15th International Symposium on Flow Visualization
June 25-28, 2012, Minsk, Belarus

# TEMPERATURE AND VELOCITY MEASUREMENTS IN 90 DEGREE BEND MICROCHANNEL FLOW

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**KEYWORDS**:
**Main subjects**: temperature and velocity measurements, flow visualization
**Fluid:** microchannel flow
**Visualization method(s):** molecule-based temperature sensor, micro-particle image velocimetry
**Other keywords:** 90 degree bend microchannel, secondary flow

**ABSTRACT**: This paper examines the temperature and velocity profiles in a 90 degree bend microchannel using molecule-based temperature sensor and micro-particle image velocimetry (micro-PIV) techniques. These techniques are capable of providing both detailed and global profiles for velocity and temperature investigations in microfluidic research. The molecule-based temperature sensor technique used Rhodamine B as the temperature probe to provide non-invasive and straightforward temperature measurements with accuracy around 1 °C. To further resolve the luminescence deviation/reflection of luminescence-based temperature measurements around the bend, pixel-by-pixel correction was applied along with in-situ calibration method. The temperature and velocity measurements were performed in a 200 μm wide, 67 μm deep and 2 cm long PDMS microchannel with 90 degree sharp bend at the center. The temperature profile was measured at a Reynolds number of 27.66 with DI water as working fluid, and the bottom of channel was heated at a constant temperature of 50 °C. The velocity profile around the 90 degree sharp bend was acquired at the same Reynolds number using micro PIV technique. Secondary flow structure around the corner was observed with multiple layers measurements along the depth of the microchannel. The temperature distributions before and after the corner in axial(x) and crosswise(y) directions show enhanced heat transfer as a result of flow mixing from the secondary flow while passing through the corner. This study not only measured and analyzed the flow and thermal fields in the microchannel but also provided essential information of the flow structure resulting in the heat transfer enhancement.

## 1. Introduction

With the intensively increased applications of microelectromechanical systems (MEMS) in various areas, the heat transfer enhancement in limited space has become an important issue to be resolved and improve device performance. Micro-sized heat exchangers have been installed in electronic devices to provide heat transfer. In order to improve the heat transfer with various designs in micro heat exchangers, different kinds of microchannels such as straight, 90 degree bend, and serpentine have been constructed and integrated in micro heat exchangers as key components for fluid delivery as well as heat dissipation. The temperature variations inside such microchannel designs have drawn great attentions due to its importance in characterizing micro heat exchangers. Conventional experimental approaches study the temperature distribution inside microchannels using thermocouples installed at channel inlet and exit to acquire the temperature data, and further elaborate the temperature profile inside the channel by extrapolating or through simulation. In the past decades, with the advance of MEMS technology, microscale thermocouples have been constructed and applied inside microchannels to obtain temperature data. However, the temperature data inside microchannel acquired with micro-sized thermocouples are limited and discrete. Furthermore, disagreements between experimental data and theoretical calculations have also been reported. The inconsistency is assumed to be attributed to the heat loss during experiments, slip-flow boundary condition in the microchannel flow, accuracy of applied experimental technique…etc. The micro-sized thermocouples can only measure temperature for restricted positions due to the sensor implementation and placing on the surface of microchannel, i.e., only surface temperature data can be acquired. Furthermore, micro-thermocouples have a size around hundred micrometers and only limited number of sensors can be applied inside the channel and only able to obtain discrete data.

In order to acquire detailed temperature information inside microchannels, molecule-based temperature sensor has been applied. It is adapted from the conventional macro scale experimental technique known as Temperature-Sensitive Paint (TSP). Similar techniques like Laser-Induced Fluorescence (LIF) technique have been applied in the microfluidic research in the past years. These techniques use luminescence molecules that change their intensity of emitted fluorescence according to the temperature level in the environment. With careful calibration, the fluorescence intensity can be translated to temperature profiles for further analysis. Due to the small size of these luminescence sensors, which is usually less than one nanometer, these sensors can be dispersed in fluid and filled inside the microchannel to provide temperature data with spatial resolution around a few micrometers. LIF was applied in the microfluidic research for temperature measurements and heat transfer analysis in various microchannel devices [1]. Temperature sensitive molecules, Rhodamine B, have been applied in the microchannel to investigate the temperature distribution in the straight microchannel and to acquire temperature variation due to localized heating in the microchannel [2, 3]. Chamarthy et al. have applied ratiometric LIF thermometry with Rhodamine B as temperature probe for temperature measurements at T-junction in microchannel devices to observe heat transfer in the mixing of a cold and a hot water flow [4].

In this work, temperature-sensitive molecules were dispersed in the fluid to acquire the temperature around a 90 degree bend microchannel under constant wall temperature thermal condition. The velocity profiles have also been analyzed with micro-PIV technique in order to investigate the enhanced heat transfer due to the secondary flow pattern around the corner.

