Proceedings of
The Second National Congress on Fluids Engineering
August 22-24, 2002, Muju, Korea

PIV Measurements of the Pressure Driven Flow Inside a T-Shaped Microchannel

Jayho Choi*, In-Seop Lee**

T형 마이크로채널 내부 압력구동 유동의 PIV 계측

최제호*·이인섭**

Key words : *PIV, Microfluidic , T-Shaped, Microchannel, pressure-driven microscale flow*

Abstract

A custom micro-PIV optics assembly has been used to measure the flow field inside a T-shaped microchannel. The micro-PIV system consists of microscope objectives of various magnifications, a dichroic cube, and an 8-bit CCD camera. Fluorescent particles of diameters 620nm have been used with a Nd:YAG laser and color filters. A programmable syringe pump with Teflon tubings were used to inject particle-seeded distilled water into the channel at flow rates of 20, 40, 60μL/hr. The microchannels are fabricated with PDMS with a silicon mold, then O_2-ion bonded onto a slide glass. Results show differences in flow characteristics and resolution according to fluid injection rates, and magnifications, respectively. The results show PIV results with vector-to-vector distances of 2μm with 32 pixel-square interrogation windows at 50% overlap.

1. Introduction

A lab-on-a-chip, the integration of various biochemical / biomedical analyses onto a single chip, consists of numerous microfluidic components such as valves, pumps, and channels of different geometry for various mixing, sorting, and dispersion processes involved. The fluid inside the whole channel system is generally pressure-driven, or electrokinetically-driven, and various literatures involving the physical phenomena inside microchannels have been published[1,2].

Until recently, microfluidic researches were carried out with scalar pressure or temperature measurements or the calculation of pixel intensity distribution by the use of a CCD camera and uncaged fluorescent dye[2,3]. With the development of microfluidic devices in various fields such as biomedicine and chemical analysis, the need for quantitative flow field measurement inside microchannels of various geometry are growing in interest. Although fluid flows in microchannels are of low Reynolds number and the general flow pattern predictable, the velocity field of the fluid inside the whole channel was difficult to measure. Also, many such channels are used for microscale analyses such as chemical mixing, particle/molecule sorting, and dispersion control, for which the specific flow characteristics are difficult to analyze quantitatively[3]. Flow visualization and quantitative analysis of flows in microchannels are necessary for the development of efficient active and passive mixers.

Particle image velocimetry(PIV), which has become an indispensable tool in fluid flow field measurements, have been successfully applied for flow measurements in microscale structures. Santiago et al.[4] measured the Hele-Shaw Flow around a microscale circular structure, at a vector resolution of 3.2μm × 3.2μm. Meinhart et al.[5,6] also applied PIV to measure the flow inside a microfabricated inkjet printhead, and a straight microchannel at a resolution of 5.0μm × 1.3μm. Santiago et al. and Meinhart et al. both used intensified CCD cameras with an epi-fluorescence microscope system.

In this paper, a home-assembled epi-fluorescence optic system was used for the measurement of a T-shaped microchannel with a non-intensified 8-bit CCD camera, relatively low cost compared to any intensified CCD camera. Early versions of the micro-PIV system used in this paper, with the 50X magnification objective, was first used in 2001 by Lee et al.[7] then improved with the addition of CFD analysis and a micropositioner[8,9]. In this paper, the resolution of the optic system was drastically improved by doubling the magnification of the objective and optics adjustments. This system, improved with higher resolution CCD cameras and multiple syringe pumps, will be used as a high-resolution analysis tool for further research in microscale mixers.

2. Method and Apparatus

2.1 Seeding Particles

Certain requirements must be met in order for particles to be used in micro-PIV: its size must be small enough to accurately follow the flow, but large enough to be imaged through the optics and onto the CCD cell. Red fluorescing particles of 620nm in diameter were used, having excitation and emission wavelengths of 530nm and 612nm respectively.

Also, the Brownian motion of the particles is in effect and its error must be taken into account. According to Santiago et al.[4] the relative error of the velocity gradient due to the Brownian motion can be estimated by:

$$\varepsilon_B = \frac{1}{u}\sqrt{\frac{2D}{\Delta t}} \qquad (1)$$

where D is the diffusion coefficient, and Δt the time interval.

