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A Micro Particle Image Velocimetry System for Velocity Field Measurement in a Microchip Droplet-Forming Flow

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Abstract

A micro particle image velocimetry (microPIV) system incorporating a trigger device that enables the repeat measurement of velocity fields around droplets generated in microfluidics has been developed. The system includes a microscope, a double-pulse laser system, a trigger system and a double shutter camera. Water droplets are generated in a continuous oil phase within a polydimethylsiloxane microchip using a co-flow focusing method. Fluorescent particles are incorporated into the oil phase as seeding particles, and the oil and water are pumped into the microchip through microbore tubes. As a droplet travels through a detection zone and passes the trigger point, the microPIV imaging system takes double images of the droplet. These double images are subsequently used in calculating the field using a double-frame cross-correlation function and in-house software. The system significantly increases the calculation quality by using the average of 100 sets of the double PIV images.

Introduction

Over the past decade, droplet generation in microfluidic structures has been widely studied. Monodispersed droplets have attracted attention for their possible applications in the fields of physics, chemistry, mechanics, electronics, materials science and biology [1-5]. However, the mechanisms of droplet generation, especially the liquid flow fields around droplets immediately after formation, are not yet well understood.

Particle image velocimetry (PIV) is a well-established measurement technique for macroscopic flows. It is a whole-field, non-intrusive measurement technique, whereby fluid velocity is measured by recording the displacement of small tracer particles added to the fluid. A single PIV measurement produces a velocity vector field of high spatial resolution. Fluorescent imaging is typically used to enhance the signal and overcome diffraction effects due to small particle size.

To access the small scales of microfluidic devices, resolution can be improved to less than one micrometre using a microscope equipped with the appropriate optics. A microPIV system normally consists of a CCD (Charge Coupled Device) camera, a microscope with a fluorescence unit, fluorescent tracer particles, and a Hg arc lamp or pulsed Nd:YAG laser for continuous or pulse illumination [6-8]. Multiple experimental images are acquired and analysed using particle tracking or spatial correlation methods to obtain the fluid's velocity from the displacement of particles [7]. The use of double PIV images of flow around droplets/bubbles at the same position would be very advantageous in CFD applications, as it would increase the quality of the velocity vector imaging and thereby aid in comparing the results from CFD calculations with those from experimental observations[9].

The aim of this study is to increase our understanding of the mechanisms of droplet formation in microfluidics, and in particular the velocity fields around these droplets, using a microPIV system incorporating a trigger device.

Methodologies

The microPIV system presented in this paper has been developed for measuring flow fields around water droplets formed in a polydimethylsiloxane (PDMS) microchip using a co-flow focusing method (figure 1). The 70 µm deep PDMS microchannel was fabricated using a nickel shim as a moulding system [10]. A 50 µm wide nozzle was designed for droplet formation and a 200 µm wide expanded channel was used to reduce the speed of droplets and oil. The continuous phase comprised mineral oil incorporating fluorescent microspheres, and the dispersed phase was purified deionised water. To prepare the oil phase, a fluorescent microsphere solution in deionised water at 1% solid by weight was purchased. The 0.6 µm diameter microspheres were made of polystyrene and were dyed with red fluorescent dyes (emission wavelength of 612 nm). The microspheres were mixed with the mineral oil to a concentration of 1% via a two-hour ultrasound treatment. The stock solution of fluorescent particle oil diluted to 0.2% and was filtered through a 1.2 µm filter (Pall) to remove stacked particles before each experiment. The oil and the water were injected into the PDMS microchannels through a 0.3 mm internal diameter microbore tube at designed flow rates using syringe pumps.

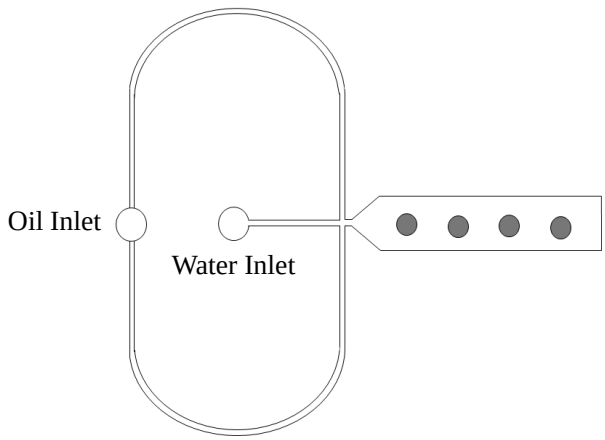

Figure 1. Schematic of co-flow focusing droplet generation chip. All channels are 70 µm deep and 50 µm wide, except the droplet collection channel which is 200 µm wide.

