

Investigating the Flow Structure of Dean Vortices in a Curved Microchannel, Implementing 3D- μ PTV Using FVM and Near Wall Data Refinement

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ABSTRACT

Microfluidic devices are now more commonly used for various applications in medical diagnosis, pharmaceutical and agricultural applications. Flow structure in these devices can be useful for passive manipulations. Therefore, developing an experimental investigation to study a common geometry in micro devices such as the flow in a curved channel can be a booster in designing high performance microfluidic devices. The paper provides a study on the implementation of the scanning μ PTV in a micro device. It also investigates the application of a tessellation approach to refine the near wall data using a high quality triangular mesh. The out-of-plane velocity calculation method is also developed to reconstruct the 3D velocity field inside the microchannel device.

1. Introduction

Microfluidic devices are used in different applications for particle sorting (Sajeesh & Sen, 2014), encapsulation (Li et al., 2019), and micromixing (Der & Bertola, 2020). Among different geometries, curved channels are employed in the design of most microfluidic devices (Kumar et al., 2006). The geometry and flow conditions, such as the curvature radius and Reynolds number within these curved channels can produce two or more counter-rotating vortices due to the generated centrifugal force in the bend. These so-called Dean vortices (Dean, 1928) can affect the performance of the microfluidic devices, for instance, by changing the equilibrium position of the particles and enhancing the mixing index (Dean, 1928)(Nivedita et al., 2017). For every application, there is an optimum working window that depends on the properties of the Dean vortices (Nivedita et al., 2017). Understanding the flow structure and properties of the Dean vortices provides important information for determining the optimum working window to improve the performance of microfluidic devices (Nivedita et al., 2017).

In order to determine the flow structure and calculate the velocity field of a flow domain in a three-dimensional flow geometry, there are several 3D optical velocimetry methods such as defocused

particle image/tracking velocimetry (PIV/PTV) (Pereira & Pereira, 2000), tomographic PIV/PTV (Atkinson et al., 2011) and scanning PIV/PTV (Sabbagh et al., 2020)(Kashanj & Nobes, 2021). There are few experiments on 3D visualization of the flow structures in a curved microchannel by applying optical methods and these include holographic PTV (Kim & Lee, 2008) and confocal microscopy (Nivedita et al., 2017). However, they do not provide enough three-dimensional quantitative information about the flow domain to study the Dean vortices (Nivedita et al., 2017)(Kim & Lee, 2008).

Experimental investigation of a complex flow structure such as Dean vortices in a microscale curved channel is challenging. This paper investigates the application of enhanced 3D micro-shadowgraph particle tracking velocimetry (3D- μ SPTV) to study the 3D flow structure inside a curved microchannel. The use of a tessellation approach and out-of-plane velocity calculation method is investigated to respectively enhance near wall data resolution and reconstruct the 3D velocity domain.

2. Experimental Setup

A schematic of the experimental setup used to apply 3D- μ PTV to investigate Dean vortices at the microscale is shown in Fig. 1(a). A high-speed camera is used to capture the seeding particles in the curved region of a microchannel flow. This camera is mounted on a micro stage with the minimum displacement of 10 μ m and moves in the z direction to scan the depth of the channel. A compact high intensity LED light (SL191, Advanced Illumination) is utilized as the backlight illuminator to visualize the motion of particles in a shadowgraph configuration. Tracer particles used for this purpose are 2 μ m polymer beads. A programmable syringe pump (PHD4400, Harvard Apparatus) is used to set the flow rate using water as the working fluid.

The microfluidic chip shown in Fig. 1(b) is designed and built using an additive manufacturing technique. The channel has a square cross section with the width $d = 2$ mm and radius of curvature, $R_c = 3$ mm. Inlet and outlet channels are considered to be long enough (greater than $10 \times d$) to eliminate the effect of inlet and outlet joints. The test cell is fabricated in 3 different layers including the top window (optical window layer), a seal and the main flow channel. The optical window layer is built using a laser cutter out of an acrylic sheet with the thickness of 6.35 mm. A silicone sheet with Shore A hardness of 60 ± 5 and thickness of $t = 0.5$ mm is implemented as the sealing layer between the optical window and the main flow channel. The main flow channel which contains support connections to the optical table, connections to the flow source via a printed Luer

connection and the flow channel, is printed using an SLA 3D printer (Form 3, FormLab Inc.) with the semi-transparent resin. To improve the surface finish, the main device is printed at the highest resolution setting, 25 μm printing layer thickness. The field of view captured by the camera is also shown and highlighted by light blue in Fig. 1(b).