* LG Electronics Core Technology, jayho@LGE.com
** LG Electronics Core Technology, islee@LGE.com

Taking into account the diffusive uncertainty, which is proportional to $\varepsilon_B / \sqrt{N}$, [4], for this experiment u~37mm/s and Δt~5μs, and 100 instantaneous velocity vector fields were ensemble averaged to obtain the mean velocity field, the error due to Brownian motion can be approximated to be less than 1%. Particle density in the working fluid was set to 0.1% by volume.

2.2 Microchannel

The 3D draft and the specifications of the T-Shaped microchannel used in the experiment are shown in Fig. 1. The depth of the channel is 50μm, with the main straight channel width of 300μm, and 5000μm in length. A 50μm width channel exists perpendicular to the main straight channel at the mid section, forming a T-shape with a 300μm width for the horizontal channel and a 50μm width for the vertical channel. The channel was cast on PDMS from a silicon mold, which was then O_2-ion bonded onto a glass slide. The three circular holes that can be seen in Fig. 1 were bored on the PDMS for the insertion of Teflon tubings. Only the leftmost hole was used as the input for the flow, leaving the other two holes open at atmospheric pressure, each with a 100mm long tubing attached.

The channel can be firmly bolted in front of the microscope objective on a slot structure which is mounted on a 5 degree-of-freedom(DOF) microstage. The 5 DOF microstage is a home-made assembly of multiple translation stages, and provides rotation in all three directions, in addition to translations within the focal plane.

2.3 Imaging and Optics

The schematic of the micro-PIV system optics is shown in Fig. 2. It consists of the microscope objective, a custom-made dichroic cube, the focusing tube, and a 8-bit 1K×1K CCD camera.

Figure 2(a) shows an example on how the custom made optics may be used for PIV measurement. The two microscope objectives used in this experiment were of magnifications 50X and 100X, with working distances of 13mm, and 6mm respectively. Also, these infinity-corrected long working distance objectives are plano apochromats, with depths of focus of 0.9μm and 0.6μm, and resolving powers of 0.5μm and 0.4μm for the 50X, 100X magnifications.

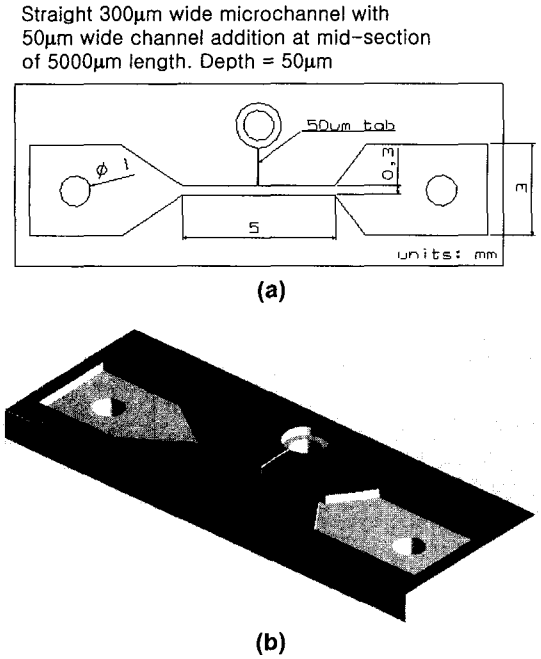

Fig. 1 Dimensions and geometry of the microchannel

The microscope objective is attached to a hollow tube, which was mounted on a micro-stage, enabling precise movement along the z-axis, as seen in Fig. 2. The hollow tube is then connected to the dichroic cube via a sliding tube to isolate the beam path in darkness even when the hollow tube's horizontal position is adjusted. The dichroic cube is then connected to the focusing tube, which is a series of lenses used to focus the emission beams onto the CCD cell of the camera. The focusing tube is firmly attached to the CCD camera, and all optic components were setup on an optical rail for precise alignment of the beam path. The beam path shown in Fig. 2(a) is typical for epi-fluorescence microscopy, and this setup was used for measurements with the 50X objective.

