

Parameter Measurements of Bubble Plume Structure

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Abstract

Gas injection through a bottom nozzle is very popular and has wide applications. Hence, many researchers have carried out extensive model experiments by focusing on flow field's structure using air bubbles. The bubble plume, which is a typical form of bubble flow, is known as one of the transport phenomena that have the capability to drive a large-scale convection due to the buoyancy of the bubbles. The technique of using a surface flow generated by the bubble plume is utilized as an effective way to control and collect surface floating substances in naval systems, lakes, seas, rivers, oceans especially the oil layer formed during large oil spill accidents. Furthermore, the surface flows generated by bubble plumes are considered to be key phenomena in various kinds of reactors, engineering processes and industrial processes handling a free surface. The motivation of this research is to broaden the knowledge of the relationship between the parameters of bubbly flow that are demanded to describe the characteristics of the bubble generating surface flow. Such flow depends on the gas flow rate, the bubble size (mean bubble diameter), void friction, bubble velocity, the internal two-phase flow structure of the bubble plume and the distance between the bubble generator and the free surface which is equivalent to the water height in the experimental tank. Laboratory experiments have been carried out in order to investigate the motion of bubbles in order to calculate the mentioned bubble parameters and to find their relationship. The data are obtained by applying image processing of visualized images of bubble flow structure for the different sections of bubble regions. It is confirmed that the flow structure and bubble parameters are sensitively modulated by the gas flow rate. As the gas volume flow rate increases the bubble velocity along the bubble plume increases. Furthermore, the bubble velocity increases as the water height in the experimental tank increases.

Introduction

Bubble plumes are observed in various engineering disciplines, e.g. in industrial, material, chemical, mechanical, civil, and environmental applications such as chemical plants, nuclear power

plants, naval engineering, the accumulation of surface slag in metal refining processes, the reduction of surfactants in chemical reactive processes, chemical reactions, waste treatment, gas mixing and resolution, heat and mass transfer, aeronautical and astronautical systems, biochemical reactors as well as distillation plants, etc.

As the model of gas injection (the technique that has been widely utilized for improving the engineering process) is the most popular and has wide applications and since bubble plumes have been used with varying degrees of success more information on these subjects should be accumulated because there is still possible improvement to get higher efficiency for generating the surface flow.

Surface flows generated by bubble plumes are considered as a key phenomenon in many processes in bioreactors, chemical plants, modern industrial technologies, such as metal refinement, and future-type nuclear power plants, in addition to the many applications of bubble plumes mentioned above. These processes, which are expected to be improved by applying the bubble plume, require the control of both concentration and transportation of surface-floating substances, i.e. solidified materials or impurities, as well as the stabilization of the interface motion itself in order to guarantee their designed performances. Hence, the flow in the vicinity of a free surface induced by a bubble plume was utilized as an effective way to control surface floating substances on lakes, rivers, seas, oceans, as well as in various kinds of reactors and industrial processes handling a free surface in references [1-18].

The flow pattern of the internal liquid flow (the whole field flow structure around the bubble plume) in water tank was clarified in our earlier paper [8]. The resulting flow is steady and symmetric relative to the bubble plume center. The flow pattern depends on the gas flow rate, and as the gas flow rate increases, the magnitude of velocity (the mean velocities of liquid phase and gas phase) increases and the effective area of the bubble plume (of the surface flow) expands in horizontal direction. Inside the bubble plume and near the free surface, the bubble velocity and hence the velocity of the two-phase flow is higher while it is slower in other regions. Hence, the generation of this high speed flow is considered a main

contribution to induce a strong surface flow.

The bubble parameters and their relation (mean bubble diameter, gas flow rate, void fraction and the distance between the bubble generator and the free surface which is equivalent to the water height in the tank) are calculated in our earlier paper [8]. It was confirmed that the flow structure is sensitively modulated by the gas flow rate and bubble size, and as the gas volume flow rates increases the mean (average) bubble diameter increases. Moreover, the void friction increases with the gas flow rate at a power index of around 0.8 to 1.0. Moreover, the bubble size increases as the water height in the tank increase.

This paper is concerned with the characteristics of bubble and their parameters that induce surface flow. Image processing is applied after carrying out flow visualization for different sections of bubble regions in order to clarify the relationship between bubble parameters such as: gas volume flow rate, water height in the tank (the height of the bubble plume which is equivalent to distance between the bubble generator and the free surface) and bubble velocity along the bubble plume. The relationship between the bubble parameters is explained. The flow structure and bubble parameters are sensitively modulated by the gas flow rate.

