Investigation of Single Phase Frictional Pressure Loss in Circular Micro Tubes

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Single phase pressure drops in micro tubes were investigated through an experimental measurement and a numerical simulation. Experimental Po was obtained in circular micro tubes with 87 and 118 μm diameter with distilled water. Experiments were carried out in laminar flow region with varying the Re 15-450 for the 87 μm diameter tubes and 60-1300 for the 118 μm diameter tube. No early transition from laminar to turbulent flow was detected for the experimental range. The computational estimation of pressure drop in the 87 μm diameter tube was performed with the aid of CFD software. Boundary conditions from experiments were used for the numerical simulation. The results of experimental and numerical studies showed a good agreement with the conventional macro theory.

Key Words : Microfluidics, Pressure Drop, Circular Micro Channel, Polyetheretherketone, Viscous Dissipation, Entry Length, Roughness, Developing Region

Nomenclature

D : Diameter [m]
e : Roughness height [m]
G : Mass flux [kg/m^{2}s]
K : Loss coefficient [dimensionless]
L : Test section length [m]
m : Mass flow rate [kg/s]
P : Pressure [N/m^2]
Po : Poiseuille number [dimensionless]
Re : Reynolds number [dimensionless]
T : Temperature [K]
u : Local velocity [m/s]
U : Uncertainty [dimensionless]
V : Averaged fluid velocity [m/s]
y : Distance from wall [m]
z : Distance along the flow direction [m]

Greek symbols

Δ : Difference [dimensionless]
μ : Dynamic fluid viscosity [kg/m s]
ρ : Density [kg/m^3]

Subscripts

d : Developing region
e : Roughness
f : Frictional
in : Inlet
m : Momentum
max : Maximum
out : Outlet
p : Port
t : Total

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1. Introduction

With the improvement of micro-fabrication technology, interests on the micro-fluidic devices have increased. The key element for the development of the bio-technology and the micro-devices is the understanding of flow characteristics in micro-channels. Although a lot of researchers have been devoted for the experimental pressure loss measurements in micro channels, discrepancies among the previous experimental results still exist. Urbanek et al. (1993), Papautsky et al. (1998), and Mala and Li (1999) reported that pressure losses in micro channels were about 5-40% higher than that of macro theory. Contrary to these reports, the works of Pfahler et al. (1991), Yu et al. (1995), and Jiang et al. (1997) showed an opposite behavior. Their results showed 20-100% pressure drop decreases in microchannels. On the other hand, the results of Judy et al. (2002), Xu et al. (2000), Lelea et al. (2004) agreed well with the conventional macro theory. Besides, Mala and Li (1999) reported that significant disparity was detected for tubes with diameter less than 150 μm. Experimental Po by Peng and Peterson (1996), and Peng et al. (1994) depended on tube diameter and Re. To explain the inconsistency between the macro prediction method and the experimental results in micro-channels, several micro-effects like surface roughness (Mala and Li, 1999), microscopic particles (Ghiaasiaan and Laker, 2001), viscous dissipation (Xu et al., 2003), the irregularity of inner channel geometry (Xu et al., 2000), and the polarity of the surface (Grutin and Tadrist, 2003) were introduced. Generally, most of micro-channels in previous researches had rectangular or trapezoidal cross sectional shape with fused silica or stainless steel material. Tube material may affect the flow characteristics by its polarity and surface roughness. Usually, fused silica and cheap stainless steel tubes have roughness up to 0.5 μm and 5 μm, respectively. Therefore, surface condition can be varied as tube materials. Moreover, experimental reports on circular tube with diameter less than 100 μm are not enough. In this study, frictional pressure drops were measured in circular tubes with 87 μm and 118 μm diameter with distilled water. Tube material is polyetheretherketone. Polyetheretherketone tubes have the advantage of flexibility over rigid fused silica and stainless steel tube. Therefore, polyetheretherketone tubes can be useful to construct the microfluidic system. According to the manufacturer, the tested polyetheretherketone tubes can withstand up to 3.5 MPa internal pressure and their operating temperature is less than 250℃. The polyetheretherketone tube has chemical resistance to acids, alcohols, alkalis, aromatic hydrocarbons, greases, oils, halogens, and ketones. Hence, polyetheretherketone tubes can be applied for the bio-tech nology and the microfluidic systems. A numerical analysis was performed to investigate the applicability of a conventional CFD software for the design of micro-fluidic systems.

