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Characteristics of slug flow with inertial effects in a rectangular microchannel

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HIGHLIGHTS

- Detail characteristics of slug flow with inertial effects are investigated.
- The transition of bubble formation regime mainly depends on the liquid velocity.
- The inertia of the forming bubble would lead to a faster rupture process.
- The inertial effects greatly thicken the liquid film thickness.
- A leakage flow is proposed to explain the bubble velocities and slug length.

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ABSTRACT

Slug flow behavior and characteristics have been studied in a rectangular microchannel with Y-junction. Two simple bubble shape models are proposed to calculate the film thickness, gas hold-up and the specific surface area. The results show a significant effect of inertia on the bubble generation process. The liquid film thickness was greatly thickened by the inertial effect. The main forces on the rupture of the gas bubbles present a shifting from pressure (squeezing regime) to shearing stress and dynamical pressure of the liquid (shearing regime). The transition was found to mainly depend on the liquid velocity. A strong leakage flow of the liquid film around the gas bubbles was suggested as the liquid slug lengths decreased instead when liquid velocity increased. This leakage flow is also the reason of the over-prediction of the bubble velocity based on the stagnant film hypothesis.

1. Introduction

Gas–liquid two-phase flow pattern is an important research area for the multiphase systems in the microreaction technology. Among the flow patterns (Triplett et al., 1999; Zhao et al., 2013), slug flow is easily obtainable for a large range of operating conditions, and characterized by sequences of a gas bubble and a liquid slug. The figuration of slug flow contains regular sized gas bubbles that are longer than the channel diameter or width. The gas bubbles are surrounded by a thin liquid film with the bubble area occupying almost the entire channel cross-section (Fries et al., 2008; Thulasidas et al., 1995). Low axial mass transfer or back mixing occurs between two adjacent liquid slugs. Moreover, both radial mass and heat transfer can be intensified by internal circulation in the single slugs (Günther et al., 2004; Thulasidas et al., 1997). These merits make slug flow an ideal regime for improving the reaction performance. Wide attention has been paid to the bubble formation process (Fu et al., 2009; Garstecki et al., 2006; Pohorecki and Kula, 2008; van Steijn et al., 2007), the gas bubble and the liquid slug length (Garstecki et al., 2006; Leclerc et al., 2010; Qian and Lawal, 2006; Sobieszuk et al., 2010), the liquid film thickness around bubbles (Fries et al., 2008; Han and Shikazono, 2009a; Thulasidas et al., 1995), the phase distribution (Choi et al., 2011; Kawahara et al., 2005; Saisorn and Wongwises, 2010), the pressure drop (Kreutzer et al., 2005a, 2005b; Yue et al., 2009), and the mass transfer (Sobieszuk et al., 2011; van Baten and Krishna, 2004; Vandu et al., 2005), etc. However, a full understanding of slug slow for optimizing the design of microreactor remains pendent.

The characteristics of gas bubbles and liquid slugs have a direct impact on the gas–liquid transport and multiphase reaction

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(Sobieszuk et al., 2011; Vandu et al., 2005). Their lengths are mainly affected by the gas bubble generation process at the junction, which can be attributed to the competition among the surface tension, the pressure, the shear stress, and the inertia. At low capillary numbers (*Ca*) and neglecting inertia, Garstecki et al. (2006) proposed the squeezing regime, in which the breakup of the gas bubbles is chiefly driven by the buildup of pressure upstream of an emerging bubble. In this case, the gas bubble length is independent of the fluid properties, and only depends on the two-phase flow rate ratio and the inlet geometry (Garstecki et al., 2006; van Steijn et al., 2010). At high *Ca*, the shearing regime occurs, which is characterized by the gas bubble partly occupying the cross section of the channel (Guo and Chen, 2009; Yue et al., 2008). Under this regime, the shear stress and inertia play an important role in the pinch-off. Thus, the fluid properties would have an influence on the bubble lengths (Abadie et al., 2012; Guo and Chen, 2009; Qian and Lawal, 2006). The gas bubble lengths, as well as the gas hold-up, are also affected by the aspect ratio of channels as indicated by Choi et al. (2010).

