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Experimental investigation on submerged gas-liquid mixture injection into water through a micro-channel

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ABSTRACT

Submerged gas-liquid mixture injection into water through a micro-channel shows unique fluid characteristics by various flow regimes in the micro-channel generating special jetting phenomena which have never been systematically studied. We injected air-water mixtures into water through submerged 1.0 and 1.5 mm diameter micro-channels. Bubbly, Taylor, bubble-train Taylor, churn and Taylor-annular flows were observed, and generated respective jetting flow regimes. Overall, two flow regimes namely “unstretched bubbles” and “stretched bubbles” were identified in the jet region. The former consists of three flow patterns, namely discrete bubbles, gathered bubbles and grown irregular bubbles. The latter occured when liquid slugs having strong enough momentum to stretch the bubble interface, from which single-bubble stretched, twin-bubbles stretched and even bubble rupture were further identified. We compared flow regime maps in micro-channels with those of submerged jets, and proposed the correspondence relationship, whose universality was confirmed by the consistency for different sized micro-channels. Transitions between two overall flow regimes of submerged jets, as well as flow patterns of unstretched bubbles were found determined by flow regime transitions in the micro-channel. Besides, transition laws between flow patterns of stretched bubbles were affected by the uniformity of slug length throughout the micro-channel, which were quantitatively analyzed.

Introduction

The process of submerged jets which commonly means a fluid being injected into a bulk fluid through a submerged nozzle is widely applied in many industrial activities. Apart from single-phase jets (such as water jet into water), the submerged jets can be classified as “submerged gas jets”, “submerged gas-solid mixture jets” and “submerged gas-liquid mixture jets” and so on according to the injected fluid type. Submerged gas jets are very prevalent in natural environment and widely applied in metallurgical processes, chemical and nuclear industries, as well as underwater propulsion. Submerged gas-solid jets formed by the injection of powder with inert carrier gas are commonly practiced in industry to decrease the impurity level of steels (Chang and Sohn, 2012). As to submerged gas-liquid jets, it is considered a potential technique to improve the efficacy of mass transfer in the process of decreasing the impurity contents of steel (Akhmetbekov et al., 2010). In addition, the injection of air-water mixtures into water is used to produce small bubbles to achieve artificial aeration and mixing in tanks, lakes, reservoirs, and rivers (Ghorai, et al., 2004). That mixture jet also happens in various flow systems, such as the immersion lithography machine which was fast developed in past ten years as its super high exposure resolution. Good control of the gas-liquid mixture jet behavior is needed to weaken vibration disturbance during exposure in immersion lithography (Lagrange et al., 2006).

Compared with single-phase jets, submerged gas injection into water is quite different due to the occurrence of bubble coalescence and breakup events, as well as the unsteady motion of the gas-liquid interface. Thus, it has attracted many researchers to carry out a large number of theoretical and experimental studies, mainly including the characteristics of bubbling, jetting flow regimes and their transition criterions. Bubble diameter and its generating frequency were experimentally measured and agreed well with the developed theoretical models (Gutiérrez-Montes et al., 2013). In jetting regime studies, the flow structure including pressure and void fraction distributions, entrainment rates, as well as the unsteady interface characteristics were experimentally studied and predicted by theoretical methods (Weiland and Vlachos, 2013). In the transition region, the jet pitches off and results in the co-occurrence of bubbles and residues. Pinch-off frequency, jet penetration distance, as well as the transition point were experimentally studied (Ruzicka, et al., 1997) and explained based on the instability theory (Chen and Richter, 1997).

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In contrast, the study on the injection of two phase mixtures (gas-solid mixture or gas-liquid mixture) into water is still inadequate. Much less open literatures have been published. For gas-solid jets which have been commonly practiced in steel making technology, the effect of the density and size of solid particles on the bubbling-to-jetting phenomena (Farias and Irons, 1985) and penetration behaviors (Chang and Sohn, 2012) has been studied. As to submerged gas-liquid jets, investigations on submerged liquid slag injection into liquid metal can be found in only a few papers and mainly focused on the mass transfer rate, which was found to increase with gas flowrate and liquid injection rate or lance depth obeying a linear relationship. As a result, an empirical correlation was developed to estimate the overall mass transfer rate (Ghorai et al., 2004). However, no further study on the flow structure or interactions between the gas and liquid slag has been performed. Another research area, injecting gas-liquid mixtures into water to produce small bubbles for sufficient gas-liquid interfacial area to achieve efficient mass transfer, has raised great interest. Among early studies, bubble diameters with low gas volume fractions have been experimentally measured; besides, a correlation for bubble break-up in a non-vertical submerged gas-liquid jet was proposed (Varley, 1995). Systematic experiments were then conducted to investigate liquid flow structure and bubble properties (Neto et al., 2008a; Neto et al., 2008b; Neto et al., 2008c). More recently, characteristics of bubbles generated by injecting air-water mixtures vertically in cross flow were also experimentally studied (Zhang and Zhu, 2013; Zhang and Zhu, 2014). It is worth noting that the mixing tubes and nozzles chosen by the researchers were all macro-systems, which were in centimeter scale. Besides, for the purpose of achieving efficient mass transfer, the mixing tubes usually generated bubbly flow. As a result, the bubble characteristics investigated were merely concerned with group behaviors of the bubble plume consisting of a large number of bubbles.

