MEASUREMENT OF THREE DIMENSIONAL FLOW STRUCTURE OF DROPLET FORMATION MECHANISM IN T-SHAPED JUNCTION USING PHASE-LOCKED CONFOCAL MICRO-PIV

M. Oishi1 , H. Kinoshita1 , T. Fujii1 and M. Oshima1,2

1Institute of Industrial Science, The University of Tokyo, JAPAN and
2Interfaculty Initiative in Information Studies, The University of Tokyo, JAPAN

ABSTRACT

This paper aims to investigate a mechanism of microdroplet formation at a micro T-shaped junction using a “phase-locked multicolor confocal micro-PIV (Particle Image Velocimetry)” technique[1]. The multicolor system can measure dynamic behavior of each phase of multiphase flow separately and simultaneously. Additionally, the phase-locking technique enables picking up same condition of droplet formation frequency and translational velocity of droplet to minimize instability of droplet formation phenomenon.

The phase-locking technique is necessary to reconstruct three-dimensional flow field from two-dimensional confocal micro-PIV measurement data. We successfully obtained each phase of periodic phenomenon non-invasively by detecting passage of droplet from transmitted light of optical proximity sensor. As a result, three-dimensional flow structure of the droplet formation was successfully reconstructed and the differences in droplet formation mechanisms associated with flow conditions was investigated.

KEYWORDS: Droplet Formation, T-shaped Junction, Confocal Micro-PIV, Phase-locked, Three-dimensional Flow

INTRODUCTION

The droplet-based microfluidic systems are developed for many kinds of useful applications such as mixing[2], sensing, chemical reaction and so on. In these systems, micro droplets are formed in a micro junction using two or more different types of immiscible liquids like an oil and a water. The small volume of droplets has many advantages such as rapid reaction, sample saving, quantitative analysis and easy handling due to separated compartment without diffusion.

It is important to clarify the mechanism of micro-droplet formation in simple T-shaped junction in order to predict a droplet size and production rate. The droplet formation mechanism changes from “squeezing” to “dripping” at a critical Capillary number \(Ca\), which indicates the force balance between viscous force (product of continuous flow viscosity \(\mu_c\) and velocity \(u_c\)) and interfacial tension \(\gamma\) in following equation (1) [3, 4].

\[
Ca = \frac{\mu_c u_c}{\gamma}
\]  

(1)

Although temporal and continuous information of three-dimensional interfacial geometry and velocity distribution are required to clarify this mechanism, previous measurement techniques couldn’t measure the transient behavior of interface and flow structure. In order to evaluate these mechanisms, quantitative measurement technique is necessary. Confocal micro PIV [5] can measure the two-dimensional in-plane velocity distributions with high spatial and temporal resolution by analyzing fluorescent images of tiny tracer particles, which are dispersed into the fluid. In addition, since the out-of-plane velocity can be derived from the continuity equation using in-plane velocity measured by PIV. The present method can provides us not only three-dimensional geometry of flow structure but also three-dimensional velocity field of each phase.

In order to reconstruct three-dimensional flow structure, we have developed phase-locking technique using noninvasive optical proximity sensor with programmable logic controller(PLC) for camera trigger. The optical fiber sensors are inserted near the micro junction and it can detect the evolution of droplet formation. The droplet size and production timing are computed and selected with narrow threshold by the PLC, and this information is used for making camera trigger. Although Nguyen et al [6] developed similar system, they just measured droplet formation frequency and didn’t use these information for making camera trigger.

EXPERIMENTAL CONDITIONS

Figure 1 is a schematic illustration of a droplet formation device with a T-shaped junction, which has width \(w = 100 \mu m\) and depth \(h = 80 \mu m\). And conditions of micro-PIV measurement are shown in Tab. 2. From the preliminary experiment, the droplet changes between \(Ca = 2.0 \times 10^{-3}\) from squeezing to dripping in our experimental condition. Thus we chose two condition of \(Ca = 1.63 \times 10^{-3}\) and \(9.81 \times 10^{-3}\) varying flow rate of continuous phase.

