Internal Pressure Measurements in Microchannels of Different Shapes

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Abstract This paper presents the experimental results of determining friction factors for two microchannels with circular cross-sections: rectilinear and curvilinear. The inner diameter of the channels is 68.9 and 70.3 μm. The Reynolds numbers ranged from 320 to 3215. Pressure measurements are carried out simultaneously in 16 locations along the straight microchannel and in 12 locations for the curved microchannel. The friction factor for the straight microchannel is in good agreement with the theoretical value for the round smooth tubes. For the curved microchannel, the friction factor value of the curved section is less than the reference value for smoothly curved tubes. The Reynolds number for the laminar-turbulent transition in a straight microchannel is 2300–2600. In the curved microchannel the transition is not observed. The length of the developing region was identified, and the inlet minor loss coefficient is calculated.

Keywords: Micro Flow, Microchannel, Internal Pressure Measurements

1. Introduction

Micro- and nanotechnologies are becoming more and more common in our days, and they dictate the need for miniaturization of liquid systems. The use of microfluidic systems for cooling microelectronic components is an attractive and promising solution because of high efficiency of such systems. In addition to cooling systems, microfluidic systems are used for biomedical applications. The optimization of the design of microfluidic systems requires a clear understanding of the mechanisms of fluid transport both in laminar and turbulent fluid flow.

Over the past 15–20 years, many research groups presented their results on the pressure drop and the friction factor data for laminar and turbulent flow in microchannels.

Usually there are two ways for calculating the coefficient of hydraulic resistance. The first way is to measure the pressure in the collectors at the inlet and outlet of the microchannel. The pressure measured in this way is the sum of pressure losses in different parts of the microchannel. The reference values of the minor loss coefficients are often used to account for the influence of end effects, which are a pressure drop at the inlet and the outlet of the microchannel, as well as in the developing region (Weilin et al. 2000, Chen et al. 2004, Hsieh et al. 2004, Judy et al. 2002, Li et al. 2007). A method of two channels (Mala and Li 1999, Celata et al. 2006 (a), Celata et al. 2006(b), Aniskin et al. 2011) is used to eliminate the influence of end effects.

The second way to calculate the friction factor is to measure pressure directly in the developed flow area (Kandlikar et al. 2003, Kohl et al. 2005, Costaschuk et al. 2007, Dutkowski 2008, Baviere and Ayela 2004). Measuring the pressure inside the microchannels is hampered by the small size of the channels and the complexity of their production technology.

As far as fluid flow in curved microchannels is concerned, the need for such studies is very significant for the development of passive micromixers. However, experimental studies for determining the friction factor for curved parts of microchannels are virtually absent.

In the study (Yang et al. 2005) the authors investigated the fluid flow in a curved microchannel of rectangular section with a hydraulic diameter of 167–182 μm with Reynolds numbers ranging from 70 to 2000. The calculated value of the friction factor was compared with the empirical formula from the hydraulic resistance handbook by Idelchick (1986). The authors point to the inapplicability of the reference formula for fluid flow in curved microchannels.

The aim of this work is to develop the technology for manufacturing microchannels of rectilinear and curvilinear shapes with the possibility of pressure measuring along the length of the channel, as well as to determine the friction factor of straight and curved microchannels and to define the length of the developing region based on the pressure distribution result.

2. Microchannels

The technology of “pre-production” was developed for making the microchannels. The technology involved making the cast for the microchannel and the outlets from the microchannel using solid material. Then the pre-made cast is filled with liquid polymer, and, after polymerization, the cast is removed. The result is a polymer with a microchannel inside.

In the process of making the microchannels, particular attention was given to creating the same geometry at the inlet and the outlet of the microchannels. The same geometry at the ends of the microchannels made it possible to combine the captured data on the distribution of pressure while pumping fluid from either side of the microchannel, thereby increasing the information value of the data.