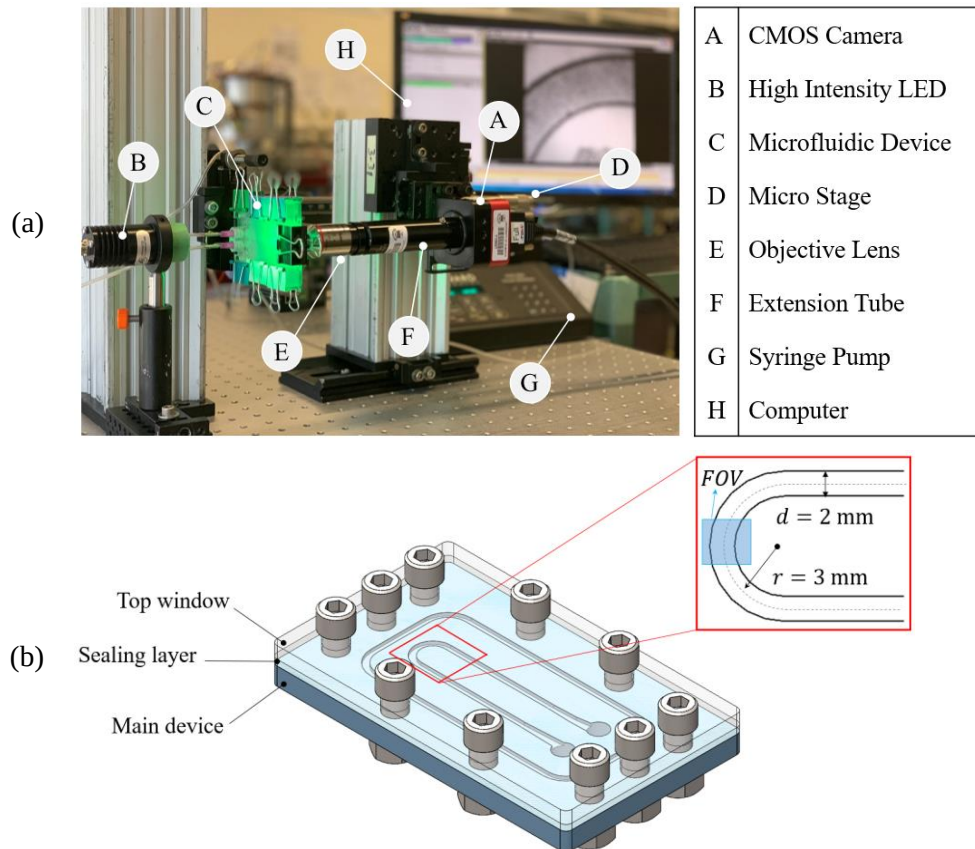


Fig. 1 (a) Experimental setup applying shadowgraph technique, (b) fabricated microchip designed to study the Dean vortices

3. In-plane velocimetry

A raw image of the middle section of the curved channel is shown in Fig. 2(a). The flow is investigated using PTV at each measuring plane. A tessellation approach is applied to calculate the velocity vectors in missing regions where there are not enough particles to obtain the velocity components. To generate the mesh for the tessellation approach the boundaries of the channel need to be detected. To detect the channel walls, unwanted shadow regions are eliminated from the raw images and velocity calculations. A raw data image shown in Fig. 2(a) shows the geometry of the channel with seeding particles and other extra shadows around the channel.

