Chemical Engineering Science 128 (2015) 11–20

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Experiments and modeling on bubble uniformity of Taylor flow in T-junction microchannel

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HIGHLIGHTS

- Uniformities of bubbles were researched experimentally and theoretically in T-junction microchannel.
- A model of pressure variations was established.
- Interval of stable operation was determined by Capillary number and the model.

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form
16 January 2015
Accepted 30 January 2015
Available online 7 February 2015

Keywords:
Bubble uniformity
Taylor flow
Capillary number
Pressure model

ABSTRACT

Bubble uniformity of Taylor flow in a T-junction microchannel characterized by the bubble length variation coefficient (CV_b) was studied via both experiments and theoretical derivations. On the one hand, the correlation between bubble uniformity and the Capillary number (Ca) ranging from 0.00027 to 0.0071 was established at operating conditions with different flow rates of gas and liquid and various liquid phases. A sudden increase of CV_b was observed when the value of Ca was below a certain threshold indicating compromised bubble uniformity. Pressure sensors and a high-speed camera were used to analyze the causes of such a phenomenon by monitoring the bubble breakup process at outlet. As Ca was smaller than 0.0008, bubble breakup generated a large pressure variation which seriously affected the gas flow rate and bubble uniformity. On the other hand, a pressure model was derived to quantize pressure variations and to estimate CV_b, which were validated by experimental data and showed promising performances. Moreover, the model for calculating CV_b can also be used to optimize operating condition and ensure the bubbles uniformity.

1. Introduction

In the field of fluid dynamics, the study on Taylor flow is gaining popularity, especially in designing microchannels and microreactors (Al-Rawashdeh et al., 2013; Gao et al., 2011; Kashid et al., 2011; Lang et al., 2012; Su et al., 2010). In Taylor flow, the generation of bubble is highly monodispersed with an equal space between slug (Fries et al., 2008; Ganapathy et al., 2013). Besides, due to the recirculating flows in liquid slug and a thin liquid film between the wall and bubble, both the mass transfer and heat transfer between the slug, the wall and the bubble are enhanced in Taylor flow (Kashid et al., 2007, 2011). In order to fully utilize the strengths of Taylor flow, bubbles with uniform and controllable sizes should be generated in microchannels or microreactors. Therefore, many efforts have been made to study the dynamics of bubble formation process and to control bubble size (Garstecki et al., 2006; Gupta et al., 2010; Van Steijn et al., 2010; Xu et al., 2008). However, these studies on Taylor flow were mainly based on steady state flows with a uniform bubble size. At some operation conditions, significant fluctuations and disturbances might cause non-uniform bubbles in Taylor flow (Abadie et al., 2012; Ide et al., 2009; Qian and Lawal, 2006; Santos and Kawaji, 2010; Yamamoto and Ogata, 2013). Those non-uniform bubbles with uneven sizes and surface areas will jeopardize a precise control of heat transfer, mass transfer and reaction in microchannels and microreactors (Houshmand and Peles, 2014; Sobieszuk et al., 2011), and will lead to a lower conversion rate (Al-Rawashdeh et al., 2013) and an inaccurate measurement of reaction kinetics (Li et al., 2012). Moreover, this undesirable phenomenon will also cause disordered splits (Hoang et al., 2014), coalescence (Wu et al., 2014) and array storage (Xu et al., 2013) for microfluidic. Therefore, bubble uniformity is critical to taking advantage of Taylor flow in

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http://dx.doi.org/10.1016/j.ces.2015.01.064
0009-2509/

microreactors and microfluidics, and the acceptable deviation of bubble size normally is smaller than 5–10% in practice (Fries et al., 2008; Yue et al., 2008a, 2008b; Al-Rawashdeh et al., 2013).

What affects the bubble uniformity has been studied, including the usage of a syringe pump (Garstecki et al., 2006; Korczyk et al., 2011), the bubble formation process (Glawdel and Ren, 2012), the bubble leaving process (Van Steijn et al., 2008), the toroidal vortices (Qian and Lawal, 2006) and the dynamic feedback (Glawdel and Ren, 2012). The non-uniformity of bubble size induced by syringe pump can be attributed to the processing precision of the thread on the lead screw of the pump, which results in a variable driving speed and an oscillating rate of inflow (Korczyk et al., 2011). Variable bubble sizes during bubble formation and leaving processes are caused by pressure pulses generated by the variation of the interface between the two phases in the flow (Glawdel and Ren, 2012; Van Steijn et al., 2008). The toroidal vortices also generate non-uniform bubbles through an uneven squeezing process when two streams with high velocity meet at the mixing junction (Qian and Lawal, 2006). The dynamic feedback effects arise from the periodic changes in the hydrodynamic resistance of the microchannel as bubbles enter and exit the system (Glawdel and Ren, 2012). In order to avoid non-uniform bubble sizes, a few measures have been taken: A high resistance feed line has been used to dampen the flow rate fluctuations caused by the syringe pump (Korczyk et al., 2011); surfactants such the SDS (Rajesh and Buwa, 2012) or the Tween-80 (Xu et al., 2014) have been added in liquid to reduce surface tension to mitigate bubble formation pressure changes. Recently, a method has been proposed which attempted to erase the effects of flow rate variations on bubble sizes by improving the channel structure (Dangla et al., 2013; Van Steijn et al., 2013).

