Chemical Engineering Journal 293 (2016) 182–188

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

A capillary-assembled micro-device for monodispersed small bubble and droplet generation

Y.K. Li, K. Wang, J.H. Xu, G.S. Luo *

The State Key Laboratory of Chemical Engineering, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- A capillary-assembled micro-device making small bubbles and droplets is presented.
- Monodispersed 35 μm bubbles and 15 μm droplets are generated with jetting regime.
- General bubble and droplet size scaling law by dynamic interfacial tensions is got.

ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form 10 February 2016
Accepted 19 February 2016
Available online 27 February 2016

Keywords:
Capillary microfluidics
Flow focusing
Micro-bubbles
Micro-droplets
Dynamic interfacial tension

ABSTRACT

Fabrication of micro-devices for small bubble and droplet generation is usually tedious or costly. Here we present a simple capillary-assembled micro-device by modifying the capillary embedded step *T*-junction microchannel. Besides a capillary in the side channel, another same size capillary is placed at the downstream of *T*-junction. The two vertically embedded capillaries inherently guarantee the device symmetry by forming an arch orifice. And it could be applied to both L/L and G/L micro-dispersion with focused continuous phase flows. Monodispersed small bubbles of 35 μm (CV = 3.52%) and droplets of 15 μm (CV = 2.12%) are generated with stable flow-focusing jetting regime, by thin jets deriving from the large interface and arch orifice in the device. A general bubble and droplet size scaling law is obtained, and it could predict the bubble and droplet size very well. The device could provide a more convenient approach for adjusting bubble and droplet sizes than usual methods. The device shows its significant advantages of easy assembly, low cost and high versatility for both small bubble and droplet generation.

1. Introduction

Monodispersed small bubbles and droplets are important spaces and mediums for ultrasound imaging [1], targeted drug delivery [2], single-cell sequencing [3], chemical reactions and material preparations [4–8]. Compared with conventional bubble and droplet generation methods, microfluidic chip shows its significant advantages for producing monodispersed (CV < 5%) bubbles and droplets in recent years [9–13]. Researchers have realized monodispersed bubble and droplet generation within micro-devices with different means for wide applications [14–19]. However, generating monodispersed small bubbles and droplets (<50 μm) remains technically challenging, for small bubbles and droplets often come with small channels, which always demands for tedious fabrication and costly materials.

Capillary microfluidics could produce bubbles and droplets with low cost, excellent chemical robustness and simple modification, especially when compared with soft lithography in PDMS and glass etching [17]. A summary of capillary microfluidic bubble and droplet generators is listed in Table 1. It should be noted that most capillary devices with commercially available standard capillaries can produce large bubbles and droplets (>100 μm) easily. But for small bubble and droplet (<50 μm) generation, specially fabricated capillaries with small sizes are often required. Additional "art-dependent" techniques like capillary stretching are always used. For some cases, high-level clean room and solutions are demanded to avoid clogging in small size capillaries. These limitations confine the applications of capillary microfluidics and thus simple capillary micro-devices are needed for small bubble and droplet generation.

In our previous work, we developed capillary embedded and extended step *T*-junction microchannels [30]. Jets with diameters which is much thinner than orifice widths were formed by large interfaces when two phase flows clashed at the orifices. As the absolute instability of jets would be strengthened by unsymmetrical flow-field, small droplets could be generated in large size microchannels in jetting regime with much wider operating ranges and ultra-high frequencies. However, large orifice areas in the step

* Corresponding author.
E-mail address: gsluo@tsinghua.edu.cn (G.S. Luo).

http://dx.doi.org/10.1016/j.cej.2016.02.074
1385-8947/

Table 1
Capillary microfluidic bubble and droplet generators.

Flow pattern	Structure	Typical size	Bubble/droplet size	Additional technique	References
Jetting	Coaxial capillary flow focusing	50–80	75/–	No	[20]
Jetting	Coaxial capillary flow focusing	2	3.5/–	Yes	[21]
Dripping	Coaxial capillary flow focusing	50–350	50/–	Yes	[22]
Jetting	Coaxial capillary with tapered tip	3.2	–/7.5	Yes	[23]
Dripping	Two adjustable flamed-tip capillaries	100–200	–/20	Yes	[24]
Dripping	Micro-cross with capillaries	150	–/37.7	No	[25]
Dripping	Capillary extended *T*-junction	5	–/2	No	[26]
Dripping	Capillary embedded *T*-junction	50	120/75	No	[27,28]
Dripping	Capillary extended *T*-junction	180	120/100	No	[29]
Jetting	Modified capillary embedded and extended *T*-junction	108	35/15	No	This work

*Sizes on the basis of micrometer (μm).

channels lead to ultra-high volume flow rate ratios for small droplet formation, significantly increasing the consumption of continuous phase. Furthermore, when implementing the step microchannel with G/L dispersion process, we experienced unstable bubble break-up under all conditions with jetting flow. To solve the problem and expand the applications of the devices, a modified structure must be designed.

