Preparation of micro water droplets in micro-channel by digital jetting

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Abstract. For the precise manipulation in lab-on-a-chip, the slug flow of two-phase or multi-phase forming in the micro-channel has been highly concerned to develop the new digital jetting technology. This paper focused on the water-oil two-phase slug flow to realize the digital jetting by micro water droplets. The water and oil streams entered the nozzle simultaneously to form water-oil two-phase slug flow steadily. The water droplets presented the monodispersion property in micro-channel before jetting out of nozzle, however, they took the polymerization property in container after jetting out of nozzle under some conditions.

Introduction

Microfluidics has drawn considerable attention to deal with devices and methods, and it also can control and manipulate fluids in micro-channel. The behavior of two-phase flow in microfluidics has some characteristics to enhance and extend the performance of single-phase microfluidic systems [1]. The gas-liquid and liquid-liquid flows are the common two-phase flows in the field of biology and medicine research, e.g. the protein crystallization, to synthesize the nanoliter-size droplets or reagents in micro-channels [2, 3]. Liquid-liquid slug flow is different from gas-liquid slug flow in that the interfacial shear can be significant, depending upon the viscosity of the dispersed phase, resulting in non-negligible flow in the liquid film surrounding the droplet [4].

The two-phase and multi-phase slug flows have some unique advantages which can separate the streams to droplets, therefore, the digital jetting is easy to realize and widely used in necessary. Many researches have been done on the physical properties of slug flow, e.g. surface tension, viscosity, flow rate, micro-channel geometry, droplet size, jetting frequency, and so on [5-10].

Two-phase microfluidic flows are generated when the two partially miscible or immiscible fluids are brought into contact in microfluidic devices. In this article, the two immiscible fluids, water and oil, were the dispersed phase and continuous phase, respectively. The aim was to find the effectors of jetting frequency and droplet size on forming homogeneous droplets in micro-channel.

Experimental

The experimental system of water-oil two-phase slug flow was set up withtwo injector pumps, a microscope, a nozzle, and other fluidic parts (Fig. 1a). During the experiments, the water and oil streams controlled by the injector pumps were injected into the nozzle, simultaneously. The pulse dampers were applied to eliminate the stream pulsation of water and oil and maintain the flow rates steadily. The dish under the nozzle collected the water droplets from the slug flow which was formed in the nozzle. The observation of water droplets adopted the microscope (TK-C9201EC).

Figure 1b gives the structure of jetting nozzle, which consists of two parts, the water tube inside and the oil tube outside. The water tube inserts into the oil tube, and the distance between the end of water tube and nozzle outlet is defined as the length of micro-channel. The stream oil and water flows into the outer and inner tubes from the side and top, respectively, and they mix in the micro-channel to form the two-phase slug flow before jetting.

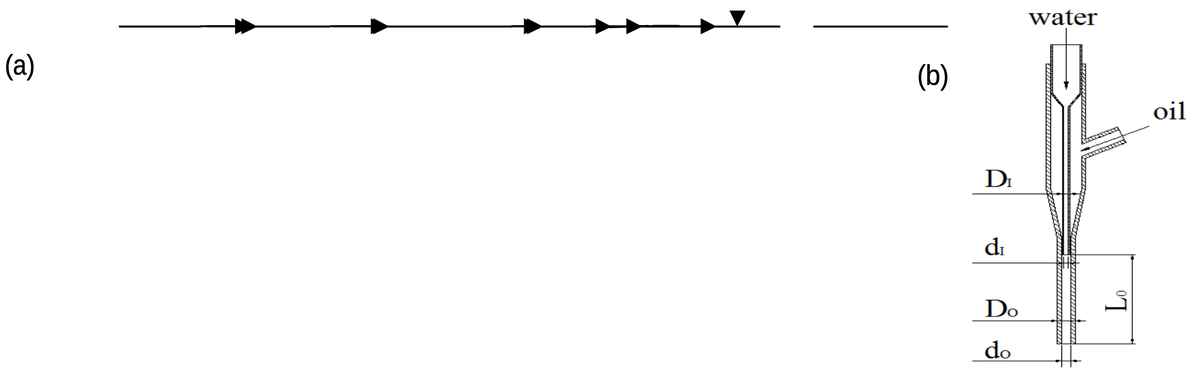


Fig. 1 The schematic diagram of set up and nozzle structure

The parameters of the nozzle structure are listed in table 1.

