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Shear-induced tail breakup of droplets (bubbles) flowing in a straight microfluidic channel

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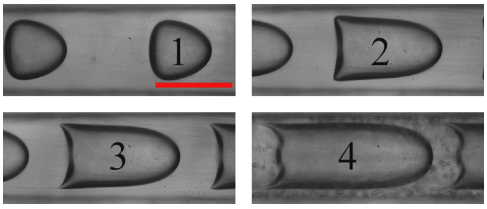
HIGHLIGHTS

- The interface instability of droplet (bubble) in a microchannel was investigated.
- The formation mechanism and influencing factors of the tip stream were studied.
- The critical droplet size was proposed to predict the appearance of the tip stream.

GRAPHICAL ABSTRACT

Four kinds of shape were observed by changing the flow rates ratio from $\varphi = 0.27$–1.15 with constant $Ca = 0.55$: (1) droplet with blunt butt, (2) droplet with concave butt, (3) droplet with a tail stream which ejects transiently small daughter droplets, (4)droplet with two tail streams which eject stably small daughter droplets.



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ABSTRACT

Dispersed droplets and bubbles were generated in a microfluidic flow-focusing device to investigate the morphological developments of the droplets (bubbles) flowing in the downstream straight microchannel by a high speed camera. The present study is mainly aimed at the influences of both the dispersed droplet (bubble) size and two-phase average flow velocity on the formation of tip stream in the rear of a droplet (bubble). It was found that the particle deformation increased with the droplet (bubble) length or the capillary number. There exists a critical droplet (bubble) length dependent on capillary number, beyond which the tip stream ejecting tiny daughter droplets will take place. The generated tiny droplets are usually three orders of magnitude smaller than primary droplet. This study provides the possibility to avoid a high polydispersity index in microchannels.

1. Introduction

Emulsion by the dispersion of a liquid into another immiscible one is usually a basic and necessary operation in many industrial applications such as skin care products like shampoo, foods like mayonnaise, drug and chemical analyzing (Carrier et al., 2015; Whitesides, 2006). Generally, the high shear processes are used to produce emulsions, for instance, highly efficient mixing and agitation. Unfortunately, these traditional processes are often temporarily discontinuous and could lead to a wide droplet size distribution over even three orders of magnitude. The polydispersity of the droplet size will sacrifice the quality of the product and debase the value.

Compared to the traditional production equipment, the microfluidic devices show many advantages with the controllability, small size and excellent monodispersity for bubbles and droplets (Fu et al., 2014; Wu et al., 2015). Several basic microfluidic

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configurations such as T- and Y-junctions, flow-focusing and co-flowing junctions have been applied to produce emulsions (Panizza et al., 2008; Wang et al., 2011; Wu et al., 2013).

Although microfluidic devices have attained significant improvements, the formation of undesirable satellite droplets could still be frequently observed due to the interface breakup in T-junctions and flow-focusing junctions (Carrier et al., 2015; Wu et al., 2013). Because of the tiny and different sizes of these satellite droplets, the polydispersity index of the system would certainly be increased remarkably. Moreover, tip stream was also reported in microfluidic systems (Anna and Mayer, 2006; Carrier et al., 2015; Mulligan and Rothstein, 2011). The daughter droplets ejecting from the sharp tip usually are three orders of magnitude smaller than the mother droplets, which will also inevitably increase the polydispersity index. Therefore, several studies have been devoted to the formation mechanism of the satellite droplets or the tip stream. Zhao et al. (2011) studied the influence of the interfacial elasticity on the formation of the satellite droplets. They utilized peptide as surfactants to form network in the interface for increasing the elasticity in order to suppress the formation of the satellite droplets. Carrier et al. (2015) studied the formation mechanism and the sizes of satellite droplets in the flow-focusing device. They found that the formation of satellite droplets depended greatly on the continuous flow. There is a critical capillary number $Ca=0.01$, below which the size of the satellite droplet remains unchanged, while beyond which the size would increase until entering the tip stream region. Anna and Mayer (2006) also reported the tip stream in flow-focusing device similar to Carrier et al's. (2015) observations. In their experiments, the tip stream could occur only when the bulk surfactant concentration exceeds 0.5 time of the critical micelle concentration and the capillary number locates in a limited range. Besides the droplet formation stage, the tip stream was also found in a contracting microchannel (Mulligan and Rothstein, 2011). The influence of the wall confinement on the phenomenon was comprehensively studied, and the results indicated that the confinement was mainly responsible for the formation of the tip stream.

