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Visualization study of emulsion droplet formation in a coflowing microchannel

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ABSTRACT

An experimental visualization study is conducted to investigate the hydrodynamic characteristics of emulsion droplet formation in a coflowing microchannel. Both monodisperse and polydisperse patterns of drop formation are observed, including dripping regime, jetting regime (widening jetting and narrowing jetting). Especially, two dripping-to-jetting transition regimes and wavy regime with no individual droplet produced are captured and analyzed. A corresponding phase diagram is provided to characterize the transitions between different emulsification patterns through the control of flow rate of continuous phase. In addition, the dependence of generated droplet size on the Capillary number of the continuous phase (*Ca*) and the Weber number of the dispersed phase (*We*) is presented. It is indicated that, when *Ca* is below 3, the generated droplet size is sensitive to the viscous force and the drop formation regime is widening jetting and dripping. However, when *Ca* exceeds 3, the generated droplet size is approximately independent of *Ca*, and the droplet formation regime is thinning jetting.

1. Introduction

Emulsion droplet formation by microfluidic devices is more and more widely used in engineering application [1–13], such as pharmaceutics, chemical industries, food and lab on a chip. To accurately control the emulsion droplet monodispersity and size in a manipulated and reproducible manner, a lot of microfluidic devices have come out. There has been considerable interest in emulsion droplet formation by microfluidics over recent years [11–16].

Microfluidic approaches to produce emulsion droplets include two types, passive method and active ones. Most microfluidic techniques are passive, and they produce droplets via special flow fields to deform the interface and promote the natural growth of interfacial instabilities [12]. In general, these passive techniques can be classified into coflowing stream [17], T-junction [18], and flow focusing [19]. Compared with the two latter methods which are usually based on quasi-two-dimensional (2D) and fabricated in PDMS, the coflowing stream is usually implemented on 3D configurations by using a set of concentric channel [12]. 2D devices possess the advantages of easy fabrication and visualization while bring the drawbacks of the dispersed phase contact with the channel walls and the possibility of leaking [20]. On the contrary, the 3D devices may be inconvenient for fabrication but the dispersed phase is surrounded entirely with the continuous phase and protected from wetting the channel wall, which are beneficial to stabilize the process of drop formation. In addition, the coflowing stream offers a simple route to produce emulsions and possesses inherent capability of creating true three-dimensional flows which is critical for many applications [21].

In coflowing devices, the dispersed phase liquid emerges from the tip of the inner capillary tube, which generates droplets distributed inside the continuous phase liquid near or far away from the tip. The droplet formation at the tip of the capillary tube is an unsteady-state process accompanied with complicated liquid-liquid interface interaction and behaviors. Due to this fact, it is of significance to understand the process of drop formation in a coflowing microchannel so as to actively control the droplet production. There have been several attempts to experimentally and numerically study the droplet formation and the effects of operating parameters on such a complicated process. Umbanhowar et al. [17] implemented coflowing stream by inserting a micropipette which acts as the channel of the dispersed phase into a rotating bath of the continuous phase and produced highly monodisperse emulsions with minimum achievable polydispersity below 3%. Precise control over emulsion size is achieved by varying the velocity of the continuous phase. With dispersed phase injected through a needle into another coflowing immiscible fluid, drop formation at a capillary tip under various flow conditions is

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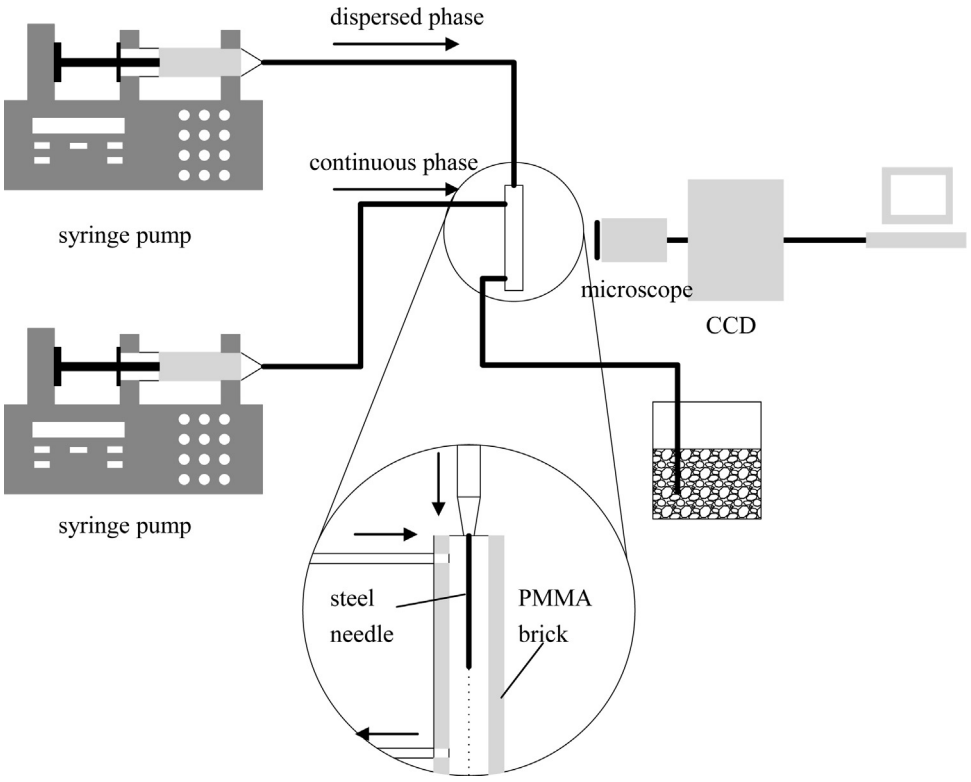

