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# Bubble characteristics of air–water bubbly jets in crossflow

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ABSTRACT

This paper presents a detailed experimental study on bubble characteristics of bubbly jets in crossflow by injecting air–water mixtures vertically via a circular nozzle. Bubbles were observed to separate from the water jets after some distance from the nozzle. Bubble properties were measured at different sections along the gas-phase centerline trajectory. The results show that the radial distributions of void fraction, bubble frequency and bubble specific interfacial area generally follow the Gaussian distribution. The distribution of bubble velocity was found to be larger in the downstream side of a cross-section, but Gaussian in the transverse direction. The distribution of bubble diameter was found to be affected primarily by air and water injection rates and the distance from the nozzle. At a cross-section, the gas-phase exhibits an ellipse-shape for pure air injection, while a kidney-shape for a mixture of air–water injection. Bubble properties along the gas-phase centerlines were also investigated, and their values decay along the centerlines until reaching some terminal values. Finally, relation of bubble slip velocity with bubble diameter in crossflow was found close to that of single isolated bubbles in stagnant water, rather than that of bubbly jets in stagnant water.



## 1. Introduction

Air injection into ambient water has been commonly used to enhance mixing and aeration in lakes and rivers, wastewater treatment, heat exchanger and industrial reactors, bubble breakwaters and ice prevention in harbors, among others (Milgram, 1983; Sun and Faeth, 1986a; Fanneløp et al., 1991; Wüest et al., 1992; Socolofsky and Adams, 2002; Sahoo and Luketina, 2003, 2006; Rensen et al., 2005; Lima Neto et al., 2007; Seol et al., 2007; Norman and Revankar, 2011). Injected air forms bubble plumes. In the rising process, bubbles entrain ambient water into the bubble plume and enhance mixing of ambient water. Meanwhile, oxygen in air bubbles dissolves into ambient water through the air–water interface of bubbles to achieve aeration.

Compared to pure air injection, a mixture of air–water injection has been found to be more efficient for artificial aeration and have lower construction and maintenance costs (Fonade et al., 2001; Lima Neto et al., 2008b,d). The additional water injection helps to break large air bubbles into smaller and more uniform ones, and thus enhances aeration. To study the aeration ability of air–water injection, it is important to investigate the bubble characteristics. Early studies measured the radial distribution of one or two bubble parameters in air–water bubbly jet experiments with low values of initial gas volume fraction at the nozzle exit (Sun and Faeth, 1986a,b; Kumar et al., 1989; Stanley and Nikitopoulos, 1996). Iguchi et al. (1997) measured bubble diameter in air–water bubbly jets and reported that it was almost independent of the initial gas volume fraction up to 50%. Recently, Lima Neto et al. (2008b,d) conducted systematic experiments with nozzles of different sizes and initial gas volume fraction up to 83%. While they obtained detailed measurements of bubble behavior at a fixed section, the development of bubble characteristics along its trajectory is still unknown.

Existing studies on either air or air–water injection in large setups were conducted mostly in stagnant ambient water and very limitedly in crossflow. However, crossflow is typically present in many applications, for instance, Lima Neto et al. (2007) reported a crossflow of 0.3 m/s for an aeration project in the ice-covered Athabasca River, Canada. Socolofsky and Adams (2002) conducted bubble plume experiments in crossflow, but they focused on the trajectories of the gas-phase without measurement on bubble characteristics. Recently, Rezvani and Socolofsky (2012) measured the water velocity field inside and outside a bubble plume in crossflow, but they did not provide the information on bubble velocity.

Current knowledge of air–water bubbly jets in stagnant water is unable to fully predict bubble characteristics in crossflow. One distinct feature in crossflow is the separation of the gas-phase (bubbles) from the entrained or injected liquid-phase (water jet) as shown in Socolofsky and Adams (2002), but its effect on bubble

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plume property has not been reported. Another feature is that bubbly jets are bent over by crossflow. It is unknown whether or not the bent-over affects the gas-phase structure, say, producing two counter-rotating vortices as in single-phase jets in crossflow (Rajaratnam, 1976; Lee and Chu, 2003). Milgram (1983), Sun and Faeth (1986a,b) and Lima Neto et al. (2008b) found that bubble characteristics in stagnant water are approximately self-similar. The self-similarity might not be valid in crossflow (Rezvani and Socolofsky, 2012). Lima Neto et al. (2008b) found that bubble slip velocity was substantially larger in bubble plumes in stagnant water due to the wakes of preceding bubbles, compared to that of single-isolated bubble in stagnant water. Crossflow might flush bubble wakes downstream and is expected to have a less impact on the slip velocity of trailing bubbles. Even in stagnant water, experimental data on the changes of bubble parameters along the axial distance is limited (see Sun and Faeth, 1986a,b; Stanley and Nikitopoulos, 1996). Their prediction typically relies on integral models as reported in Lima Neto (2012); however integral models are based on self-similarities of the gas-phase, which are questionable in crossflow as stated earlier. In crossflow, it is unknown how bubble parameters changes along the gas-phase centerline trajectory and what is their terminal values if any. The present study intends to address the above knowledge gaps.

This study probably is the first one on bubble characteristics of air–water bubbly jets in crossflow. Distributions of bubble parameters, namely void fraction, bubble frequency, bubble velocity, bubble diameter and specific interfacial area, were measured using an optical probe at different sections along the gas-phase centerline trajectory, and the results were compared with those in stagnant water (Sun and Faeth, 1986a,b; Lima Neto et al., 2008a–d; Lima Neto, 2012). Mechanisms were explored for the distributions and their evolution along the gas-phase centerline trajectory. Relation of Bubble slip velocity with bubble diameter was also investigated in crossflow. This study improves the understanding of bubbly jets in crossflow, and thus guides their application in artificial aeration and mixing in crossflow. Moreover, the present experiments also serve as rare benchmarks for the development and validation of computational fluid dynamics models on multiphase flow (Milenkovic et al., 2005), as well as help to understand the fate of accidental blowout of sub-sea oil and gas wells (Milgram, 1983; Socolofsky and Adams, 2002).

