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Bubble formation process from a novel nozzle design in liquid cross-flow

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An experimental study is reported that investigated the bubble formation from a novel nozzle design in a liquid cross-flow using high speed imaging. Different configurations and orientations of the novel nozzle design were considered over a range of gas-to-liquid flow rate ratios (GLR) from 0.00031 to 0.00204. The results show that for all cases, the novel nozzle generated smaller bubbles at higher detachment frequency compared to the standard nozzle. At low liquid velocities, the novel nozzle generated bubbles that were 30% smaller in size at a detachment frequency 2–3 times higher than that for the standard nozzle. It was also found that the bubble diameter and the detachment frequency are almost independent of the liquid velocity. The underlying physical process of bubble formation and detachment in the novel nozzle under liquid cross-flow was also investigated. It was observed that the process comprised of three phases: expansion, collapse and pinch off. It was also found that the rebound force of the bubble from a side-hole under the influence of liquid drag force and hydrostatic pressure plays a key role in the early bubble detachment. The results demonstrated that the novel nozzle design performs better than the standard nozzle in the liquid cross-flow, especially at high GLRs.

1. Introduction

Gas injection into a liquid stream and the dispersion of gas-liquid mixture into spray have great importance in several industrial processes such as combustion (Lefebvre, 1988; Roesler and Lefebvre, 1988), food processing (Kim et al., 2001), metal casting (Bai and Thomas, 2001), bubble column reactors (Marshal, 1990; Deckwer, 1992) and wastewater treatment (Kim et al., 2001; Takemoto et al., 2000). In such applications, the gas-liquid interfacial area is a critical parameter which affects chemical/biological reactivity of two phases as well as heat and mass transport. The larger surface area of gas bubbles per unit volume implies larger gas-liquid interfacial contact, which is achieved through smaller bubbles in numerous quantities than fewer large size bubbles. That is, the generation of smaller size bubbles at higher detachment frequency.

The generation of smaller bubbles at higher detachment rate can be achieved by injecting the gas in liquid cross-flow (Forrester and Rielly, 1998; Loubiere et al., 2004; Tan et al., 2003; Ghosh and Ulbrecht, 1989; Oguz and Prosperetti, 1993; Maier, 1927; Stich and Barr, 1979). The liquid motion affects the bubble formation in two ways: (i) Flowing liquid induces drag force on the bubble attached to the gas injector. The shearing effect of the liquid drag force causes an early detachment of bubbles from the gas injector, which leads to the generation of smaller bubbles (Ghosh and Ulbrecht, 1989). (ii) Flowing liquid also forces bubbles to move away from the gas injector reducing the possibility of bubbles' coalescence, which increases and randomizes the bubble size hence affects the bubble size distribution (Oguz and Prosperetti, 1993).

The injection of gas into a liquid stream may result in three regimes of two-phase flow: (1) flow of individual bubbles (no coalescence and no mutual interactions), (2) bubbly flow where bubbles could interact and may result in coalescence, (3) jet flow (Sovani, 2001). In individual bubbly flow, the bubbles are smaller in size and/or far apart from each other. An increase in the gas flow rate results in the transition of individual bubbly flow regime into the interacting bubbly regime. The bubble size in this regime is relatively large compared to the individual bubbly regime and bubbles could easily deform. Furthermore, bubble collision and coalescence may also occur in this regime. This regime is also considered as a transition mode from the bubbly flow to the jet flow (Sovani, 2001). Eventually at very high gas flow rates, jet flow regime becomes dominant where a continuous jet of gas forms within the liquid stream. However, further downstream, this jet may break up

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into bubbles of different sizes (Forrester and Rielly, 1998; Silberman, 1957).

The bubble dynamics are characterized by many parameters such as, bubble size, detachment frequency, velocity, trajectory and formation mode. A number of computational and experimental studies have investigated the bubble formation in the liquid cross-flow. A large number of experimental studies utilized imaging techniques for bubble visualization (Bai and Thomas, 2001; Forrester and Rielly, 1998; Lorcher et al., 2003; Nahra and Kamotani, 2000; Siddiqui and Chishty, 2010; Nabavi et al., 2009; Ghaemi et al., 2010; Iguchi et al., 1998).

Siddiqui and Chishty (2010) experimentally studied the effect of channel orientation at various gas and liquid flow rates on the bubble detachment frequencies and trajectories. They conducted the experiments in a two-dimensional Plexiglas channel using high speed imaging and image processing to investigate the effect of gas to liquid flow rates ratio (GLR) on the bubble detachment frequency. They also investigated the impact of channel inclination angle on the bubble trajectories. They observed that an increase in the channel inclination angle results in steeper bubble trajectories. They also found a linear relationship between bubble detachment frequency and GLR at low inclination angles of the channel which becomes nonlinear at higher inclination angles.

