13th International Symposium on Particle Image Velocimetry – ISPIV 2019
Munich, Germany, July 22-24, 2019

Flow characteristics inside droplets moving in a straight microchannel with rectangular section

Mengqi Li [1], Zhaomiao Liu [1*], Yan Pang [1], and Ju Wang [1]

1 College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China

*Corresponding author: lzm@bjut.edu.cn

Abstract

In this paper, the internal flow characteristics of droplets travelling in a straight microchannel is studied by means of Micro Particle Image Velocimetry (Micro-PIV) system, focusing on the effects of capillary number, viscosity ratio, droplet size and the distance between droplets on flow field inside droplets. It is found from the experiments that the internal flow topology changes from four eddies at low capillary number to six eddies at high capillary number, which is in the opposite transition direction in a lower viscosity ratio system. And the spherical droplets always maintain double eddies at any capillary number. The change of the distance between droplets will disturb the boundary velocity of droplets, even cause a velocity contrary to the droplet's motion in the contact position between droplets and microchannel wall. The results of this study will help to develop microfluidic flow cytometry further.

1 Introduction

Due to its capacity of accurate control and avoiding cross contamination, droplet microfluidic technology has great application value in biochemical reaction and microfluidic flow cytometry (Seemann et al. (2012)). Different applications require various microenvironment inside droplets. The rapid convection inside droplet can achieve the millisecond level mixing (Song et al. (2010)), but also may cause the cellular level damage such as stem cell dysfunction (Williams et al. (2007)). It thus, the studying of flow characters insides droplets is useful for controlling the biochemical reaction efficiency and further developing flow cytometry. Based on this, the formation and development mechanism of the flow field inside droplet have been researched in this paper.

2 Effect of capillary number on the flow field inside droplet

Figure 1 shows the flow field inside droplets at different *Ca*. It is found that the topological structure of internal flow field has an obvious gradient process with the increase of *Ca*. When Ca=4.4×10^{-4}, the flow pattern is shown in Fig. 1(a), there are two clockwise eddies on the upper part of droplets moving to the right, and the direction of velocity near the wall boundary is consistent with the direction of droplet movement. The high-speed area is located at the front and rear ends of the oil film. At Ca=3.5×10^{-3} the flow pattern is shown in Fig.1(b), The area of the eddy in front of the droplet increased significantly, while the area of the other eddy shrank to almost disappear. As *Ca* goes to 1.8×10^{-2}, the flow field is shown in Fig. 1(c), the upper part of the droplet is occupied by just an eddy, which has been captured before (Ma et al. (2014), Liu et al. (2017), and Bergeles et al. (2018)). And the boundary velocity near the wall is consistent with Fig. 1(a). Thinner oil film and more recirculation zones at lower *Ca* inside the droplet mean stronger wall resistance and internal viscous dissipation, both of which may lead to increased flow resistance.

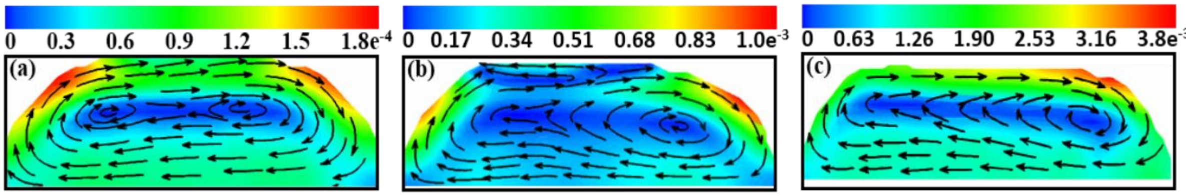

Fig. 1 The flow field inside droplets at different *Ca*. (a), (b) and (c) are the flow topologies of *Ca*=4.4×10^{-4}, 3.5×10^{-3} and 1.8×10^{-2}separately.

3 Effect of viscosity ratio

The two-phase viscosity affects the flow resistance in the microchannel and determines the gradient ratio of velocity inside and outside droplet (Ma et al. (2014)). Fig. 2 shows the internal flow field of droplets in a lower viscosity ratio system. When viscosity ratio decreases from 6.6 to 0.4, there are only a pair of vortexes inside the droplet at *Ca*= 4.4×10^{-4} and four eddies at *Ca*= 3.5×10^{-2}. Compared with Fig. 1, the transition of internal flow field in low viscosity system is contrary to that in high viscosity system. When *Ca*= 4.4×10^{-4}, the droplet velocity in the high viscosity ratio system is 270 μm/s, while the droplet velocity in the low viscosity ratio system is only 80 μm/s. The droplet is similar to the plunger to block the micro-channel. At the same flow rate, the shear stress and the pressure difference before and after the droplet decrease with the decrease of the viscosity of the continuous phase. The droplet is more difficult to be driven forward, and the continuous phase bypasses the droplet from the oil film and corner flow. In terms of energy, most of the energy provided by the continuous phase is used to drive the fluid around the droplet, rather than the whole droplet.