## 2. Background

Molecule-based temperature sensor has been applied in aerospace and mechanical engineering applications in macro scale experiments in the past few decades. Molecule-based temperature sensor has been used in the macro scale experiments not only to provide temperature profiles on the test models but also to help indentify flow characters such as the location of transition from laminar to turbulent [5]. Molecule-based temperature sensor is generally constructed with temperature sensitive luminescent molecules and polymer binder, and it can be further applied using air-spray as regular paint or spin-coating for micro scale measurements [6]. In order to prevent oxygen quenching changing the luminescence intensity, oxygen non-permeable polymer binders are selected to attach the temperature sensitive molecules on the measurement region. With proper binder selection, the luminescence from temperature sensitive molecules will be solely affected by the chemical reaction of thermal quenching, i.e. the increase of temperature decreases luminescence. For the temperature measurement using the molecule-based temperature sensor dispersed in the fluid, uniform distribution of sensors in the fluid is assumed as well as homogeneous oxygen concentration in fluid. The measurements of molecule-based temperature sensor use a light source with specified wavelength for excitation and a photo detector of CCD camera to collect the emission signal from temperature sensitive molecules. The Arrhenius equation is commonly used to translate the luminescence intensity to temperature data:

$$\ln\frac{I(T)}{I(T_{ref})}=\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right) \tag{1}$$

Where $E$ is the Arrhenius activation energy, $R$ is the universal gas constant, $I(T)$ and $I(T_{ref})$ are the intensities acquired at specified temperature and reference temperature either during the measurement or calibration. $T$ and $T_{ref}$ are the temperature reading during the measurement and reference condition in the unit of Kelvin, respectively. For practical applications, a high order polynomial equation is applied for the calibration.

$$\frac{I(T)}{I(T_{ref})}=F(T/T_{ref}) \tag{2}$$

The schematic of molecule-based temperature measurements in a PDMS microchannel is shown in Fig. 1. The application range of molecule-based temperature sensor is between -196 and 200 $^{o}$C with a resolution around 0.5 $^{o}$C [7].

For velocity measurements in microfluidic research, micro-PIV technique has been used to provide detailed velocity profiles inside micro devices for decades. By tracking tracer particles sizing around a few micron to sub-micron, micro-PIV technique can provide detailed micro scale flow fields at a spatial resolution around couple micrometers [8]. During the measurements, a fluorescence microscope installed with a CCD camera, which has double shutter function, is used to acquire pairs of images for further calculating the particles displacement between these images. Cross-correlation and central difference image correction could be applied during calculation to improve the accuracy. The time controlled by a signal generator between image acquisitions was used to calculate the velocity vector in the images. However, the size and density of tracking particles need to be carefully considered to render particles truthfully following the fluid and therefore representing the correct flow fields. The micro-PIV also provides non-intrusively measurements like molecule-based temperature sensor.

## 3. Experimental

For temperature measurements in the 90 degree bend PDMS microchannel, Rhodamine B was selected as the temperature probe. It was dispersed in DI water and the mixture was served as the temperature sensitive fluid inside the microchannel. The temperature sensitive fluid was prepared based on the ratio of 1 mg Rhodamine B to 10 ml DI water. The 90 degree bend microchannel was 2 cm long with 90 degree bend at center, 200 μm wide, and 67 μm deep. It was made by standard soft-lithography using PDMS as the constructing material. PDMS was Sylgard 184 obtained from Dow Corning, USA and was prepared at the ratio of 10 to 1 (A to B) for the silicone elastomer and elastomer curing agent. Two circular reservoirs were positioned at the channel inlet and exit to provide uniform and smooth flow inside the microchannel. Thermocouples were installed at the inlet and exit reservoirs for monitoring the temperature conditions at inlet and outlet during the measurements and serving as the temperature reading during the in-situ calibration. The PDMS microchannel was then placed on top of an electric heater which is used for temperature control during the constant wall temperature experiment. A 7 cm long, 5 cm wide and 3mm thick copper plate was positioned in between the heater and the PDMS microchannel to provide constant and uniform temperature distribution during the measurements. A white base coat was applied on the top of copper plate surface to cover the machining scratch and a layer of PDMS was applied on the top of white paint for bonding to the PDMS microchannel. The heater was attached underneath the copper plate and a k-type thermocouple couple was attached to the surface of copper plate for temperature control. The temperature distribution on the copper block surface was examined at different locations and less than 0.5 °C deviation was observed on the surface while the temperature was set as 50 °C. The heater with current experimental setup provided constant and uniform temperature condition for the measurements. The mixture of Rhodamine B and DI water was filled in a syringe then infused into the microchannel by a syringe pump (KDScience 120). The luminescence profiles were acquired with a 14 bit high resolution CCD camera (PCO 1600, 1400x1600 pixel, PCO). Two UV LED arrays (405 nm) provided illumination from the sides for sensor excitation. A 600nm long-pass optical filter along with a set of extension tube on a 105 mm macro lens was installed on the CCD camera to provide the magnification up to 144 μm per pixel resolution, which can be translated as 2700 data points in single image acquisition. During the experiment, in-situ and pixel-by-pixel calibration was performed before every measurement to ensure the identical sensors and illumination conditions for both calibration and measurements. Typical calibration curve of Rhodamin B in DI water is shown in Fig. 2. Fig. 3 shows the experimental setup of molecule-based temperature measurements in PDMS microchannel. During the measurements, it has been observed that the luminescence molecules trapped in the channel surface due to the porous structure of PDMS and resulted in the luminescence accumulation. In order to resolve this situation, Rhodamine B / DI water solution was injected into the PDMS microchannel 6 hours before the measurement to saturate the luminescence intensity accumulation [3].

