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Micro-PIV measurement of internal flow in a micro droplet

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Abstract: Visualization and PIV measurements of the symmetrical recirculation flow in a nanoliter-sized droplet have been performed using the micro PIV system. The airflow sweeps over the nanoliter-sized liquid droplet fixed in a microchannel and the frictional force drags the liquid on the round interface, which causes the symmetrical recirculation flow in the droplet. The internal recirculation flow in the droplet has been visualized and measured successfully. The results of micro PIV measurement show the maximum speed of the recirculation flow is up to 10 mm/s. The high-speed recirculation can enhance a stirring effect and generate strong shear in the droplet, resulting in acceleration of mixing.

Keywords: Micro-PIV, Droplet, Recirculation flow, Microfluidic device

1. Introduction

In the commonly used micro bio/chemical analysis devices, the sample liquid and reagent are delivered continuously from the inlet port to the destination through the long microchannel. The bio/chemical analysis using a microfluidic device essentially requires only a few picoliters (pL) to nanoliters (nL) of samples in each analytical process. But, microliters (μL) to milliliters (mL) of sample volume are prepared and introduced to the inlet port of the microfluidic device in order to fill up the meandering and long microchannel with the sample liquid. This means that most of sample volume is unused. The amount of dead volume of sample liquid is not negligible if only tiny amount of sample is available or if the sample or reagent is difficult to obtain. Recently, the droplet-based microfluidic devices have been developed and investigated for the purpose of reduction of dead volume (Jones et al., 2001). The droplet-based microfluidic devices utilize discrete droplets or plugs instead of continuous flow to transport the sample liquids or materials. Only the volume required for analysis or chemical reaction is measured and transported as the form of droplet, so that the amount of dead volume is reduced.

The key issue of the droplet-based devices is handling of liquid droplets, such as transportation, metering, or mixing. Above all, the effective mixing of different liquid samples is a major issue in developing microfluidic devices since the Reynolds number is usually too small to cause turbulence in micro scale. On the other hand, the volume of pL to nL is so large in quantity that it takes long time to mix different samples completely only with molecular diffusion.

In this study, we focus on the flow in a nanoliter-sized droplet in order to develop a new effective mixing method. The internal recirculation flow in a nanoliter-sized liquid droplet is created actively by the frictional force between the droplet and the surrounding high-speed airflow to achieve effective mixing. Creating recirculation flow in a droplet is assumed to be an effective way for high-speed mixing of different liquid droplets at micro scale (Hosokawa et al., 1999). The authors have investigated the flow phenomena inside the droplet through the visualization and micro PIV measurement (Meinhart et al., 1999).

2. Experimental set-up

2.1 Micro-PIV system

The micro PIV system has been developed such that microscopic flow can be visualized and measured readily (Kinoshita et al., 2003). The schematic diagram of the micro PIV system is illustrated in Fig. 1. The micro PIV system consists of a custom-built fluorescence microscope, a cooled CCD camera with 1280 x 1024 pixels resolution and 12-bit intensity dynamic range, high-power double-pulsed Nd:YAG lasers as an illumination device, a PC workstation for analysis, a synchronizer, etc. The key feature of this micro PIV system is the reflected-light optic system with high-power pulsed lasers (Fig. 2). The laser beam passes through the objective lens and illuminates the whole flow field. Tracer particles used in this study are fluorescent particles, "Red Fluorescent Microspheres R0100" (Duke Scientific Corp.), 1.0 μm diameter. The particles are tagged with a fluorescent dye that has a peak excitation wavelength of 542 nm and a peak emission wavelength of 612 nm. The emitted light from the particles passes through an objective lens, a dichroic mirror and a long-pass filter where the reflecting illumination light (532 nm) is filtered out and only the emitted light (612 nm) was recorded onto the CCD sensor. The particle images are recorded with the cooled CCD camera using the frame-straddling technique.