Experimental Apparatus, Method and Conditions

Experimental apparatus for carrying out the experiments of bubble parameters measurements is constructed as shown in figure 1. The inner tank size is 1300 mm in length, 1000 mm in height, and 110 mm wide, made of transparent acrylic resin. The experimental conditions are listed up in Table 1. The bubble generator is installed at the center of the bottom part of the tank. Four kinds of bubble generators (with different injector nozzles) are applied for the experiments as shown in figure 1. Table 2 shows the experimental conditions for bubble generators. The gas flow rate is precisely controlled by a pressure regulator and a flowmeter. A lighting setup (direct lightning method) with a black back sheet background and two halogen lamps of 1000 W is used to clearly visualize and capture the images of the experiments for the measurements. The visualized flows are recorded by a digital video camera (Panasonic DMC-GH2H) that captures 30 fps. The digital images are preprocessed through the video to JPEG converter

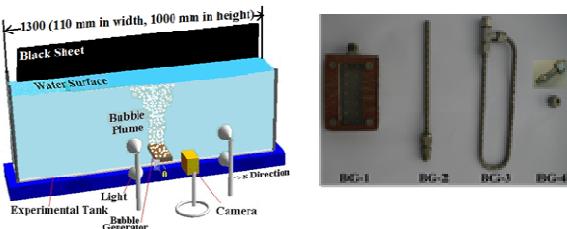


Figure 1. Experimental setup and photo of bubble generators.

image software and Adobe After Effects CS6 image processing software. The preprocessing entails sharpening, binarizing, smoothing of the images, and labeling bubbles.

Parameter	Value
Density of water	$\rho = 1000 \text{ kg/m}^3$
Kinematic viscosity of water	$\nu = 10^{-6} \text{ m}^2/\text{s}$
Initial water height	$H = 0.2 \sim 0.6 \text{ m}$
Atmospheric pressure	101 kPa
Temperature of environment	22-25 °C
Density of gas (air)	1.25 kg/m³
Maximum gas flow rate	$Q_g = 8.0 \times 10^{-6} \text{ m}^3/\text{s}$

Table 1. Experimental and simulation conditions.

(BG) Bubble Generator	BG-1	BG-2	BG-3	BG-4
Type	Block	Straight Tube	Round Shape	Single Nozzle
Number of Nozzles	14	16	39	1
Nozzle Diameter	0.75 mm	1 mm	1 mm	5 mm
A Injector Surface	65×20 (mm²)	120×1 (mm²)	150×45 (mm²)	19.63 (mm²)
Air Tube/ Room Dimension	80×55×25	6.5 mm	6.5 mm	6.5 mm

Table 2. Experimental conditions for bubble generators.

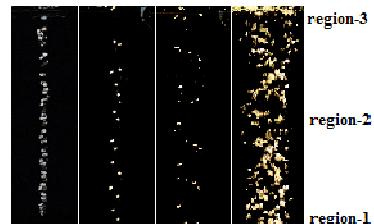


Figure 2. Samples of Bubble Images for Different Condition.

Bubble Parameters Calculations

The parameters of bubbles (bubble velocity, gas flow rate and the distance between the bubble generator and the free surface which is equivalent to the water height in the tank) are calculated and their relation is demonstrated. Seventy-two cases (conditions) are handled in these experiments. The values of the parameters are calculated by using the time average of 180 consecutive frames in the image processing (6 seconds). The bubble velocity, the width of bubble injection and the standard deviation are calculated by measuring more than 1200 bubbles in the local VTR images inside the bubble plume using image processing. The experiments for measuring bubble velocity are conducted in three regions of the bubble plume: the first region is over the injector region of the bubble generator, the second region is the middle regions of the bubble plume and the third region is just under the free surface.

Figure 2 shows samples of bubble images for different condition of bubble generator including these regions.

Figures 3, 4 and 5 illustrate samples of the relationship between bubble velocity and water height in the tank for the four bubble generator types and for $Q_{g4}=2.22 \times 10^{-6} [\text{m}^3/\text{s}]$. The bubble velocity is calculated for three regions or level of the height of the bubble plume the first level is over the bubble generator (over the injector region of the bubble generator) and the second level is in the middle level height (the middle region) of the bubble plume and the third one is just under the free surface. It is clear from these figures that the bubble velocity increases as the water height in the tank increases. Hence, the magnitude of bubble velocity increases along the bubble plume. It is also recognized that the bubble velocity magnitude in the middle region is almost 1.5 times of the bubble velocity magnitude over the bubble generator. Moreover, the bubble velocity magnitude under the free surface is almost twice of the bubble velocity magnitude over the bubble generator.

