Three-dimensional measurement of micro- multiphase flow using digital holographic microscopy

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ABSTRACT

This study aims to develop three-dimensional measurement method using digital holographic microscopy (DHM) to investigate the unsteady micro- multiphase flow phenomena. The advantage of DHM is the direct three-dimensional measurement method using single camera based on analysis of phase information obtained from holographic images. Furthermore, we tried simultaneous measurement of two important information about the micro- multiphase flow. There are the interfacial geometry and the inner flow structure of micro droplet by applying frequency separation technique.

1. Introduction

During the last decade, many microfluidic devices have been developed for bio- chemical fields (Reyes et al., 2002). Especially the droplet-based microfluidic systems are applied for many kinds of useful applications such as mixing, sensing, chemical reaction and so on (Song et al., 2006). They use two immiscible fluids like oil and water, or liquid and gas.

The efficiency of mixing depends on the intensity of three-dimensional flow inside the droplet that is generated by the drag forces from surrounding flow and channel wall. On the other hand, micro droplets are generally formed at the micro junction. The mechanism of droplet formation is based on the relative effect of viscous force versus interfacial tension between two liquids. Therefore, the measurement of three-dimensional interfacial geometry and flow structure is necessary to clarify these phenomena.

Previously, we succeeded to measure the velocity field of droplet phenomena using confocal micro-PIV (Particle Image Velocimetry) (Oishi et al., 2011). It can reconstruct three-dimensional flow structure by piling up two-dimensional PIV results and using continuity equation to
calculate out-of-plane velocity component. But it’s not a direct three-dimensional measurement method and it has many difficulties in measuring interfacial geometry.

In order to measure the three-dimensional flow and the interfacial geometry, digital holographic microscopy (DHM) is an ideal tool. The DHM is a kind of interferometry and it takes two-dimensional interference pattern (hologram) into single digital imaging device. This hologram includes three-dimensional information of a target object and it can be reconstructed numerically by computer. It means the DHM can obtain three-dimensional information without spatial scanning.

2. Method

Figure 1 shows the schematic illustration of developed DHM system (UDHM-01, Ushio Inc., JAPAN), which consists of an off-axis holographic/interferometric optical components (Matsuo et al., 2012). A single-mode green laser (Juno 532nm, Showa Optronics Ltd., JAPAN) was used as a light source, and a High-speed CMOS camera (FASTCAM SA-Z, Photron Ltd., Japan) was used as an imaging device. This system also has GPU-powered GUI software which can reconstruct the intensity and the phase image from original holographic image in real time (Figure 2). This feature also helps intuitive understanding of flow phenomena during experimental setup.

![Fig. 1 Optical design of the DHM system.](image-url)
The target microfluidic channel with T-shaped junction, which generates droplets, is shown in Figure 3. The working fluids are a Silicone oil (KF-6001, Shin-Etsu Chemical Co., Ltd., Japan) as a continuous phase and water/glycerol solution as a dispersed (droplet) phase. Since DHM detects the difference of refractive index between two materials, the silicone oil was chosen to match the refractive index of 1.4125, the same as that of the PDMS material of the channel wall in order to prevent optical distortion between the channel wall and the continuous phase. On the other hand, the refractive index of water/glycerol solution was adjusted to make difference between that of continuous phase. The adjusted value of 1.3093 is an ideal for detecting entire interfacial geometry with high dynamic range. The other information of working fluids and flow conditions are shown in Tab. 1.

Table 2 lists the configurations of the DHM measurement setup. φ 2 µm tracer particle (R0200, Thermo Scientific, USA) which has a refractive index of 1.59 was mixed into the dispersed phase for the measurement of flow velocity with PTV (Particle Tracking Velocimetry) algorithm. Since the particle volume density is limited to avoid overlapping of each particle images, the temporal phase-locked measurement is effective for increasing the number of velocity data points. Then, the phase adjustment system (Oishi et al., 2013) was applied to make a camera trigger for adjusting temporal phase and droplet conditions. As a result, only the droplets which have generation period of 385 msec were measured.

The key technique for simultaneous measurement of interfacial geometry and flow structure is separating phase information between that from interfacial geometry and that from tracer particles. Although these two phase information are overlapped on the phase image, we developed the separation technique using different frequency of phase pattern which comes from different size scales.
Fig. 3 Schematic illustration of droplet formation device with T-shaped junction.

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<th>Tab. 1 Specifications of working fluids and flow conditions.</th>
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<td>Working fluid</td>
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<td>Reflective index</td>
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<td>Specific gravity [g/cc]</td>
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<td>Flow rate [µl/min]</td>
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<td>Bulk flow velocity [mm/s]</td>
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<th>Tab. 2 DHM Setup.</th>
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<td>Tracer particle</td>
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<td>Objective lens</td>
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<td>Measurement region</td>
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<td>Camera frame rate</td>
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<td>Camera exposure time</td>
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<td>Particle volume density</td>
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3. Results

As shown in Figure 4, intensity images (b) and phase images (b) can be reconstructed from holographic images (a) at each height with desired gap. The three-dimensional interfacial geometry (Fig. 5(a)) is successfully obtained by unwrapped phase image (Fig. 5(b)). Although
there are small phase deformation derives from tracer particles in the phase image, they are canceled out by filtering high frequency information. On the other hand, we can detect tracer particles inside the dispersed phase by canceling out the low frequency phase information of interfacial geometry. After canceling out the effect of interface, three-dimensional position of tracer particles are identified by pattern matching of wavefront just above the tracer particles. Finally, three-dimensional flow structure can be calculated by using simple PTV algorithm (Figure 6).

Fig. 4 Original holographic image (a) and reconstructed Intensity image (b) and phase image (c) at center height of the channel.

Fig. 5 3D interfacial geometry of droplet formation (b) obtained from the unwrapped phase image (a)
Fig. 6 (a) Low frequency-cut phase image of dispersed phase. (b) Particle trajectory between consecutive nine time frames. (c) Three-dimensional velocity distribution inside the dispersed phase (PIV result of 10 droplets are overlapped).

4. Conclusions

Our developed DHM system has high applicability for the measurement of micro three-dimensional phenomena due to the off-axis formation and powerful GUI. It has great advantages of real-time observation and quantitative phase measurement. Additionally, the
frequency separation technique enables simultaneous measurement of large scale interfacial geometry and flow structure inside the working fluid. So this system has a great potential for the measurement of the random motion of living target and the high-speed imaging because the hologram doesn’t need strong illumination.

By applying DHM for the droplet microfluidics, we successfully measured not only the three-dimensional interfacial geometry, but also three-dimensional flow in the emerging droplet. These information is necessary to estimate the force balance between interfacial tension and interfacial shear stress for the investigation of droplet formation mechanism.

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**References**