For the velocity measurements, 0.71 μm fluorescent polymer microspheres (Fluoro-Max) were used as the tracking particles and dispersed in DI water in the weight ratio of 0.2%. The density of tracking particle is 1.06 g/cm$^3$ and can be uniformly dispersed in the DI water. Since the luminescence signals from temperature sensitive molecules and fluorescent particles for PIV measurements have similar emission spectrum, the temperature and velocity measurements were done separately using different devices and instrumentation; *i.e.* no Rhodamine B was mixed in the fluid during velocity measurements. A 532 nm double-pulse Nd:YAG Laser (LOTIS LS-2134U) was used to provide the excitation for tracking particles. A Nikon E800 fluorescence microscope installed with a double shutter CCD camera (PCO Sensicam, 1280x1024 pixels) was used to acquire images for the velocity measurements. Precisely adjustment of time interval between double pulse laser and shutter control from the camera was provided by a pulse generator (BNC 555 pulse/delay generator). The fluid was driven and controlled by a syringe pump (KDScience 120). After the images of flow with tracking particles were acquired, they were analyzed with commercially available PIV software, EdPIV, with cross-correlation to retrieve the velocity profiles. Up to 400 images were recorded for the PIV analysis and the velocity data presented in this work are the results after averaging 200 velocity profiles.

# 4. Results and discussion

## *4.1 Temperature measurements in the 90 degree bend microchannel*

The temperature profiles in a 90 degree bend PDMS microchannel were acquired with DI water /Rhodamine B mixture at the flow rate of 12.65 ml/hr, as shown in Fig. 4. Fig. 5 shows the temperature distribution along the central line at different locations. It should be noted that the temperature measurements using molecule-based temperature sensor were obtained with optical access through the top of microchannel; therefore, the results are depth-averaged temperature of fluid ($T_m$) in the channel regardless of the single sided (bottom) heating. The temperature distribution was acquired under constant wall temperature (50 °C) thermal boundary condition. The corresponded Reynolds number was 27.66. The fluid was injected into the inlet reservoir and the fluid temperature was around 36 °C at the channel entrance. The fluid temperature increased to 40 °C in a distance about 10% of $L_{ref}$ behind the entrance. Then it gradually increased to 42 °C while approaching to the corner. There was a 2 °C temperature jump while the flow passing through the corner, which shows the enhanced heat transfer around that region. After the corner, the fluid temperature continued increasing to 46 °C at the location of 0.6 $X/L_{ref}$.

With the advantages of global measurements using molecule-based temperature sensor, the temperature profiles at the regions of interest could be further examined not only in the axial but also crosswise direction. The lateral temperature distribution near the channel inlet ($y/L_{ref}$ =-1.0) is shown in Fig. 6. The temperature data acquired at the entrance shows the developing temperature profile: the fluid temperature near the side wall was around 40 °C while the fluid temperature at center was close to 36 °C. To discuss the enhanced heat transfer at the 90 degree bend, the temperature profile at the corner is examined in Fig. 7. High temperature region was identified at the area near the outer corner where the flow decelerated. Several lateral temperature profiles are plotted with normalized location with respect to the channel width (w=200μm) starting from inner side wall (x/w=0) at different upstream locations from y/ $L_{ref}$ of -0.035 to -0.010 immediately before the corner. The temperature near the inner wall gradually decreased and this can attribute to the flow accelerating at inner wall while approaching the 90 degree corner. On the other hand, the temperature at outer wall gradually increased to attribute to the flow decelerating at the outer region. For more detailed investigation, the variations of temperature profiles near the corner need to be confirmed by velocity profiles acquired by micro-PIV measurements.