The paper is organized as follows. Section 2 provides a brief literature review. Experimental setup and procedures are given in Section 3. Section 4 presents the detailed measurement results of bubble parameters (void fraction, bubble diameter, bubble velocity, etc.) and their changes along the centerline trajectory of the gas-phase. Section 5 discusses the conservation of air mass flux and bubble slip velocity. Main results are summarized in Section 6.

## 2. Literature review

A brief review is provided below on bubble characteristics of air–water bubbly jets in stagnant water. Of all bubble parameters, bubble size is considered to be the most important as it directly controls the mass transfer coefficient and specific interfacial area, as well as bubble velocity and thus residence time in ambient water. Generally, smaller bubbles are believed to better promote oxygen transfer process (Motarjemi and Jameson, 1978). To achieve smaller size, one efficient way is to inject water simultaneously with the injection of air as shown in Lima Neto et al. (2008b,d). Lima Neto et al. (2008b) proposed a criterion for the onset of large air-bubble breakup in stagnant water: a nozzle Reynolds number based on the superficial water velocity at the nozzle exit and nozzle diameter should be larger than 8000. Once this criterion is met, bubble diameter can be reduced to 2 mm or less without the use of porous airstone nozzle as summarized in Zhang (2012). In fact, for pure air injection, even with an airstone nozzle, bubble diameter can be over 4 mm at a discharge of 2 liters per minute (LPM) as reported in Lima Neto et al. (2008a). The optimum bubble size for artificial aeration and mixing has been studied by Motarjemi and Jameson (1978), Wüest et al. (1992), Sahoo and Luketina (2003, 2006) and Zhang (2012).

Bubble velocity affects residence time of bubbles in ambient water. Due to buoyancy, bubble rises faster than ambient water velocity. The difference is defined as bubble slip velocity, which was reported in the range of 0.2–0.8 m/s depending on bubble diameter (Clift et al., 1978; Milgram, 1983; Simonnet et al., 2007; Lima Neto et al., 2008b; Lima Neto, 2012). Lima Neto et al. (2008b) reported that: in stagnant ambient water, bubble slip velocity in bubbly jets was 2–6 times higher than the rise velocity of single isolated bubble of the same size. This phenomenon is caused by the drag reduction for the trailing bubbles in the wakes of the preceding bubbles (Krishna et al., 1999; Ruzicka, 2000; Lima Neto et al., 2008b). For bubbly jets in crossflow, the wakes of preceding bubbles might not be directly above the trailing bubbles and thus bubble slip velocity might be different.

The radial distributions of bubble parameters such as bubble velocity and specific interfacial area are important to understand bubble plume behavior and quantify oxygen transfer. For void fraction, bubble frequency and specific interfacial area, the measurement result of Lima Neto et al. (2008b,d) showed that they approximately followed the Gaussian distribution. For bubble velocity, Milgram (1983), Sun and Faeth (1986a,b) and Lima Neto et al. (2008b) measured approximately the Gaussian distributions, while Stanley and Nikitopoulos (1996) reported a distribution not substantially different from the Gaussian, and Seol et al. (2007) presented a distribution between the Gaussian and top-hat. For bubble size, Stanley and Nikitopoulos (1996) stated that bubble size distribution may not be Gaussian, and Lima Neto et al. (2008b) measured approximately Gaussian distribution for bubble plumes with bubble diameter >4 mm and top-hat for with bubble diameter of 2–4 mm. In crossflow, these self-similarities of bubble characteristics have not been reported, and will be studied experimentally in this paper.

For the evolution of bubble parameters along the gas-phase centerline trajectory, Sun and Faeth (1986a,b) and Stanley and Nikitopoulos (1996) reported in bubbly jets that bubble velocity continuously decayed in the measurement distance of up to 60 times of nozzle diameter due to the decay of water jet velocity. With the increase of axial distance, it is expected that bubble velocity will finally reach a terminal value balanced by buoyancy and drag forces. No simple relations have been proposed for bubble parameters along the axial distance as those for single-phase jets or plumes. This requires numerical models such as integral models (Milgram, 1983; Fanneløp et al., 1991; Wüest et al., 1992; Socolofsky et al., 2008; Norman and Revankar, 2011; Lima Neto, 2012). Computational fluid dynamics (CFD) models have also been used, e.g., $k$–$\varepsilon$ model by Sun and Faeth (1986a,b), direct numerical simulation by Esmaeeli and Tryggvason (1998, 1999) and large eddy simulation by Dhotre et al. (2009) and Fox (2012). The restriction with numerical simulation is that the mechanisms related with bubbles are generally not well understood, including bubble–bubble and bubble–liquid interactions, bubble breakup/coalescence, bubble deformation, oscillation and rotation, etc. Obviously, more measurements on bubble properties, in either stagnant water or crossflow, will advance the understanding on bubble plumes and thus the development of numerical models.

Non-intrusive and intrusive methods have been used to measure bubble characteristics. Non-intrusive method can only be used for the case of low void fractions (typically a few percents), including photography technique (Krishna et al., 1999), laser Doppler anemometer/velocimetry (Sun and Faeth, 1986a,b), phase