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Effect of surface wettability on internal velocity profile during droplet formation process in microfluidic devices

Guotao Liu[a], Xi Wang[a,b,*], Kai Wang[a], Chris P. Tostado[a], Guangsheng Luo[a,**]

[a] The State Key Laboratory of Chemical Engineering, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China
[b] China Automotive Battery Research Institute Co., Ltd, General Research Institute for Nonferrous Metals, Beijing 100088, China

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ABSTRACT

The present work is dedicated to experimental measurement of internal velocity profile within a forming droplet in micro-channels. Velocity distributions are obtained by a micro-particle image velocimetry (Micro-PIV). Three liquid working systems were used to study the effects of surface properties on the droplets' internal flow field. Internal flow velocity increases and a pair of symmetrical vortices develop as the droplet grew in size. Vortices developed earlier in cases where the dispersed phase exhibited stronger wettability on the channel wall while later in cases of weak or partially wetting conditions. One of the most interesting findings was that the direction of internal circulation depends on the wetting state of dispersed phase on the channel wall. In addition, a swirling strength parameter was employed to characterize the developing vortices throughout the formation process.

1. Introduction

In microdispersion devices, mass transport during both droplet formation and moving stages is dependent on molecular diffusion through stagnant layers within the droplets. Undoubtedly, the existence of internal circulation could make a significantly contribute to intensifying the chaotic advection of micro dispersion process. Considerable investigations have been presented both experimentally (Wang et al., 2015; Timgren et al., 2008; Oishi et al., 2011; Mandal and Bakshi, 2012) and numerically (Sarrazin et al. 2006; Savino and Fico, 2004) that internal circulation can be generated insides moving droplets. Thus, an in-depth characterization of the actual velocity flow fields occurring inside these droplets during formation, as well as identification of the system parameters that can affect these flow fields is very important. A central role which surface wettability plays in determining the flow regime in microchannels has been proposed in numerous studies (Wang et al., 2012; Wielhorski et al., 2012; Zhao et al., 2010). Surface property has been accepted as a key factor for micro-flow. However, detailed information regarding the influence of interfacial forces on the internal flow in micro-dispersed droplet has not yet been presented.

In this initial study, our objective is to characterize the internal circulation during droplet formation process. Unlike previous studies, here we focus on the changes induced by the variation of surface property to internal vortices.

2. Experimental details

2.1. Micro-PIV measurement system

Micro particle image velocimetry system (Dantec Dynamics A/S, Denmark) was used for the measurement of velocity distribution. Flow field of view was illuminated by a 30-mJ double-pulsed Nd: YAG laser. A 12-bit CCD camera equipped with 10× microscope objective lens (NA = 0.3) was used to capture the images. Rhodamine B marked tracer particles with the diameter of 1 μm (Sigma-Aldrich Co. LLC., USA) were chosen to trace the local fluid flow. A cross-correlation algorithm was selected to determine the flow field. The captured images were divided into an interrogation area of 64 × 64 pixels squared with an interrogation area overlap of 50%. An adaptive window scheme incorporated in the commercial software was adopted to offset the calculation error. The spatial resolution and the accuracy of Micro-PIV system were limited by factors such as particle size, diffraction, depth of flow field. All measurements in this work were conducted at the same depth.

2.2. Test section

Co-flow junction and cross junction channels were adopted as shown in Fig. 1. All the microfluidic devices were fabricated on a 60 mm × 30 mm ×3 mm polymethylmethacrylate (PMMA) substrate. For the co-flow junction, a glass capillary embedded

* Corresponding author. Tel.: +86 10 82241193; fax: +86 10 82241190.
** Corresponding author. Tel.: +86 10 62783810; fax: +86 10 62770304.
E-mail addresses: wangxic60@hotmail.com (X. Wang), gsluo@tsinghua.edu.cn (G. Luo).