## *4.2 Velocity measurements with micro-PIV technique in the 90 degree bend microchannel*

For the velocity measurements inside the 90 degree bend microchannel, the region of interest was focused at the corner. The averaged velocity profiles were acquired at the center in the z-direction, *i.e.* the center of depth of microchannel, as shown in Fig. 8. Fig. 9 shows the velocity profile in the area around the 90 degree corner. In Fig. 9, the flow velocity at the inner region accelerated while the flow velocity at outer region decelerated as the fluid approaching to the corner. However, after passing the corner, the flow velocity at the inner region decelerated while the flow velocity at outer region accelerated. The change of the flow velocity at inner and outer regions indicated the forming of secondary flow around the corner. To further investigate the secondary flow pattern around the corner, the velocity profiles at different z-directions (depth) have been acquired to show the pattern of secondary flow after the corner. The depth resolution of micro-PIV measurements depends on the particle size, pixel resolution of image, the magnification and N.A value of objective lens, and the wavelength from excitation light. In this study, the resolution of measurement depth in the system was calculated as 3.04 μm. The velocity profiles along the z-direction were acquired at a 4μm interval to provide detailed information regarding the flow pattern.

In Fig. 10, the v-component velocity profiles at different layers (z-location) are plotted along different y locations with the outer wall located at right hand side (y/w=0.5) and inner wall at left hand side (y/w=-0.5). The x, y, and z locations are normalized by the hydraulic diameter of the channel ($D_h$), the width of microchannel (w), and the depth of microchannel (h) respectively. The velocity profiles were acquired at the x location equal to one hydraulic diameter downstream of the corner. Every connected line in the profile represents the v-component velocity acquired at the same y location but with data points measured at different z locations. The positive and negative v-component velocities (corresponding to the zero velocity line as the straight line at y location) indicate the direction and magnitude of flow velocity. By observing the trend of velocity profiles at this region, a pair of circulation flows was indentified near outer wall region. In the mean time, a pair of small circulation flows was also found near the inner wall. It shows the flow was pushed to the outer wall from the center and re-circulated after reaching the outer wall. The schematic of flow pattern with secondary flow around the corner is also drawn in Fig. 9.

## 5 Conclusions

In this work, the temperature and velocity profiles have been successfully acquired in a 90 degree bend PDMS microchannel using molecule-based temperature sensor and micro-PIV technique. The acquired temperature data reveal the evolution of temperature profiles from entrance to the 90 degree corner, where the fluid experiences enhanced heat transfer and a 2 °C temperature jump. The detailed temperature profiles acquired around the corner show the temperature variations at inner and outer wall while approaching the corner, and the temperature results agree with the velocity profiles measured by micro-PIV technique. Two pairs of circulations were identified at the location of one hydraulic diameter downstream of the corner and they validated the secondary flow profile. The secondary flow after the corner effectively increased the heat transfer even at the low Reynolds flow in this study.

### Acknowledgement

The author would like to thank Prof. S. Wereley from Dept. of Mechanical Engineering at Purdue University, USA for the help of EdPIV software for micro-PIV analysis. The author would also like to thank the financial support from NSC project NSC100-2221-E-007-107.

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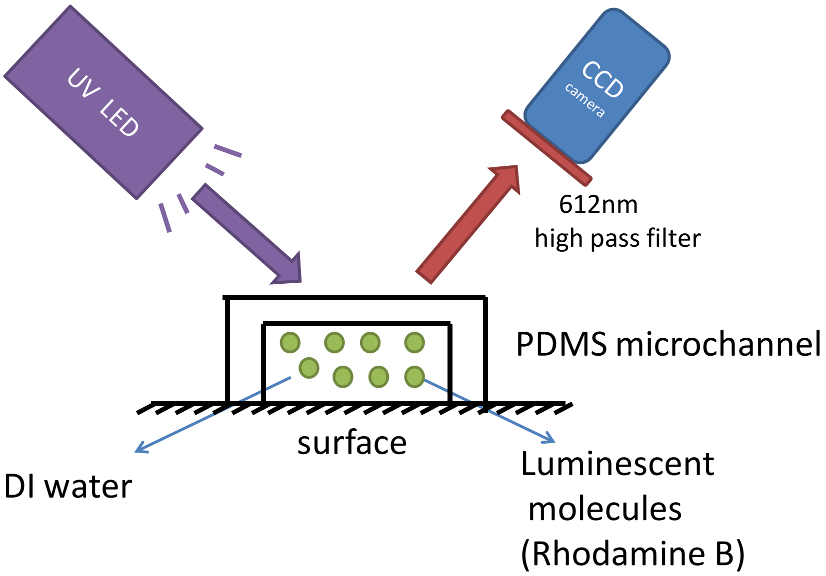

Fig. 1 Schematic of molecule-base temperature measurement in PDMS microchannel.