On the basis of this technology, two stands were made: one with a straight microchannel, and another one with a curved microchannel. Photographs and designs of the microchannels are shown in Figure 1. The curved microchannel was a U-shaped channel with a radius of curvature of 1 mm. The length of the curved channel was 10.7 mm; the length of the straight channel was 11.33 mm. The photographs clearly show the outlets for measuring pressure.

a)

b)

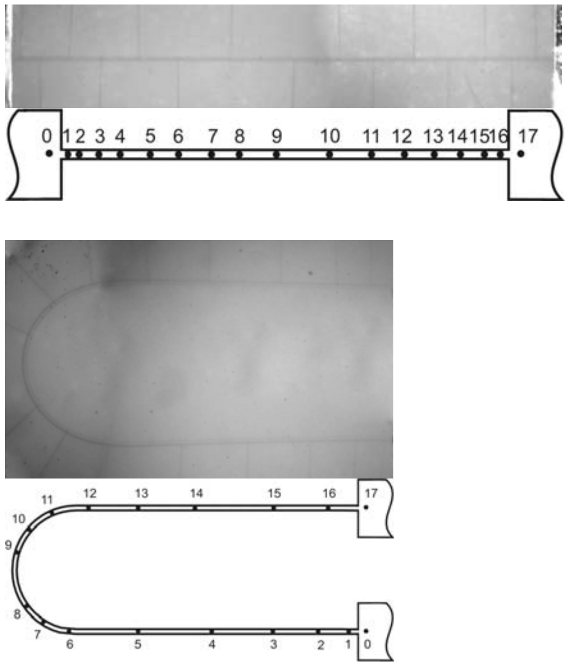

Fig. 1. Straight (a) and U-shaped (b) microchannels (not in scale)

The diameter of the microchannels was identified on the basis of SEM images of the microchannel cross-section (Fig. 2a). The diameter of the straight microchannel was 68.9 ± 0.56 μm, the diameter of the curved microchannel was 70.3 ± 2.3 μm.

a) б)

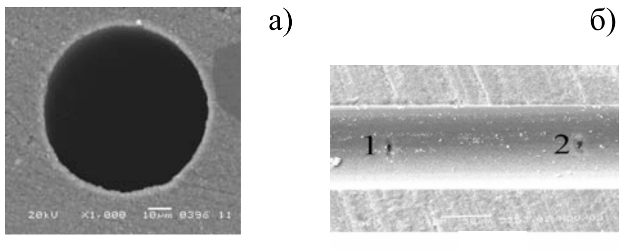

Fig. 2. Cross-section (a) and longitudinal section (b) of the microchannel

Figure 2b shows the SEM image of the longitudinal section of the microchannel with clearly visible holes for pressure measurement (1 and 2). Sixteen pressure taps were made along the length of channels for measuring static pressure. The pressure taps had an irregular oval shape and their size was 5 × 10 μm. Unfortunately, after the production of the curved microchannel, it turned out that not all pressure taps were functional and only 12 taps worked.

In the experiments the injection of liquid was carried out both from one side of the microchannel (forward flow) and from the other side (reverse flow). This made it possible to combine the obtained pressure values for the same fluid consumption. This meant that at 16 pressure taps it was possible to get 32 pressure data points along the microchannel length. This approach ensured the reliability of the data and increased their information value, which is especially important for the developing region. The location of the pressure taps was chosen in such a way that they would not coincide during forward and reverse flow. The coordinates of the pressure taps for the microchannels with forward and reverse flow are shown in Table 1.

3. Determination of the Friction Factor

The main characteristics of fluid flow in a microchannel are flow rate and pressure drop. The total pressure drop along the entire length of the microchannel is made up of pressure drops in different parts of the microchannel. Pressure drop associated with abrupt change in the areas along the fluid flow emerges at the entrance to the microchannel and at the exit from the microchannel. The change of pressure occurs in the developing region due to the establishment of the profile of fluid flow from a uniformly distributed profile at the entrance to the profile of the Poiseuille flow.

In the developed region, where the profile of Poiseuille flow is realized, pressure drop happens only due to viscous friction. Pressure drop in this area is defined as:

$$\Delta P = \frac{f \rho V^2 L}{2D},$$

where D is the channel diameter, V is the average velocity of the fluid, L is the channel length, and f is the coefficient of proportionality between the pressure drop in the microchannel and velocity pressure.