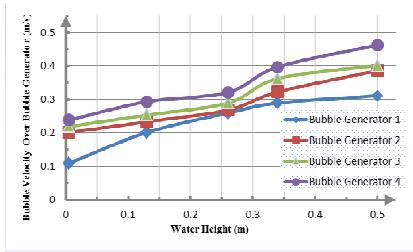


Figure 3. A sample of the relationship between the bubble velocity and water height in the tank for different bubble generators for region 1.

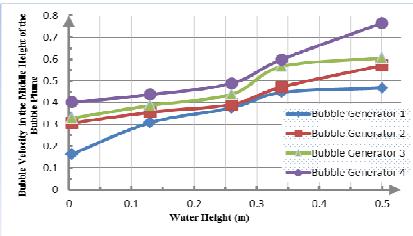


Figure 4. A sample of the relationship between the bubble velocity and water height in the tank for different bubble generators for region 2.

Figure 6, 7 and 8 show samples of the relationship between bubble velocity calculated in the three regions of the bubble plume (over the bubble generator, in the middle region and just under the free surface region) and the gas flow rate for the different bubble generators. It is clear from this figure that as the gas flow rate increases, the bubble velocity increases.

Figure 9 presents the relationship between gas flow rate and the width area of the bubble plume on the surface (the area which contains bubbles on the free surface “the width of the surface

flow” in the horizontal direction), which is measured from video images. It is confirmed that this area increases approximately proportional to the square root of the gas flow rate.

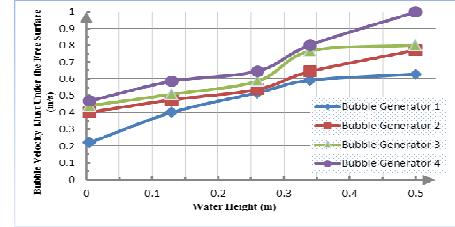


Figure 5. A sample of the relationship between the bubble velocity and water height in the tank for different bubble generators for region 3.

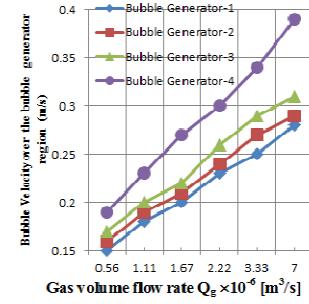


Figure 6. A sample of the relationship between the bubble velocity and the gas flow rate for different bubble generators for region 1.

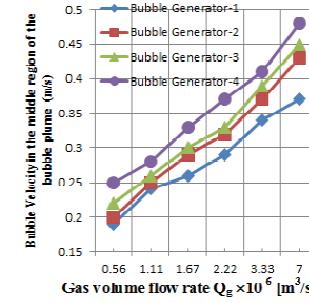


Figure 7. A sample of the relationship between the bubble velocity and the gas flow rate for different bubble generators for region 2.

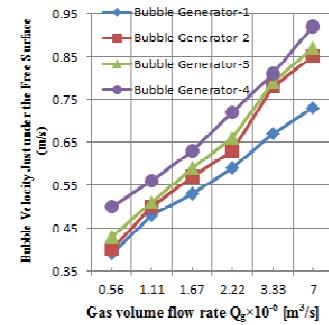


Figure 8. A sample of the relationship between the bubble velocity and the gas flow rate for different bubble generators for region 3.

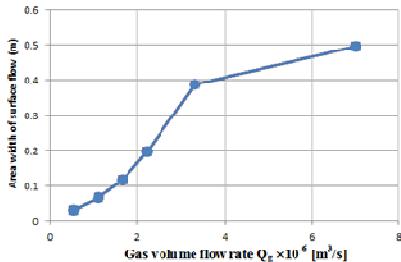


Figure 9. The relationship between gas flow rate and area width of the bubble plume on the free surface.

