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Zonal description and quantitative methodology of air–water distribution in comb-like microchannels

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HIGHLIGHTS

- Flow patterns and distributions were investigated in easily-fabricated microchannels.
- Feasible physical models were proposed for predicting bubble flow parameters.
- Operating limits were determined for achieving desired flow patterns.

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ABSTRACT

The goal of this study was to determine feasible numbering-up laws to model the gas–liquid distribution in multiple microchannels. Comb-like microchannels were constructed by closely arranging eight capillaries of 0.5-mm inner diameter. The air–water flow in the parallel microchannels was recorded by a high speed CCD camera. After collecting and analyzing a very large number of images, the flow patterns were classified into two zones, zone I and zone II, which were the bubble flow and phase splitting zones, respectively. A model was established to describe the mean sizes and velocities of bubbles and liquid slugs in the two zones at different inlet flow rates of air and water, as well as to distinguish the two-zone operating limits by determining inlet flow rate intervals of the fluids. The calculated results agreed well with the experimental data. Therefore, the model showed a potential application to numbering up comb-like microchannels.

1. Introduction

Over the past two decades, researchers in chemistry, physics, biology, medicine and electronics have been very interested in the rapid emergence of literature about microtechnology experiments, fluidic principles, physical models and numerical simulations of gas and/or liquid in microchannels (Amador et al., 2008; Song et al., 2011; Chen et al., 2013; Camburn et al., 2014). Because of its greater mass and heat transfer, larger specific surface area, the substitution of numbering-up for scale-up, and a high level of operational flexibility and safety, microtechnology is a promising, cutting-edge technology.

Most microreactor researchers are inclined to adopt active mixing principles rather than passive mixing principles (Hessel et al., 2005). Single and multiple stages can be used to number up microreactors for multiphase flow, depending on whether the distributors are integrated (Lexiang Zhang et al., 2015). Therefore, meticulously designed multi-stage structures, such as the pulmonary airway tree type (Song et al., 2011), the quadrant shape (Amador et al., 2008), leaf-like channels (Camburn et al., 2014) and the circular disk shape (Chen et al., 2013), give good uniformity of multiphase fluids, but they often have the drawbacks of inferior quality of machining and economic efficiency.

To experimentally and numerically understand the multiphase distribution mechanism, single stage structures are almost always investigated because they are easily fabricated. Most researchers have investigated multiphase fluid dynamics in variant distributors via bifurcated channels. Baroud et al. (2005) found that velocity differences remained constant in branch channels at a low flow rate but that the differences increased rapidly when the velocity exceeded a threshold value. Chen et al. (2013) explored the influence of branch angles on gas–liquid flow splitting in microchannel junctions. Lianget al. (2014) investigated the flow patterns of a novel distributor with two nozzles and concluded that phase splitting was effected by both the inlet flow pattern and the resistance relationship of the downstream side arms. Quite a few studies about the characteristics of gas–liquid flow in more than two microchannels have been published. Chen et al. (2012)

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investigated the flow behavior and gas–liquid distribution in five parallel micro-T channels with a horizontal orientation and a trapezoidal cross-section and concluded that the different inlet flow patterns had a variant phase distribution and that an even phase distribution could possibly be achieved at the inlet slug flow. Yue et al. (2009) experimentally and mathematically studied CO_2-water distribution and mass transfer in a microchannel contactor containing 16 parallel microchannels with a hydraulic diameter of 667 μm, and observed and analyzed a significant two-phase maldistribution. Their experimental characterization is useful for understanding the non-uniformity of bubble size in a gas–liquid flow; however, in practice, localized and biased phase distribution due to non-uniform flow results in the local failure of efficient heat and mass transfer (Yue et al., 2009) and consequently, the results of the reaction are impossible to predict (Falk and Commenge, 2010). Until now, a general methodology for describing multiphase flow in microchannels has not been established because of the geometric diversity and hydrodynamic complexity of microchannels. Actually, the numbering up of microchannels in commercial demonstrations should not be limited to a small number of channels; complicated initial distributors, such as tree branch, are obviously unsuitable for extension to very large-scale channel bundles.

Currently, comb-like microchannels are the simplest distributor and have the advantage of a low cost of fabrication. Undoubtedly, this structure will also lead to maldistribution of multiphase distribution *per se*, and the challenge is to model the fluid distribution in each microchannel and employ it for scale-up. The purpose of this study is to use a quantitative methodology to predict the gas–liquid distribution in microchannels as a variant strategy to number up analogical comb-like capillary microchannels.

