Experimental characterization of gas-liquid flows in splitting distributor for parallel microchannels

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Highlights

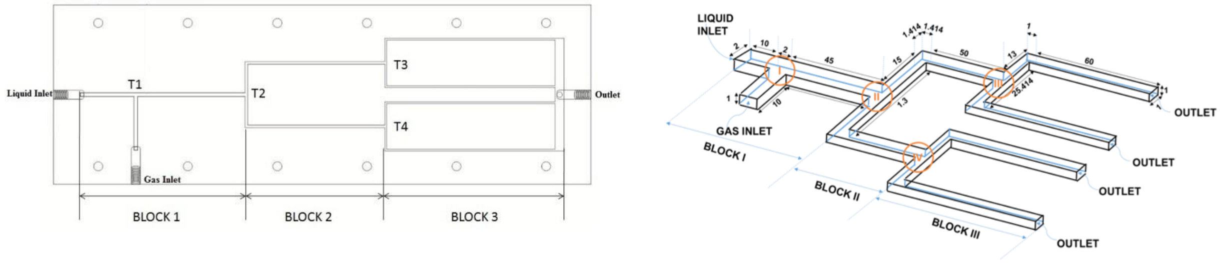
- Splitting distributor was designed to ensure the flow uniformity in parallel channels.
- Effect of $Q_{kerosene}$ on bubble/slug splitting mechanism, relative lengths of bubbles/slugs in parallel channels were studied.
- Uniform relative lengths of bubble/slugs were observed in all blocks for Ca ranges 0.0041-0.0071.

1. Introduction

Microreactors technology have evolved rapidly over the past two decades with extensive application in chemical synthesis [1]. A diversity of experimental studies of gas-liquid flows in microchannels have also been performed to understand the flow physics (formation dynamics of bubble/slugs and flow regimes). However, most of the reported study are restricted to single microchannel [2]. In spite of key advantages of improved control over reaction and high surface area to volume ratio (5000-50000 m^2/m^3), increasing the throughput pretence a serious challenge for microreactors. The scale up of microreactor processes is highly desired to make micro-reaction technology applicable to industrial production which is done by numbering up single micro channels [3]. Recently, a new numbering up approach of designing a splitting distributor has evolved [4,5] in which a single microchannel is fabricated on a plate through etching and branched into multiple microchannels to form a tree like structure. Although, it is an effective scaling route to increase throughput but the application of parallel microchannels pose a challenge of maintaining a uniform fluid flow distribution in the microchannels. Current work reports experimental investigations of gas-liquid flow in parallel microchannel contactor that has been designed using splitting distributor. The main objectives of the present work are to study the effect of continuous phase flow rate ($Q_{Kerosene}$ = 3-16 ml/min) on the flow regimes, formation dynamics, splitting mechanisms of air bubbles/slugs and relative slug/bubble lengths while keeping a constant flow rate of dispersed phase (Q_{air}= 3 ml/min). The primary aim of this work is to achieve flow uniformity in all parallel channels through splitting distributors in terms of relative lengths of bubbles/slugs ($L_{slug/bubble}/W_{channel}$) in all blocks (see Figure 1) at different Ca (=0.0022 – 0.0071).

2. Methodology

The test microchannel reactor was fabricated on a transparent polymethyl methacrylate (PMMA) sheet using laser machining as shown in Figure. 1, wherein, the reduction in width of the successive blocks is by a factor of 2^{β} (where β=0.5) for ensuring constant $L_{slug/bubble}/W_{channel}$ ratio in all the blocks. The depth of channels in all the blocks was 1 mm. At the 1st T-junction, air was injected perpendicular to the T-junction whereas, liquid (kerosene) was pumped through the main inlet. The gas flow rates were measured and controlled by using mass flow controllers (Bronkhorst, Germany). Liquid was pumped using a continuous push-pull type syringe pump (Coleparmer, USA) ranging from 3-16 ml/min. A high speed digital camera was used to visualize and record the flow behavior and distribution within the microchannels. The images were recorded at a speed of 1000 frames/second. A fiber optic quad white Sugar CUBE LED light source was used to illuminate the system. The formation and splitting frequency as well as the relative slug lengths were measured for ten successive bubbles/slugs and the mean values were used for further analysis. The analysis of formation dynamics of air bubbles and slugs is highly dependent on the relative magnitudes of surface tension and viscous forces. Hence, the analysis is done with the help of dimensionless number such as Capillary Number (Ca= $\mu U/\sigma_{oil}$).