As shown schematically in figure 2, the microPIV system set-up consists of a Nd:YAG double-pulsed laser system (NEW WAVE minilase-3/15 Hz, each with 5 ns pulse length), a red laser (model 155SL helium-neon laser, 0.95 mW) with a high-speed mechanical shutter, a microscope equipped with a PIV filter cube, a high-speed CCD camera (sensicam/670KD) with a double shuttle mode, a syringe pump system, a multifunction card (NI), a photo receiver, and a PC for synchronisation, acquisition and system control.

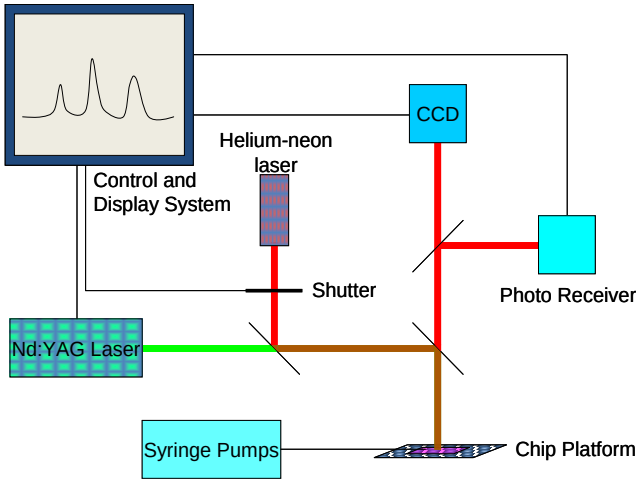

Figure 2. Schematic of microPIV system set-up.

Imaging is performed via a NIKON ECLIPSE TE2000-E system microscope equipped with a NIKON Planfluo 60× objective lens and a PIV filter cube. The PIV filter cube is equipped with a dichromatic mirror to reflect the illuminating wavelength of 532 nm, and a barrier long pass (emission) filter with a pass wavelength of 570 nm, i.e. allowing the fluorescent signal emitted from seeding particles to pass. The excitation filter is removed from the PIV cube to let red laser beam pass through. The fluid flow is illuminated by the Nd:YAG double-pulsed lasers, which are optically connected by half-mirrors such that the beam from each exiting laser has the same direction and appears to originate from the same point in space. The trigger system applies the red laser beam to detect a droplet passing through the detection zone and trigger the microPIV imaging system. As a droplet passes through the detection zone, the direction of red laser is changed and a photo receiver detects the variation of the red laser beam. In-house software using Labview coupled with a multifunction NI card is used to control the shutter to cut off the red laser. Subsequently, the camera and the double-pulsed lasers are triggered to take the double images, which are recorded with a matrix of 1,024×512 pixels and a 12-bit intensity resolution. The velocity field can then be computed with a double-frame cross-correlation function using Matlab software.

Results and Discussion

Fluorescent particles emit a long wavelength light when excited by a short wavelength light. The fluorescence helps to improve the contrast and visibility relative to the background, and thus optimise the PIV image quality. Therefore, the choice of seeding particles is extremely important for microPIV experiments, as particle properties directly affect the accuracy and spatial resolution of measurements. One of the inherent assumptions in PIV is that nano-sized tracer particles faithfully follow the flow without exerting any influence on the flow itself. Thus, particle density should closely match the density of the fluid so that, in zero velocity conditions, particles remain suspended in the fluid without sinking or floating to the surface, due to the balance between gravitational force and buoyancy. While a great variety of water-based solutions containing polystyrene beads at a density of 1.05 kg/L are commercially available, no oil-based fluorescent particle solutions are, and thus our need to source seeding particles for the continuous oil phase from the fluorescent microsphere/water solution.