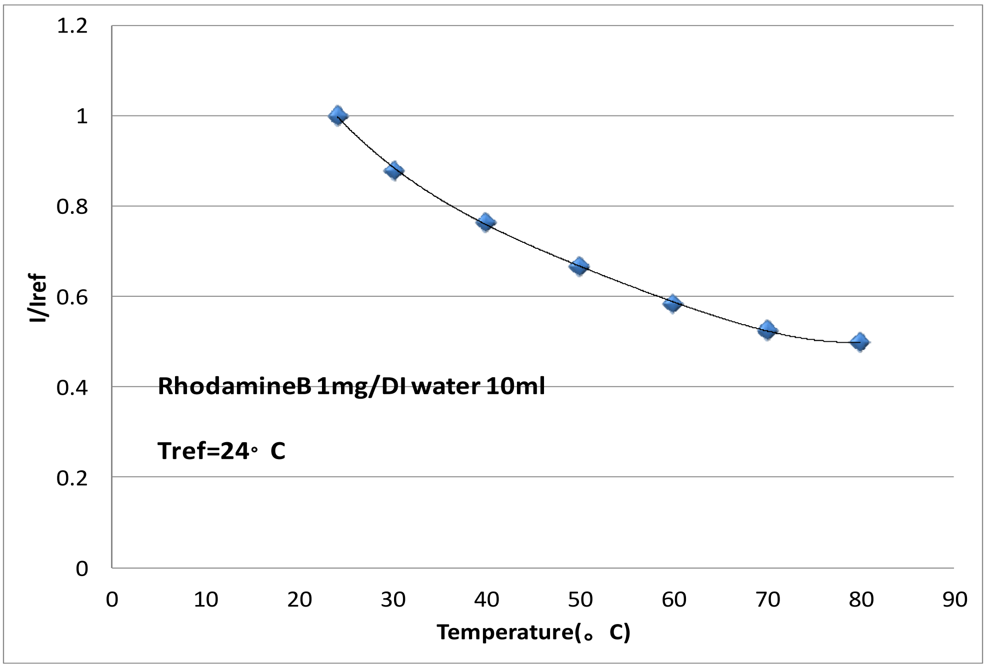

Fig. 2 Typical calibration curve of Rhodamine B and DI water solution.

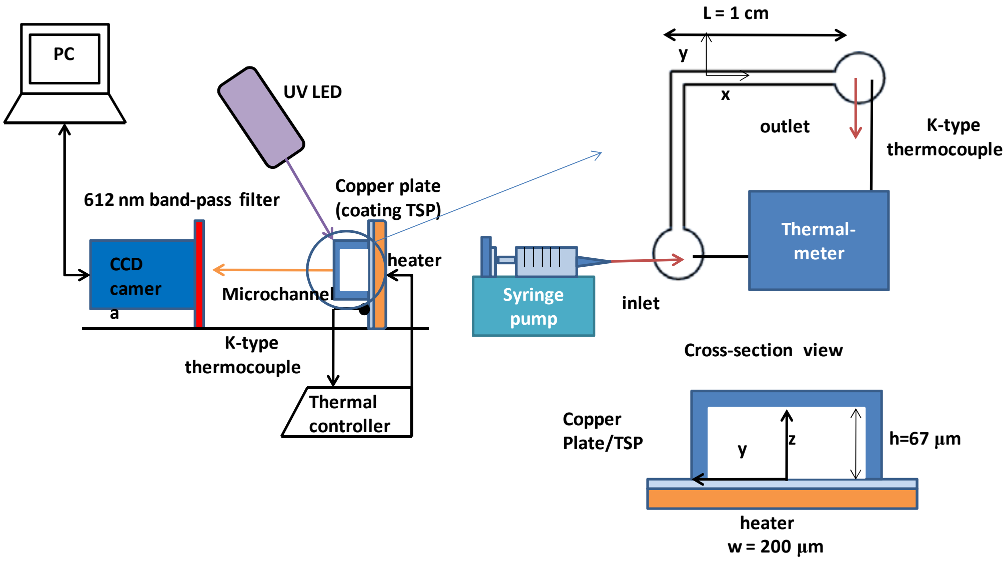

Fig. 3 Experimental setup of molecule-base temperature measurements in PDMS microchannel.