Tab. 1 The parameters of the nozzle structure

d_o	D_o	d_I	D_I	L_0
0.88	1.7	0.42	0.72	10.38

Controlling the flow rates of water and oil appropriately, the mixed two-phase flow in the micro-channel formed the water-oil slug flow to jet out of the nozzle. To view the water droplets in micro-channel before jetting, they took the shape of slug with red color due to the light scattering (figure 2a). After jetting, the water droplets submerged into oil had been collected by dish to be the numerous black dots in figure 2b. Figure 2c shows the water droplets were in sphere shape uniformly by microscope.

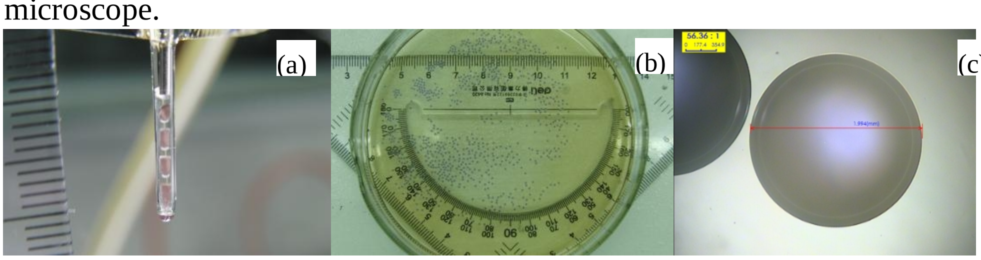


Fig. 2 The water droplets before and after jetting, (a) the water-oil two-phase slug flow in micro-channel, (b) the oil full of water droplets in dish, (c) one water droplet in oil

Results and discussion

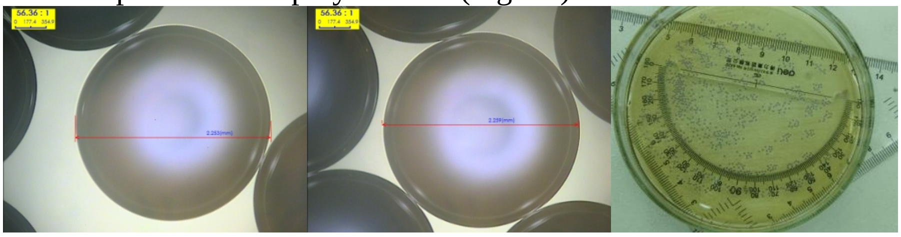
The physical properties parameters of experimental materials are listed in table 2. Since the surface tension of the water is higher than that of the oil, the stream water can form water droplets after be dispersed by the stream oil. In addition, the water density is also larger than that of the oil, and the formed water droplets can submerge into the oil to maintain the sphere shape. As a result, the water is the dispersed phase and the oil (Shell HX8 5W-40) is the continuous phase in the water-oil slug flow.

Tab.2 The physical properties of the experimental materials

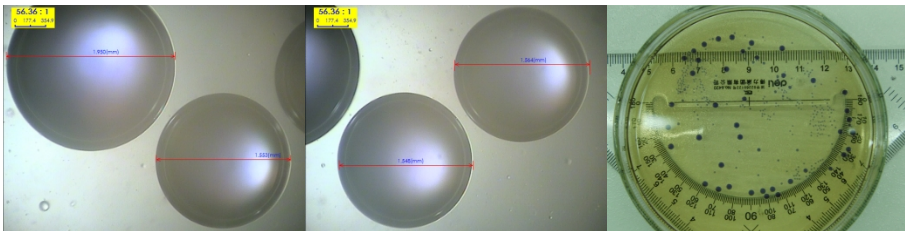
	Density[g/cm^3]	Dynamic viscosity[cp]	Senfacetention[dyn/cm]
water	1.0	0.6560	72.75
Oil	0.851	64.9	63.4

The ruler scale in microscope was calibrated to be 2:1, and that means 2 mm measured by microscope is 1 mm in real size. The water-oil two-phase slug flow existed in micro-channel at all experiments conditions, and the water droplets were in slug shape separated by oil before jetting. However, the water droplets changed its characteristic from monodispersion to polymerization in dish after jetting at certain conditions.