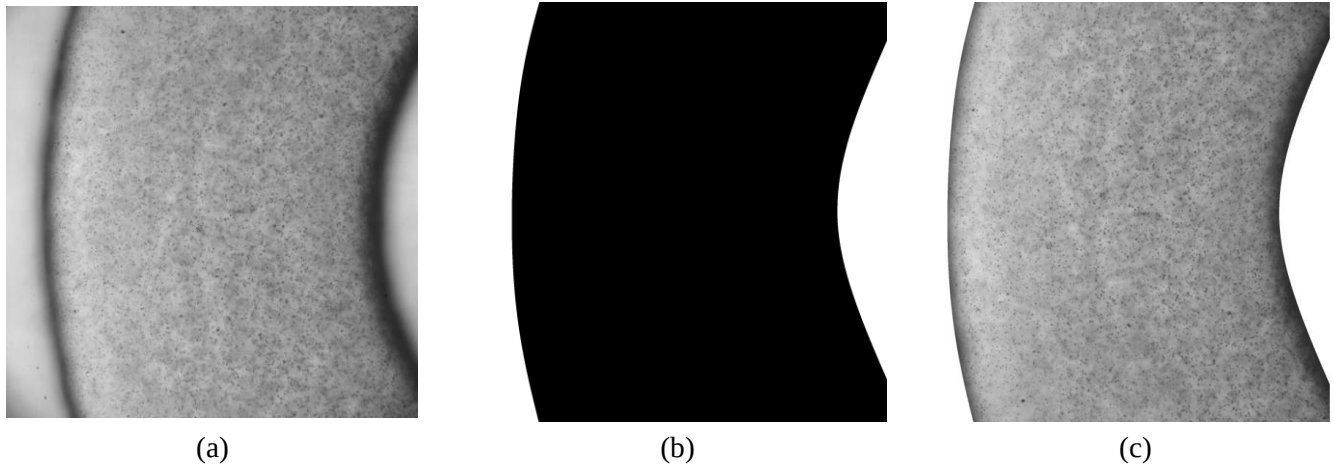


Fig. 2 Image processing steps to obtain the wall boundaries of the geometry, (a) a raw image showing the initial domain, (b) the masked generated by image processing of the intensity standard deviation of 1000 images, (c) a masked image with seeding particles.

Since uncommon geometries, as in Fig. 2(a), are challenging to be masked using mathematical approaches, raw images of the flow field are alternative sources that can be used in the masking process. To overcome the masking problem, 1000 frames containing flow and tracer particles are used to calculate the standard deviation of the image's intensity. With the high contrast apparent between the channel and the background in the intensity standard deviation of the raw images, the edge of the channel walls is detected using an in-house developed image processing algorithm in MATLAB. Fig. 2(b) shows the final binarized mask of the geometry generated from the raw images. Applying such a mask to the images allows isolation of only the region containing the seed particles as shown in Fig. 2(c). These data images are used to define the region-of-interest where the velocity field is calculated.

A commercial software (DaVis V8.4 LaVision GmbH) was used for time resolved PTV calculation. Particles with a shadow diameter of smaller than 6 pixels were tracked. PTV algorithm calculates the velocity vector for each detected particle which leads to a dispersed velocity field. To apply the continuity law and calculate the out-of-plane velocity component the obtained dispersed velocity field should be distributed on a discretized domain. In curved geometries the near wall result of the velocity calculations from PTV on the structured grid is not reliable. This is due to the structure of the grid not well representing the curved geometry of this flow.

4. Scanning

To generate a full 3D flow vector field, PTV can be applied over multiple imaging planes through the channel depth (z-axis). The distance between the planes was chosen based on the channel

geometry and optical access. A higher number of scanning planes provides more information for the full 3C3D velocity field reconstruction, but there is a limit for the minimum achievable depth of focus. The depth of focus of the lens is $\sim 100\ \mu\text{m}$, and considering that the depth of the channel is 2 mm, a configuration of 20 evenly distributed scanning planes on the z-axis was selected for the experiment. Since it is known that the Dean flow is a steady flow under a constant geometry and certain flow conditions (Berger et al., 1983), the average of the velocity field for a number of frames can be used in further calculations.