A consequence of volume illumination is that all particles in the illuminated fluid volume emit fluorescence, not only those residing in the focal plane of the imaging optics. Particles outside the focal plane generate a background noise, and thus reduce the signal-to-noise ratio (SNR) of the PIV images, however measurements show that higher SNR can be obtained by either reducing the channel depth or the particle concentration. In most cases where the microchannel of interest is designed to serve a certain microfluidic purpose, the geometrical dimensions of the channel are predefined and hence channel depth cannot be altered. In such cases, particle concentration is the major adjustable parameter, and it is apparent that this should be chosen with great care in order to obtain particle images of adequate quality for correlation analysis. After a series of experiments with different particle concentrations, the fluorescent particle oil solution with a weight concentration of 0.2% has been chosen for the PIV imaging.

Droplets were generated at a liquid flow rate of 1 µL/h and an oil flow rate of 10 µL/h. A sample image of the visualised flow field is shown in figure 3, where it shows that at these flow rates, the droplets kept reasonable pace with each other in the oil flow.

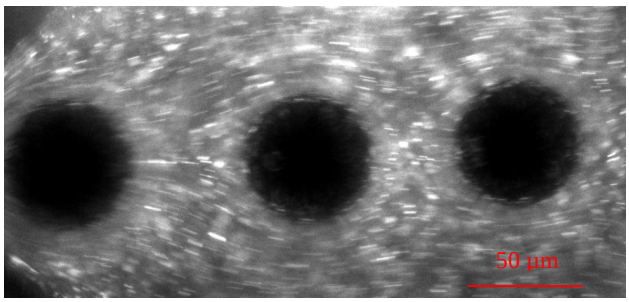

Figure 3. CCD image of the droplets generated at a liquid flow rate of 1 µL/h and an oil flow rate of 10 µL/h.

The microPIV system's red laser is focused on the middle of the detection zone in which the main channel for droplet generation is positioned at the centre. When a droplet passes through the detection zone, the direction of the red laser is varied and the photo receiver responds to this change (figure 4). In-house software using Labview has been developed to recognise the peaks and control the trigger system that activates the microPIV imaging system. The photo receiver responds by triggering a shutter to cut off the red laser, and after a 5 ms pause, the double shutter camera is triggered to record a set of double images. After a 50 µs delay, the dual-Nd:YAG laser system flashes at 50 ms intervals. With this trigger system, the microPIV imaging system records all images of droplets at the same position and provides repeatable flow around droplet in the microchannel, which increases the quality of velocity profile simulation using CFD methods.

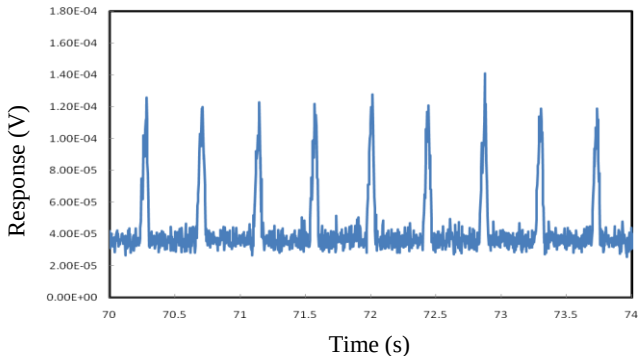

Figure 4. Signal of droplets passing through the red laser detection zone.

With careful control of droplet generation rate, each set of PIV images only contains one droplet (figure 5) and the position of the droplet in the image can be reproduced. The velocity vector field is calculated by in-house software using Matlab and clearly demonstrates the flow around the droplet (figure 6). Due to the benefit of repeatability, 100 sets of PIV images can be averaged to obtain the computational velocity field (figure 7). Obviously, the velocity field calculation obtained from the averaged images provides a clearer picture than the calculation from one set of images.

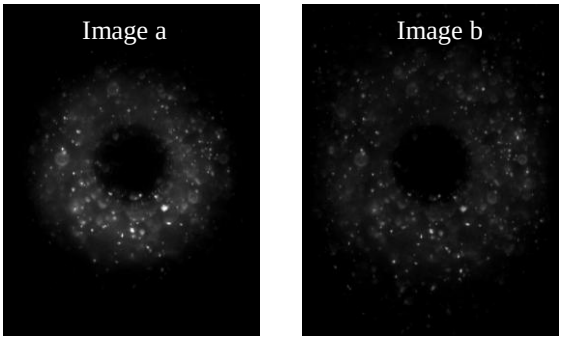

Figure 5. The double PIV images of droplet-forming flow.

