Development of a High-speed Scanning Micro-PIV system

K. P. Angele, Y. Suzuki, J. Miwa, N. Kasagi and Y. Yamaguchi

Abstract A novel high-speed scanning micro-PIV system has been developed in order to provide time-resolved, pseudo-three-dimensional flow-field information. The focal plane is moved rapidly in the out-of-plane direction by changing the optical length using a rotating disc having ten glass windows with different thickness. In the present prototype system, the extent of the scanning depth is 50 μm, and the maximum scanning frequency is 100 Hz. Through a series of experiments in a two-dimensional micro-channel, it was found that the velocity data are in good agreement with the analytical solution. The fluctuation in the flow rate delivered by a syringe pump is successfully measured with the present system, and this demonstrates the applicability of the present scanning system for unsteady flow measurements.

1 Introduction

Recently, micro thermal fluids systems such as those for micro total analysis (μTAS) and micro energy conversion (Power MEMS) attract much attention. Although the flow mostly remains laminar in micro conduits of such systems, physical experiments should still play an important role in the analysis of the flow field. For instance, bio-fluid flows often include cells and/or particles and can exhibit non-Newtonian characteristics, for which numerical analysis sometimes becomes difficult. Furthermore, the cell diameter is often comparable to the channel size and consequently the velocity field is three-dimensional and unsteady.

With the recent development of micro-PIV, it has become possible to quantitatively measure the velocity field in micro-channels; see (e.g., Santiago et al., 1998; Meinhart et al., 1999; Kim et al., 2002; Devasenathipathy et al., 2003). Conventional micro-PIV is essentially a two-dimensional measurement technique, with which the velocity field in a focal plane is obtained. On the other hand, scanning micro-PIV systems, which are capable of measuring the velocity in different sections of a flow field, have also been proposed. In such, the objective lens is often moved in the out-of-plane direction using PZT drives. The drawback of such systems is that the scanning frequency is limited to a few to 10 Hz, which implies that they cannot be employed for time-resolved measurements.

The aim of the present study is to overcome this deficiency and develop a scanning micro-PIV system that can provide time-resolved, pseudo-three-dimensional flow-field information. To accomplish this, we employ a rotating disc with glass windows having different thickness in order to vary the optical length underneath the objective lens.

2 Experiments

Figure 1a shows a schematic picture of the experimental setup. The optical setup designed for micro-PIV (Seika Corp.) equipped with an objective lens having a magnification of 50 and NA=0.42 is employed. It has a relatively large working distance, which allows us to integrate the rotating scanning disc underneath the objective lens at the expense of somewhat low NA. Figures 1b and 1c show the concept of the present scanning micro-PIV. The displacement of the focal plane Δh is determined by the difference of the optical length using glass windows with different thickness. When the difference in thickness of two subsequent glass windows is ΔD, Δh is given by $\Delta D(1-n_0/n_1)$, where $n_0=1$ (air) and $n_1=1.5$ (glass). Figure 1d shows the scanning disc, which has ten small glass windows with a thickness between 500 and 625 μm with ΔD=12.5 μm. With the present configuration, Δh is 5 μm when measuring in water. Unlike conventional scanning systems, the locations of the focal plane are well defined by the thickness of the glass window, and the scanning depth can be made much larger. Moreover, the scanning frequency can be much higher regardless of the scanning depth. The disk rotates with the aid of a brushless DC motor and the rotation speed can be varied. In the present experiments, the disc rotates at 6000 rpm, which corresponds to a scanning frequency of 100 Hz.

