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Effect of crossflow velocity on underwater bubble swarms

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ABSTRACT

We investigate the effect of crossflow velocity on submerged bubble plumes or swarms by employing the use of high-speed photography and an image-processing method to measure bubble rise velocities. Particle image velocimetry (PIV) was used to accurately determine the crossflow freestream velocity as well as boundary layer information. We varied the gas flow rates from 2 to 25 L/min. This range exceeds those of previous studies we could find in the open literature which were mostly less than 5 L/min and involved isolated bubbles. Combined with the crossflow velocities, this resulted in the investigation of a wide range of flow conditions providing a database of 36 experimental data points and constitutes a substantial addition to the bubble swarm/crossflow literature. Because our experiments involved larger gas flow rates than previously reported, we had to develop a digital image-processing algorithm using standard functions in Matlab to measure swarm rise velocities, and angles of inclination under crossflow. Results were validated against reported data at similar experimental conditions. It was established that increasing freestream velocity strongly suppressed bubble rise velocities and resulted in bubble breakup. Relationships for predicting rise velocity and inclination angle were derived as non-dimensional functions of the crossflow velocity, fluid properties and inlet gas flow rates. These showed good agreement with the current as well as reported experimental data.

1. Introduction

Gas is dispersion by under-liquid injection from submerged orifices is a useful operation in many industrial processes. These include wastewater treatment, absorption towers, aerated stirred tanks, metallurgical smelting and biological processes such as nitrification, and microorganism metabolism. In these applications, the gas–liquid interfacial surface area per unit volume is an important parameter that determines heat, concentration and mass transfer rates. It has been reported that smaller bubbles (and hence increased interfacial area) are created by having the continuous phase to flow normally across the path of the emerging gas bubbles (Ghosh and Ulbrecht, 1989; Jobehdar et al., 2016; Loubiere et al., 2004; Tan et al., 2000; Forrester and Rielly, 1998). Such crossflows allow bubble ejection frequency to be controlled and they ensure that detached bubbles are likely to be swept away from the region of the nozzle, thus reducing the likelihood of coalescence (Loubiere et al., 2004; Tan et al., 2000). Forrester and Rielly (1998) noted that drag force created by the flowing liquid and increased boundary layer transport are responsible for the generation of smaller bubbles as well as their rapid detachment from the orifice. The bubble's rise velocity as well as trajectory are now affected by the momentum of the liquid crossflow. In addition to the buoyancy, virtual mass, surface tension, and inherent drag forces the bubbles experience in liquid, there is an additional drag force normal to the plane of the rising bubbles and this greatly impacts the bubbles rising profile as there is now a horizontal component.

Manasseh et al. (1998) studied the effect of liquid crossflows on bubble trajectory for single bubbles as well as for bubble swarms. They noticed that bubbling rate increased with increasing continuous phase crossflow velocity and the formation of trajectory bifurcations (when viewed from above) at high crossflow velocities. However, their study did not consider the effect of crossflow velocity on the bubble rise velocities. Socolofsky and Adams (2002) investigated bubble swarms (referred to as plumes in their work) under liquid crossflow in a flow channel using air as the dispersed phase and oil and alcohol as the continuous phases. Using an organic dye in the continuous phase, a characterisation of the various bubble regions of the swarm were carried out and were categorised as “separation”, “mixed plume”, “buoyant jet” and “fractionation” regions. An empirical correlation was derived via dimensional analysis relating the freestream velocity with the critical separation height, defined as the height when horizontal motion strips entrained fluid away from the dispersed phase.

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Nomenclature

A. Roman

Ca	Capillary number [-]
d	diameter [m]
Fr	Froude number [-]
I	Image intensity [pixels]
p	Swarm width [-]
Q	Volumetric flow rate [L/min or m^3/s]
Re	Reynolds number [-]
u	Velocity specified by a subscript [m/s]
x	Horizontal spatial coordinate [m]
y	Vertical spatial coordinate [m]

B. Greek

α	Void fraction [-]
γ	Velocity profile shape parameter [-]
κ	Von Karman constant [-]
μ	Dynamic viscosity [kg/s-m]
ρ	Density [kg/m^3]
σ	Liquid surface tension [N/m]
θ	Swarm angle of inclination or trajectory (for linear and quasi linear swarms) [°]
τ	Cross-correlation time lag [s]

C. Subscripts

b	bubble
g	Gas phase
l	Liquid phase
noz	Nozzle
s	Slip, used for slip velocity
sg	Superficial gas
T	Terminal
τ	Shear as used with Re and u for the crossflow liquid
∞	freestream

They argued that this separation height causes a stratification of the bubbly flow under crossflow and is important in the study of deep-sea blowouts of oil and gas. Nevertheless, their study also did not examine the effect of the crossflow on the swarm rise velocities.

