval was 10 s. The trigger signal was simultaneously inputted to both high-speed video cameras and PC-controlled precision-linear lifts. The fluctuations in bubble diameters launched from the needles were smaller than 0.44 mm (i.e. 2.6% of the average equivalent diameters of 5.44 mm).



(1) Water vessel, (2) Honeycomb table, (3) High-speed video cameras, (4) Stroboscope, (5) Precision-linear lifts, (6) Control PC, (7) Controllable delay circuit, (8) Controllable delay circuit

(a) For visualizing the motion of a bubble swarm.

(1) LDA system, (2) LDA probe, (3) Automatic 3-axial stage, (4) Control PC, (5) Stroboscope, (6) Laser-optic sensor for the LDA trigger, (7) Laser-optic sensor for detection of a bubble swarm, (8) A/D converter, (9) Controllable delay circuit

(b) For measurement of the liquid-phase motion.

Fig. 1. Experimental setup of a single bubble-swarm. (a) For visualizing the motion of a bubble swarm. (1) Water vessel, (2) honeycomb table, (3) high-speed video-cameras, (4) stroboscope, (5) precision-linear lifts, (6) control PC, (7) controllable delay circuit, (8) controllable delay circuit. (b) For measurement of the liquid-phase motion. (1) LDA system, (2) LDA probe, (3) automatic 3-axial stage, (4) control PC, (5) stroboscope, (6) laser-optic sensor for the LDA trigger, (7) laser-optic sensor for detection of a bubble swarm, (8) A/D converter, (9) controllable delay circuit.