The particle images are analyzed based on the two-frame cross-correlation method to estimate the flow velocity vectors. This optical system offers the field of view 510 μm x 410 μm, resulting in 0.40 μm/pixel in digital images. Velocity vector fields can be measured at 12.8 μm vector-to-vector intervals using two-frame cross-correlation method with 32 x 32 pixels interrogation spot. The measurement depth (Meinhart et al., 2000) of this micro PIV system results in 17.8 μm, which means the measurement resolution in the depth direction.

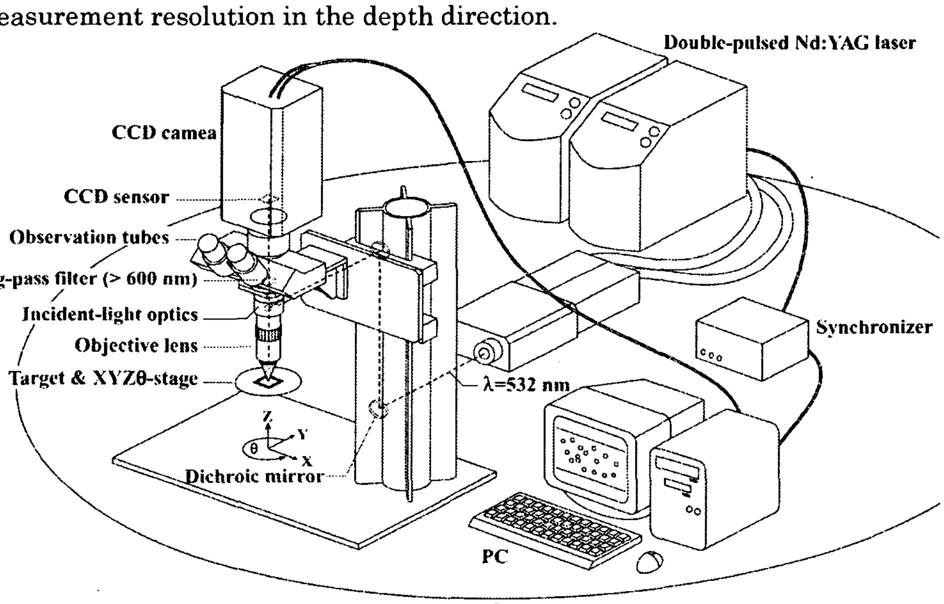


Fig.1 Schematic diagram of micro-PIV system

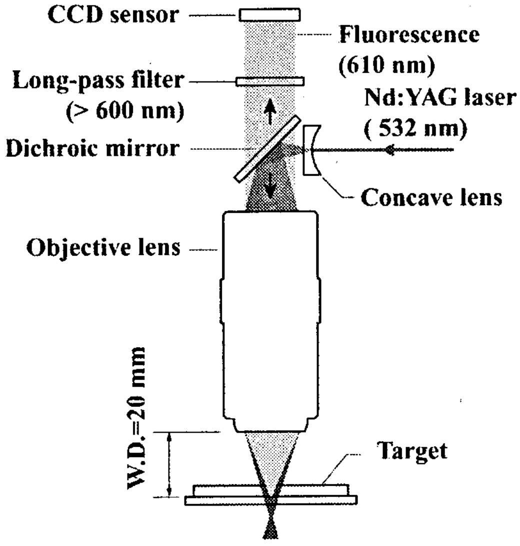


Fig.2 Optical configuration of reflected-illumination

2.2 Droplet configuration

Figure 3 shows the schematic diagram of a liquid droplet and a rectangular microchannel. The microchannel, patterned on the PDMS microchip, has the size of 200 μm (W) X 130 μm (H). The patterned PDMS replica is covered and sealed with a slide glass (Hong et al., 2001). A droplet of distilled water, mixed with the fluorescent particles (1.0 μm diameter), is fixed on the bottom surface of the channel, and then the high-speed airflow is generated around the droplet by the syringe. The water-based small droplet becomes attached to the bottom surface consequently because the bottom glass surface of the microchannel is hydrophilic and meanwhile the PDMS top surface is hydrophobic (McDonald et al., 2000). The PDMS-glass microchip is placed on the stage of the microscope for flow visualization and PIV measurement. The inside of the droplet can be observed from the bottom surface of the microchannel using both the microscope and the micro PIV system.