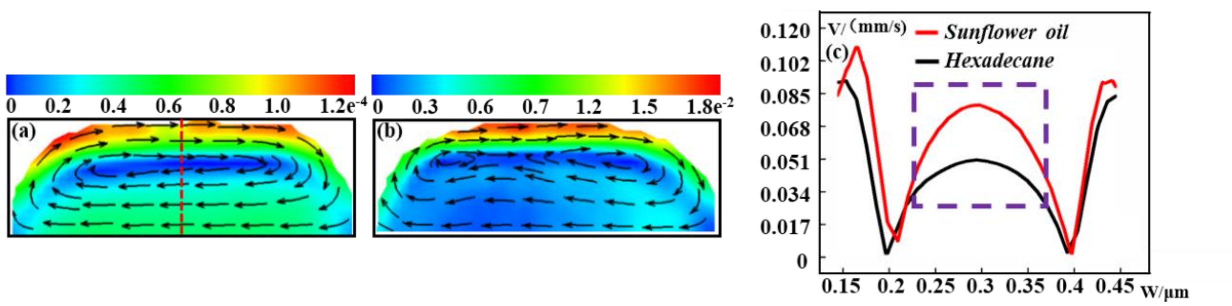

Fig. 2 The flow field inside droplets under lowed viscosity ratio system. (a) and (b) are the flow topologies of *Ca*=4.4×10^{-4} and 3.5×10^{-3} separately. (c) is the flow rate along the droplet axis.

4 Effect of droplet size

Droplet size directly affects the blockage degree (flow resistance characteristic) of the channel and the formation of corner flow, and corner flow will make the internal flow field in the rectangular cross section channel more complex(Lai et al. (2007), Dore et al. (2012), and Kurup et al. (2012)). Fig. 3 shows the internal flow field of spherical droplets with different Ca. Combine Figs. 1 and 3, it can be inferred that the spherical droplets always maintain double eddies at any capillary number, however, the topological structure of plunger droplet will shift with the change of capillary number. It can also be understood that the droplet volume will affect the internal flow field structure under low capillary number, but not under high capillary number. For plunger droplets, the boundary velocity on the left and right sides attenuates to zero at two positions, so two vortex centers are formed, and four eddies appear in the droplet. The droplet boundary velocity and shear rate increase with the increase of capillary number, leading to the expansion of double vortices in the upper and lower parts, mutual influence and fusion, and the final formation of double vortex structure in the droplet under high capillary number. For spherical droplets, due to their small size, even at low capillary number, the boundary velocity of the droplet declines directly to zero in the same region under the action of viscous dissipation. Therefore, under any capillary number, the droplet presents a double-vortex structure.

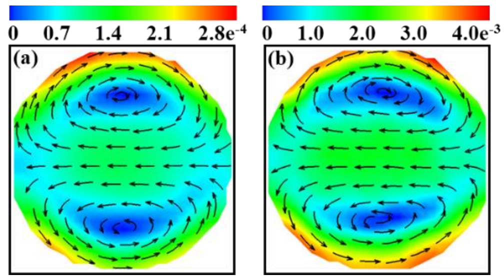

Fig. 3 Internal flow field of spherical droplets under different Ca. (a) and (b) are the flow topologies of of Ca=4.4×10^{-4} and 3.5×10^{-3}separately.

