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Uniformity of gas and liquid two phases flowing through two microchannels in parallel

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HIGHLIGHTS

- Uniformity of slug flow in parallel microchannels is quantitatively measured and described.
- Interaction between dual microchannels is investigated.
- Retraction of gas head is captured and its impact on uniformity is reduced with phase velocity increasing.
- A scaling law for bubble lengths in both channels is proposed.

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ABSTRACT

Uniformity of slug flow in multiple microchannels, defined as homogeneity of emerging bubbles, was quantitatively measured and described in two parallel microchannels, each one of 500 μm width, 500 μm depth and 50 mm length interconnected with two dichotomic distributors for gas and liquid phases, respectively. The inlet superficial velocities of gas and liquid were ranges from 0.017 to 0.937 m/s. The results showed that increasing gas or liquid velocity would narrow the distributions of length and frequency of bubbles in each microchannel but worsen the uniformity between microchannels. Interaction between dual channels was investigated by analyzing pressure differences at distributors. Retraction of gas head was captured by a CCD camera and its impact was reduced with increase of phase velocity, leading to an operation interval of nearly uniform distribution in each microchannel. Subsequently, bubble lengths in both channels were correlated to the ratio of volumetric flow rates of two phases and the Weber number of liquid phase. All of the findings will facilitate numbering-up the microchannels for gas–liquid flow.

1. Introduction

Microreaction technology has been widely studied in the past two decades due to its great potentials in high heat and mass transfer efficiency, excellent controllability, low risk and compactness [1,2]. The typical applications of gas–liquid two-phase flow in microchannels have following processes, microparticle syntheses [3], liquid phase oxidation [4], hydrogenation [5] and direct fluorination [6].

In order to enlarge the benefits emerging from small scale, the fundamental strategy for approaching commercial throughputs is numbering-up or scaling-out, i.e., the multiple, parallel repetitions of microchannels. There are two ways to number-up microchannels of double-phase flow: single-stage branching and multi-stage branching. Geologically, the single- and multi-stages are distinguished by any phase flowing through parallel microchannels without or with distribution. Typical structures of single-stage branching are depicted in Fig. 1a and b, whose advantage, obviously, is omitting the unit of distribution; however, the uniformity of biphasic mixture passing parallel channels is a serious challenge. A sophisticated distributor facilitates the uniformity, while the large size limits commercial practice. Trading off between the simplicity and availability, most of the researchers chose the multi-stage branching. Furthermore, according to the order of mixing and bifurcating, the multi-stage branching can be subdivided into internal numbering-up and external numbering-up as shown in Fig. 1c and d. In the internal numbering-up structure, fluids of two phases are split into bubble trains and liquid slugs by a series of successive junctions before going through the microchannels. Finally, the segmented flows can be obtained with a relative uniform bubble volume and bubble spacing in all channels on the conditions that breakup happens at all junctions and asymmetries in flow are minimized [7,8]. Recently, Hoang et al. [9] found

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all bubbles to be broken at junctions if capillary number was larger than a critical value. Tesař [10] concluded the self-similar and isokinetic relationships over multi-stage microchannels always generating much even distribution due to the more pronounced equilibration of the driving pressure. Yue et al. [11] investigated gas–liquid flow in an external numbering-up structure of 16 parallel microchannels, and found that a nearly uniform gas–liquid distribution and desired mass transfer performance were achieved when the ideal flow pattern was slug-annular flow. Saber et al. [12,13] analyzed the impact of the channel arrangement on the global performance of the multi-channel network, and proposed guidelines for rapidly selecting multi-channel networks for homogeneous flow. Obviously, there are two basic structures for multi-stage branching as shown in Fig. 1e and f. Chen et al. [14] studied gas–liquid flow in a comb-like parallelization system (Fig. 1e) and summarized the distribution characteristics highly depended on inlet flow patterns; Al-Rawashdeh et al. [15] introduced barrier-based channels with large constrictions in the upstream (Fig. 1f), which resulted in uniformity larger than 90%.

Besides numbering-up fashion, constructible structures have been used for microreactor scaling out. A general approach was realized by stacking cross or helical elements [16,17]. Tondeur et al. [18] used a constructal distributor composed of multistage channels and optimized by a compromise between minimal viscous dissipation and void volume.