No. of the point	Straight channel (mm)		Curved channel (mm)	
	forward flow	reverse flow	forward flow	reverse flow
0	0	0	0	0
1	0.08	0.17	0.10	0.30
2	0.39	0.58	0.47	0.75
3	0.90	1.19	1.06	1.46
4	1.44	1.87	1.87	2.42
5	2.21	2.63	2.75	3.22
6	2.93	3.47	3.68	3.91
7	3.78	4.54	4.22	4.46
8	4.49	5.90	4.73	4.99
9	5.44	6.85	5.69	5.94
10	6.79	7.56	6.22	6.46
11	7.87	8.40	6.76	7.00
12	8.70	9.13	7.45	7.93
13	9.47	9.89	8.26	8.81
14	10.15	10.44	9.21	9.62
15	10.75	10.94	9.92	10.20
16	11.16	11.25	10.37	10.58
17	11.33	11.33	10.7	10.7

Table 1. The coordinates of the points

f depends on the shape of the cross-section of the microchannel, the roughness and the Reynolds number. f is called the friction factor. Therefore, for determining the friction factor it is necessary to know the pressure drop in the area of the developed flow. The coefficient of hydraulic resistance is calculated as:

$$f = \frac{\pi D^4 \Delta P_{ij}}{2 \,\mathrm{Re}\, Q \mu \Delta L_{ij}} \quad (1)$$

where Q is the volumetric flow rate, ΔP_{ij} is the pressure difference between the points of pressure measurement, ΔL_{ij} is the distance between the points of pressure measurement.

In the case of a curved channel in which a vortex motion occurs on a large part of the channel length, we compared the friction factor for the curved part of the microchannel with reference empirical data for smoothly curved tubes (Idelchick 1986), for which the relative radius of the curvature $\frac{R_0}{D} \geq 1.5$, where R_0 is the radius of the channel curvature, which, in our case, was 1 mm.

It follows from Idelchick (1986) that for the Reynolds numbers implemented in the present study, the coefficient of resistance for smoothly curved tubes f_{curve} is determined by the formula:

$$f_{curve} = \frac{20}{\mathrm{Re}^{0.65}} \left(\frac{D}{2R_0} \right)^{0.175},$$

The experimental value of the friction factor for the rounded area was defined by the formula (1), where $i = 6, j = 11$.

The inlet minor loss coefficient, K_{in}, of the microchannels was determined by the differential pressure at the inlet of the microchannel between the points 0 and 1 (ΔP_{01}) as follows:

$$K_{in} = \frac{2\Delta P_{01}}{\rho V^2}.$$

4. The Experiment

Distilled deionized water was used as a working fluid. The liquid was degassed by passing helium through it. A small but constant amount of helium was passed through the water during the whole experiment.

Figure 3 shows the design of the experiment. Liquid (2) is directed with liquid pump (4) through the filter (3) into the microchannel (6), located on the experimental stand. During the experiment the pressure was measured at the entrance of the channel and at the exit of the channel, as well as along the length of the microchannel. The fluid consumption was controlled with the help of the scales (5).

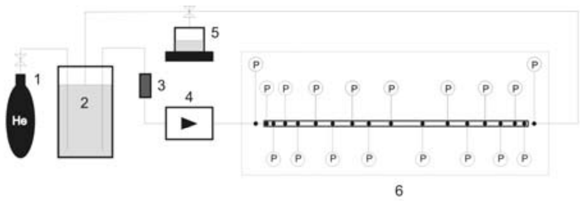

Fig. 3. The design of the experiment

Thermocouples for measuring the liquid temperature were placed inside the collectors near the entrance and the exit of the microchannel. The thermocouples of T-type were made of wire with a diameter of about 20 μm.