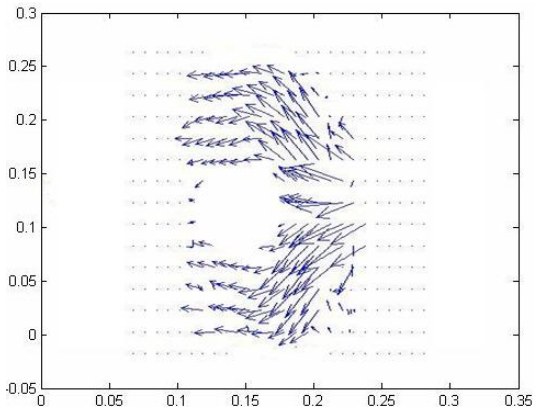

Figure 6. The computational velocity field from one set of double images.

Conclusions

A new approach of the microPIV technique has been developed that is applicable to the measurement of velocities in a liquid–liquid (water–oil) flow. A trigger device provides a microPIV system that is capable of taking repeatable images of droplet-generating flow. This technique increases the quality of experimental data for CFD simulations of velocity fields, in turn providing deeper insight into the physical phenomena occurring

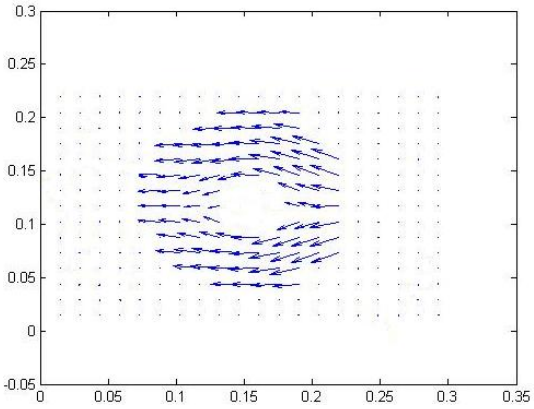

Figure 7. The computational velocity field from averaging 100 sets of double images.

during drop formation and detachment in a two-phase system. The results will also be valuable in validating future numerical simulations in numerous fields such as the investigation of gas–water flow.

References

[1] Wu, N., Oakeshott, J., Brown, S., Easton, C., Zhu, Y., Microfluidic Droplet Technique for In Vitro Directed Evolution, Australian Journal of Chemistry. 63 (2010) 1313–1325.

[2] Zhu, Y., Power, B.E., Lab-on-a-chip in Vitro Compartmentalization Technologies for Protein Studies, in: Werther, M, Seitz, H (Eds.), Protein-Protein Interaction, Springer-Verlag, Berlin, 2008, pp. 81–114.

[3] Wu, N., Zhu, Y., Brown, S., Oakeshott, J., Peat, T.S., Surjadi, R., et al., A PMMA microfluidic droplet platform for in vitro protein expression using crude E. coli S30 extract, Lab Chip. 9 (2009) 3391–3398.

[4] Wu, N., Courtois, F., Zhu, Y., Oakeshott, J., Easton, C., Abell, C., Management of the diffusion of 4-methylumbelliferone across phases in microdroplet-based systems for in vitro protein evolution, ELECTROPHORESIS. 31 (2010) 3121–3128.

[5] Cristini, V., Tan, Y.-C., Theory and numerical simulation of droplet dynamics in complex flows-a review, Lab on a Chip. 4 (2004) 257–264.

[6] Lindken, R., Rossi, M., Gro, Westerweel, J., Micro-Particle Image Velocimetry ([micro sign]PIV): Recent developments, applications, and guidelines, Lab on a Chip. 9 (2009) 2551–2567.

[7] Williams, S., Park, C., Wereley, S., Advances and applications on microfluidic velocimetry techniques, Microfluidics and Nanofluidics. 8 (2010) 709–726.

[8] Zhang, H., Chon, C., Pan, X., Li, D., Methods for counting particles in microfluidic applications, Microfluidics and Nanofluidics. 7 (2009) 739–749.

[9] Walsh, P., Egan, V., Walsh, E., Novel micro-PIV study enables a greater understanding of nanoparticle suspension flows: nanofluids, Microfluidics and Nanofluidics. 8 (2010) 837–842.

[10] Chen, C., Zhu, Y., Leech, P.W., Manasseh, R., Production of monodispersed micron-sized bubbles at high rates in a microfluidic device, Applied Physics Letters. 95 (2009) 144101.