5 Effect of distance between droplets

Distance between droplets is directly determined by the generation condition (two-phase flow rate), and under the condition of constant flow rate of continuous phase, all droplet sizes have their shortest initial spacing, which decreases with the increase of droplet size. Therefore, the influence of distance between droplets on the internal flow field is rarely considered in all current studies. Fig. 4 shows the internal flow field of droplets with β=1.5 under different distance between droplets, $\beta = L_d/W_c$, L_d represents the distance between the leftmost and rightmost side of droplets and W_c is width of the channel. When the dimensionless distance L_r= L/W_c <1, where L is the distance between droplets, a region of low speed appears at the contact place between the droplet and the wall surface of the channel, and even the speed direction is opposite to the droplet movement, as shown in the red dashed frame in Fig. 4(a). When the1.5<L_r<2, the area of the low-speed region significantly decreases, and the negative velocity completely disappears, as shown in the red dashed frame in Fig. 4(b). When β increases to 1.7, a large area of low speed and negative velocity are generated at the contact point between the droplet and the boundary, as shown in Fig. 4(c). The above experiments show that the obstruction from the wall to droplet motion decreases with the increase of droplet spacing and decrease of volume. In the study of Ca and viscosity ratio, droplet spacing L_r are much larger than 2, so there is no evident inverse velocity at the boundary.

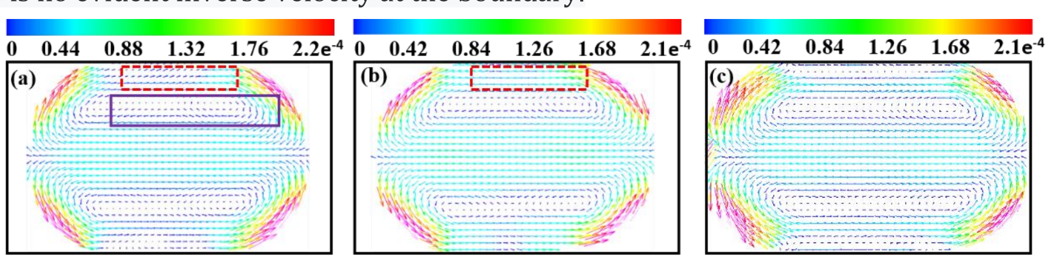

Fig. 4 internal flow field of droplets with different L_r and droplet size. (a) and (b) are the flow topologies when L_r<1 *and* 1.5<L_r<2 with β=1.5 separately. (c) internal flow field of droplets with β=1.7 when 1.5<L_r<2.

6 Conclusion

The effects of capillary number, viscosity ratio, droplet size and distance between droplets on flow field inside droplets in microchannel are investigated by Micro-PIV system. The plunger droplet presents two eddies at high capillary number, and four eddies at low capillary number. However, there are always two eddies inside the spherical droplet. The decrease of shear stress and deformation degree of droplet under the same capillary number in the low viscosity ratio system lead to the reverse trend. The obstruction from channel wall to droplet decreases with the increase of droplet spacing and decrease of volume. Results are helpful to understand the complex dynamic behavior of droplets in microchannels, establish their relationship with the resistance characteristics of two-phase flow, and provide theoretical guidance for practical applications such as extraction, synthesis, heat and material transfer and microfluidic flow cytometry, which are directly affected by the internal convection of droplets.

Acknowledgements

This work was financially supported by the NSFC (Nos.11572013, 11702007 and 11872083).

References

Seemann R, Brinkmann M and Herminghaus T P (2012) Droplet based microfluidics. *Rep. Prog. Phys*. 75:016601

Song H, Tice J D and Prof R F I (2010) A Microfluidic System for Controlling Reaction Networks in Time. *Angew Chem Int Ed Engl* 115:792-796

Williams L and Peter Y (2007) Adult stem cells of the lung in organ dysfunction. *Journal of Organ Dysfunction* 3:31-35

Ma S, Sherwood JM, Huck WTS, and Balabani S (2014) On the flow topology inside droplets moving in rectangular microchannels. *Lab on a chip* 14:3611-20

Liu Z, Zhang L, Pang Y, Wang X, and Li M (2017) Micro-PIV investigation of the internal flow transitions inside droplets traveling in a rectangular microchannel. *Microfluidics and Nanofluidics* 21:180

Lai A, Fuerstman M and Thurlow M (2007) The Pressure Drop along Rectangular Microchannels Containing Bubbles. *Lab on a Chip* 7:1479.

Dore V, Tsaoulidis D and Angeli P (2012) Mixing patterns in water plugs during water/ionic liquid segmented flow in microchannels. *Chemical Engineering Science* 80: 334-341

Kurup G K and Basu A S (2012) Field-free particle focusing in microfluidic plugs. *Biomicrofluidics* 6:1644-1659

Bergeles K, Hardalupas Y, and Taylor A M K P (2018) On the transient flow inside and around a deforming millimetre class oil droplet falling under the action of gravity in stagnant air. *Physics of Fluids* 30:013305.