In this study, we demonstrate a modified micro-device by just placing another capillary at the downstream of *T*-junction besides a capillary in the side channel, for both monodispersed small bubble (~35 μm) and droplet (~15 μm) generation. Device symmetry is guaranteed inherently by the two same capillaries. Arch orifices by two vertically embedded cylinder capillaries make both continuous and dispersed phase flows focusing much easier and more stable than planar flow-focusing devices. Thus both G/L and L/L dispersions with jetting flow would be easily realized. The arch orifices with smaller areas also decrease the continuous phase consumptions. Further, large interface areas in the micro-devices may help the movement and concentration of surfactant molecules. The dynamic interfacial phenomena induce a general scaling law for bubble and droplet sizes and enable the device with more convenient adjustment approach for bubble and droplet sizes than usual methods.

2. Experimental section

Fig. 1 shows the modified step *T*-junction microchannel. One capillary is embedded in the downstream of flow direction and closely contacts the other capillary in the side channel. Two vertically embedded capillaries guarantee the channel symmetry, form a 3D arch orifice geometry and increase the stability of jetting flow, especially with gas flow. Different from conventional flow-focusing micro-devices, jets in this unsymmetrical device are formed from large interfaces squeezed by two phase flows' vertical crash at the orifice. And thus much thinner jets could be obtained in large microchannels. It should be noted that the arch geometry focuses continuous phase flow from a direction of π radians and it would fasten jet thread collapses [25,31]. And detachment points of dispersed phases would be fixed at the edge of the capillary by focusing continuous phase flows. As the 3D orifice structure is too complex to analyze, we simplify the orifice as a 2D arch geometry (Fig. 1C). Thus the area of the 2D orifice could be obtained by:

$$S_{\text{orifice}} = \theta\, R^2 - (R-D)\sqrt{R^2 - (R-D)^2} \tag{1}$$

where $\theta = \arccos\left(\frac{R-D}{R}\right)$. Thus the average shear velocity of CP would be got:

$$u_c = \frac{Q_c}{S_{\text{orifice}}} \tag{2}$$

Actually, considering the flow rate distribution dominated by flow resistance distribution at the orifice, most of the CP fluid flows across the orifice besides the channel central line (red dot line box in Fig. 1C) [30]. It would be difficult to calculate how much of CP fluid flows into the channel middle region, but we could approximate the shear velocity is in inverse proportion to D^2 in further physical analysis, namely:

$$u_c \propto \frac{Q_c}{D^2} \tag{5}$$

We could get capillary number and Reynolds number of CP with u_c as:

$$\text{Ca}_c = \frac{\mu_c u_c}{\gamma} \tag{3}$$

$$\text{Re}_c = \frac{\rho_c D u_c}{\mu_c} \tag{4}$$

and for Re, we choose orifice width D as the featured diameter. In this work, Ca_c ranges from 0.05 to 0.3.

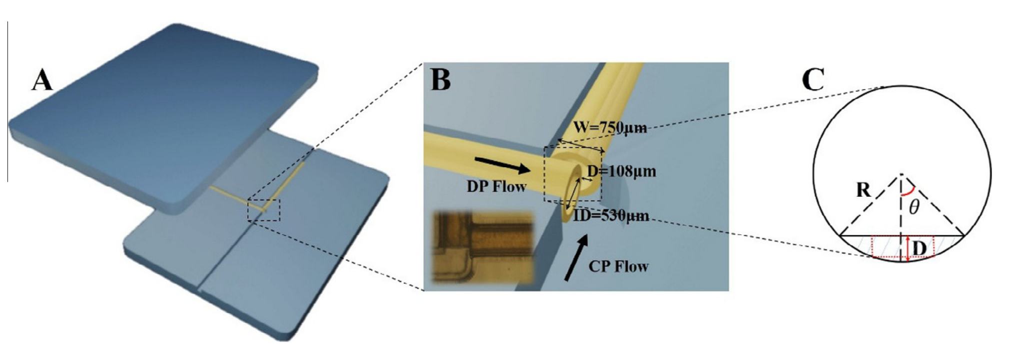

Fig. 1. Sketch diagrams of the modified step *T*-junction microchannel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)