Figure 2(b) shows another optics setup, which was used for measurements with the 100X objective, and enables maximum laser power for better illumination of the field of view without endangering the optic system to the high intensity of the laser beam.

The green pulse laser used is a two-head Nd:YAG laser with a maximum power output of over 300mJ with a wavelength of 532nm. The dichroic cube consists of three main optic components: the excitation filter, the dichroic mirror, and the emission filter, for which the characteristic wavelengths were order-made to meet the 530nm excitation and 612nm emission wavelengths of the fluorescent particles.

The CCD camera was synchronized with the pulse laser with the camera's shutter feedback as the master signal. Time delays of 3~5 μs between particle images were needed for the flow.

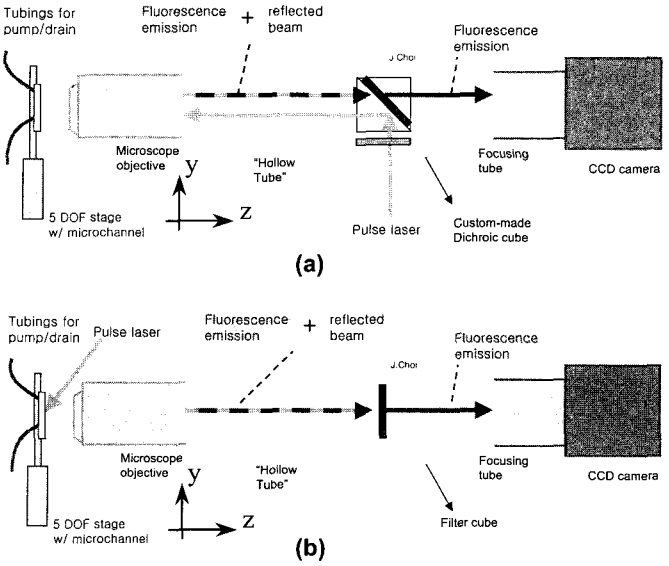

Fig. 2 Schematics of the custom-made Micro-PIV optics
(a) 50X setup, used with 50X objective
(b) 100X setup, used with 100X objective