2. Experiments

Fig. 1 shows the comb-like microchannels that were constructed by inlaying eight capillaries in parallel on two PMMA plates. The constructed microchannels were divided into four sections: the first section included gas and liquid inlets that were perpendicularly plugged into the plate surface, the second section was a T-junction for the initial mixing of the gas and liquid, the third section was fluid distributor in the distribution zone that was connected perpendicularly to eight parallel capillaries and coaxially to the main channel, and the fourth section was the comb-like sub-microchannels. The diameter of the gas and liquid inlets was 2 mm, and both the height and width of the three rectangular channels connected to the T-junction was 1 mm. The contacted gas and liquid passed through a 1 cm long main channel forming a fully developed slug flow. The capillaries, purchased from the Instrument Factory of the West China Medical Center of Sichuan University, had an inner diameter of 0.5 mm and were 5 cm long (±5%) and transparent, which facilitated the visualization of the fluids inside. The upper and lower plexiglass plates were initially manually bonded by epoxy resin adhesive and then fastened with multiple screws to guarantee airtightness. A gas tightness test and a hydrostatic test were conducted prior to the experiments in order to verify the sealability of the microchannels.

A schematic diagram of the setup is shown in Fig. 2. The feeding system employed syringe pumps (Longer Precision Pump Co., Ltd., Baoding, China, LSP02-1B) because of their high accuracy and negligible variation compared to plunger pumps or impeller pumps. The data collector was integrated with a microscope and a high speed CCD camera (AOS TECHNOLOGY AG, Switzerland, X-PRI F2). The microscope had a 20× lens and provided a visual field with a diameter of 10 mm, and the CCD camera recorded the dynamic images with a maximum shutter speed of 1/1000 s and a resolution of 640(H)×480(V) pixels. The embedded data acquisition system stored sequential images or movies via built-in software.

Deionized water and clean air were selected as the liquid and gas phases, respectively. Table 1 lists the physical properties of the water and air at 0.1 MPa and 25 °C. The operating conditions covered a range of inlet flow rates from 1 mL/min to 20 mL/min (*Ca* from 0.000555 to 0.01109) for both air and water. All experiments were conducted at ambient temperature and pressure, and the outlets of the eight microchannels were directly exposed to the atmosphere. Before each experiment, water was injected into the microchannels to rinse them and eliminate possible disturbances. To ensure stabilized initial conditions, experimental data recording began several minutes after the air and water syringe pumps were turned on.

Similarly to other studies (Lee et al., 2004; Mohammadi and Sharp, 2013), Image-Pro Plus 6.0 software (Media Cybernetics, Inc., Rockville, MD, USA) was employed to automatically distinguish the bubble margins from the sequential images of air and water flow. Bubble size was measured by counting the semi-spherical front and rear parts of a bubble. The accuracy of the experimental data was assured by processing hundreds of bubbles, and the error was confirmed to be less than 10% after mass conservation verification of the measured mean velocity and length parameters.

3. Results and discussion

3.1. Bubble lengths in the main channel

Because the inlet flow pattern prominently affects the two-phase distribution, the inlet flow rates of air and water were identical to

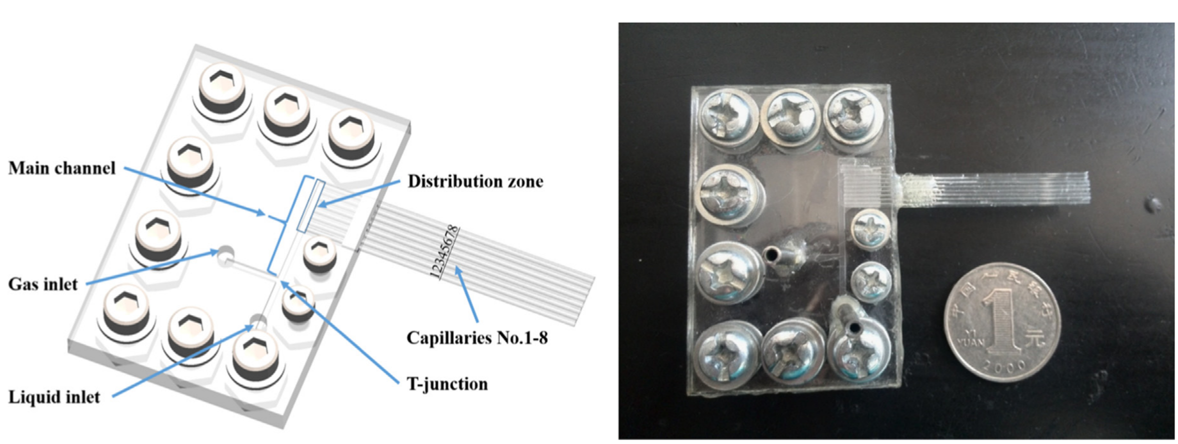

Fig. 1. Design drawing of the comb-like microchannels (left); photo of the actual device (right).