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Flow Measurements in Microchannels Using a MicroPIV system

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Abstract

High quality PIV experiments in micro-channel flow geometries to get detailed and accurate flow measurements can be difficult and involves paying attention to a variety of aspects. In the experiments, the reasons could be ranging from uncontrolled transients in the fluidic flows systems to fouling of the micro-channels by impurities, bubbles, the seed particles themselves. Another factor which could have a significant effect is the distortion of the boundary of the channel caused by the difference in the refractive indices. Experimental measurements were taken on two channels in a PDMS (polydimethylsiloxane) micro-channel test facility shown in Figure 1. The two micro-channels under study were (a) the expansion channel with fully developed flow in a 150 µm wide rectangular section to a 750 µm wide channel, and (b) a 'T' junction with two 100 µm wide outflow channels branch at two 90 degree elbow turns from a 100 µm inflow channel. Both micro-channels are 100 µm deep across the entire channel length. The measurements were performed for Reynolds number of 1, based on the centerline velocity of the channels. The experiments were performed using a PIV system equipped with an inverted microscope. Fluorescent particles of about 1 µm in size were employed as seed particles. Typical particle number concentration was around 2 to 3 particles per interrogation volume. Hence, the ensemble average of the correlation function was used to obtain the velocity vectors. Channel geometry imperfections, fouling and bubble formation affect the flow development and the nature of the flow, especially near the wall.

Introduction

Flows in micro-channels are of interest in a wide range of areas such as aerodynamics, fluid mixing, propulsion, microsprays, chemical and biological analysis, bio-MEMS applications and bio-fluid mechanics [1]. The high surface-to-volume ratio and the small volume of flow associated with microchannels provide unique advantages in the area of transport, especially heat transfer.

Generally, micro-channels are defined to be smaller than 1mm, and for measurement purposes, more than tens of microns. Fabrication of the channels is a complex process that can have strong impact on the surface texture, cross sectional geometry and hence the affect the velocity field, especially, close to the wall boundaries. In microflows, unlike in ordinary flows, the entire flow field is influenced by the presence of wall boundaries. Hence, the entire flow field could be affected by the imperfections in the channels caused during the manufacturing process.

Various types of fabrication techniques are used to obtain different desired microchannel (cross section) properties [2]. Lithography is one of the most common techniques for fabricating microchannels. Although the channels could be made out of different polymeric materials, PDMS (polydimethylsilooxane) is often chosen for the many properties it exhibits that are suitable for flow measurement applications. Transparency to laser light illumination, mechanical durability, good surface chemistry and stability against humidity and temperature are among them. A rapid prototyping method based on lithography is used to fabricate the microchannels [3 - 5]. The microchannel flow model used here is a test bed that contains multiple flow elements or channels of different geometries. Velocity measurements are carried out in two different channels in the test bed.

Experimental details

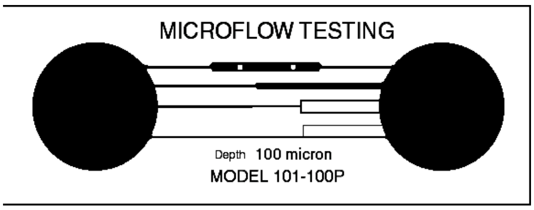
The microchannel flow model used here for the experiments is a Model 101-100P test bed. The details of the construction of the Model 101-100P PDMS test facility are as follows.

The mask for photolithography containing a negative image of the micro-channel device is created in a CAD program then printed on a transparency by a high-resolution printer. The mold is made from a silicon wafer coated by a 100 micron thick layer of photo resist (Nano XP SU-8 100, Microchem Corp., Newton, MA) by spin-coating at 2900 rpm for 30 s, followed by a soft-bake (95C for 30 min.), UV lithography (650 mJ/cm2), a post-bake (95C for 30 min), and development for 10 min. A pre-polymer of PDMS is then cast onto the mold and cured. The PDMS replica is then peeled from the silicon wafer leaving the channels cast into the surface of the cured PDMS.

To create closed channels a cover glass slip is bonded to the PDMS surface by oxidizing both the surface of the PDMS replica and glass by oxygen plasma treatment (70W, 85mTorr for 20s). When the two oxidized surfaces are brought into contact they bond covalently creating a seal, which can withstand up to 5 bars. The tightly sealed channels are necessary for pressure driven flow experiments to be conducted over a wide range of speed. Since the surfaces of the glass and the PDMS are each hydrophilic, filling the channels with liquids is relatively easy.

A gravity feed approach (pressure driven) was used to generate the flow in the microchannel. The two reservoirs (Fig.1) in the test bed provide a stable pressure differential to drive the flow.

The two micro-channels in the test bed used are
(a) expansion channel with fully developed flow in a 150 µm wide rectangular section to a 750 µm wide channel and (b)‘T’ junction with two 100 µm wide outflow channels branch at two 90 degree elbow turns from a 100 µm inflow channel.



Both micro-channels are 100 µm deep across the entire channel

Figure 1: PDMS Microchannel test bed

length. Distilled water was used as the fluid medium. The flow was seeded using fluorescent particles of about 1 µm in size.