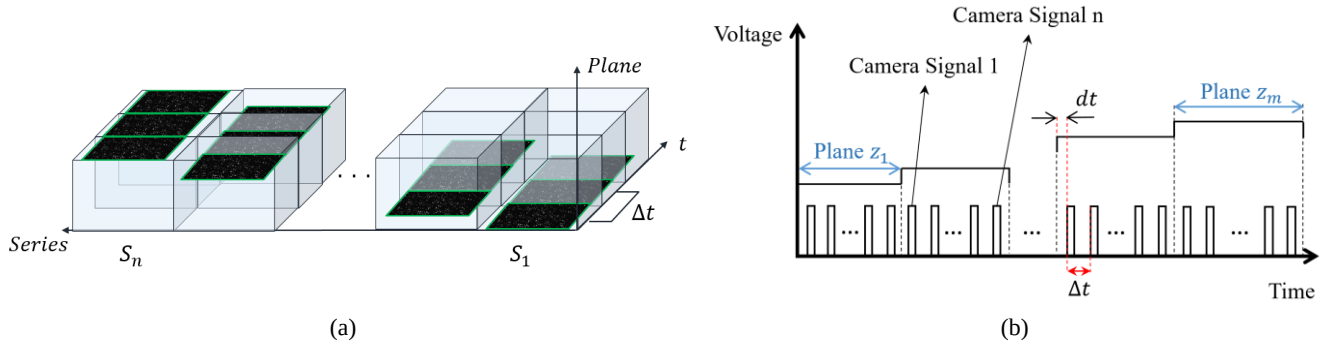


Fig. 3 (a) The diagram of the scanning imaging along the depth of the channel, (b) schematic of the timing diagram that is applied to synchronize the scanning signal with camera signal using a double frame approach.

The sequence of imaging and scanning shown in Fig. 3(a) depends on the time scale of particle movements in the flow field and changes in the flow structure. This figure shows the volumetric scanning schematics. S_{1-n} that represents the series of scanning of each plane used for velocimetry and Δt is the time step between each two frames. The relation between the camera shifts and signals is shown in Fig. 3(b). Scanning starts from the plane at $z_1 = 0$ and after recording the frames for that plane the camera shifts to plane z_2 . The first camera signal has dt delay after which the camera shifts to a new plane. This provides the required time for the system to become stable before imaging. Following the first signal, 2000 frames capture particle motion with time step Δt .

5. Tessellation

Distributing the dispersed PTV velocity field from each individual plane on a discretized domain and reconstructing the 3D velocity field, allows the calculation of flow properties such as the pressure distribution (Azadi et al., 2021). A structured/rectangular grid reduces the calculation expense. However, it is typically applied to simple geometries where the geometry does not reduce the grid quality (Azadi et al., 2021). For cases with curvature, moving boundaries or complex geometries such as a curved channel in a microfluidic device, producing a high quality

mesh is more challenging. To overcome this issue, a tessellation approach can be used. This approach maps the dispersed PTV velocity data onto an optimized high quality triangular node structure (Azadi et al., 2021)(Saffar et al., 2021).