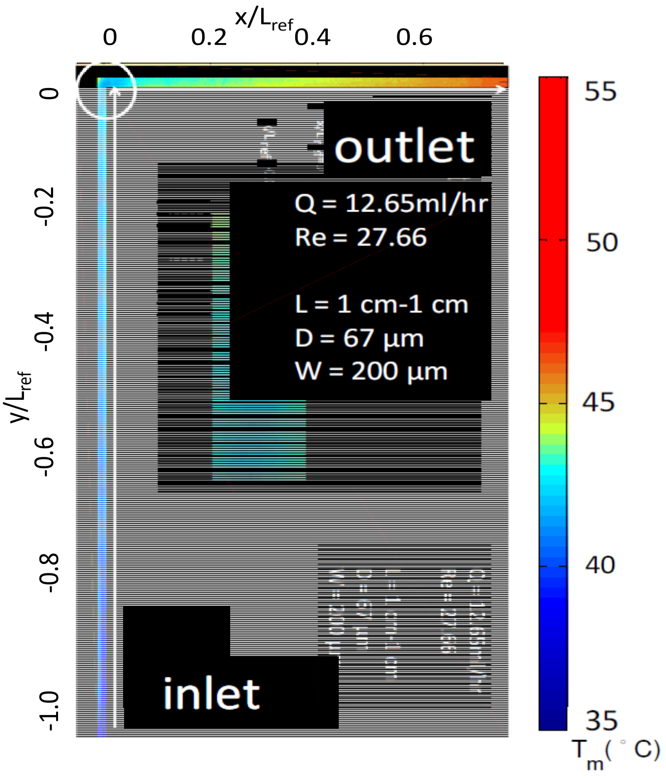

Fig. 4 Temperature profile of 90 degree bend PDMS microchannel at the flow rate of 12.65 ml/hr

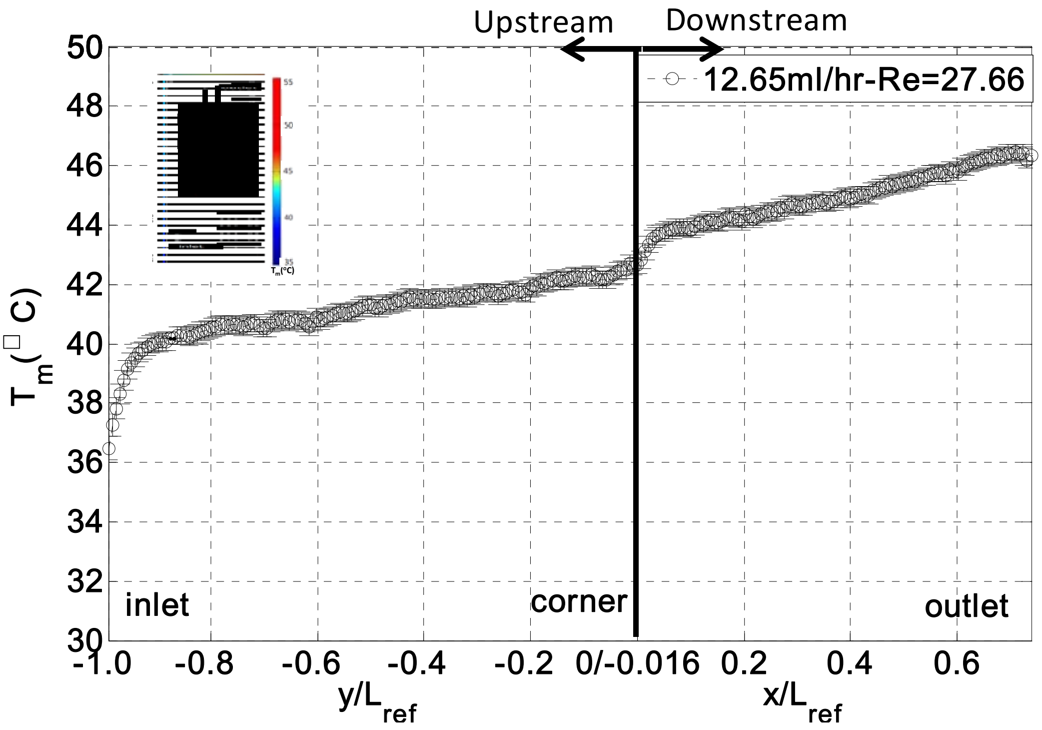

Fig. 5 Temperature distribution along the central line inside the 90 degree bend microchannel. : inlet ($y/L_{ref}$ =-1.0), 90 degree bend ($y/L_{ref}$ =0), outlet ($x/L_{ref}$ =0.75). $L_{ref}$ : 1 cm, the distance between inlet and bend as well as from the bend to the outlet.

