A Silicon/Glass –Based Microfluidic Device For Investigation Of Lagrangian Velocity Field In Microdroplets

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Abstract. We have measured the flow field inside microdroplets formed by two immiscible fluids in a microchannel using micro particle image velocimetry (micro-PIV) technique. An aqueous liquid with fluorescent particles was injected in an immiscible carrier flow. Both velocity fields during the droplet formation process and during the passage in straight, rectangular microchannels were measured and evaluated. We observed that at a certain layer the direction of the outer circulation flow in the droplet is the same as that of the droplet motion. The results indicate that the immiscible carrier fluid flows through the gaps between the aqueous droplet and the rigid channel wall at a velocity faster than the droplet itself.

Keywords: micro droplet; digital microfluidics, multi-phase flow, MEMS.

1. Introduction

Monodisperse droplets were traditionally used in the fields of food science, cosmetics, and pharmaceuticals. Recently, the formation of microdroplets in microchannels attracts the interest of research community on microfluidics and lab-on-a-chip [1]. The main application of this phenomenon is microreaction technology [2]. Micro droplets have been used for DNA analysis, protein crystallisation [3], analysis of human physiological fluids, encapsulation [4], and production of polymeric micro beads [5]. Uniform droplets can be prepared using a simple T-junction [6] or a cross junction [7]. Most of the recently reported works are based on droplets formed between immiscible fluids. The flow field inside a moving droplet causes chaotic advection and improves mixing significantly. Although this effect was well known and widely used in several applications, understanding of the flow field inside the droplet were limited by speculation [2]. The main difficulty of measuring this flow field is the Eulerian nature of available measurement techniques such as micro-
PIV, while the velocity field inside a moving droplet requires the Lagrangian description. In our study, we first used micro-PIV to determine the velocity field of tracing particles in the Eulerian coordinate, which is fixed by the observation window of the recording camera. Next, the droplet velocity is determined by averaging velocity vectors over the measured droplet area. Since the Eulerian velocity vector of the droplet is constant in a straight microchannel, subtracting this droplet velocity vector from the measured Eulerian velocity field of the tracing particles results in the Lagrangian velocity field inside the moving droplet.

2. Device Fabrication and Experimental Setup

Our microfluidic device was fabricated by deep reactive ion etching (DRIE) in silicon. The fluidic access was etched through the silicon wafer. A glass wafer was bonded on the etched silicon wafer to seal the microchannel and to act as the optical access to the formed micro droplets. The microfluidic network consists of a large carrier channel of 150 µm×150 µm cross section and a small injection channel of 50 µm×50 µm cross section. The aqueous liquid with tracing particles enters through the injection channel, while an immiscible carrier liquid is introduced into the carrier channel. The two channels form a T-junction, at which droplet formation occurs.

The silicon chip is mounted in an adapter made of Perplex glass. Syringe needles (19G, Terumo) and tubing (1/16" ×1/8", Cole-Parmer) were used as fluidic interconnects for the adapter. Figure 1 shows the silicon/glass chip and the Perplex adapter. The inserted figure explains the concept of droplet formation at the T-junction.

![Fig. 1. The silicon/glass chip and the adapter used in our experiment. The inserted figure shows the concept of droplet formation investigated in our experiments. The inserted optical fibers are not shown here.](image)

Our micro-PIV measurement system consists of a double pulsed Q-switched (quality switched) Nd:YAG laser (wavelength of 532 nm, maximum energy of 160 mJ, Quantel Brilliant, France), an inverted epi-fluorescent microscope (ECLIPSE TE2000-S, Nikon, Japan) with a 20× objective and a PC-based control unit. Details about this system were reported previously [8]. Duke red particles (930 nm in diameter, Duke scientific Co.) were used as tracing particles. The particles have a maximum excitation wavelength of 540 nm (green, very close to the characteristic wavelength of Nd:YAG) and a maximum emission wavelength of 610 nm (red). The two-laser-head system allows the realization of two laser pulses with a very short time delay. The shortest time delay about 300 ns for the two PIV images is determined by the interframe transfer time of the CCD camera. In our experiments, the mode
of double exposures in double frames was used because of the high signal-to-noise ratios and the better quality of the cross-correlation technique.

In our experiments, oil with a viscosity of $6.52 \times 10^{-2}$ Pa.s enters the larger carrier channel, while the aqueous liquid with tracing particles joins through the smaller injection channel. The aqueous liquid is DI-water with a viscosity of approximately $10^{-3}$ Pa.s. The two liquids were delivered by a precision micro-syringe pump (Lomir Biomedical Inc.). A 500-µl syringe and a 5-ml syringe (gastight, Hamilton) were used for the aqueous liquid and oil, respectively. Since both syringes are driven by the same stepper motor, the flow rate ratio between the carrier liquid and the aqueous liquid is kept constant at 10:1. The total flow rate mentioned in this paper is the sum of both flow rates of oil and the aqueous liquid.