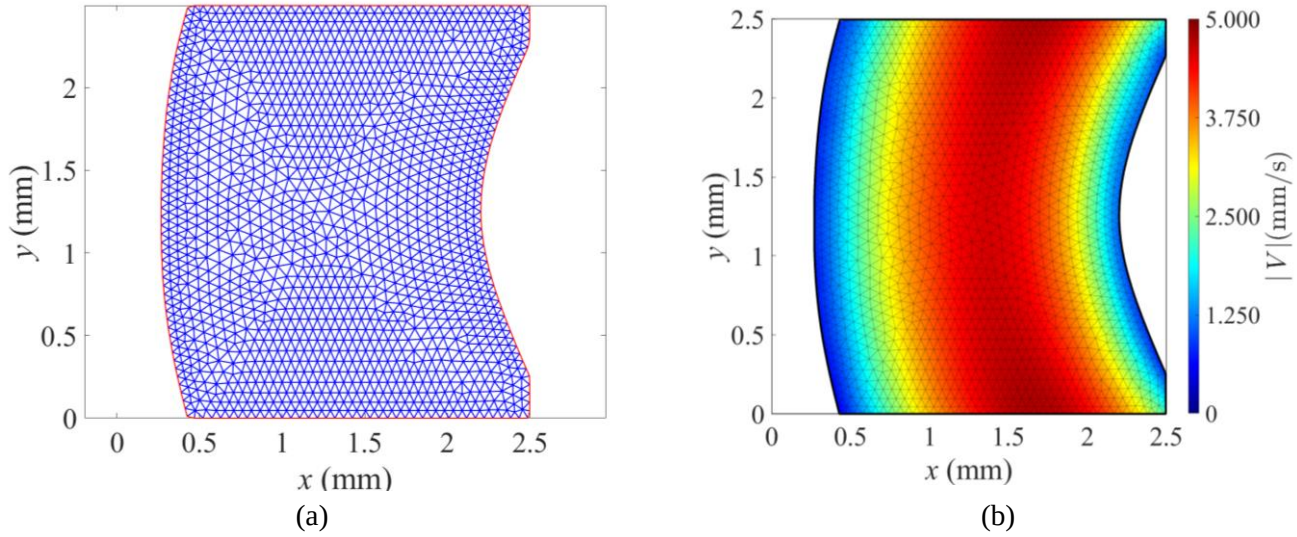


Fig. 4 (a) The triangular mesh generated using the tessellation approach, (b) velocity field of the middle plane of the channel distributed on the rectangular mesh.

To map the velocities, the boundaries of the domain are identified first and nodes are distributed along these boundaries. A triangular high-quality mesh is generated based on the node distribution on the boundaries. Maximum and minimum sizes of the grid as shown in Fig. 4(a) are chosen in a way that $h_{max} \leq 2 \times h_{min}$. The mesh size and the node distribution depend on the geometry of the channel and flow conditions (Azadi et al., 2021). The Delaunay triangulation algorithm (Azadi et al., 2021) used in this approach adjusts itself to the proper position in order to make a high quality mesh. This adjustment produces a mesh which can be easily matched to the boundaries of the domain. Consequently, refined, near wall data shown in Fig. 4(b) can be determined using the proper mesh size and PTV velocity results. Fig. 5(b) shows the effect of distribution mesh on the velocity field. As the generated rectangular grid shown in Fig. 5(a) does not match the curved and oblique boundaries, the resultant velocity field contains missing data in the near wall area. Fig. 5(b) represents the uniformly distributed velocity contour mapped to the triangular mesh obtained from the tessellation approach. Since this unstructured mesh is well adjusted to the boundaries of the channel, the near wall data is refined to cover all the channel.