The liquid film around gas bubbles is also of great importance for mass and heat transfer. The thickness of liquid film has mainly been studied in circular capillaries that it was considered as a function of the capillary number (*Ca*) (Aussillous and Quéré, 2000; Bretherton, 1961; Han and Shikazono, 2009b; Kreutzer et al., 2005b). More recently, attention has been paid to microchannels with other cross sections (Fries et al., 2008; Han and Shikazono, 2009a; Kolb and Cerro, 1991; Kuzmin et al., 2011; Thulasidas et al., 1995). The liquid film distribution in square capillaries is not cylindrically symmetric due to the corners, which differs from that of their circular counterparts. The gas bubble shape in the cross section is also non-axisymmetric as the corners is affected by larger viscous forces than the regions near the center of the walls (Kolb and Cerro, 1991). However, the gas bubble shape presents a shifting from non-axisymmetric to axisymmetric above a transitional value of *Ca* ($O(10^{-2})$) (Fries et al., 2008; Han and Shikazono, 2009a; Kolb and Cerro, 1991; Kuzmin et al., 2011; Thulasidas et al., 1995), as shown in Fig. 1(b) and (c). Kreutzer et al. (2005a) developed an empirical correlation for estimating the liquid film thickness in the corners of square channels. Their results show that even at extremely low *Ca*, the liquid film does not vanish in the corners. Research on rectangular channels was motivated by the interest in monolithic reactors and by the easy fabrication of rectangular cross sections with MEMS techniques, such as photolithography and etching techniques. Moreover, the slug flow in rectangular channels presents different behaviors (Choi et al., 2011; Hazel and Heil, 2002; Kuzmin et al., 2011). Hazel and Heil (2002) investigated the steady propagation of a semi-infinite bubble into rectangular channels. Their numerical results indicated that at a given *Ca*, an increase in the aspect ratio caused a decrease in the liquid film thickness in the planes of the shorter semi-axis. The gas bubble shape turned into ellipsoid as the liquid film thickness increases (Fig. 1(e)). Kuzmin et al. (2011) found similar results from the simulation of the slug flow in rectangular channels using lattice Boltzmann method.

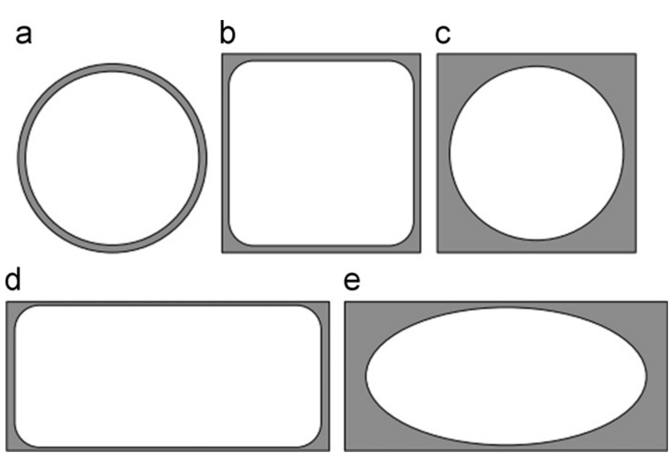

Fig. 1. Scheme of the liquid film distribution around gas bubbles in microchannel with different cross sections. (a) Circular channel, (b) square channel under transitional *Ca*, (c) square channel above transitional *Ca*, (d) and (e) rectangular channel.

In most of the literatures considering the liquid film thickness, *Ca* was varied by increasing the liquid viscosity, so the Reynolds number (*Re*) was always small (Kolb and Cerro, 1991; Thulasidas et al., 1995). Many results have shown that the inertia has a considerable influence on the liquid film thickness and the gas bubble shape (Aussillous and Quéré, 2000; Han and Shikazono, 2009a; Heil, 2001; Kreutzer et al., 2005b). For a given *Ca*, a decrease in the liquid film thickness up to *Re* of about 100, followed by an increase for higher *Re* was numerically discovered by Kreutzer et al. (2005b) and Heil (2001). Aussillous and Quéré (2000) reported the thickening effect of inertia with low viscosity fluid and proposed an inertia-dependent scaling law for qualitatively explaining this effect as $\delta/D_H \sim Ca^{2/3}/(1+Ca^{2/3}-We)$. Han and Shikazono (2009a) investigated the effect of inertia in square capillaries using different working fluids and developed a similar correlation, which showed good agreement with experimental data. In the present study, the thickening effect of inertia in the rectangular channel with an aspect ratio of 2.68 has been shown to be more obvious.

The present work aims at improving the fundamental understanding of slug flow in rectangular microchannel with inertia effect. Information about the gas bubble generation process, the length of the gas bubble and the liquid slug, the liquid film thickness, the gas bubble velocities, and the gas hold-up, will be investigated through visualization methods in a rectangular microchannel with Y-junction.

2. Experimental section

2.1. Microchannel specification

A rectangular microchannel contactor with Y shaped junction was used in this work. All the channels, with a cross section of 750 μm (width) and 280 μm (depth), were fabricated on polymethal methacrylate substrate (PMMA, A grade, 92% of light transmittance, ShenZhen HuiLi Acrylic Products Co., Ltd) using micromachining technology (FANUC KPC-30a) in our CNC Machining Center. The schematic representation and actual picture of the microchannel reactor construction are displayed in Fig. 2. The two PMMA plates were sandwiched between two stainless steel plates and sealed by screws. The angle between gas and liquid inlets is 60° and the length of the mixing channel is 60 mm.

2.2. Experimental setup

The experiments were mainly conducted with deionized water–carbon dioxide and a small number of experiments were by deionized water–nitrogen. The schematic diagram of the experimental setup was shown in Fig. 3. Gas flow was provided via the pressure regulator and controlled by mass flow controller (D07-7B, Beijing Sevenstar Electronics Co., Ltd., China) with an accuracy of 0.5% full scale. Deionized water was pumped by a high precision digital piston pump (Series II, Chrom. Tech. Inc.). The actual flow rate under each run was determined by weighing method. In order to eliminate the pulsation of the liquid flow rate, a buffer tank was introduced before the microreactor inlet. After