The piezoelectric device can control z-position of objective lens precisely. Each measurement plane is set every 3 \(\mu m\) pitch in the z-direction, and we can calculate three-dimensional velocity field by piling up velocity data of these planes. In order to calculate out-of-plane velocity component, the continuity equation and the boundary condition are applied.

RESULTS AND DISCUSSION

The phase-locking system can pick up the same size of droplet. It reduces deviation of droplet formation period and translational velocity from over 5% to less than 1%. It can also improve accuracy of estimation of out-of-plane velocity component when we apply three-dimensional reconstruction of velocity field.
As a result of Micro-PIV measurement and three-dimensional reconstruction of flow structure, we obtained distributions of vertical velocity component and streamlines of each liquid shown in Figs. 2 and 3. In this study, we considered the symmetry of flow structure at the mid plane (center height). Therefore, the vertical velocity component becomes zero at the mid plane, and we use this assumption for the boundary condition. The calculation proceeds from the mid plane to the near wall plane. The normalized time phase of these pictures is $t / t_{\text{period}} = 0.45$ from droplet formation.

In case of low Capillary number “squeezing” condition, the tip of to-be-dispersed phase almost attaches to the opposite channel wall and clogs up the main channel. It results in low shear stress on the interface of to-be-dispersed phase and planer flow structure inside to-be-dispersed phase.

In contrast, in case of high Capillary number “dripping” condition, the curvature of the interface becomes larger than that of low Capillary number condition because of strong shear stress by continuous phase flow. This interfacial geometry also produces strong three-dimensional flow structure and vortex in the tip of to-be-dispersed phase, and it results in smaller droplet generation.

**Figure 1: PDMS-based T-junction microchannel**

**Table 1. Conditions of Micro-PIV Measurement**

<table>
<thead>
<tr>
<th></th>
<th>Continuous phase (inlet A)</th>
<th>To-be-dispersed phase (inlet B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working fluid</td>
<td>Silicone oil: KF-6001</td>
<td>Water / Glycerol solution</td>
</tr>
<tr>
<td>Flow rate [μl/hr]</td>
<td>8.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Average flow velocity [mm/sec]</td>
<td>0.494</td>
<td>2.469</td>
</tr>
<tr>
<td>Capillary number</td>
<td>$1.63 \times 10^{-3}$ (Squeezing)</td>
<td>$9.81 \times 10^{-3}$ (Dripping)</td>
</tr>
<tr>
<td>Tracer particle</td>
<td>$\phi$ 0.9 ~ 1.4 μm</td>
<td>$\phi$ 1.0 μm</td>
</tr>
<tr>
<td></td>
<td>Green Fluorescent / silica</td>
<td>Red fluorescent / polystyrene</td>
</tr>
<tr>
<td>Measurement Depth [μm]</td>
<td>3.10 ~ 3.84</td>
<td>3.34</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.412</td>
<td></td>
</tr>
<tr>
<td>Interfacial tension [mN/m]</td>
<td>11.1</td>
<td></td>
</tr>
</tbody>
</table>

(a) Low Capillary number condition  
(b) High Capillary number condition

**Figure 2: Distribution of ratio of vertical velocity component**
CONCLUSION
By applying phase-locking technique with optical proximity sensor, the accuracy of three-dimensional reconstruction of two-dimensional confocal micro PIV data improves drastically. It enables to measure and estimate three-dimensional flow structure of transient droplet formation mechanism. From the investigation of flow structure of different droplet formation mechanism, the ratio of $w$ velocity component and vortex structure play an important role for the mechanism.

For further investigation, we have to analyze results along with entire time period and under the different physical conditions. From these results, the force balance between interfacial tension and viscous force will be able to be investigated.

ACKNOWLEDGEMENTS
This research was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) – Japan through “Grant-in-Aid for Young Scientists (B), 21760121, 2010”.

REFERENCES

CONTACT
*M. Oishi, tel: +81-3-5452-6205; Oishi@iis.u-tokyo.ac.jp