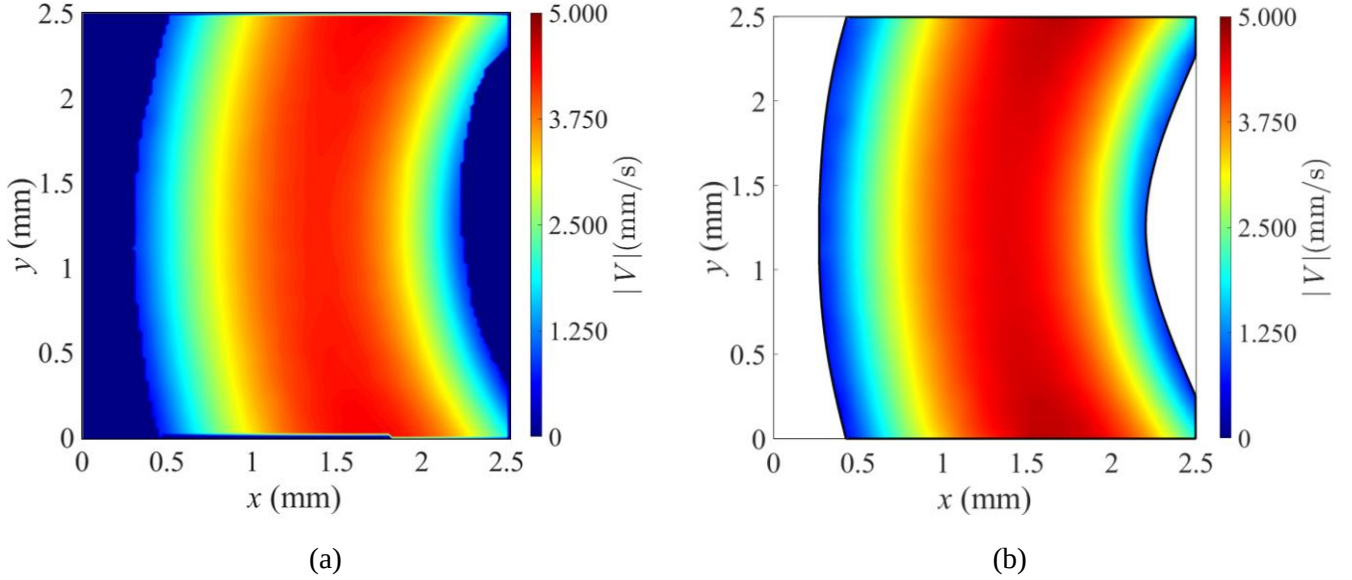


Fig. 5 Near wall data refinement using the tessellation approach; (a) PTV velocity field mapped to a structure grid with low resolution near wall data and (b) velocity field on a triangular mesh with smooth boundaries and high resolution near wall data.

6. Out-of-plane velocity calculation

The 2D velocity fields resulting from the scanning process over the channel depth provides u and v , components of velocity on each plane (each z position). The 2D velocity fields are used to calculate the out-of-plane velocity, w , using the continuity equation (1) in a control volume (cell). By applying the non-slip boundary condition ($u_{wall} = v_{wall} = w_{wall} = 0$), the out-of-plane velocity component of each cell can be calculated on a structured mesh.

$$\frac{\partial u}{\partial z} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial y} = 0 \quad (1)$$

$$\left(\frac{\partial V_x}{\partial x}\right)_{i,j,k} = \frac{V_{x,i+1,j,k} - V_{x,i,j,k}}{\Delta x} \quad (2)$$

$$\left(\frac{\partial V_y}{\partial y}\right)_{i,j,k} = \frac{V_{y,i,j+1,k} - V_{y,i,j,k}}{\Delta y} \quad (3)$$

$$\left(\frac{\partial V_z}{\partial z}\right)_{i,j,k} = \frac{V_{z,i,j,k+1} - V_{z,i,j,k}}{\Delta z} \quad (4)$$

First order discretized continuity (equations (2)-(4)) is employed to calculate the out of plane velocity as the first step. In order to validate the out of plane calculation, flow in the curved channel is simulated (flow simulation tool, SOLIDWORKS). A similar channel geometry with the width $d = 2$ mm and radius of curvature, $R_c = 3$ mm is used in the simulation. The in-plane velocity data of the simulation is used to calculate the out-of-plane component of the velocity. Fig. 6 represents

the result of these calculations. Fig. 6(a) shows the velocity contour and vector field on the channel cross section from the simulation. Fig. 6(b) shows the velocity field calculated using the continuity equation and 2D velocity components. Two counter rotating Dean vortices are visible in both figures and it can be seen that the resultant velocity field is similar to the simulations.