Honeywell pressure transmitters (250 and 100 psi) and two Druck pressure transmitters (250 bar) were used for measuring pressure. At flow rate of 5 ml/min or less, Druck transmitters (250 bar) were connected to the zero measurement tap and the first measurement tap. The Honeywell transmitters (250 and 100 psi) were connected to all other measurement taps. At flow rate of more than 5 ml/min, when the inlet pressure was large enough and exceeded the measurement range of the Honeywell transmitters, we used a custom made switchboard for 10 channels. One Druck transmitter (250 bar) measured the pressure at the inlet of the microchannel (point 0), and the other Druck transmitter measured the pressure at points 1–10 through the switchboard. The Honeywell transmitters were connected to the remaining taps for pressure measurement. Before connecting the switchboard and all the transmitters, all the connecting tubes were filled with distilled water. This was done to exclude the presence of air bubbles and to minimize the response time of the transmitters when changing the flow regime and using the switchboard.

5. Error Assessment

In order to analyze the influence of experimental parameters on the friction factor, we used the standard procedure for error assessment.

The friction factor was determined using the Darcy formula (1). Rewriting this formula in the measured values, we obtain:

$$f = \frac{\pi^2 \Delta P_{ij} D^5}{8 \rho Q^2 L_{ij}},$$

where D is the diameter of the channel, Q is the volumetric flow rate, ΔP_{ij} is the pressure difference between the taps of pressure measurement, and ΔL_{ij} is the distance between the pressure taps.

The relative error for the friction factor depending on the error of the independent variables was determined as:

$$\frac{e_f}{f} = \sqrt{\left(\frac{1}{\Delta P} e_{\Delta P}\right)^2 + \left(\frac{5}{D} e_D\right)^2 + \left(\frac{2}{Q} e_Q\right)^2 + \left(\frac{1}{\rho} e_\rho\right)^2 + \left(\frac{1}{L} e_L\right)^2}$$

The above formula shows that the maximum error in determining the friction factor may be caused by the error in determining the diameter of the microchannel. The accuracy of determining the diameter was 1 percent for the straight microchannel and 3 percent for the curved microchannel. The accuracy of determining the flow rate at low Reynolds numbers was 4 percent; at large Reynolds numbers it was 2 percent. The length of the channel was measured with an accuracy of ± 50 μm. Instrument rating for the accuracy of the pressure transmitters was 0.25 percent. Thus, the error of the measurement of the friction factor ranged from 8 to 15 percent.

6. Results

The pressure distribution along the normalized channel length for both straight and curved microchannels is presented in Fig. 4. The graphs show the pressure distribution in the case of forward flow with shaded symbols, in the case of reverse flow with hollow symbols. It can be seen that for the straight microchannel for both laminar and turbulent flow, the pressure distribution for forward and reverse flow are in good agreement. In the range of Reynolds numbers from 1900 to 2600, where a transition regime occurs, the pressure distribution during forward flow and reverse flow differed significantly.

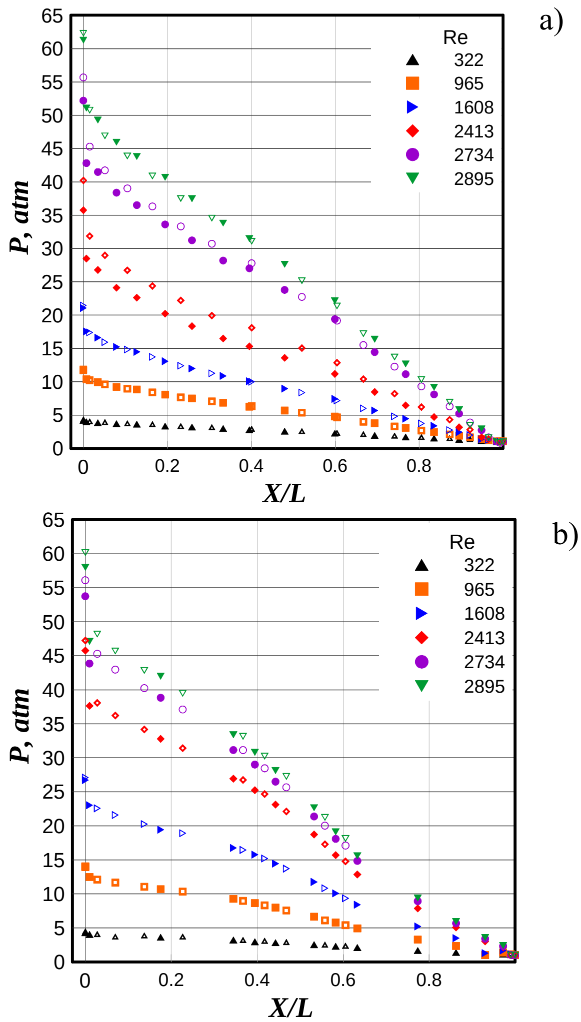

Fig. 4. The pressure distribution on the normalized length of the microchannels: straight (a) and curved (b)