Ghaemi et al. (2010) experimentally studied the influence of nozzle length on the bubble characteristics in a liquid cross-flow. They investigated the bubble size, shape, location and velocity at various gas and liquid flow rates for different injector lengths that varied from zero length (i.e. a wall orifice) up to the nozzle length equal to half of the channel dimension. They found that with an increase in the liquid flow rate, the bubble size decreased and detachment frequency increased. They also argued that at higher gas flow rates and lower liquid flow rates, the probability of coalescence occurrence increases. Marshal (1990) experimentally investigated that three bubble formation modes appear in the liquid cross-flow: "single bubbling", "pulse bubbling" and "jetting". They also found that the bubble formation mode is influenced by gas and liquid velocities and nozzle diameter. Tsuge and Hibino (1983) studied the bubble formation in the liquid cross-flow both experimentally and theoretically. They used high speed imaging and photo-transistor to detect the bubble detachment frequency. They investigated the influence of gas physical properties, orifice diameter and surrounding liquid velocity. They observed an increase in the bubble size with a reduction in the gas density. They concluded that at the constant operating conditions, the bubble size increases with an increase in the orifice diameter while higher liquid velocity produces smaller bubbles.

Nahra and Kamotani experimentally (Nahra and Kamotani, 2000) and theoretically (Nahra and Kamotani, 2003) investigated the effect of liquid cross-flow on the bubble formation. They conducted experiments under normal and reduced gravity and found that wall orifice diameter, gravity, liquid velocity and gas flow rates affect the bubble formation process. Bai and Tomas (2001) numerically and experimentally studied the bubble formation from a wall orifice into the liquid cross-flow in a vertical channel. Volume of fluid (VOF) method and high speed imaging were used for numerical simulation and experimental observation, respectively. They concluded that the gas compositions (air, helium and argon) and orifice diameter have relatively insignificant effects on the bubble size and that the bubble size reduces by increasing liquid velocity and/or decreasing gas flow rate. Forrester and Rielly (1998) conducted an experiment study on the bubble formation from various shapes of submerged blades in liquid cross-flow and found that liquid cross-flow, gas velocity and blade shape influence the bubble size and bubble formation regime. Iguchi et al. (1998) experimentally investigated the bubble detachment frequency for different nozzle diameters in a rotating water tank using high speed imaging. Five nozzles with different inner and outer diameters were used during the experiments. They concluded that when the ratio of outer to inner diameters of the nozzle was lower than 3.5, the outer diameter of the nozzle has a weak effect on the bubble detachment frequency.

As the above literature review shows, the bubble characteristics in liquid cross-flow have been extensively studied in the past. However, there is a scarcity of studies investigating the impact of the shape of the nozzle on the bubble formation in the liquid cross-flow. Recently, Gadallah and Siddiqui (2013) developed a novel nozzle design that significantly increases the bubble detachment frequency and generates smaller bubbles. They tested the nozzle in the stagnant liquid under various gas flow rates and observed that over a given range of gas flow rates, the novel nozzle increases the bubble detachment frequency by 58% and reduces the bubble diameter by 25%. The present study is focused on investigating the bubble formation process in a liquid cross-flow from this novel nozzle with some modifications, and studying bubble characteristics over a range of gas and liquid flow rates and comparing them with the standard nozzle.

2. Experimental setup

The experiments were conducted in a channel with square cross-section (5 cm × 5 cm), 100 cm long. Air and water were used as the gas and liquid mediums, respectively. The channel was made of acrylic. A honeycomb was placed near the upstream end of the channel to straighten the flow and remove flow disturbances. Tap water was used as the working fluid. The water was stored in a 60 gallon tank for 1–2 days prior to measurements and periodically stirred to allow air to escape. During experiments, water was circulated through the channel via a magnetic pump (Little Giant, 5 MD) from the storage tank at the room temperature (see Fig. 1). Water flow rates were adjusted using a rotameter (FP 1-35-G-10/83, F&P Co) which was installed downstream of the pump. The pressurized air was injected into the liquid stream in the channel via a nozzle to generate bubbles. To maintain steady supply of air, the compressed air from the main supply line was first passed through a 0.16 m^3 tank which served as a settling chamber, to remove pressure fluctuation. The air from the settling chamber then passed through a needle valve into a long capillary tube that was connected to the nozzle. The needle valve was used to control the air flow rate, which was measured by a rotameter located upstream of the needle valve (see Fig. 1). The uncertainties in liquid and gas flow rates based on the rotameters used were ±3 and ± 0.08 cm^3/s, respectively. The nozzle was located 70 cm downstream of the channel inlet. A prior set of experiments in the channel using Particle Image Velocimetry (PIV) technique confirmed that the channel flow was fully developed at the nozzle location.

As mentioned earlier, a novel nozzle design developed by Gadallah and Siddiqui (2013) was used in this study. The unique feature of this nozzle design was the presence of side holes near the main nozzle rim, which generates small bubbles with higher detachment frequency. Two side-holes nozzles are referred to as configuration A. Two orientations of the novel nozzle were considered in the study. In the first orientation (I), the side holes were located perpendicular to the liquid flow direction and in the second orientation (II), the nozzle was rotated by 90^o thus, the side holes were aligned with the liquid flow direction, hereinafter referred to as configuration A-I and A-II (see Fig. 2). A standard nozzle was also considered which served as a reference case.

Two sets of experiments were conduction; one was focused on the study of underlying bubble formation and detachment mechanism and the gas behavior inside and outside the nozzle during bubble formation. For this set of experiments, both standard and