An experimental investigation was carried out by Zhang and Zhu (2013) on the effect of water crossflow on an air/water two-phase bubbly jet. A key feature of this study was that pure air injection (i.e. a bubbly plume or swarm) was not done but premixed air/water (a bubbly jet) using a Venturi ejector and then through nozzle to the freestream. Their air flow rates at the nozzle used in their experiments were 1, 3 and 5 L/min. Void fraction was measured using a computer-controlled optical fibre probe inclinable according to the angle of the jet. Dye premixed with the incoming water was used to visualise the different trajectories assumed by the bubbles from the liquid crossflow indicating a phase slip. The optical fibre probe was double tipped, as such, signals obtained from both sensors were cross-correlated to determine bubble velocity profiles at different heights. From this study, Zhang and Zhu (2013) established that with the air/water jet and crossflow, bubble size was more uniform than in the quiescent liquid condition and their interfacial area followed a Gaussian distribution. They also found that bubble property values decay along the gas-phase centreline trajectory until terminal values are attained. An empirical relationship for void fraction was proposed to describe such a trend. More importantly, they established that bubble induced water velocity inside the gas phase is substantial and was caused mainly by the passage of bubble clusters. But in the case of bubbly jets with large water superficial Reynolds numbers, induced water velocity is negligible, meaning the overriding controlling phase is the water crossflow. However, their study significantly differs from the current one since two-phase air/water rather than single phase gas injection was done. Their case is more common in environmental conditions where wet gas blowouts occur either in underwater pipe bursts or from natural gas reservoirs. Single phase gas injection into bulk liquids is however common in industrial processing where their contacting is used to promote heat, mass, and concentration transfer. Furthermore, while the use of an optical fibre probe in determining bubble velocity, void fraction, and bubble size, offers a very fast method of measurement, it is rather intrusive especially in high Reynolds number crossflow conditions. For many bubbles the probe does not penetrate diametrically, and as such, bubble size can be grossly underestimated. Another drawback in using optical fibre probes is their fragility for high Reynolds number flows, and the complication involved in their manufacture since bespoke sensors have to be manually fabricated for specific channel geometries.

Unlike low Reynolds number single bubbles, rigorous theoretical treatment of bubble swarm properties is difficult due to intense turbulence. However, attempts have been made in the past using numerical methods such as integral models (Milgram, 1983; Wüest et al., 1992; Socolofsky et al., 2008; Lima Neto, 2012). Computational fluid dynamics (CFD) has also been used, such as the simulations using the k-epsilon turbulence model (Sun and Faeth, 1986), large eddy simulations (Dhotre et al., 2009), and direct numerical simulations (Esmaeeli and Tryggvason, 1998; Esmaeeli and Tryggvason, 1999). Zhang and Zhu (2013) noted that the main shortcoming with numerical simulation is the lack of full understanding of bubble–bubble and bubble–liquid interaction mechanisms, as well as bubble breakup and coalescence and bubble deformation mechanisms.

Here, we investigate the effect of crossflow velocity on submerged bubble swarms with a high gas flow rate and crossflow velocity than has been previously reported. A high-speed image-processing method was used to measure ejected bubble swarm properties. Particle image velocimetry (PIV) was used to accurately measure the crossflow freestream velocity as well as boundary layer information. We varied the gas flow rate and the values investigated were 2, 5, 10, 15, 20, and 25 L/min. This range exceeds those of previous studies in the open literature on bubble swarms which were mostly within the range of 1–5 L/min. Air injection flow rates were between 0.03 and 0.9 L/min resulting in single bubbles ejected at steady frequencies. However, these conditions are far from those found in industrial applications. Due to the comparatively large gas flow rates involved in the current study, it is more suited to conditions found in field conditions. As a result, a custom digital image-processing algorithm was developed to measure bubble rise velocities, trajectories, and size distribution in contact with the crossflow. Mean bubble sizes and rise velocities were determined and are correlated using the dominant dimensionless numbers. Comparisons are made with previous data and models and improved correlations were obtained for the inclination angle (trajectory) as well as the rise velocity.

2. Experimental setup and image processing

2.1. Experimental facility

The present experiment was conducted in a low-speed recirculating water channel with the working section of 3000 mm × 600 mm × 700 mm (length × width × height) in Beihang University. The water channel is made of smooth reinforced glass for full optical access to the flow inside. The free-stream velocity U_∞ could be adjusted up to 500 mm/s by a digital motor controller and the free-stream turbulence intensity is less than 0.5%.