Some concepts of achieving uniform distribution for two-phase flow have been conceived. A common approach was to use a big manifold to uniform the inlet pressure across all channels, while such a manifold can deviate the pattern from slug flow [19]. Ahn et al. [20] presented droplet synchronization of two parallel droplets trains using a railroad-like channel network, which balanced automatically by the cross flow of carrier oil through the ladder network due to the pressure difference between two channels.

Numbering-up effect of parallel microchannels is defined as different outcomes from multiplying that of one microchannel by channel's number. The effect makes the technological and economic indexes irreproducible or non proportional. Various influences on the effect include phase contact area, mass transfer coefficient and reaction rate. Of course, uniform distribution of two-phase can decrease the numbering-up effect. Although significant experimental efforts have been devoted to the optimal design of parallelization systems, practical demo of numbering up is rare yet [21–23] because of lack of a solid understanding of the numbering-up effect. It is a challenge to find a robust way to realize two-phase equidistribution over microchannels. Maldistribution, especially for gas–liquid flow, can result in a deformation of flow

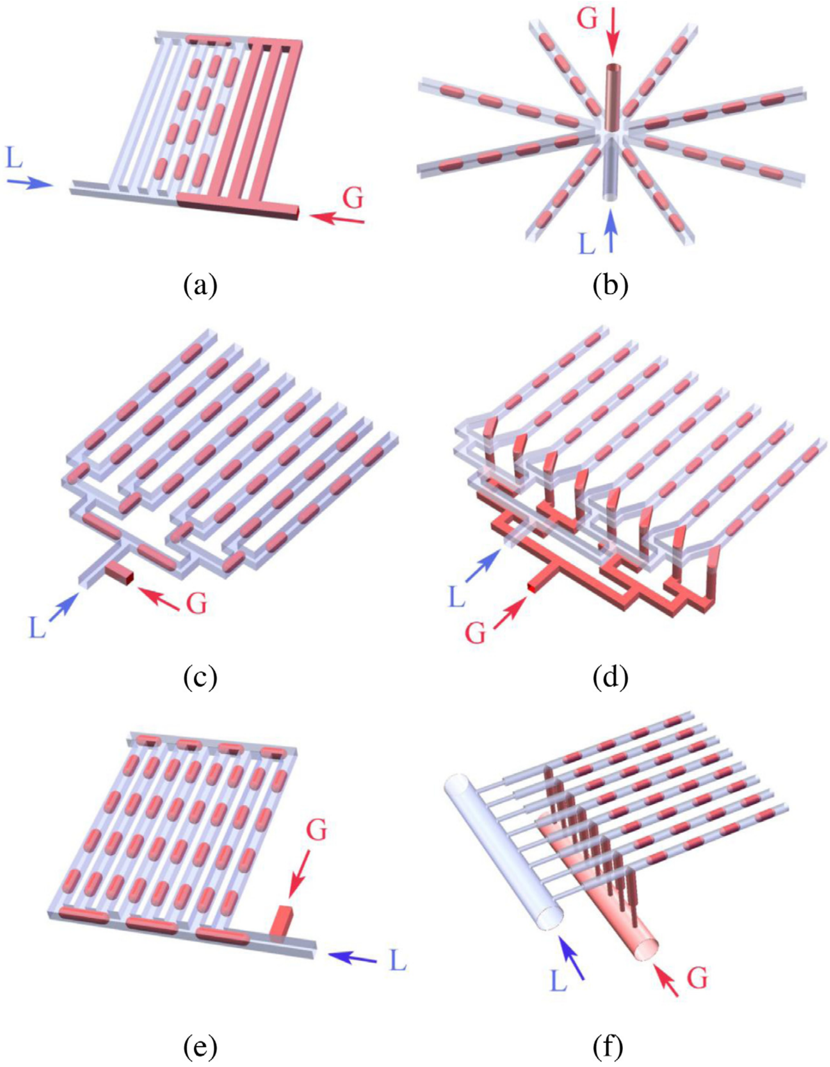

Fig. 1. Numbering-up concept of microchannels for two-phase flow: single-stage branching: (a) comb-like without premixing and (b) radial; multi-stage branching: (c) internal type, (d) external type, (e) comb-like with premixing and (f) barrier-based.