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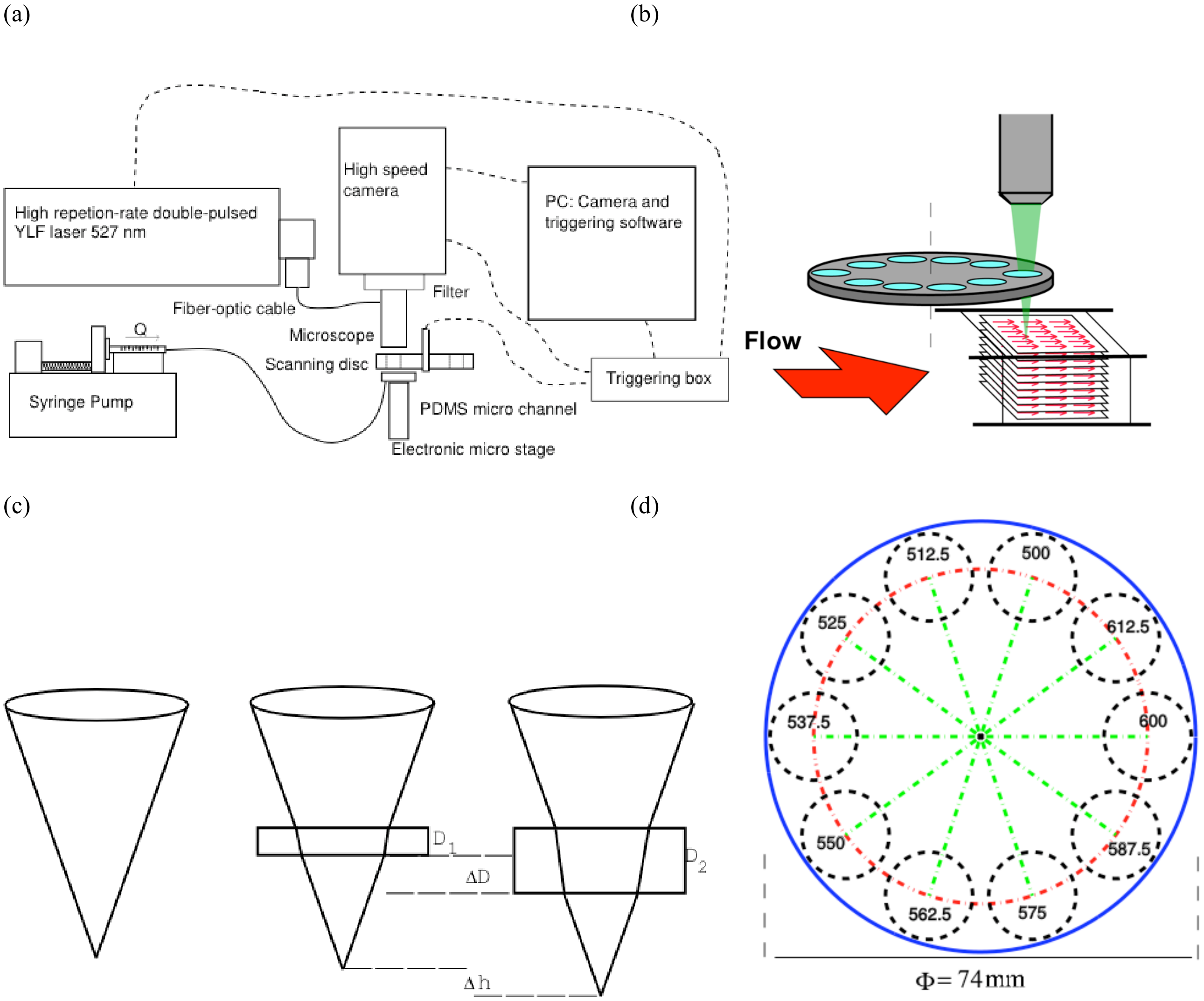

Figure 1. High-speed scanning micro-PIV system. (a) A schematic picture of the experimental setup. (b,c) Conceptual picture of the scanning principle. (d) The thickness of the ten glass pieces (μm). The thinnest glass piece is referred to as number 1 and the thickest is referred to as number 10.

The positions of the focal plane were investigated by traversing a slide glass with steady fluorescent particles using an electrical stage. The accuracy of the position of each measurement plane is within what can be determined with the electrical stage (1 μm).

A two-dimensional in-house built PDMS channel of 200 μm in width and 60 μm in depth was used in the experiment. The accuracy of the channel height and width is within about 1% of the designed value. A syringe pump (Harvard 22, Harvard Apparatus) provides a nominally-constant flow rate of water at 0.2 μl/min. A high-speed CMOS camera (Phantom VII, Vision Research) was employed for capturing particle images. The camera contains 600 x 800 pixels, which renders a spatial resolution of 0.5 μm/pixel in the present setup. A high-repetition-rate double-cavity YLF laser (Pegasus, Newwave Research) with a wavelength of 527 nm was used for whole-field illumination. Willert et al.(1996) showed that random errors due to poor light intensity became significant once the light intensity was below 4 bits. The light intensity in the present images is of the order of 8 bits, which is orders of magnitude larger than the criterion. The time difference between successive images can be made as low as 10 μs, when two laser pulses are introduced to the same focal plane in one scanning cycle. However, in the present experiment the flow velocity is rather low and a single laser pulse is applied for each focal plane at a repetition rate of 1 kHz. Ten different wall-normal