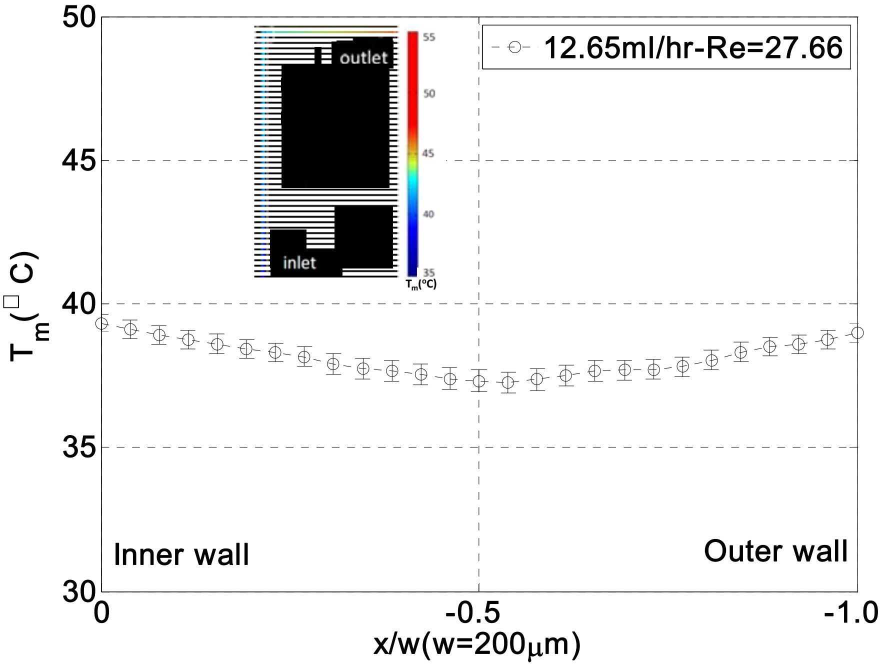

Fig. 6 Lateral temperature distribution at channel inlet.

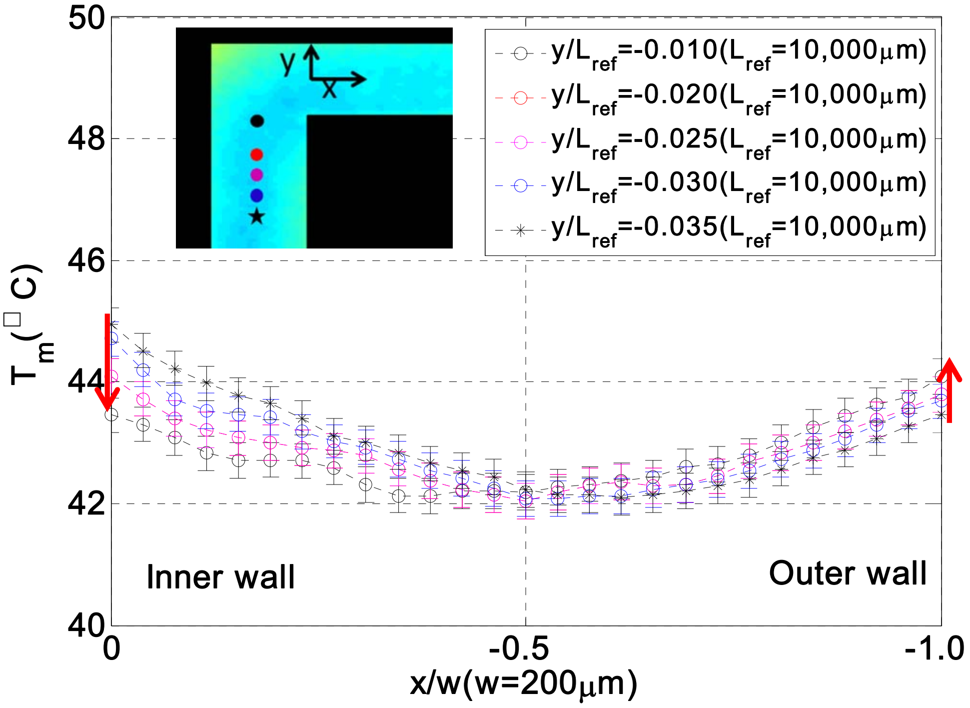

Fig. 7 Lateral temperature distributions acquired at different locations immediately before the 90 degree corner.

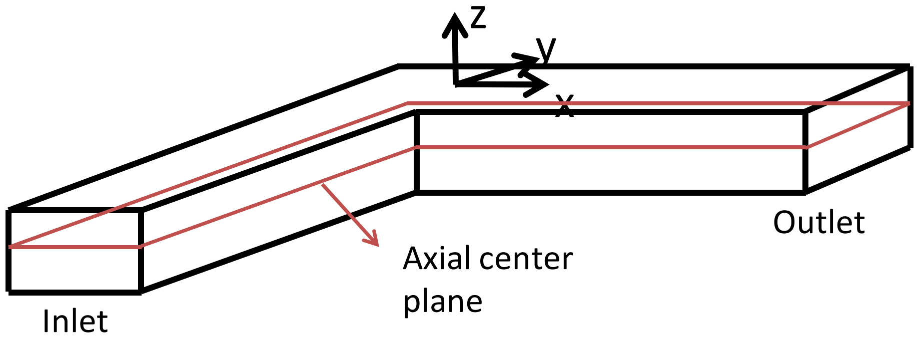

Fig. 8 The schematic for the axial center plane for velocity measurements around the 90 degree bend.