Since volume illumination (as opposed using a light sheet illumination in macro flow PIV applications) is used in measuring microflows, the number concentration of seed particles need to be controlled [6]. The out-of-focus images becomes the background noise that, if not properly controlled, could overwhelm the particle images and hence can result in poor signal quality. The number of out-of-focus images can be reduced by controlling the seed number concentration, C or selecting the proper depth, L, of the channel. The visibility V of the in-focus images [6] is

$$V \sim 1/(CL) \qquad (1)$$

In the present study, the approach was to rely on the depth of the channel (100 microns) to reduce the background or out-of-focus images. The Reynolds number based on the channel hydraulic diameter is about unity.

MicroPIV system

An inverted microscope-based MicroPIV system was used for making measurements in the channels. It uses a multiport design that allows for different illumination and imaging systems. The components include a binocular with eyepiece; universal stage holder and traverse; nosepiece sextuple; illumination lamp kit; F-mount adaptor; epioptics attachment housing; and microscope objectives. This approach, using epifluorescence, allows illumination and scattered light collection to use the same optical access to the flow channel. A 12-bit, 4 Megapixel camera (POWERVIEW 4M) was mounted on the side of the microscope optical system to get the greatest flexibility, stability and ease of use. A lens system attached between the microscope and the camera increases the image field magnification and allows more uniform illumination of the flow field. A light guide system was used for the convenient delivery of the laser light. It consists of a light guide, a diffuser and lens to provide uniform beam intensity, along with adaptors for the microscope and the laser. A laser light attenuator used with the laser provides good control of the laser energy.

INSIGHT Data Analysis and display software was used to analyze the image fields. Iterative processing combined with window shifting was used to get high spatial resolution. Both local and global signal enhancement techniques were used. A TSI Synchronizer system provided precise timing and synchronization for the operation of the Dual-YAG Laser and the 2K x 2K camera and other hardware.

Since the typical particle number concentration was around 2 to 3 particles per interrogation volume, the approach of ensemble averaging of the correlation function was used. This approach improves the signal-to-noise level of the image, and increases the spatial resolution of the measurement [7]. The flows in this channel are steady and hence ensemble correlation approach can be advantageously used. An ensemble average of the correlation of 100 captures was used to calculate the velocity vector on each interrogation region. The background reference image computed using the mean intensity was used for background subtraction. This improves the signal quality of the images and/or the removal of "unwanted objects" in the image field. Other tools that are part of the ***Micron Resolution Particle Image Velocimeter*** patent are also incorporated into the INSIGHT software package [8]. The typical spatial resolution obtained in the experiments was about 4 microns.

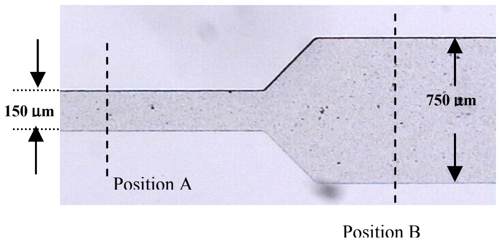


Figure 2: Diffuser channel

The measurements in the diffuser channel are shown below. Position A is 1500 microns upstream of the diffuser. Measurements were carried out in two different planes in the Z-direction (depth of the channel). Z = 50micron corresponds to the mid-plane of the channel.

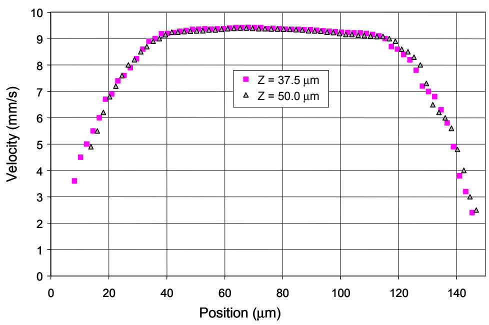


Figure 3: 1500 mm upstream of diffuser

The velocity profile (Figure 3) indicates the expected behavior in the center region of the channel. The measured velocity values near the wall indicate some departure from the ideal distribution.

It appears that the deviations of the velocity profile are caused by a variety of factors relating to geometrical imperfections and potential fouling of the channel.

Figure 4 shows the velocity distribution downstream of the expansion. Here, the velocity distribution is close to the expected profile.

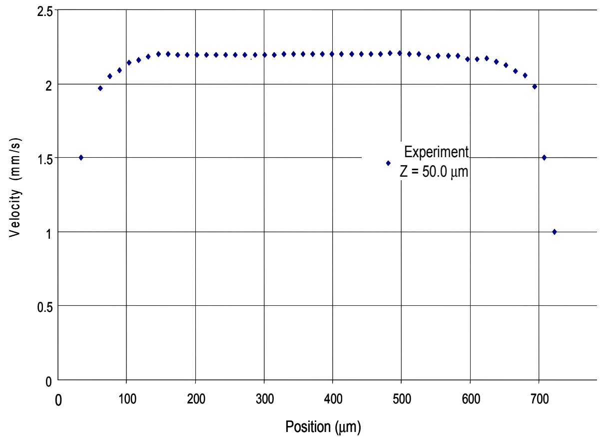


Figure 4: 750 microns downstream of diffuser

The dimensions and the measurement locations in the T-channel are shown in Fig.5. Measurements were carried out at multiple locations upstream and downstream of the t-junction.