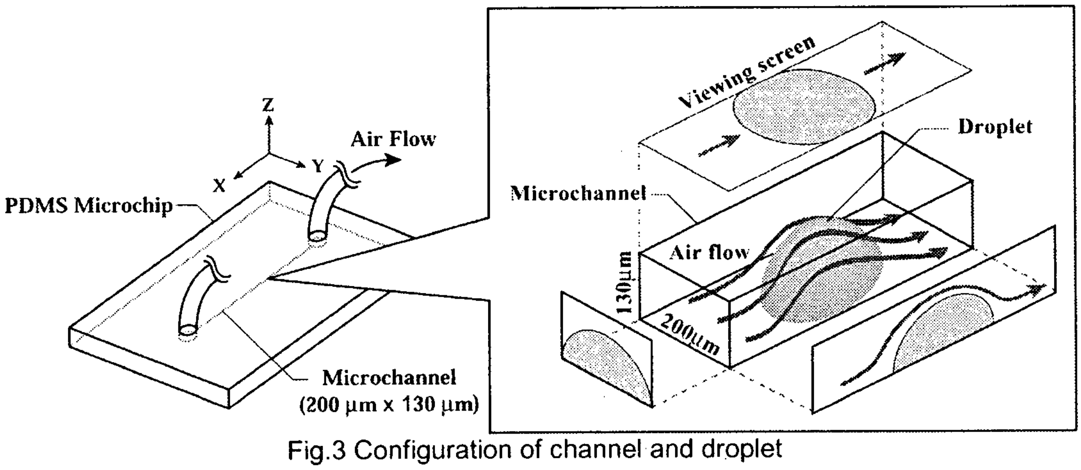
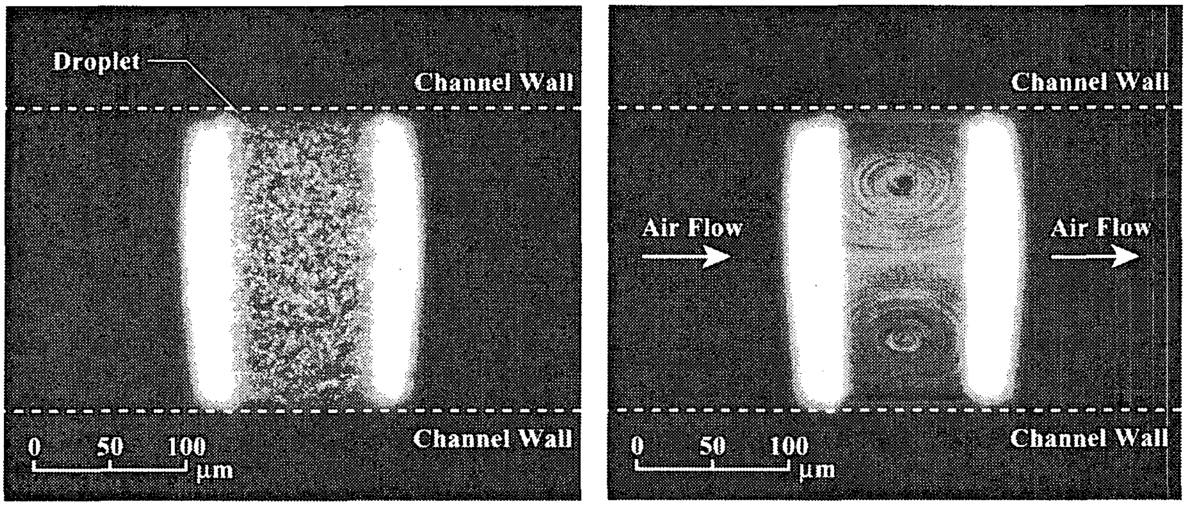