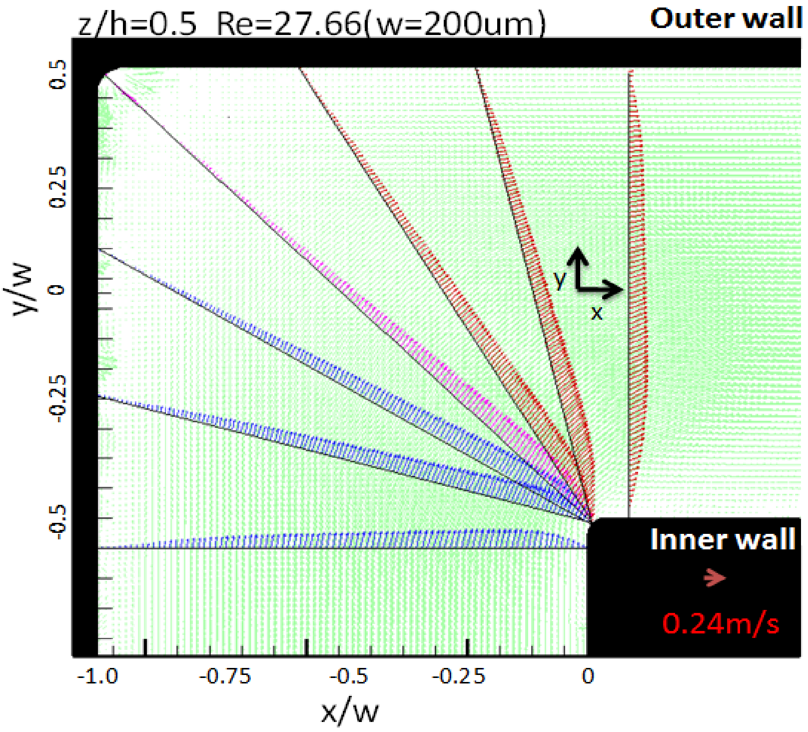

Fig. 9 Velocity profiles in the axial center plane around the 90 degree bend.

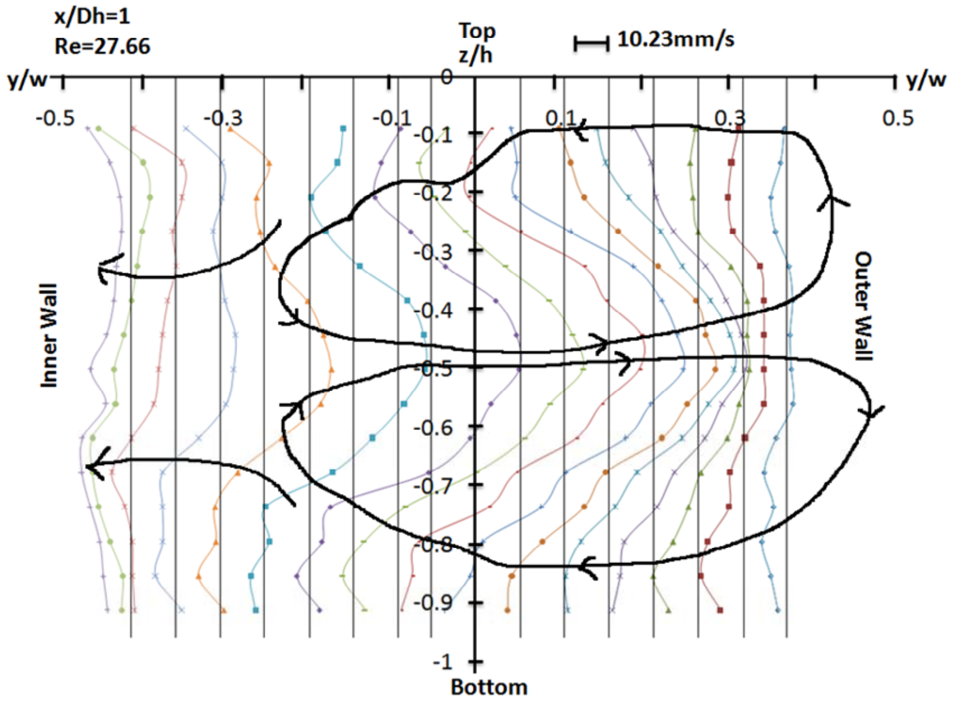

Fig. 10 Velocity profiles along the depth at different y locations acquired one hydraulic diameter downstream of the 90 degree bend.