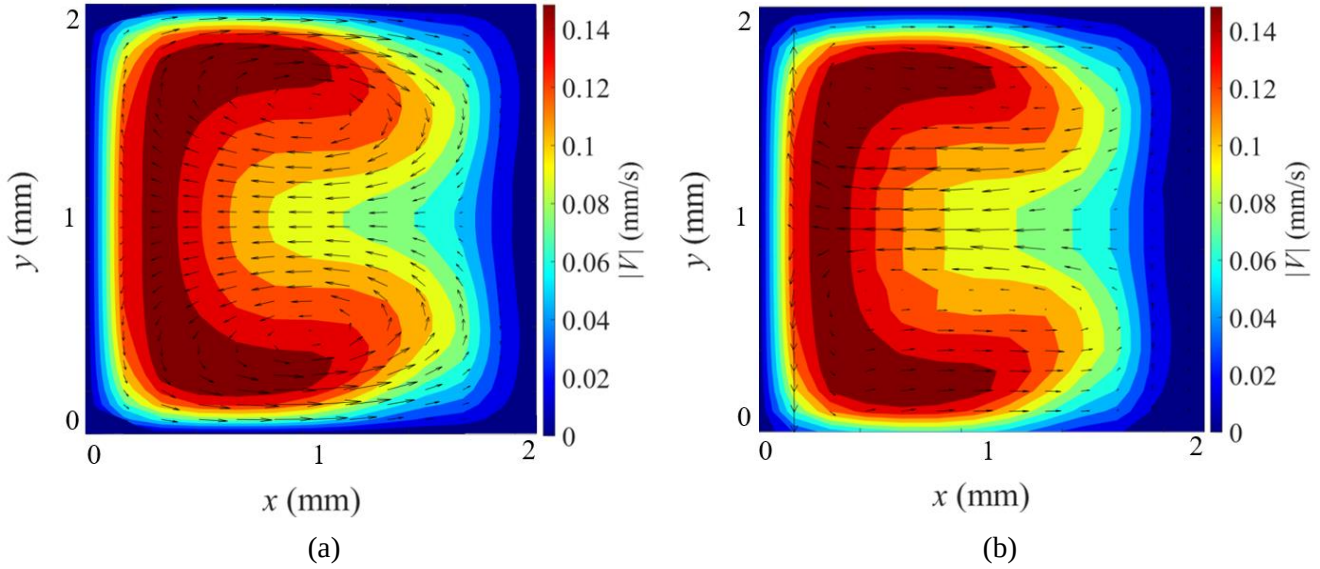


Fig. 6 Velocity contour and velocity vector in the cross section of a curved channel (a) velocity results from simulation, (b) velocity results from continuity equation and 2D velocity components.

7. Results

The velocity contours and vector fields in scanning planes among the channel depth are shown in Fig. 7. This figure also represents the maximum velocity magnitude in each scanning plane. It can be seen that the parabolic velocity diagram is captured well at the low flow rates in the microchannel. Velocity contour and vector fields for planes 2, 4, 6, 8 show experimental results among the depth of channel. Flow velocity near the wall is well refined and adjusted to the edges of the curved channel using the tessellation approach.