The pressure distribution in the curved microchannel was nonlinear. The calculations show (Aniskin et al. 2010) that Dean vortices emerge in the curved part, and this leads to nonlinear pressure distribution.

Figure 5 shows the value of friction factor for a straight channel during forward and reverse fluid flow. The friction factor was determined in the developed flow region between points 10 and 15. It can be seen that the laminar-turbulent transition occurs in different ways. In one case, a sharp transition occurs at the Reynolds number 2600. In another case the transition happens more smoothly and the transition Reynolds number is 2300. Different values of the transition Reynolds number in the same channel, apparently, can be explained by different roughness of the input edges of the microchannel. The ratio of the circumference and area of the inlet in microchannels is much larger than in macrochannels. Therefore, the influence of microroughness of the front edge of the microchannels becomes significant.

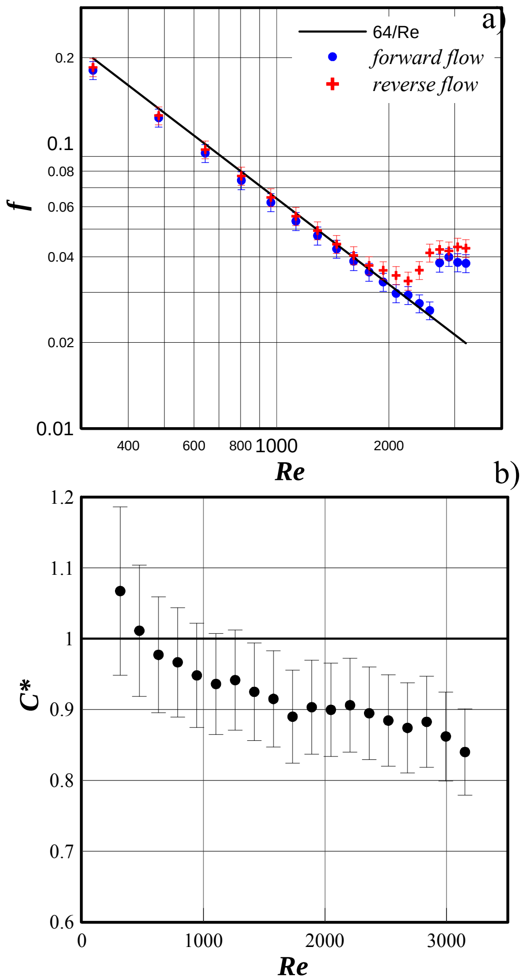

Fig. 5. The dependence of C^* on Re for the straight channel (a) and the curved channel (b)

Fig. 5b shows the dependence of C^* on Re for a curved part of the U-shaped microchannel; here

$$C^* = \frac{(f_{6-11}\,\mathrm{Re})_{\exp}}{f_{curve}\,\mathrm{Re}}$$

It can be seen that the experimentally determined value of the friction factor is less than the reference value for the parts of smoothly curved tubes at Re > 1500.

A change of the velocity profile from uniformly distributed at the inlet to a parabolic profile in the area of steady flow occurs in the initial part of the channels. The area of change in the velocity profile is called the developing region. The length of this area (L_{dev}) is defined as the length of the channel where the velocity on the channel axis is 99 percent of the velocity on the axis of the developed flow. The dimensionless length of the developing region X^* depends on the Reynolds number and the channel diameter. For macrochannels $X^*=L_{dev}/(ReD)=0.03$ (Idelchick 1986, Prandtl 2000). According to other sources, $X^*=L_{dev}/(ReD)=0.05$ (Steinke and Kandlikar 2006). Since we did not carry out velocity measurements in our experiments, the length of the developing region was determined by the pressure distribution. The length of the developing region was determined for a straight microchannel in the range of Reynolds numbers from 321 to 1125. For determining the developing region, the experimental values of pressure distribution were approximated by a polynomial of the fourth degree. The coordinate of the point where the approximation line was intersected with a straight line graphed point-to-point in the area of the developed flow, was taken for the length of the developing region. The data is presented in Figure 6.