Although, much work have been done to study the formation of the satellite droplets. Little effort was paid to understand the droplet instability and its mechanism leading to the generation of remarkable number of satellite droplets in straight microchannels. In order to avoid the polydispersity in microfluidic devices stemming from the satellite droplets, it is essential to fully understand the formation mechanism of the tiny satellite droplet. In present work, the formation of the tip stream in the rear part of the droplet flowing in the straight channel was investigated experimentally (movie S1), we expect that a quantitative criterion of the formation of the tip stream could be attained.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.ces.2015.06.046.

2. Experimental

A flow-focusing microfluidic device was fabricated in a plate ($90\times30\times8$ mm^3) of polymethyl methacrylate (PMMA) by precision milling and sealed with another PMMA plate ($90\times30\times3$ mm^3). The layout of the device was shown in Fig. 1. The dispersed phase was introduced from the central main channel at a flow rate of Q_d and the continuous phase was driven into two branches perpendicular to the main channel with the same flow rate $Q_c/2$. These three flow streams focused at the intersection downstream to generate droplets in mineral oil or bubbles in glycerol solution. Then the droplets or bubbles flowed into the outlet straight channel. The particle size, here it is characterized by the particle length L as shown in the inset, could

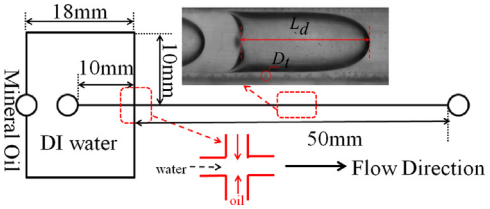

Fig. 1. Schematic diagram of the microfluidic device. All the cross-sections of these microchannels are 400 μm (height) × 400 μm (width). Inset: a droplet flowing in the straight channel with tip stream in the rear edge.

Table 1
Physical properties of liquids used in the experiments.

Liquid phase	Density ρ (kg m^{-3})	Viscosity μ (mPa s)
Deionized water	999.00	1.01
Mineral oil	838	35.2
62% glycerol solution	1150	9.76

be adjusted by changing the ratio of the two phases flow rate $s\varphi=Q_d/Q_c$. The microchannel has uniform square cross section of 400 μm wide and 400 μm high ($W_c=400$ μm).

The inlets of the dispersed phase and continuous oil phase were connected to two independent syringes (5 mL and 10 mL, Hamilton, Germany) driven by syringe pumps (Harvard Apparatus, USA). The microfluidic device was placed under an inverted microscope (Leica, Germany) equipped with a Phantom V711high-speed camera (Vision Research, USA). The droplet generation area was captured to investigate the deformation processes of the droplets. The downstream area in 1.5 cm away from the droplet generation area was recorded to study the shape of fully developed tails. All images were recorded at 10,000 frames per second. A cold fiber illumination (Jeulin S.A, France) was placed on the top of the microchannel as light source.

De-ionized water and nitrogen were employed as the dispersed phase, respectively. The mineral oil (Sigma-Aldrich, Germany) with 2% (wt) surfactant Sorbitanlauric acid ester (Span20, Sigma-Aldrich, Germany) and glycerol(Sigma-Aldrich, Germany) solution (62 wt%) with the surfactant Sodium dodecyl sulfate (SDS) (0.24 wt%) were used as the continuous phase, respectively. The surface tensions σ_g between nitrogen and glycerol solution and the surface tensions σ_l between de-ionized water and mineral oil solution were 33.1 ± 0.3 mN m^{-1}and 3.1 ± 0.4 mN m^{-1}, respectively, measured by a tensiometer on a Tracker apparatus (Dataphysics, Gemany). The viscosity of the fluids was measured by capillary viscosimetry (TA instrument, NewCastle DE, USA). The density of the liquid phase was measured using a vibrating tuber density meter (Anton Paar DMA-4500-M, Austria). The various properties of the experimental systems were gathered in Table 1. All the data were tested at room temperature and atmospheric pressure.

3. Results and discussion

3.1. Morphological shape and evolution of the tail shape

The morphological shape of the droplet flowing in a straight microchannel was systematically studied under different capillary numbers Ca ($Ca=\mu_l U/\sigma_l$) and droplet size L_d, here μ_l denotes the viscosity of the mineral oil. The capillary number Ca was adjusted by altering the two-phase superficial velocity U ($U=(Q_d+Q_c)/W_c^2$). The droplet length L_d was controlled by varying