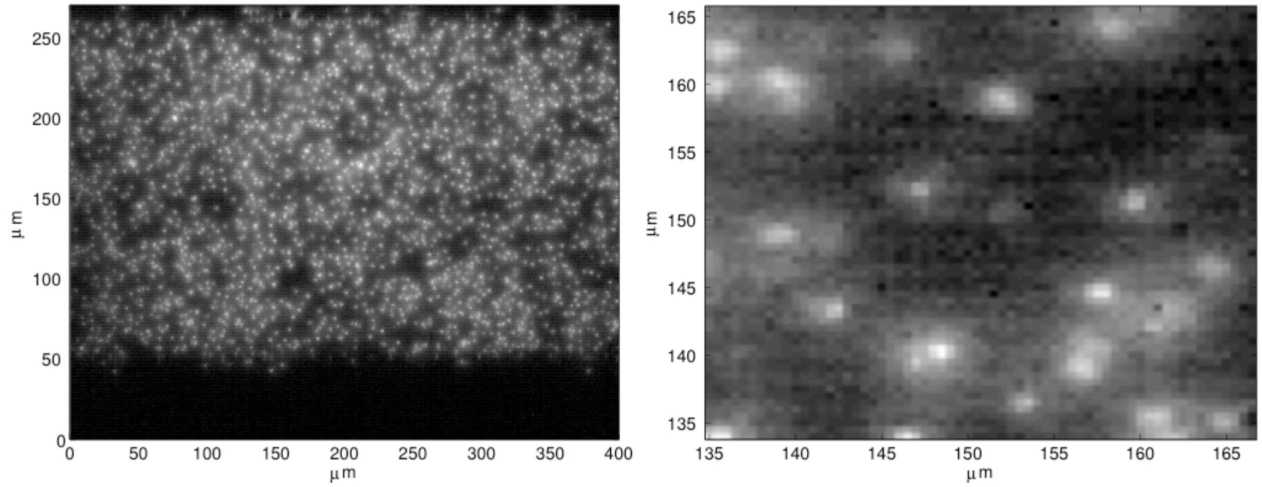

Figure 2. (a) A snap shot of the particle image at the centerline of the micro-channel with the scanning disc. (b) A sub-region of the same particle image (with the same size as the interrogation area but square, 64 x 64 pixels).

measurement positions are scanned in one cycle and hence Δt=10 ms. The laser and the camera were synchronized with the rotating disc using a trigger unit (Labsmith LC880).

Pink fluorescent particles (Duke Scientific) with a diameter of 1 μm and a volume concentration of 0.05-0.10% were used as seeding. The excitation and emission peaks in the wavelength spectra are located at 542 nm and 612 nm, respectively. The high-pass filter has a cut-off wavelength at 595 nm. The particle image diameter was above two pixels as shown in Fig 2b (the effective particle image size is 5.5 pixels according to Meinhart Werely Santiago 1999). A Gaussian peak-fit was used for the sub-pixel interpolation (Willert et al., 1996; Westerweel, 1997) in order to minimize the effects of peak-locking. Other PIV setup parameters were designed according to the criteria given by Angele and Muhammad-Klingmann(2005) to minimize errors in the velocity statistics introduced by peak-locking. The focal depth, which defines the measurement volume, is of the order of 11-12 μm (see Meinhart Werely Gray 2000 and Werely, Gui and Meinhart 2002 and Kim and Beskok 2002) and the depth of correlation, as given by Olsen and Adrian(2002), is 13 μm.

The images were evaluated by a modified version of a MATLAB-based software (MATPIV), which was developed by Sveen(1999). The cross-correlation technique was applied using elongated interrogation areas (IA) of 16 x 256 pixels in the wall-normal and streamwise directions respectively with an overlap of 50%. The number of particles in each IA is well above five, recommended by Keane and Adrian(1992), to assure a good performance of the correlation technique.

As a means of detecting spurious vectors we employ the peak value ratio (PVR), which is the ratio between the highest and the second highest peaks in the correlation plane. The lower limit recommended by Keane and Adrian(1992), is PVR=1.2. This was used together with a range-validation, discarding negative velocities and velocities which were larger than the centerline velocity.

Vibrations induced by the rotating disc were estimated by capturing images of a slide-glass with steady particles. It was found that the root-mean-square value of the displacement is about 0.1 pixels, which is of the order of the accuracy of the PIV evaluation technique. The effect of Brownian motion on the measured velocity was estimated using the expression given by Santiago et al.(1998). It was found to be 0.13%.

3 Results

The effect of introducing the scanning disc on the quality of the PIV data was investigated by a direct comparison to a conventional micro-PIV measurement. The measurements were carried out at the centerline of the channel under steady flow conditions. The light intensity was reduced by 13% when inserting the disc. As shown in Fig. 3a, the peak of the PVR is shifted from 1.9 to 1.6 when the scanning disc is introduced. Thus, the PVR is somewhat deteriorated in the present system. We believe that this is related to the defocusing effect of the glass window. Figure 3b shows the instantaneous velocity data. They are scattered around the analytical solution with u_{rms}/U_{cl} of the order of 2-3% in both cases. However, the mean velocity agrees well with the analytical solution even for the scanning micro-PIV system.