Fig. 1. Schematic of the experimental setup.

investigated experimentally by Carmer et al. [22]. Both dripping and jetting were observed and investigated. The effects of flow rates of fluids, viscosity ratio and interfacial tension on the drop formation were discussed to provide a comprehensive experimental data set for validating the feasibility of this technique as a dispersing tool. In addition, the transition points from dripping to jetting were also presented, where the breakup dynamics changes significantly. Subsequently, the transition from dripping to jetting in coflowing streams was also studied by Utada et al. [23] via using a microcapillary device. The behavior is characterized by a phase diagram that depends on the capillary number of the outer fluid and the Weber number of the inner fluid. Two distinct jetting regimes were distinguished according to the significant differences in jet shape and drop formation mechanisms. It is concluded that the sum of the force exerted on the droplet must ultimately overcome interfacial tension to cause the transition. Herrada et al. [24] conducted a comprehensive investigation on the instability of capillary jets in confined space at low Reynolds number. Both analytical and numerical models were developed and validated by the experimental results of their work and Guillot et al's [25]. The behaviors of the jet were mapped under different flow rates and various geometries as well as fluid combinations providing guidance for subsequent study. The linear analysis proposed by Guillot [25] using lubrication approximation is effective for predicting transition in low Reynolds number and highly confined space, however, it is not applicable to the conditions under large space [24]. Gañán-Calvo [26,27] conducted both experimental and analytical studies of capillary jetting showing that within broad parametric regions jet flow is always supercritical independently of the dispersed liquid flow rate.

Despite there have been several previous attempts to investigate the droplet formation in a coflowing structure, the entire flow regimes have not been fully understood. Especially the majority of the available works focus on the quasi-steady flow regime (e.g. dripping and jetting), the detailed transitions between different emulsification patterns under the coflowing streams has not been well identified. In this context, an experimental study on visualization of droplet production in a coflowing microchannel via an axisymmetric needle/square groove microfluidic device is conducted to investigate the hydrodynamic characteristics of drop formation. The dripping, jetting and wavy flow regimes as well as two distinct transitions from dripping to jetting are presented and analyzed. In addition, the effects of flow rates on the droplet morphology and size are discussed on the form of non-dimensional parameters.

2. Experiments

Fig. 1 presents the experimental setup using a coflowing geometry to form liquid droplet in a second immiscible continuous liquid phase. It consists of three major components: oil/water supply and control system, test section integrated with coflowing microchannel, and visualization system. The dispersed phase, driven by a syringe pump, flows through the filter, and meets the continuous phase in the test section where the coflowing stream is formed. After the test section, the oil-water mixture is collected in a container. In this experiment, deionized water is used as dispersed phase and silicon oil is used as continuous phase.

The oil/water supply and control system is implemented by two syringe pumps (Longer Pump LSP01-1BH). The dispersed phase is injected at a constant flow rate using a syringe pump which covers a flow rate range from 0 to 2500 μL/min while the continuous phases is delivered by another syringe pump at a specific flow rate varying from 0 to 1000 mL/h.

The coflowing microfluidic device is implanted with a steel needle (outer diameter d_o = 200 μm, inner diameter d_i = 90 μm) inserted into a rectangular transparent PMMA channel (width: 2 mm, depth: 2 mm, length: 80 mm), as shown in Fig. 1. The dispersed phase is injected via the steel needle and the continuous phase is injected through the rectangular channel.