In our laboratory, submerged gas-liquid mixture jets happened in immersion lithography machine is being studied. In the machine, ultrapure water is filled into the space between the final optical lens and the wafer to extend the resolution of optical lithography. Because the water acts as an optical lens, it is required to maintain high uniform optical quality. So, in order to avoid immersion liquid contamination, the chemical products and impurities induced by the exposure process must be taken away in time through liquid renovation, which is achieved by liquid injection and liquid collection (Gnanappa et al., 2011). During the liquid collection, not only the recycled immersion liquid but also the air around it is inhaled into the micro collection holes. Thus, air-water two-phase flows are formed in the micro holes and inject into collection chambers with recycled water accumulated. The occurrence of submerged gas-liquid two-phase jets in the collection chambers is the basic reason causing vibrations in the immersion system, which could seriously damage the exposure quality, including changing the linewidth, reducing the image contrast, and lowering the process window and the CD uniformity (Lagrange et al., 2006). Thus, we try to deeply understand the complex flow behaviors of the submerged gas-liquid mixture injection through micro-channel to reduce the unacceptable vibration effect. However, few literatures have been published on this topic. Compared with existing studies on group behaviors of the bubble plume formed by bubbly flow in centimeter-scale mixing tubes, submerged gas-liquid mixture injection through a micro-channel is distinct. Under different scanning velocities and working stages of lithography, water supply flowrate and air sealing pressure both change. Moreover, motivated by the interest to increase production throughputs, wafers are scanned at increasingly high velocities and accelerations. As a result, the ratio of water and air velocity in the micro collection hole varies. Therefore, the key point lies in that flow regimes in the micro-channel are in more varied forms. Especially, bubbles or gas slugs usually travel along the micro-channel one by one, causing interaction between bubbles and liquid slugs when jetting, and resulting in special injection phenomenon which has never been systematically studied.

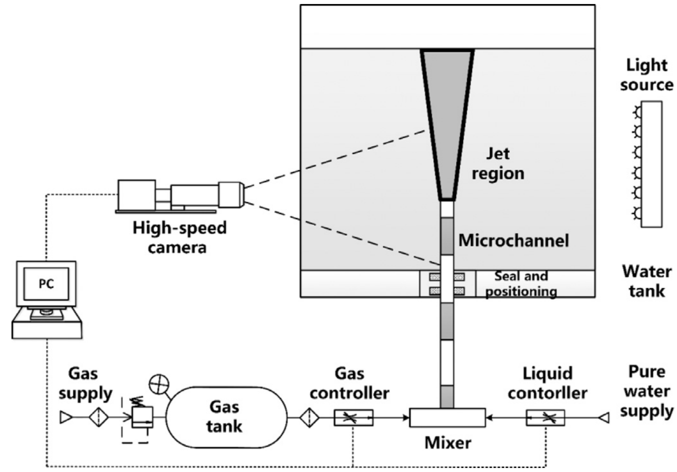

Fig 1. Schematic of experimental apparatus.

Therefore, an experimental apparatus was developed in this study to investigate the submerged gas-liquid mixture injection through micro-channel systematically. Besides, we performed experiments in a sufficiently wide range of gas and liquid velocities, ensuring to cover all operating conditions during immersion lithography. In the experiments, flow regimes in the micro-channel and the jet region around its nozzle generated by different proportion air-water mixtures were recorded simultaneously with a high speed camera, and then identified to different types according to the bubble and ejecting liquid interaction characteristics. In addition, the experimental data on the occurrence of observed flow regimes under different superfacial velocities of gas and liquid were summed up as maps. Through the analysis of above experiment results, the flow regimes of the submerged jet and their transitions were found directly determined by the flow regime behaviors in the micro-channel. Thus, the correspondence relationship between them is summarized. The occurrence uncertainty of the flow regimes were also analyzed and found dominated by the uniformity of slug length throughout the micro-channel.

Experimental apparatus

An experimental apparatus was designed to investigate the submerged gas-liquid mixture injection through a micro-channel into water. As schematically shown in Fig. 1, air supplied from an oil-free air compressor and pure water from a water treatment system mixed inside a T-type mixer. The air-water mixed flow fully developed in a vertical micro-channel and finally injected into the bulk water in a tank. Images of the flow behaviors in the micro-channel and the jet region around the channel nozzle were recorded simultaneously by a high speed camera (Phantom 320S) with a rate of 3200 frames/s and an exposure time of 15.6 microseconds. To ensure the repeatability of the experiment results, the experiments were implemented in a super clean room, whose inner temperature was kept at $22 \pm 0.5\,^{\circ}$C.

We used vertical circular micro-channels with 1.0 mm and 1.5 mm inner diameters which were close to the actual diameter of the collection hole in immersion lithography machine. The inner diameter of the horizontal tubes for air and water input flow were 3 mm and 2 mm, for 1.0 mm and 1.5 mm inner diameter micro-channels respectively, ensuring the same mixing zone volume. The outlet of the micro-channel was perfect 90 degrees. In addition,