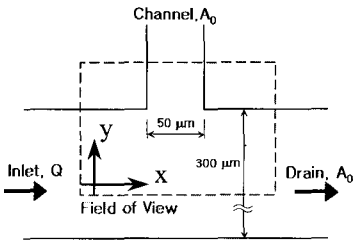

Fig. 3 Field of view of PIV measurements

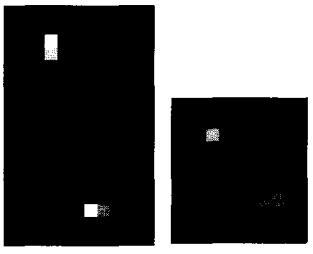

Fig. 4 Particle images with (a) 50X and (b) 100X setups

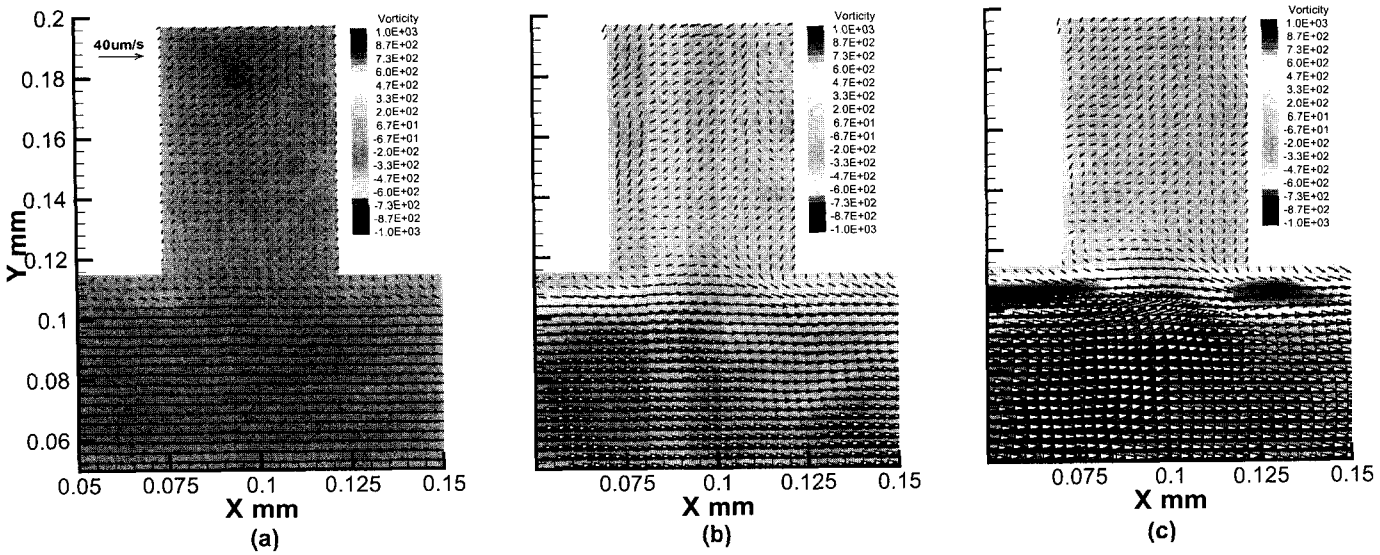

Fig. 5 Mean velocity vector field result with 50X setup

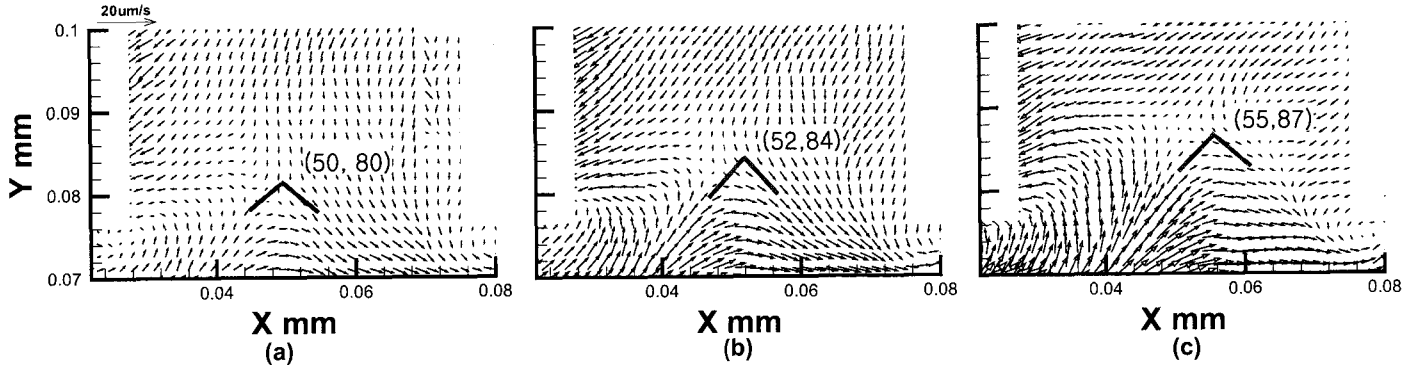

Fig. 6 Mean velocity vector field result with 100X setup

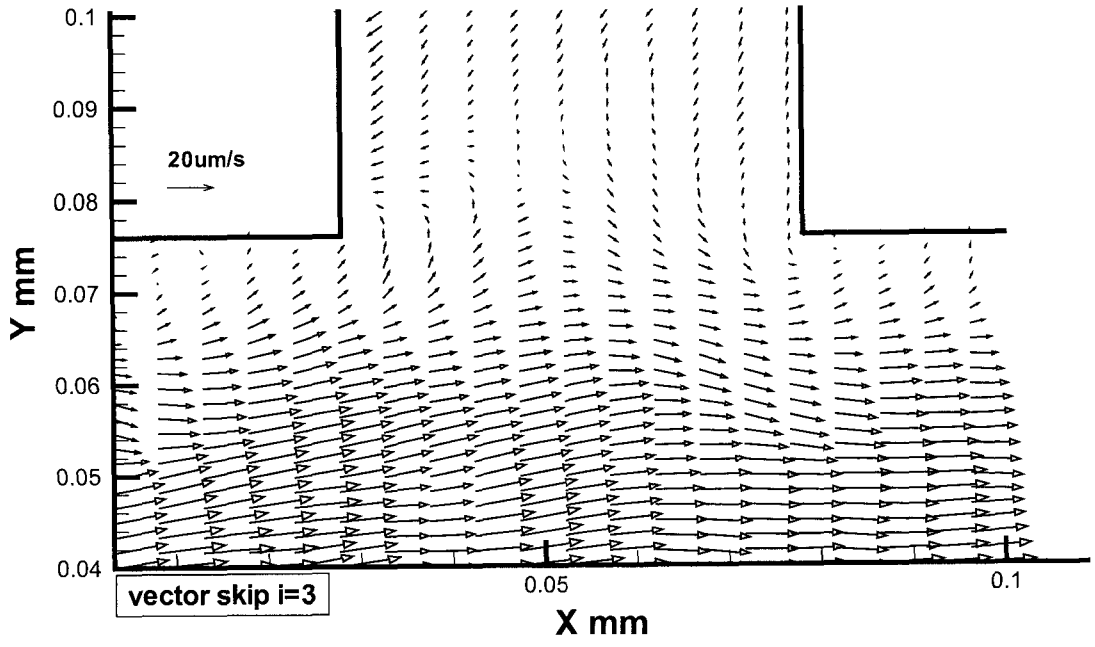

Fig. 7 Mean velocity vector field result with 100X setup
(only every 3rd vector in the x-direction is plotted)

4. Experiment & Results

The microchannel was held in front of the microscope and its position adjusted with the micrometers attached to the microstage. Angular adjustments of the microchannel were made by using the z-direction translation micrometer and angular positioning micrometers: part of the channel walls in contact with the glass slide were initially brought to focus, and by rotating the angular micrometers of the microstage with the z-direction micrometer of the hollow tube, a uniform focus along the x and y direction was confirmed, thus positioning the microchannel parallel to the object plane of the microscope objective.

The object plane was positioned at about the mid-depth of the channel, at approximately 25μ from its bottom surface. This was done by focusing on the bottom and top surface walls of the channels, and moving the microscope objective in reference to those focused z-coordinates. Translation of the microscope objective was done by the micrometer on the hollow tube.