Figure 3 explains the relationship between the water droplets and the different flow rates of water and oil. It was found that water droplets are monodisperse and uniform in the condition of low flow rates of water and oil (Fig. 3a). With the flow rate of water and oil increasing, some of the monodisperse water droplets become polymerized (Fig. 3b).



(a) $q_w=q_o=0.1$ ml/min



(b) $q_w=q_o=3.0$ ml/min

Fig. 3 Water droplets in monodispersion and polymerization with different water-oil flow rates

To analyze the water-oil slug flow, the diameter of water droplet (D) has been measured. The water droplet submerged into oil in dish is a sphere shape due to the higher surface tension of water, thus the volume of water droplet (V) is

$$V=\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \tag{1}$$

The volume of water droplets in monodispersion have been plotted in figure 4a. It is obvious that the average volume increase in a power series relationship with two-phase flow rates increasing.

In conditions of $q_w=q_o=3.0$ ml/min, several monodisperse water droplets polymerize to a bigger droplet, and the changes of diameter and volume calculated in table 3. It is note that the polymerized droplets have been combined by two monodisperse droplets.

Tab. 3 Monodispersion and polymerization of water droplets with $q_w=q_o=3.0$ ml/min

Water droplet	Monodispersion	Polymerization	Polymerization /Monodispersion
D_{avg}	0.7765 mm	0.975 mm	1.256
V_{avg}	0.245 μl	0.485 μl	1.98

The standard deviation of diameter (γ) is introduced to evaluate the diameter consistency of micro water droplets prepared by digital jetting.

$$\gamma=\sqrt{\frac{\sum_{i=1}^{n}(D_i-D_{avg})}{n-1}} \tag{2}$$

Where $i=1,2,3\ldots,10$, and D_{avg} is the average value of ten water droplets.

The diameter standard deviation of water droplet in figure 4b illustrates the diameters of water droplet take a highly consistency within γ=2%, while there is no polymerization in micro water droplets. It is interesting that the monodispersion of micro water droplets is not sensitive to the flow rates of water and oil while the ratio of flow rate is fixed to 1:1. This also sure that the slug flow produces the stable water droplets with the same volume and the monodispersion is the basic property of water droplets. The polymerization of water droplets will occur only at certain conditions and this increase the diameter of water droplets to obtain the bigger droplets either.

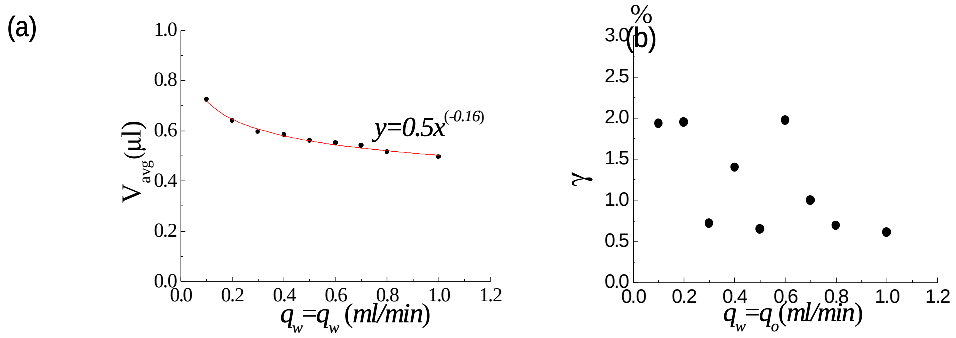


Fig. 4 The volume and diameter standard deviationof water droplets in monodispersion

Conclusions

This paper studied the water-oil two-phase slug flow in micro channel. The structure of the nozzle had an inner water tube and an outer oil tube. The water and oil streams entered the nozzle simultaneously and the water-oil two-phase slug flow had been formed steadily. The water droplets presented the monodispersion property in micro-channel before jetting out of nozzle, however, they took the polymerization property in container after jetting out of nozzle under some conditions.

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