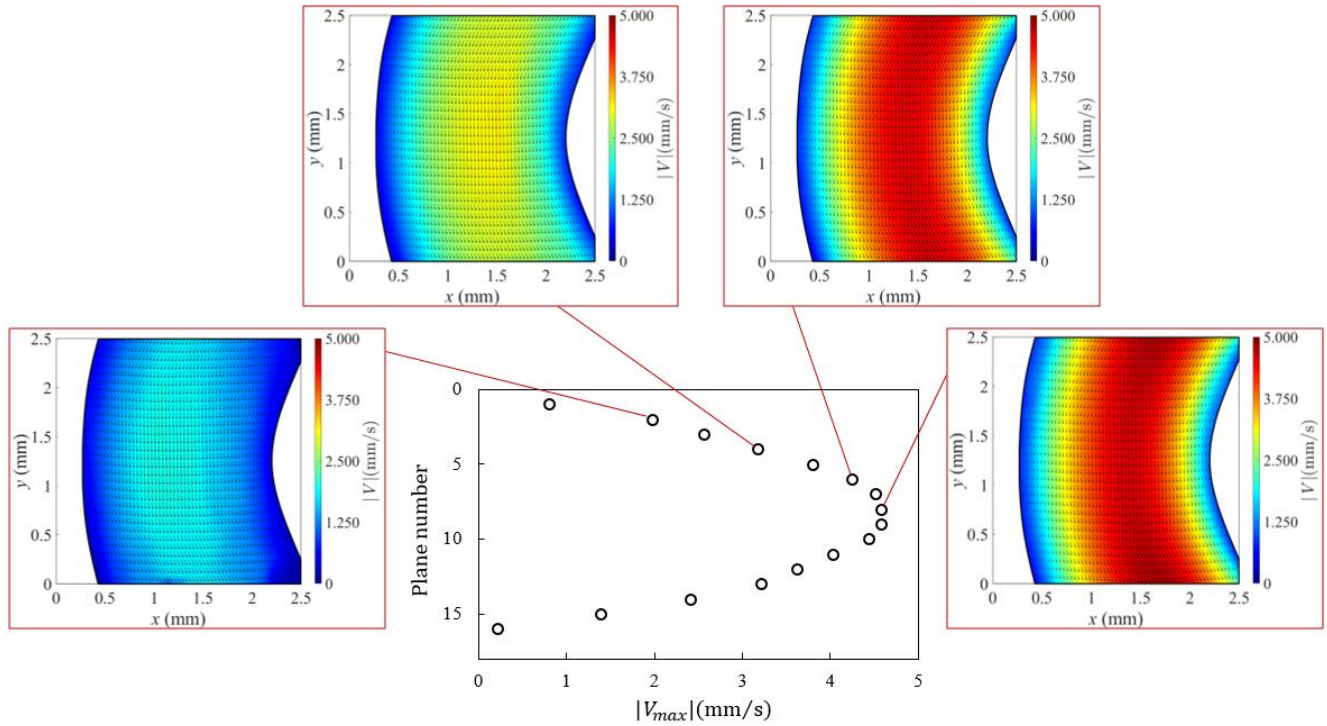


Fig. 7 Maximum velocity magnitude for each plane among the depth of channel indicating the parabolic velocity diagram, the velocity contours and velocity vector field for planes 2,4,6,8 in curved channel with flow rate 35 ml/h.

The velocity profile obtained from applying the μ SPTV on the middle plane $z = 1$ mm is shown in Fig. 8. The velocity diagram in this figure shows the location of the maximum velocity point. The deviation between the maximum velocity point and the centerline of the channel indicates the lateral movement of the high velocity region toward the inner wall. Using the tessellated velocity field it can be seen that flow velocity near the wall is well captured. In low flow rates where there is no secondary flow motion, the pressure near the outer wall is higher than the inner wall (Jing-lei, 2008). As a result, the maximum velocity location shifts towards the inner wall (Jing-lei, 2008) which is similar to the results shown in Fig. 8.

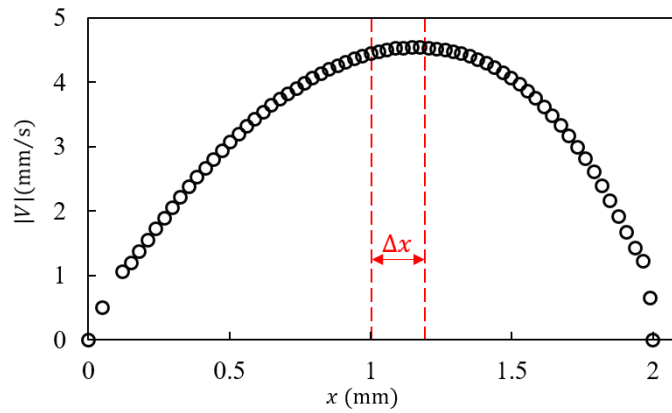


Fig. 8 Deviation of the maximum velocity point location from the channel center in the velocity diagram of the middle scanning plane for flow rate 35 ml/h.

7. Conclusions

Application of 3D scanning PTV on a curved microchannel is investigated. A custom made image processing code is employed to generate a mask using the raw images. The near wall data is refined using the tessellation method for the curved geometry using a high quality mesh. The discretised form of the continuity law is employed and validated using the simulation results to calculate the out-of-plane velocity component of the flow in a curved channel. The scanning method is conducted to capture the flow motion in the depth of a microchannel with the depth of 2 mm. The output results of each step can be used to calculate the out-of-plane component of the velocity using a 3D tessellated velocity field on a triangular mesh.

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