(a) (b)

Figure 1. Schematic representation of the microchannel used in present work. (a) Two –Dimensional view (b) Three Dimensional view (all values are in mm)

3. Results and discussion

In the present work, experiments were performed at different liquid flow rates ($Q_{kerosene}$) ranging from 3 to 16 ml/min at fixed Q_{air} (= 3 ml/min). The corresponding Ca ranges from 0.0022 - 0.0071. Two main types of formation mechanisms at 1st T-Junction were observed i.e. Squeezing and Transition of slug/bubbles. However, Figure. 2 shows the splitting mechanism of bubble/slug at 2nd, 3rd and 4th T-Junctions respectively at different $Q_{kerosene}$.

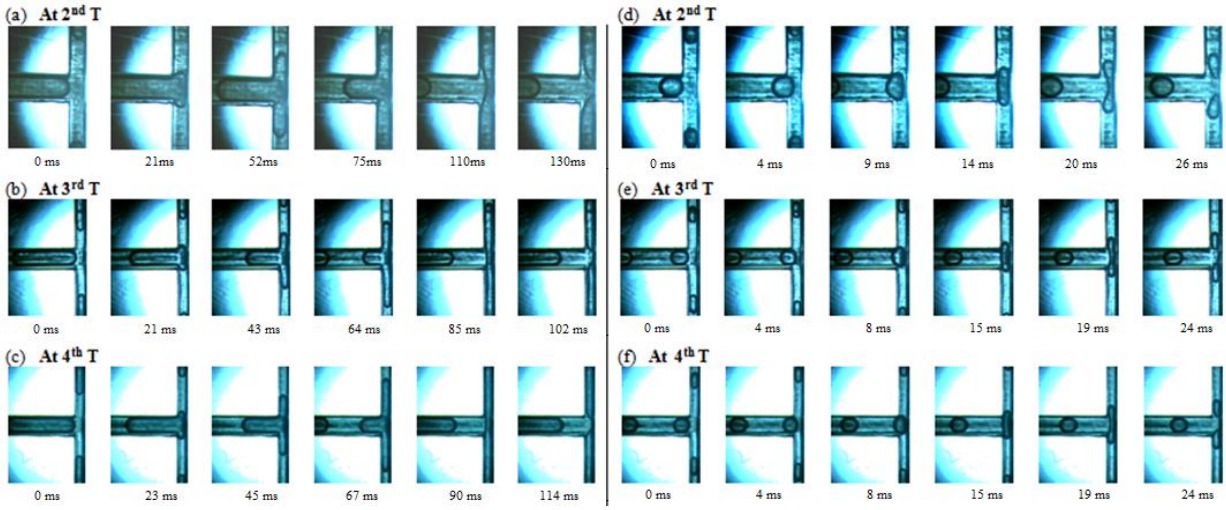


Figure 2. Bubble/slug splitting mechanism at successive T-junctions (a-c) Q_g= 3ml/min, Q_l=3ml/min. (d-f) Q_g= 3ml/min, Q_l=12ml/min.

The splitting mechanism at 2nd, 3rd and 4th T-junctions of the bubbles were found to be significantly affected by the flow rates of the continuous phase. The flow splitting was observed to be uniform at higher flow rates at all the successive junctions whereas it was observed that the splitting was considerably uneven at lower flow rates as shown in Figure. 2. The possible causes of this uneven flow splitting could be differences in hydrodynamic resistances of the channels due to fabrication inaccuracies, difference in velocities of bubbles while entering the arms of the branched channels or unequal coordination of bubbles due to backpressure generated during splitting of bubbles. The splitting mechanisms were quantified by plotting graphs of splitting time versus Ca (= 0.0022 - 0.0071) at the corresponding T-junctions, as shown in Figure 3. It was observed that at higher flow rates (Ca > 0.0041), the time of splitting of bubbles was much lower as compared to the high splitting time obtained at lower flow rates at all the T-Junctions. It should be noted that almost uniform splitting time was obtained at successive T-Junctions for higher flow rate of $Q_{Kerosene}$ =12ml/min (see Figure 2(d,e,f)) as compared to lower flow rate of $Q_{Kerosene}$ =3ml/min (see Figure 2(a, b, c)). The similar trend were also observed at 3rd and 4th T-junctions.