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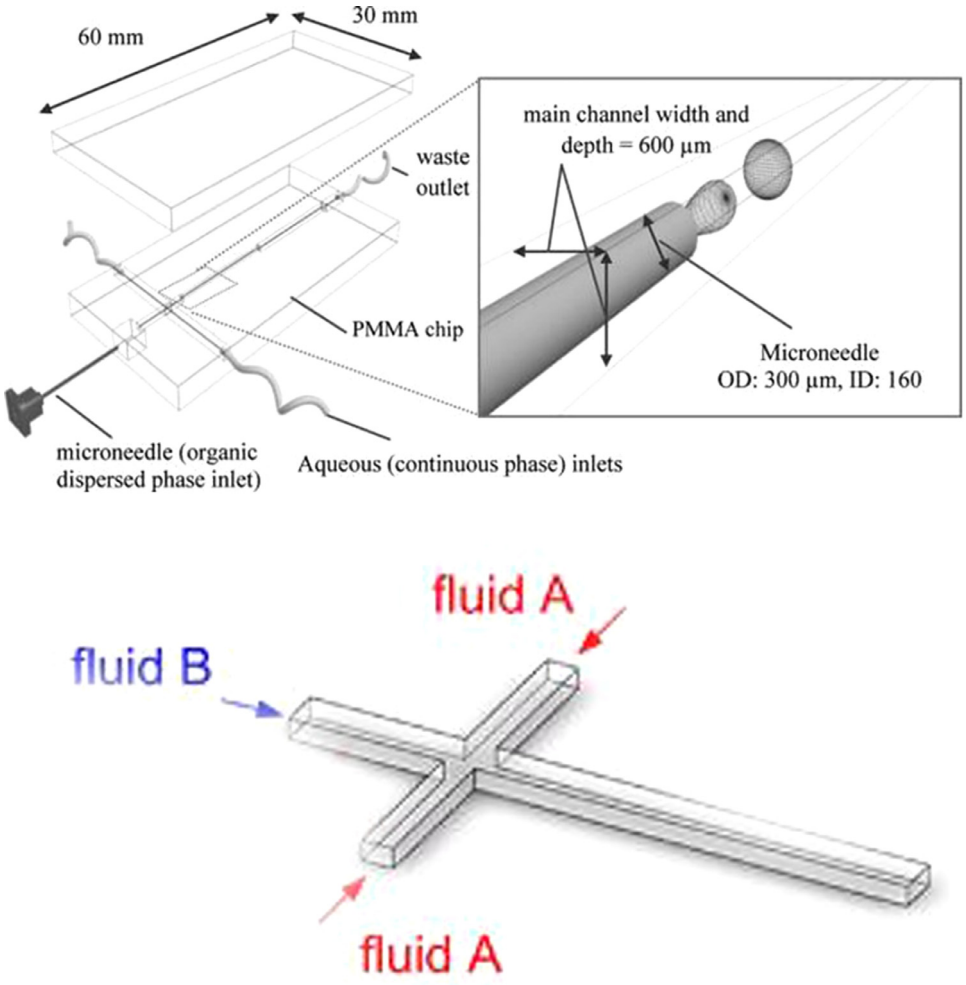

Fig. 1. Schematic images of test sections used in this work ((a) co-flow, (b) cross junction).

Table 1
Physical properties of working systems.

System number	Dispersed phase	Continuous phase	Dispersed phase Viscocity (mPa•s)	Continuous phase Viscocity (mPa•s)	Interfacial tension (mN/m)	Dispersed phase density (g/cm^3)	Continuous phase density (g/cm^3)
1	Water	n-Octane	0.92	0.52	51	0.997	0.703
2	Water saturated with butanol	Butanol	1.0	2.68	1.73	0.968	0.82
3	25% PA	n-Octane	2.3	0.52	45	1.15	0.703

Table 2
Contact angles of different wetting cases.

Case number	Liquid phase	Solid surface	Contact angle (°)
1	Water	Stainless steel	79.3
2	water saturated with butanol	Stainless steel	40.9
3	25% PA solution	Stainless steel	30.8
4	Butanol	Stainless steel	<5
5	n-Octane	Stainless steel	<5
6	Water	PMMA	80.8
7	Water saturated with butanol	PMMA	32.4
8	25% PA solution	PMMA	79.8
9	Butanol	PMMA	<5
10	n-Octane	PMMA	<5

into the PMMA substrate was used as the main channel, the inner and outer diameters of glass capillary were 1.05 mm and 1.5 mm respectively. The dispersed phase was fed into the main channel through a stainless steel micro-needle (outer and inner diameters of 0.3 mm and 0.16 mm). The continuous phase pumped into the device using two syringe pumps joined together at the cross section (1.5 mm width ×1.5 mm height). For the cross-junction device, the width and height of main channel was 0.6 mm. The length of the main and side channels were 45 mm and 15 mm respectively. All the microfluidic substrates were sealed with another PMMA plate with a high-pressure thermal sealing technique at 70 °C, 0.4 MPa. In this work, the volumetric flow rates of continuous phase in the co-flow and cross junction devices were 400 and 100 μl/min. The volumetric flow rates of dispersed phase in the two types of devices were 5 and 20 μl/min.

2.3. Working systems and wetting conditions

Butanol and n-octane (A.R., ≥98%, Sinopharm Chemical Reagent Co., Ltd., China) were employed as the continuous phase. De-ionized water and 25% (wt) phosphoric acid (A.R., ≥85%,