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UNSTEADY DYNAMICS OF BUBBLE PLUME

Hyunseok Kim[1] and Hyungmin Park[1,2*]

[1]Department of Mechanical Engineering, Seoul National University, Korea
[2]Institute of Advanced Machines and Design, Seoul National University, Korea

Abstract: In this study, we experimentally investigate the unsteadiness of bubble plume structure and induced liquid flow, while varying the bubble size distribution: one is a quasi-Gaussian distribution with a mean size of 3 mm and the other is a heterogeneous distribution with a larger (10 mm) mean size. Bubble plume motion was measured with two CCD cameras for gas-phase, and the induced liquid velocities were measured with LDA. It was quantitatively confirmed that the bubble plume with larger bubbles show a much stronger fluctuation of its width and center than that with smaller bubbles. The liquid statistics of the induced liquid plume were confirmed to follow the self-similarity based on plume width. The bubble plume with larger bubbles shows a slower development along the axial direction and has a higher radial velocity, axial and radial velocity fluctuation, and turbulence kinetic energy compared to the bubble plume with smaller bubbles. Finally, the behavior of the induced liquid flow in terms of the integrated liquid mass, momentum, and energy flow rates depending on bubble size distribution was examined.

Keywords: bubble plume, bubbly flow, bubble-induced turbulence

1. Introduction

Bubble plume is widely used in the environmental and industrial processes, such as a mixing in seawater, lake, wastewater, chemical solution, food, beverage and oil, owing to the substantial bubble-induced agitation added to the liquid-phase flow[1-3]. Nevertheless, systematic study on the unsteady structure of bubble plume is still lacking. In particular, the bubble plume dynamics can vary significantly depending on bubble size distribution even at same gas flow rate. In this study, we quantitatively studied the unsteady characteristics of bubble plumes in terms of its kinematics and induced liquid turbulence. It has been well known that the regime of gas-liquid two phase changes depending on superficial velocity and system size in pipe flow[4]. We found a similar transition of regime with the superficial gas velocity; from conventional bubble plume to churn-turbulent bubble plume. In this study, we investigated the unsteady characteristics of conventional and churn-turbulent bubble plume in terms of bubble plume motion, induced liquid velocity statistics and integrated mass and momentum flow rate.

2. Materials and Methods

We quantitatively measured gas and liquid phase information separately (Figure 1). At first, we measured bubble size, velocity field and bubble plume motion using shadowgraph with 1000 W tungsten lamp and high-speed camera (Phantom Miro M-310). In addition, liquid phase velocity was measured by laser doppler anemometry (Dantec Dynamics 1D FiberFlow) with 200—850 Hz for 5 minutes for convergence. We measured liquid velocity at total 50 points which are axially 30, 50, 100, 200 and 300 mm from the top of the sparger top and radially 0, 10, 20, 30, 40, 50, 60, 75, 90 and 150 mm from the center of the sparger.

* Corresponding Author: Hyungmin Park, hminpark@snu.ac.kr

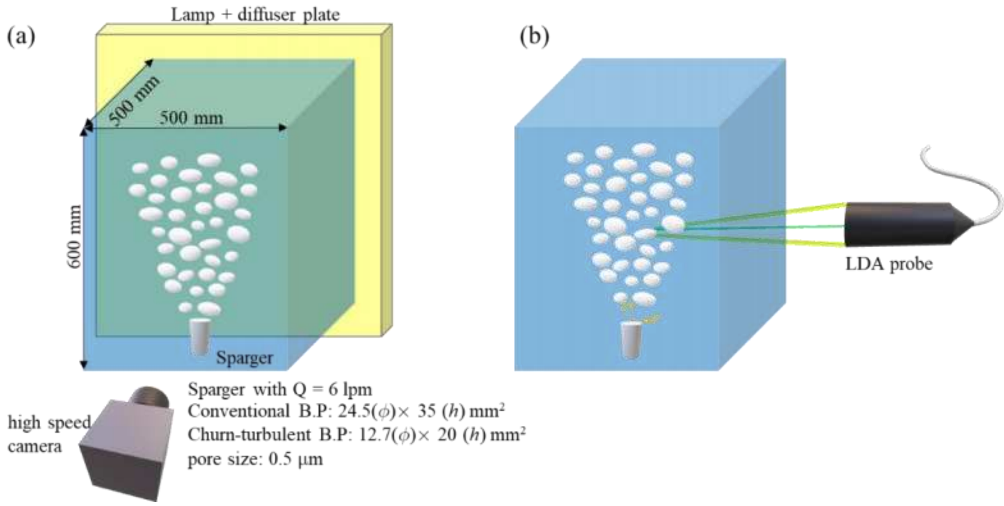

Figure 1. Experimental setup for (a) gas phase measurement (shadowgraph technique) and (b) liquid phase measurement (laser doppler anemometry)

We applied several post-processing algorithms on bubble shadow image to acquire bubble size distribution, velocity and bubble plume kinematics information. Bubble size distribution was taken by combination of image binarization and watershed transform [5]. On the other hand, we got the bubble velocity fields using Lucas-Kanade algorithm [6]. Furthermore, we decomposed bubble plume motion into precession, meandering and bulge. Before the detailed definition of each parameter, we notice the definition of bubble plume axis. We defined the left and right boundary of bubble plume as linear regression of boundary of each side. Next, we defined bubble plume center as the center point of left and right boundary at each height. Precession was defined as a distance between instantaneous displacement of bubble plume center at each height and meandering as a difference between the center of left and right boundary of bubble plume and that with the linear regression (i.e., bubble plume axis). In addition, bulge was quantified as bubble plume width fluctuation.