Measurements were also carried out under unsteady flow conditions at a nominal flow rate of 0.1 µl/min in order to demonstrate the ability of the scanning system for temporally resolved measurements. Figure 4a shows the probability density functions of the signal-to-noise-ratio for the ten measurement planes when using the scanning system. It is clear that PVR is affected by the distance from the wall, as is the scatter in the mean velocity shown in Fig. 4b. We conjecture that this is an effect of the velocity gradient across the focal plane. Figure 5a shows the results from four successive instantaneous measurements taken at a scanning rate of 100 Hz. The flow rate was estimated by integrating the instantaneous velocity profiles at the ten measurement planes throughout the entire depth of the channel. Figure 5b shows the time trace of estimated flow rate. Although the nominal flowrate is kept constant, the instantaneous flow rate

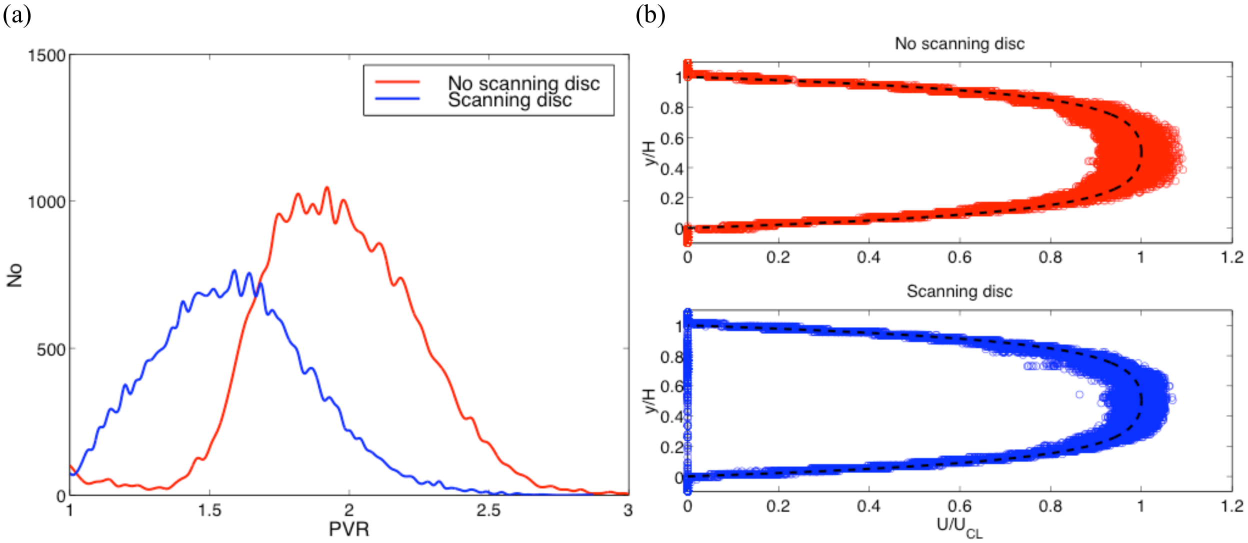

Figure 3. (a) The signal-to-noise-ratio of the PIV data at the centerline comparing the conventional micro-PIV system with the scanning system. (b) The mean velocity for the conventional micro-PIV system compared with that from the scanning system. The dashed line corresponds to the analytical solution. The zero-velocities are data which have been removed in the validation process.