T-junction configuration is one of the commonest geometries for generating Taylor flow in microfluidic devices (Dai et al., 2009; De Menech et al., 2008; Garstecki et al., 2006; Van Steijn et al., 2007). The bubble formation process in a T-junction microchannel at low Capillary numbers (e.g. $Ca < 0.01$) follows a squeezing mechanism which is mainly controlled by the force balances between interfacial stresses and a dynamic pressure of continuous phase. Based on squeezing mechanism, the bubble size is determined by the gas and liquid flow rates (Garstecki et al., 2006; Van Steijn et al., 2007). The effects of fluid properties, such as viscosity and surface tension (Yao et al., 2013; Qian and Lawal, 2006) have also been studied. Although the mechanisms of the bubble formation process at a T-junction microchannel are well understood, the knowledge of the causes and their impacts on non-uniformity of bubble size is still insufficient. Furthermore, since the irregular bubble formation processes produce non-uniform bubble sizes, it is worth studying those parameters affecting the uniformity during such a process.

In this paper, first, bubble uniformity characterized by bubble length variance coefficient (CV_b) was investigated in a T-junction microchannel under a series of conditions with different gas and liquid flow rates and various liquid phases. Second, a sudden change of bubble uniformity was observed and the causes of which were analyzed. Third, for different low behaviors, a pressure model was developed to quantize pressure variations and to estimate CV_b, which provide valuable guidance on a uniform bubble generation.

2. Experimental procedures

The T-junction microchannel used in this work was fabricated with the polymethyl methacrylate (PMMA) substrate using precision milling. The geometries of microchannel are portrayed in Fig. 1 with a rectangular cross section of 300 μm (height) × 500 μm (width) × 40 mm (length). The surface roughness of channel after machining is ±2.5 μm. Two channels are connected by a side entering T-junction. The main channel carries a liquid fluid while the side channel supplies a gas flow.

A diagram of experimental setup is shown in Fig. 2. Both flow rates of liquid and gas were controlled by precision syringe pumps (LanGe, LSP01-2A, China) with an accuracy of 0.5% full scale (10 mL/min). Due to the compressibility of the gas, we calibrated the gas syringe pump connected with microchannel by a soap-film flowmeter, the deviation of set and measured values was about 2%. A 100 mL medical plastic syringe (FengLin, China) with an inner diameter of 32.08 mm was used in this study with a 10 mL/min maximum flow rate. The liquid flow rate (Q_l) was changed from 0.05 to 5 mL/min, and the gas flow rate (Q_g) varied from 0.2 to 2 mL/min. Four different liquids listed in Table 1 were chosen as the continuous phase and the air was set as the dispersed phase. The operating conditions characterized by the Capillary number ranged from 0.00027 to 0.0071 and the Reynolds number ranged from 0.67 to 123.5. A polytetrafluoroethene (PTFE) tube with high flow resistance ($\Phi 0.5 \times 3000$ mm) was used to connect the gas phase syringe and gas inlet channel to dampen the flow fluctuation of pump (Korczyk et al., 2011). Liquid phase syringe was connected by a PTFE tube ($\Phi 3 \times 300$ mm) to liquid inlet channel. The outlet channel was connected to a PTFE tube ($\Phi 3 \times 300$ mm) and was stuck into a wild-month bottle to collect liquid. All the experiments were conducted at room temperature and at atmospheric pressure.

The bubble lengths were recorded by a CCD high-speed camera system (AOS X-PRI) whose maximum recording speed was 1000 frames per second with a resolution of 800 × 600 pixel. A cold fiber light placed at the opposite side of channel was used to illuminate the channel. In our experiments, due to the storage limitation of camera, the frame rates were chosen from 200 to 1000 frames per second depending on different flow rates in order to acquire more bubble images. The pressure of gas inlet (P_g) in microchannel was monitored by a pressure sensor (Yizhong, PY301, China) with an accuracy of 0.5% full scale (10 kPa). The pressure sensor was installed very close to gas inlet as shown in Fig. 2 to reduce buffer size. Pressure signal was collected by a data acquisition card (Art-Control, PCI8532, China) with a maximum sampling frequency of 20 MHz. The minimum response time of pressure sensor was 0.5 ms; thus, the sampling frequency was set as 0.05 MHz to collect all pressure signals. We monitored the inlet pressures of gas during the start-up and plotted Fig. 3, where Q_g was changed from 0.2 to 2 mL/min, the minimum flow rate of gas spent the longest start-up time of about 480 s. Therefore, we selected the data at least 15 min after syringe pumps began to run. One hundred bubble images at least were recorded at each flow rate in order to obtain more accurate data. The bubble length (l) including the bubble body and two menisci at the front and back of a bubble was measured by a program built in MATLAB. All the experiments were repeated triplicate and the results were in average.

3. Results and discussion

3.1. Effects of liquid flow rate on bubble uniformity

In this study, bubble uniformity was quantified by CV_b, which is defined as the ratio of standard deviation $\delta(l)$ to average length of bubbles $\bar{l}$ in Eq. (1), and was calculated by Eq. (2)

$$CV_b = \frac{\delta(l)}{\bar{l}} \quad (1)$$