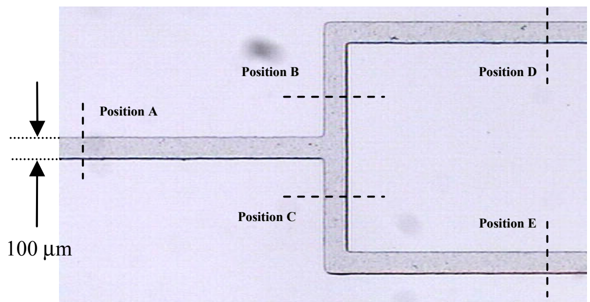


Figure 5: T- channel

Velocity profiles in the T-channel are shown below. They represent measurements at different channel depths (Z).

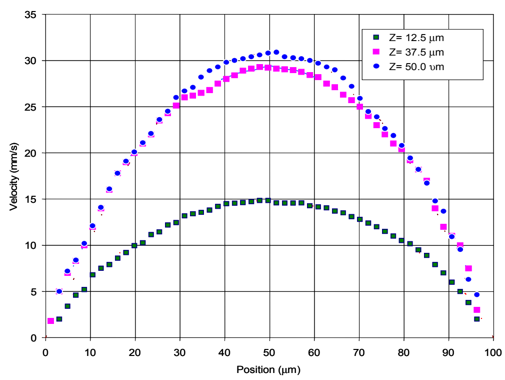


Figure 6: 2000 microns upstream of junction – position A

Position A corresponds to a location 2000microns upstream of the junction. Velocity profiles obtained at three different Z values are shown in Figure 6. Z = 50 corresponds to the mid-plane of the channel.

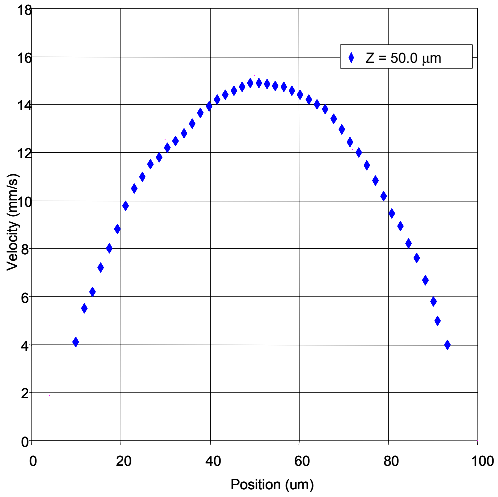


Figure 7: 200 microns downstream of junction – pos. B

Measurements at a location 200 microns downstream of the junction are shown in Figure 6. The velocity profile at this location show that the flow has not fully recovered from the influence of the corner or the junction on the flow. In addition, three dimensional effects due to out-of-plane motion downstream of the 90 degree corners can also influence the velocity profiles.

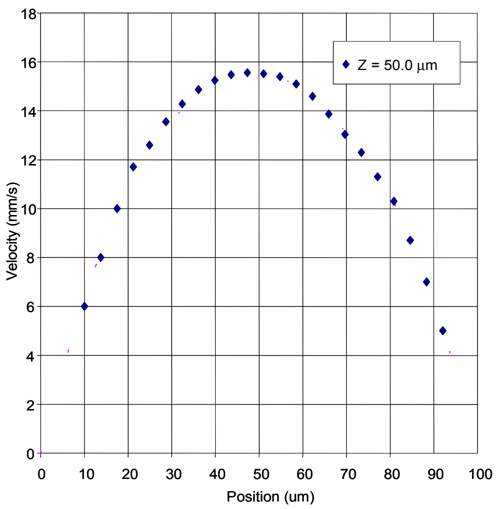


Figure 8: Velocity profile at position D
2000 microns downstream of junction

The velocity profile at 2000 microns downstream of the junction is shown in Figure 8. The flow field appears to have fully recovered from the influence of the junction on the flow profile. In microchannel flows, the surface fouling due to accumulation of particles and other material on the wall affects the velocity profile near the wall. It is also known that bubbles that develop in the channel can aggregate and adversely affect flow development. This in turn affects the velocity profile. These practical aspects associated with the microflow experiments can limit the accuracy of the results obtained.

Conclusions

Measurements in microchannels require careful consideration of the seed concentration. Special analysis techniques combined with other tools are used to reduce the background "noise" influence and enhance the signal quality. The operation of the channel so as reduce or prevent fouling of the surfaces becomes important in getting accurate near wall flow details. In addition to fouling due to particles, formation and development of bubbles can noticeably affect the flow profiles. These aspects along with the wall roughness of the PDMS model demands special attention to detail in order to get accurate detailed measurements in microchannel flows.

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