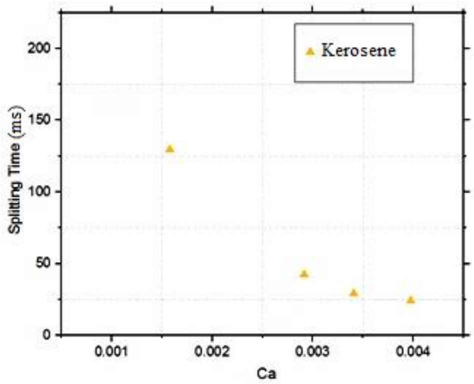


Figure 3. Effect of Ca on bubble/slug splitting time at 2nd T-junction

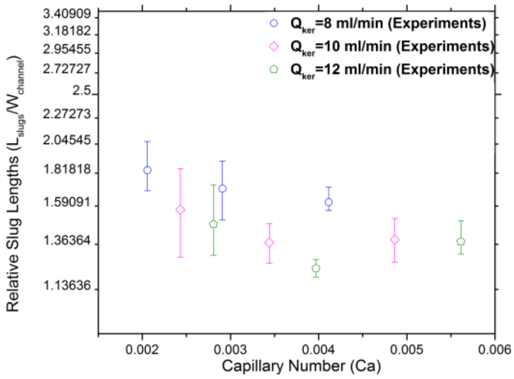


Figure 4. Effect of Ca on relative bubble/slugs length

Figure 2. Bubble splitting mechanism at T-junctions (a-c) Ca = 0.0022 (Q_g= 3ml/min, Q_l=3ml/min). (d-f) Ca = 0.0056 (Q_g= 3ml/min, Q_l=12ml/min).

The effect of $Q_{Kerosene =}$ (=8-12 ml/min) on relative lengths of air bubbles/slugs (with appropriate error bars) in different blocks at fixed Q_{air}= (3 ml/min) is shown in Figure 4. It should be noted that, Ca decreased at the successive T-junctions by $Ca_{(i+1)} = 0.5\ (W_i/W_{i+1})\ Ca_i$. It was observed that, due to increase in shear force as increase of $Q_{kerosene}$, the relative lengths of bubbles/slugs at the T-junctions were decreased. However, the relative lengths of bubbles/slugs in the successive blocks for each $Q_{kerosene}$ (8 – 12 ml/min) were almost the same as shown in Figure 4. This shows the flow uniformity in four parallel channels at different liquid flow rates. The detailed analysis of relative bubble/slug lengths, splitting dynamics and flow regimes and uniformity in parallel channels will be reported in the full length manuscript.

References

[1] Elvira KS, Casadevalli I Solvas X, Wooton RCR., Nature, vol. 5, (2013) 905-915.
[2] R.Gupta, D. F. Fletcher, and B. S. Haynes, Chem. Eng. Sci. 64 (2009) 2941– 2950.
[3] Kashid MN, Gupta A, Renken A, Kiwi-Minsker L, Chem. Eng. J. 158 (2010) 233-240.
[4] Al-Rawashdeh, M., Yu, F., Nijhuis, T., Rebrov, E., Hessel, V., Schouten, J., Chem. Eng. J. 207, (2012) 645-655.
Yue, J., Luo, L., Gonthier, Y., Chen, G., Yuan, Q., Chem. Eng. Sci. 63, 2008, 4189-4202.

Keywords
Gas-liquid flows, splitting distributor, parallel microchannels, flow uniformity