Distilled water was used as the working fluid, and a syringe pump was used with a 5ml glass syringe at flow rates of 20μL, 40μL, and 60μL. The field of view(FOV) for the experiment is shown in Fig. 3: a rectangular area was selected which included the 50μm channel in the center. The FOV for the 50X and 100X setups were approximately 200μm-square and 100μm-square, respectively. With a 32-pixel square interrogation window at 50% overlap, this lead to a vector plot with a vector-to-vector distance of approximately 4μm, and 2μm for the 50X and 100X setups, respectively.

Acquired raw particle images showed particles sizes of approximately 3~6 pixel-area and 7~10 pixel-area for the 50X and 100X setups, respectively, as shown in Fig. 4. Due to the small field of view, the particle images acquired with the 100X setup were low in brightness relative to the increase in laser intensity. 100 instantaneous velocity vector fields were averaged to obtain each mean velocity vector fields, and are shown in Fig. 5 through Fig. 7.

Figure 5 shows the mean vorticity contour plots and mean velocity vector field measured with the 50X setup, plotted with the same reference vector magnitude. The flow direction is from left to right, with the x and y axis increments shown in millimeters. Fig. 5(a), 5(b), and 5(c) are the results for fluid injections rates of 20μL, 40μL, and 60μL, respectively. It is found that the main horizontal flow from left to right slightly deforms as it passes the 50μm channel and that the flow inside the 50μm channel is negligible for all fluid injection rates. However, the vorticity field along the wall of the 300μm-wide main channel, is increased in strength as the fluid injection rate is increased. A discontinuity in the vorticity field is observed at the entrance of the 50μm channel, due to the deformation of the velocity field in that region. It is noted that the maximum vorticity value is located slightly offset from the wall surface. This is assumed to be due to the erroneous vector measurements at the wall surface.