2. Experiments

2.1 Experimental apparatus

Figure 1 shows the schematic diagram of a test facility to measure the single phase pressure drop in microtubes. A syringe pump and metering valves in bypass line and in front of the test section regulated flow rate. A relief valve was installed to protect from high pressure in whole system. The relief valve opened and released working fluid into the reservoir automatically as the system pressure exceeded 1.5 MPa. Distilled water was used as working fluid. A cylinder was placed between the syringe pump and the test section to reduce flow fluctuation that may be caused by the operation of the syringe pump and valves control. A 0.5 μm pore filter was used to prevent from the mixing of microscopic particles. The filter was changed regularly during the test. To minimize the heat loss from the test section to the surroundings, a heat exchanger was operated prior to the test section. Cold water from a chiller was delivered to the heat exchanger to make the temperature of working fluid equal to the ambient room temperature. Two 0.79 mm outside diameter T-type ther-

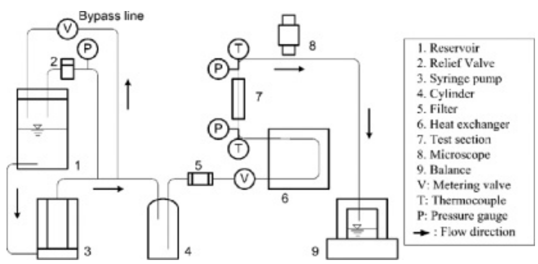

Fig. 1 Schematic diagram of experimental system

mocouples measured the inlet and outlet temperatures of the test section. The accuracy of thermocouples was ±0.05 K. Two pressure gauges were also installed to measure the pressure drops between the inlet and outlet of test section. The accuracy of two pressure gauges did not exceed ±0.1 kPa. It was impossible to make fine holes in microtubes for the measurement of pressures and temperatures. And measurement devices might disturb the flow. Hence, a thermocouple and a pressure gauge inserted into a 1.25 mm inner diameter tube and the 1.25 mm inner diameter tubes were connected to each end of the test section. All microtubes had the same 1.54 mm outer diameter. The distance between the test section and a measuring point was 4.8 mm. Air is soluble to water under atmospheric pressure. Micro air bubbles may affect the flow characteristics in microtubes. Before charging into the reservoir in the main test facility, the working fluid was stored in a metal can and the can was connected to a vacuum pump. While operating the pump, the working fluid in the can was boiled about 5 minutes. After this procedure, the boiled water was cooled at room temperature and poured into the reservoir of the test facility. With a microscope, air bubbles in working fluid were monitored in a transparent 3.2 mm outside diameter tube after the test section. Water came out from the test equipment were collected in a balance and mass flow rate was determined with the collected water and elapsed time. All experimental data were recorded at steady state. Each experiment was finished when desired amount of water (5-20 g) was collected. Before the each test, the evaporation rate of water into the environment was measured in the balance. The evaporation rate was considered to calculate the actual mass flow rate.

Table 1 shows the tube specification, uncertainty, and test condition (Re). Figure 2 shows the cross section of the test tubes. Tube diameters were measured optically with a microscope after whole experiments. After finishing experiments, test tubes were sliced into small pieces along flow direction and tube diameter was measured for each piece. Then, measured diameters were averaged and the value was used for the calculation of Re and Po. The uncertainty analysis was done for all the measured data and the calculated quantities based on the procedure of ASME standard (2000). All the uncertainties were calculated at the 95% confidence level. Table 1 shows the uncertainties of Re and Po numbers. The most influential factor for the uncertainties was tube diameter as Judy et al. (2002) reported.

2.2. Data reduction

Total pressure drop is composed of the frictional pressure drop, the port pressure drop (inlet and outlet), the pressure drop in developing region, and the momentum pressure drop.

$$\Delta P_t = \Delta P_f + \Delta P_p + \Delta P_d + \Delta P_m \quad (1)$$

Because of viscous dissipation and heat loss to the environment, inlet and outlet temperatures were slightly different from each other. Therefore, the momentum pressure drop should be considered.

$$\Delta P_m = G^2 \left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}} \right) \quad (2)$$

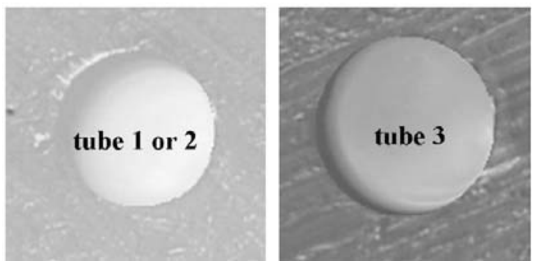

Fig. 2 Cross sectional view of test tubes

Table 1 Tube specification, test condition, and uncertainties

Tube	D [μm]	Length [mm] ±5 μm	Re	U_{Re} [%]	U_{Po} [%]
1	87.24±1.42	10.251	15-295	11.16	15.98
2	87.48±2.19	5.116	39-450	9.86	11.62
3	118.61±3.60	5.195	63-1303	11.06	13.98