Fig.3 Configuration of channel and droplet

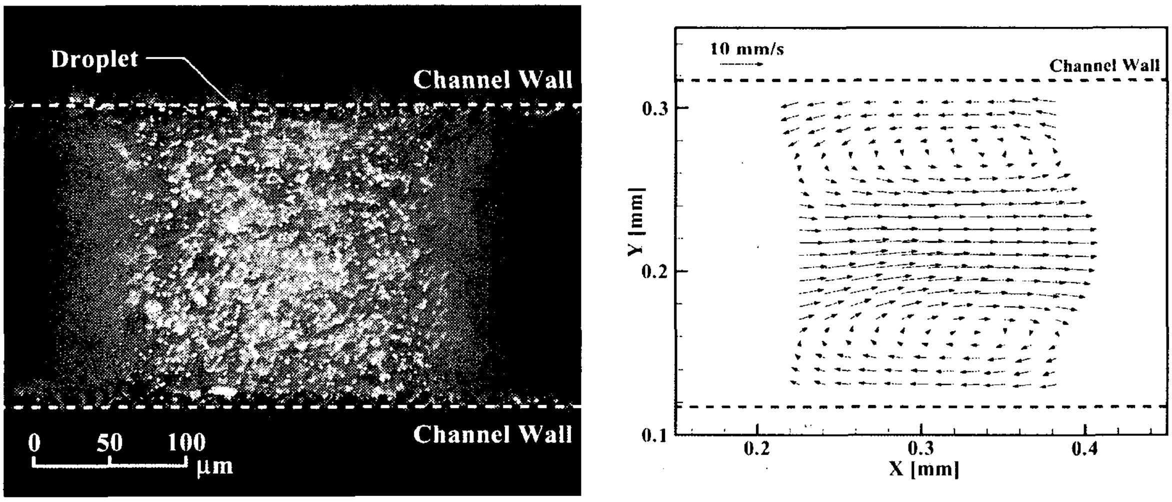
3. Flow visualization and PIV measurement

The internal flow in the nanoliter-sized droplet was visualized using a commercial fluorescence microscope and a high-resolution CCD video camera that offers 1000 x 1000 pixels resolution and a frame rate of 30 frame per second. The fluorescent tracer particles in the droplet are illuminated by a continuous light. The CCD video camera records the path lines of the fluorescent particles moving with the flow while the shutter is open. Although the recirculation flow in a small cylindrical cavity at a low Reynolds numbers was mathematically analyzed (Duda et al, 1971), no experimental data have been presented. Figure 4 shows the flow pattern in the droplet. The symmetrical pattern of the recirculation in the droplet along the axis of the airflow can be successfully visualized. The airflow sweeps over the surface of the droplet and the frictional force drags the liquid on the round interface, which leads to the recirculation flow in the droplet. Figure 5 shows the result of PIV. The velocity field of the recirculation flow is measured by the micro PIV system. This velocity vector map represents the average of 100 instantaneous velocity vector maps. The maximum speed of recirculation flow is up to 10 mm/s as shown in Fig. 5. The Reynolds number based on the maximum velocity 10 mm/s and the droplet size 200 μm is about 2. Even though the turbulent diffusion never occurs, the high-speed recirculation can enhance a stirring effect and generate strong shear, resulting in acceleration of mixing.



(a) without airflow (b) with airflow

Fig.4 Visualization of the internal flow in a droplet



(a) Particle image (b) Velocity vectors

Fig.5 Results obtained from micro PIV

4. Conclusion

The internal flow in a nanoliter-sized droplet was successfully visualized and measured using the present micro PIV. The high-speed recirculation flow (U_{max}~10 mm/s) was generated inside the droplet applying the airflow. The paper presented the effective mixing scheme based on the recirculation flow inside a droplet so as to develop the effective and useful micro mixing device.

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