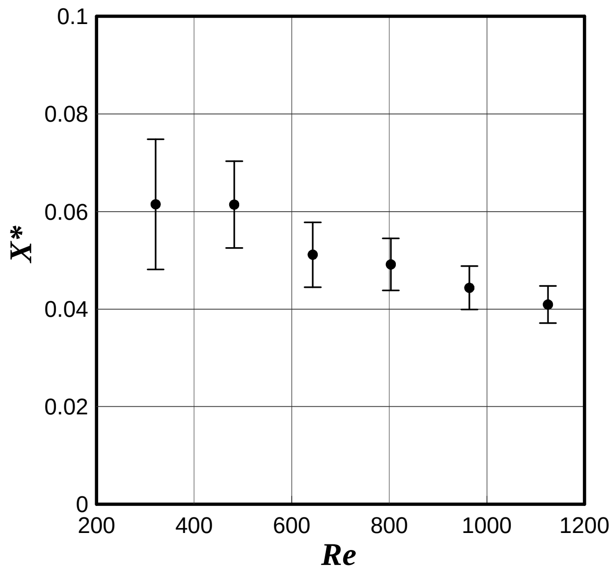

Fig. 6. Dimensionless length of the developing region

Figure 7 shows the results of calculating the inlet minor loss coefficient for the straight and curved microchannels. For comparison, the graph shows the reference values (Idelchick 1986) for macrochannels for experimental Re numbers and the corresponding input geometry. It is obvious that the experimental values are 2–3 times higher than reference values for macrochannels.

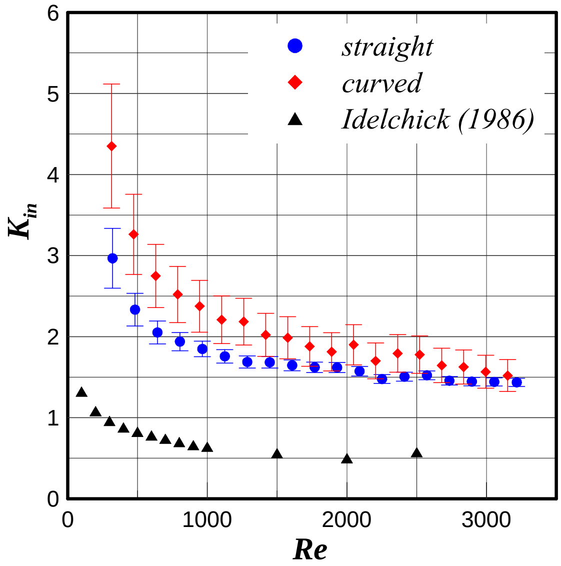

Fig. 7. Inlet minor loss coefficient

Changes in fluid temperature during the fluid flow through the microchannels were not observed.

7. Conclusions

The technology for making microchannels with pressure taps in the walls was developed and the microchannels were produced.

The pressure distribution along the straight and curved canals was determined. It was shown that for a straight microchannel, the pressure distribution in the developed flow for all the experimental Reynolds numbers is linear, and the friction factor is consistent with the theoretical value for the circular channels. The laminar-turbulent transition in a straight microchannel with forward and reverse flow occurred in different ways. The Reynolds number for the transition was 2300–2600.

For a curved microchannel, pressure distribution along the channel was nonlinear due to the formation of Dean vortices. The friction factor for a curved part of the U-shaped microchannel was 10 percent less than the reference value for Re > 1500.

The dimensionless length of the developing region is in the range from 0.04 to 0.06, which is more than indicated in Idelchick (1986), Prandtl (2000), but is in accordance with Steinke and Kandlikar (2006).

The inlet minor loss coefficients of the microchannels are 2–3 times higher than reference values (Idelchick 1986).

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