Conclusion

Flow visualization and image analysis of the bubble plume and bubble motion are carried out in order to improve the applicability of the bubble plume. The parameters of bubbles (bubble velocity, gas flow rate and the distance between the bubble generator and the free surface which is equivalent to the water height in the tank) are calculated and their relation is demonstrated. It was confirmed that the flow structure is sensitively modulated by the gas flow rate. The main results can be summarized as follows:

- 1) The bubble velocity increases as the water height in the tank increases, and the magnitude of bubble velocity increases along the bubble plume. Moreover, it is also recognized that the bubble velocity magnitude in the middle region is almost 1.5 times of the bubble velocity magnitude over the bubble generator. Moreover, the bubble velocity magnitude under the free surface is almost twice of the bubble velocity magnitude over the bubble generator.
- 2) The width area of the bubble plume on the surface (the area which contains bubbles on the free surface “the width of the surface flow” in the horizontal direction) increases approximately proportional to the square root of the gas flow rate.

References

- [1] Abdel-Aal H. K., Stiles G. B. and Holland C. D. 1966. Formation of Interfacial Area at High Rates Gas Flow Through Submerged Orifices. *ALCHE J.* 12, pp. 174-180.
- [2] Bankovic A., Currie, I. G. and Martin W. W. 1984. Laser-Doppler Measurements of Bubble Plumes. *Phys. Fluids* 27, pp. 348-355.
- [3] Chesters A. K., Van Doorn M. and Goossens L. H. J. 1980. A General Model of Unconfined Bubble Plumes from an Extended Source. *Int. J. Multiphase Flow* 6, pp. 499-521.
- [4] Gross R. W. and kuhlman J. M. 1992. Three-Component Velocity Measurements in a Turbulent Recirculating Bubble-Driven Liquid Flow. *Int. J. Multiphase Flow* 18, 413-421.
- [5] Hassan Abdulmouti, Yuichi Murai, Yasushi Ohno and Fujio Yamamoto 2001. Measurement of Bubble Plume Generated Surface Flow Using PIV. *Journal of the Visualization Society of Japan*. Vol. 21. No. 2. Pp. 31-37
- [6] Hassan Abdulmouti 2003. Visualization and Image Measurement of Flow Structures Induced by a Bubbly Plume. Ph. D. thesis. Fukui University.
- [7] Hassan Abdulmouti. Surface Flow Generation Mechanism Induced by Bubble Plume. *Yanbu Journal of Engineering and Science (YJES)*. Second issue. PS-M02-28 (50-67). 2011.
- [8] Hassan Abdulmouti, Esam Jassim. Visualization and Measurements of Bubbly Two-Phase Flow Structure Using Particle Imaging Velocimetry (PIV). Annual International Interdisciplinary Conference, IIC. Azores, Portugal. 24 -26 April 2013.
- [9] Hassan Abdulmouti. Measurement of Flow Structures Induced by a Bubbly Plume Using Visualization, PIV and Image Measurement. Scholar's Press. ISBN-13: 978-3-639-51490-2. 7, June, 2013.
- [10] Hussain N. A. and Narang B. S. 1984. Simplified Analysis of Air-Bubble Plumes in Moderately Stratified Environments. ASME. *Journal of Heat Transfer*. Vol. 106, pp. 543-551.
- [11] Iguchi M., Takeuchi H. and Morita Z. The Flow Field in Air-Water Vertical Bubbling Jets in a Cylindrical Vessel, *ISIJ International J.*, 31, 3. 1991, 246-253.
- [12] Jones W. T. 1972. Air Barriers as Oil-Spill Containment Devices. *J. Soc. Pet. Engng.*. Pp.126-142.
- [13] Leitch, A. M., and Baines, W. D. 1989. Liquid Volume Flux in a Weak Bubble Plume, *J. Fluid Mech.*, 205. Pp. 77-98.
- [14] Matsumoto Y. and Prosperetti A. 1997. Edit., Proc. ISAC'97 High Performance Computing on Multi-phase Flows.
- [15] Murai Yuichi, Ohno Yasushi, Abdulmouti Hassan, Yamamoto Fujio 2001. Flow in the Vicinity of Free Surface Induced By a Bubble Plume. *JSME*. 067, 657, B.
- [16] Sheng, Y.Y., and Irons, G.A.: Measurements of the Internal Structure of Gas-Liquid Plumes, *Metallurgical Trans.*, Vol. 23-B. 1992, 779-788.
- [17] Sun T. Y. and Faeth G. M. 1986 a. Structure of Turbulent Bubbly Jets-I. Methods and Centerline properties. *Int. J. Multiphase Flow* 12, pp. 99-114.
- [18] Szekely, J., Carlson, G. and Helle L. 1988. *Ladel Metallurgy*. Springer. Berlin.