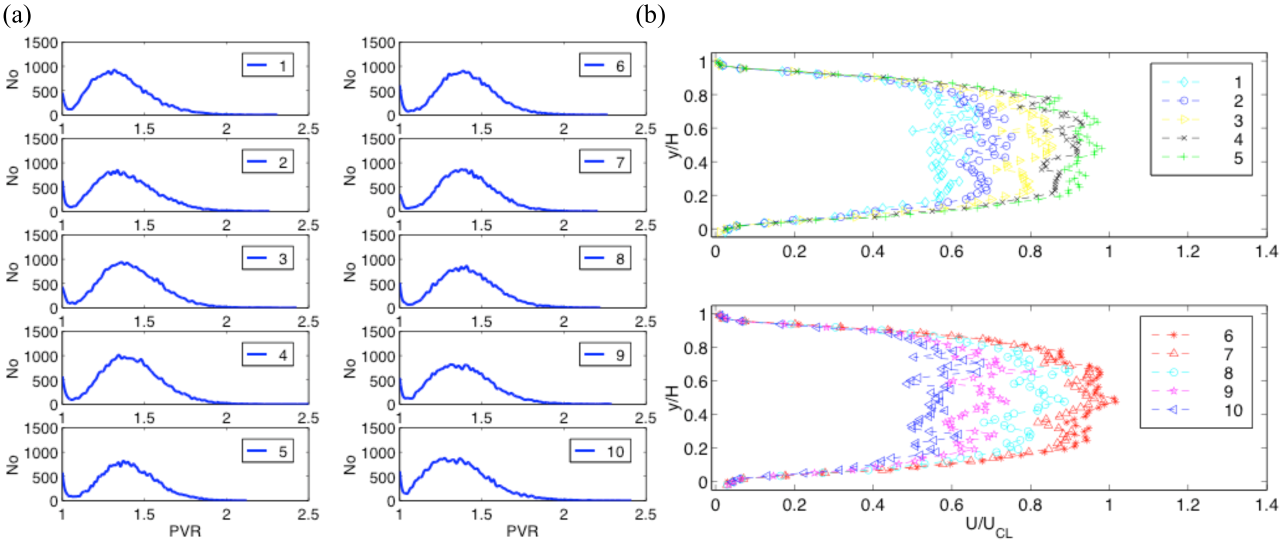

Figure 4. (a) The signal-to-noise-ratio and (b) the mean velocity profile from the 10 wall-normal measurement positions using the scanning system. The number indicates the glass window on the scanning disc.

has a large fluctuation with a typical frequency of the order of 3 Hz. This result demonstrates the ability of the present system for unsteady flow measurements.

4 Conclusions

A high-speed scanning micro-PIV system has been developed, and was evaluated through a series of experiments. It was demonstrated that it can provide time-resolved, pseudo-three-dimensional flow field information. The results compare well with the analytical solution and the data measured with conventional micro-PIV. It was found that the signal-to-noise ratio is somewhat deteriorated for the scanning micro-PIV, which is probably due to the defocusig effect of the glass windows on the scanning disc.

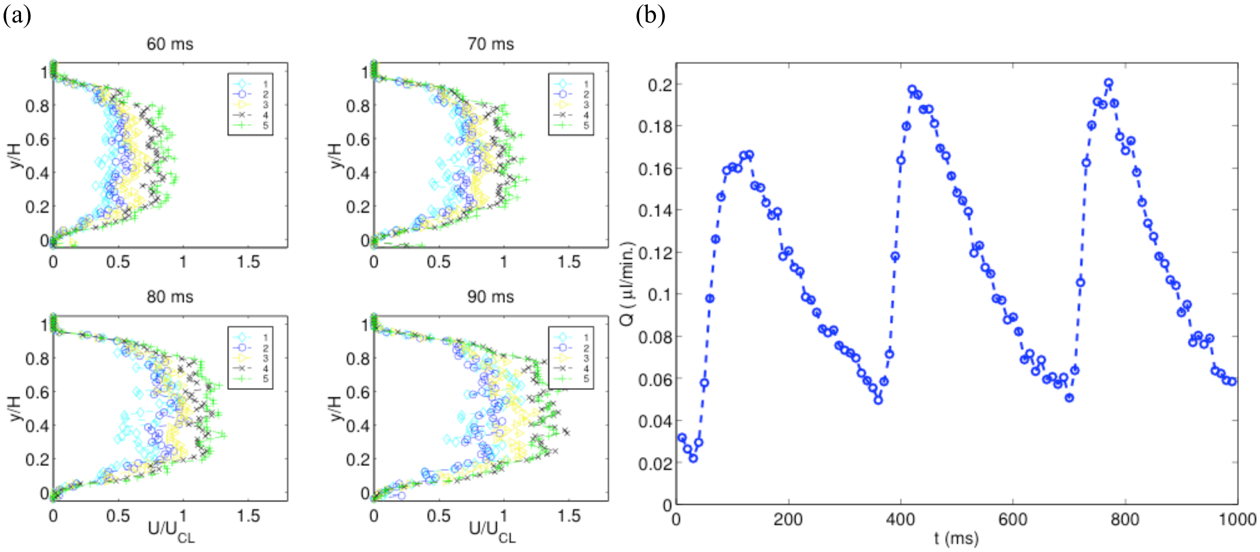

Figure 5 (a) The instantaneous velocity profiles at a scanning rate of 100 Hz. (b) The temporal variation of the flow rate, estimated by integrating the velocity profiles at all the wall-normal planes.

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