![Image of droplet formation process](image)

Fig. 2. The velocity field inside the droplet during the formation process at a total flow rate of 55 µl/h. The actual images of the droplets are shown as inserts.

The delay times between two the PIV images were selected as listed in Table 1 to suit the total flow rate and to minimize errors caused by Brownian motion. After recording the PIV images, we used commercial software (PIVview1.7, PIVTEC GmbH, Germany) to evaluate the velocity fields of the tracing particles. The algorithm in use was multiple-pass interrogation with 4 passes. The size of an interrogation window is 64 pixels×64 pixels. Subsequently, the droplet velocity vector was calculated by averaging the particle velocity over the droplet area. Subtracting the droplet velocity vector from the Eulerian particle velocity field results in the Lagrangian velocity field inside the droplet. In the case of droplet formation shown in Fig. 2 this evaluation method can be used only for a small total flow rate, where the shape change during the PIV measurement (Table 1) is negligible. While the droplet expands on one side, the base is still attached at the injection port. This fact leads to evaluation errors at the base of the droplet. In the case of a moving droplet in a straight channel, the above evaluation technique applies well. Clear recirculation flow was observed inside the droplet, Fig. 3.

| Flow rate (µL/h) | 55  | 110 | 165 | 220 | 275 | 330 | 440 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Delay time (µsec) | 700 | 400 | 250 | 200 | 150 | 150 | 100 |
3. Results

Interestingly, the outer recirculation flow inside the droplet has the same direction as the droplet motion. This fact is counterintuitive and opposes common speculation that the shear stress on the droplet interface acts in a direction opposite to the droplet motion [2]. If the shear is caused by the interface between the droplet and an immobile film of carrier liquid on the wall, the Lagrangian velocity at the interface should have the same magnitude and an opposite direction as the Eulerian velocity vector of the droplet. This behavior can be expected in the middle plane of the droplet. In the planes close to the top and bottom of the droplet, the Lagrangian velocity at the interface is about 1/5 of the Eulerian droplet velocity and has the same direction, Fig. 4.

![Fig. 3. The velocity profile across a droplet moving in a straight rectangular channel at a total flow rate of 55 µl/h. The black circles are measured data, the line is the fitting curve. The inserted figure shows the actual measured velocity field inside the droplet. Counter intuitively, the velocity at the side interface of the droplet has the same direction as the carrier flow.](image)

The results also show that the Eulerian droplet velocity is almost the same as the mean velocity calculated based on the total flow rate of the two liquids and the given channel cross section of 150 µm×150 µm.

![Fig. 3. Velocities of the droplet. The circles are the mean velocity of the droplet evaluated from the micro-PIV measurement. The dashed line depicts the averaged flow velocity in the microchannel calculated based on the total flow rate. The crosses are measured Lagrangian velocity at the interface of the droplet.](image)
The observed Lagrangian velocity field can be explained by the existence of the mobile carrier liquid around the droplet as shown in the cross-sectional view in Fig. 5. Due to the surface tension between the two liquid phases, the plug-shaped droplet does not have a square shape to occupy the whole channel cross section. Gaps between the microchannel wall and the droplet exist at the corner regions [9, 10]. Due to the decrease in cross section area (about \((4 - \pi/4)\) for the case of droplets' circular cross section), the mobile carrier liquid flows through these gaps with a higher velocity. The velocity difference between the two liquid phases causes shear stress in the same direction at the droplet interface.

The Lagrangian velocity field inside a droplet develops from a single vortex to two axisymmetric vortices, Fig. 5. This behavior promotes chaotic advection inside the droplet and has been utilized for mixing [2]. The real flow field inside the droplet is expected to be three-dimensional, which currently cannot be characterized with our experimental setup.

Fig. 3. Schematic description of the development of the Lagrangian velocity field inside the droplet.

4. Conclusions

In conclusions, we have presented the measurement results of the Lagrangian velocity field inside a droplet during formation process and during the passage in a straight rectangular microchannel. The droplet was formed in a microchannel network fabricated in silicon and glass using microtechnology. The measurement was based on the micro-PIV technique. Lagrangian velocity field was extracted from the measured Eulerian velocity field of tracing particles. The experimental results reveal that at certain plane inside the droplet, the recirculation flow at the droplet interface has the same direction as the droplet motion. This effect can be explained by a mobile carrier flow around the droplet through the gaps between the droplet and the microchannel wall. In a theoretical analysis, the interfacial tension between carrier liquid and droplet, viscous stress, and flow conditions have to be considered to determine the droplet shape [11]. The shape of the droplet affects the gaps between the droplet and the channel wall and internal flow field of the droplet. In our future work, we will focus on modeling the observed effect described in this paper.

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