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Short Paper

Measurement of Two Overlapped Velocity Vector Fields in Microfluidic Devices Using Time-Resolved PIV

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1. Introduction

Chaotic micromixers (Stroock et al., 2002) are well-known microfluidic devices with inclined ridges, which form grooves inside of the microchannel to reduce the mixing length by creating transverse velocity components and three-dimensional flows.

In micro particle image velocimetry (PIV), the thickness of the measurement volume is determined by depth-of-field (DOF) of the objective lens. Even if a large numerical aperture (NA) lens is used, the DOF may be the order of several μm's. When the depth of grooves is around 5-10 μm, which is almost equivalent to DOF, realization of the velocity field near the groove becomes problematic with the classical PIV evaluation due to the existence of the tracer particles having different velocities in the same measurement volume. Complexity of the flow and relatively high magnitude of the velocities reduce the confocal microscopy applicability to velocity measurement in the chaotic micromixers.

Time-resolved (TR) micro PIV system has been also widely used in the microfluidic measurements (Shinohara et al., 2004). Since the huge amount of temporally fine resolved flow images (~ 5GB) are captured in 1 seconds, velocity field near the groove area can be extracted using this amount of temporal information, even from the images recorded with the thick DOF's. This paper proposes two overlapped velocity field extraction method from two-dimensional (2D) TR micro-PIV images, one is the velocity field inside the groove and the other is the velocity field over the groove.

2. Experimental Setup

A high speed camera (Photron APX RS, 1K x 1K pixels@3kHz) and Nd:YAG CW laser (532 nm) were used to visualize the internal water flow, which was seeded with 1 μm diameter fluorescent particles at a concentration of 0.4 % by volume. Flow images were recorded via an epifluorescence microscope, which has the DOF of 7.1 μm with a water-immersion objective lens (M = 40, NA = 0.8). Focal plane of the optical system was fixed at the height of 6 μm from the bottom surface. Schematic view of the rectangular PDMS microchannel with obliquely oriented ridges on the bottom surface is shown in Fig. 1.

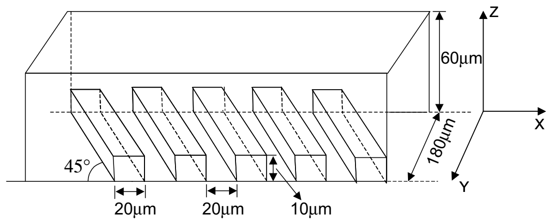

Fig. 1. Schematic of the micro channel.

3. Method of Analysis, Results, and Discussions

The particles both moving in the groove regions and moving above the ridges are in range even they are focused with different levels because of the thick DOF. That characteristic movement of particles is observed as if some particles move with smaller speeds in the direction of grooves, some particles move along the streamwise direction with relatively higher speeds on the 2D TR-PIV recordings. Unlike the normal PIV images, there are two different velocity vectors at a spatial grid position on the 2D image plane. When one applies the PIV interrogation for these images, correlation value becomes so weak and it would not yield an accurate pattern matching. In the laminar and steady flow measurements utilizing micro-PIV systems, ensemble correlation averaging method has been proposed to obtain the main correlation value whilst eliminating the surrounding noisy peaks (Wereley et al., 2002). In this present study, PIV evaluation was performed according to the Eq. (1):

$$R_{\tau}(m,n)=\frac{1}{Z}\sum_{k=1}^{Z}C_{(k,k+\tau)}(m,n) \quad (1)$$

Where, $C_{(k,\,k+\tau)}(m,n)$ is the classical cross-correlation function at a point *(m, n)* in the interrogation area between the k^{th} and $(k+\tau)^{th}$ images. Z is the total number of images. Here, τ is the most significant parameter described as time interval or number of images to be skipped.

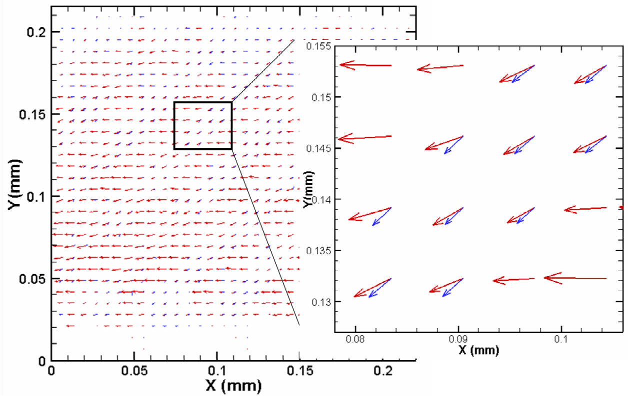

Fig. 2. Vector map (red:fast /blue:slow).

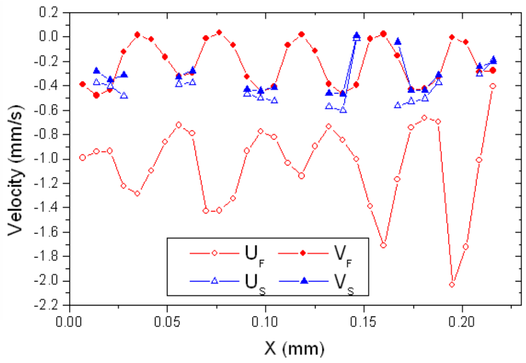

Fig. 3. Measured velocities, for a spanwise coordinate at y = 0.14 mm.

R_{τ} is the average cross-correlation value at a point *(m, n)*. Time-resolved image data of Z = 14000 were recorded with 512 x 512 pixels resolution at 10 kHz by fixing the focal plane at the altitude of 6 μm from the bottom surface of the channel. Flow images were evaluated, during the interrogation process; τ was altered as 10 (1 ms), 40 (4 ms) images in order to detect the different displacements inside an interrogation area. The flow was laminar with the Reynolds number of 0.32 with an average velocity of 1.5 mm/s. Figure 2 shows the velocity vector map of the overlapped two kinds of vector fields. The blue ones belong to slow particles which are moving in the grooves, the red ones belong to fast particles moving above the ridges.

Measured velocities at a spanwise position of y = 0.14 mm are plotted for all locations along the streamwise direction in Fig. 3 with the same color scheme; U and V denote the streamwise and spanwise velocity components respectively. The fast particles enter the groove and move along the groove by gaining a transverse velocity component, which has almost similar magnitudes with the slow particles conceivably. Then, they step into the next groove by sliding through the ridge surface with a high streamwise velocity component. The slow particles are moving along the groove with low velocities, their velocity components have almost same magnitudes, which is pertinent to the 45^{o} groove inclination. The created transverse velocity components which are responsible for the chaotic mixing by causing stretching and folding of the volumes of fluid could be visualized very clearly.

4. Conclusions

The TR micro-PIV system was applied to the 3D complex flow in a chaotic micromixer. Two different overlapped velocity vector field realizations were achieved on the same measurement plane using the huge amount of temporally fine resolved flow images. Even if the flow is too complicated and measurement plane is inherently thick, complex flow field near the groove region could be visualized.

References

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