In addition, parametric expression of integrated momentum flow rate was derived as follows referring to that of the buoyant plume case [7].

$$\mathrm{M} = 2\pi \int_0^{\infty} r \left(U_z^2 - \frac{1}{2} U_r^2 + \overline{u_z' u_z'} - \overline{u_r' u_r'} \right) dr \quad (1)$$

Here, subscript z and r designates axial and radial direction respectively. Upper- and lower-case U is time averaged and fluctuation component of liquid velocity.

3. Results

3.1. Bubble plume kinematics

Bubble plume kinematics parameters are shown in Figure 2. While conventional bubble plume shows a wider mean plume width, churn-turbulent bubble plume has more dynamic precession. On the other hand, relative intensity of bulge and meandering is different before and after around z = 100 mm. As previous research, we think that z = 100 mm is the establishment height [3]. Before this, conventional bubble plume has stronger bulge and meandering, and after this, this tendency is reversed. Also, gradient of each parameter along height changes roughly around establishment height, z = 100 mm.

* Corresponding Author: Hyungmin Park, hminpark@snu.ac.kr

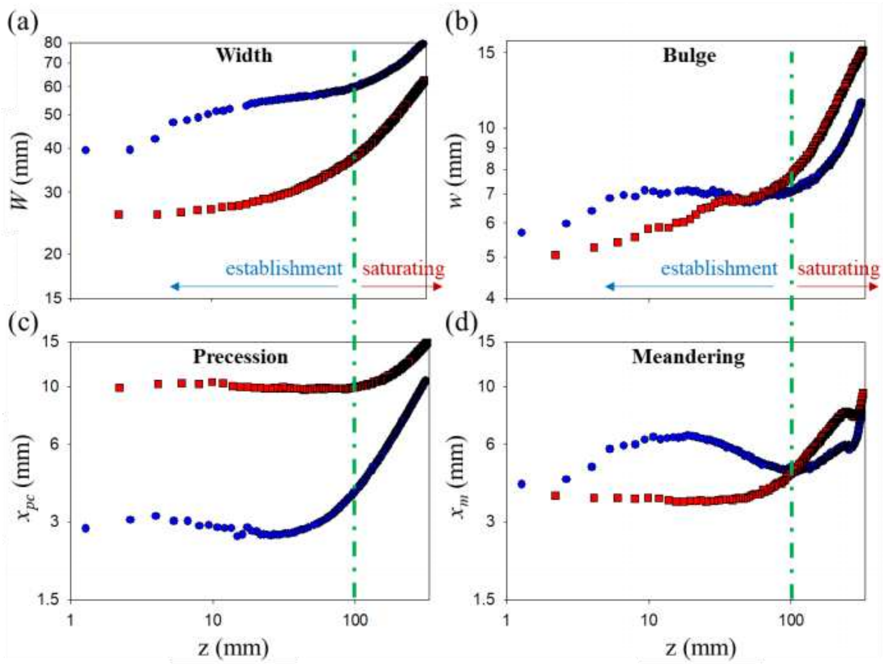

Figure 2. Bubble plume kinematics parameters (a) time averaged width, (b) bulge, (c) precession and (d) meandering for ●: conventional bubble plume, ■: churn-turbulent bubble plume

3.2. Integrated momentum flow rate

Time averaged integrated momentum flow rate is determined with equation (1). Furthermore, we split the total integrated momentum flow rate into two part. One is mean momentum flow rate (consists of mean velocity) and the other is turbulence momentum flow rate (consists of velocity fluctuation). Axial variation of each parameter is described in Figure 3. Conventional bubble plume has larger total and mean momentum flow rate through every measured height but both bubble plumes has comparable turbulence momentum flow rate.

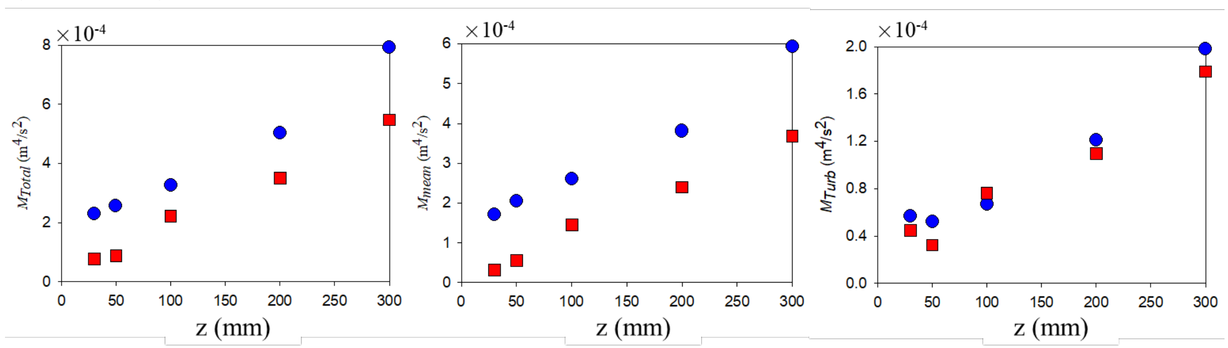

Figure 3. Time averaged integrated (a) total momentum flow rate, (b) mean momentum flow rate, (c) turbulence momentum flow rate for ●: conventional bubble plume, ■: churn-turbulent bubble plume

4. Conclusions

In this study, we quantitatively investigated unsteady characteristics of conventional and churn-turbulent bubble plume. Bubble plume kinematics and integrated momentum flow rate of induced liquid flow was determined. We found the fact that there is the establishment height and bubble plume kinematics

* Corresponding Author: Hyungmin Park, hminpark@snu.ac.kr

changes distinctively before and after this point. On the other hand, in terms of integrated momentum flow rate, two types bubble plumes have different tendencies in mean and turbulence momentum flow rate.

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* Corresponding Author: Hyungmin Park, hminpark@snu.ac.kr