The mean velocity vector field measured with the 100X setup is shown in Fig. 6, plotted with the same reference vector magnitude. The entrance region of the 50μm channel is plotted to better visualize the difference between Fig. 6(a) through Fig. 6(c). Figure 6(a), 6(b), and 6(c) are the results for fluid injection rates of 20μL, 40μL, and 60μL, respectively. Compared with the results in Fig. 5, the resolution has been doubled, and a vector-to-vector distance of approximately 2μm can be observed. Also, a difference in the amount deformation of the main horizontal flow is found: the distance at which the flow entering the 50μm channel increasing with the fluid injection rate. The coordinates of the maximum entry distances of the particles into the 50μm channel are estimated to be (50, 80), (52, 84), and (55, 87). The positions are marked in Fig. 6 with a red bracket, the corner of the bracket indicating the coordinates.

Figure 7 shows a full-field-of-view mean velocity vector field result with a fluid injection rate of 40μL, measured with the 100X setup. Only every 3rd vector in the x-direction is plotted. The erroneous velocity gradient in the y-direction near the left edge of the vector field is assumed to be due to particles attached to the wall surface, or over-sized, accumulated particle chunks that cause erroneous vector results in its vicinity.

5. Conclusion

A custom-made epi-fluorescence micro-PIV optics setup was used to measure the velocity field at the entrance region of a T-shaped microchannel. A mean velocity vector field of vector-to-vector distances of 2μm was obtained with a 100X magnification setup, used with a non-intensified CCD camera and a 300mJ pulse laser. Results showed the deformation of the main flow stream in the 300μm wide channel, when the flow passes the entrance region of a smaller 50μm wide channel. The amount of deformation was found to increase as the fluid injection rate was increased.

The advantage of the current micro-PIV setup is its low cost: making use of a relatively low-cost CCD camera, and without the need of a full-set epi-fluorescence microscope.

This micro-PIV setup, improved with, higher-resolution CCD cameras and various fluid injection devices, will be used for further studies in microscale fluid mixing.

REFERENCES

[1] M. Deshpande, K.B. Greiner, J.R. Gilbert, L. Bousse, A. Chow and A.R. Kopf-Sill, "Technical Proceedings of the 10th Int. Conf. on Solid-State Sensors and Actuators", Sendai, Japan, June 7-10, (1999).

[2] J.I. Molho, A.E. Herr, T.W. Kenny, M.G. Mungal, P.M. St.John, M.G. Garguilo, P.H. Paul, M. Deshpande, and J.R. Gilbert, "Fluid Transport Mechanisms in Microfluidic Devices", ASME International Mechanical Engineering Congress and Exposition, DSC-Vol. 66, (1998).

[3] A.D. Stroock, S.K.W. Dertinger, A. Ajdari, I. Mezic, H.A. Stone, G.M. Whitesides, "Chaotic Mixer for Microchannels", Science, Vol. 295(2002), pp.647-651.

[4] J.G.Santiago, S.T. Wereley, C.D. Meinhart, D.J. Beebe, R.J. Adrian, "A Particle Image Velocimetry System for Microfluidics", Exp. in Fluids, 25 (1998), pp. 316-319.

[5] C.D. Meinhart, H. Zhang, "The Flow Structure Inside a Microfabricated Injet Printhead", J. of Microelectromechanical Systems, Vol. 9, No. 1 (2000), pp. 67-75.

[6] C.D. Meinhart, S.T. Wereley, J.G. Santiago, "PIV Measurements of a microchannel flow", Exp. in Fluids, 27 (1999), pp. 414-419.

[7] I.Lee, J.Choi, I.S. Lee, "PIV Measurements of a microfluidic element fabricated in a plastic chip", Proceedings of the KSME 2001 Fall Annual Meeting B (2001), pp. 400-404. (in Korean)

[8] I.Lee, J.Choi, I.S. Lee, "Measurements of a microchannel flow using micro-PIV", Proceedings of 2001 Korea-Japan Joint Seminar on Particle Image Velocimetry (2001), pp. 44-52.

[9] I.Lee, Y.S. Nam, K.H. Ahn, I.S. Lee, "The Three-Dimensional Flow Structure inside a Plastic Microfluidic Element", Proceedings of the 4th Korean MEMS Conference (2002), pp. 262-267.