Microtubes were connected to 1.25 mm inner diameter tubes at the both ends of each tube. Therefore, there were abrupt flow area changes in ports. The port pressure drops were deducted with the loss coefficient concept.

$$\Delta P_p = K\frac{\rho V^2}{2} \tag{3}$$

For contraction, $K=0.41$ and for expansion, $K=0.99$ were used.

Entry length effect was estimated with Shah and London (1978) and Chen (1973) methods. They proposed pressure drop correlations for the developing flow with dimensionless hydrodynamic entrance length and the apparent friction factor concepts.

Averaged temperature between inlet and outlet was used to determine the fluid properties. With the averaged properties, mass flow rate, and tube diameter, Po and Re were obtained as

$$\mathrm{Po} = \frac{\pi D^4 \rho \Delta P_f}{8 \mu m L} \tag{4}$$

$$\mathrm{Re} = \frac{4m}{\mu \pi D} \tag{5}$$

For smooth circular tubes in macro theory, Po is 16 in laminar flow region.

3. Results

3.1 Experimental results

To verify the minor pressure loss effect on the flow characteristics in micro tubes, the ratios of the minor pressure loss and the total pressure drop for the test tubes are shown in Fig. 3. The minor pressure loss is composed of the port pressure drop, the pressure drop in the developing region, and the momentum pressure drop. Momentum pressure drop was negligible because temperature difference between inlet and outlet did not exceed 0.5 K. The minor pressure loss increases linearly in lower Re region and exponentially in higher Re region with mass flow rate. In the higher Re region (Re>400), the effect of the minor loss is not negligible. Therefore, it is highly recommended to consider the minor loss effect to calculate the frictional pressure drop. Figure 4 shows the entry length effect on pressure loss with the concept of the length ratio between the developing flow region and the whole test section. From Figs. 3 and 4, it can be seen easily that most of minor loss came from the developing flow. Especially for the higher Re region, the effect of the developing region cannot be ignored. However, one must notice that the effect of the developing flow in microtubes was evaluated with the macro prediction correlations by Shah and London (1978) and Chen (1973). Because there is no available prediction method for the calculation of pressure loss in the developing flow region in microtubes, the macro methods were used in this study. Actually, it was tried to measure the minor pressure loss using two different length tubes (tube 1 and 2) with the same diameter. However, actual diameters of tube 1 and 2 were differ-

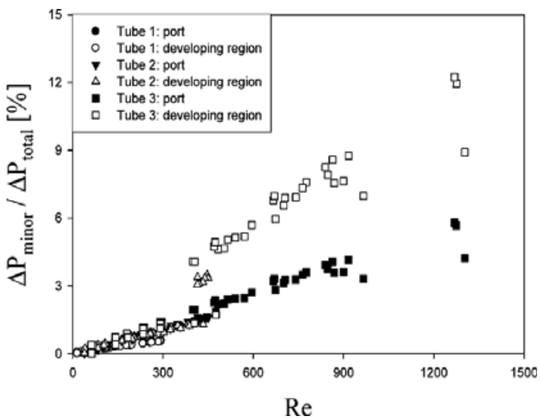

Fig. 3 Calculated minor pressure loss

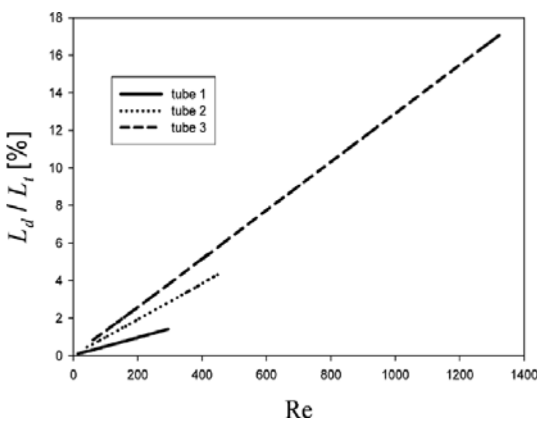

Fig. 4 The estimated length of developing flow region

ent from each other and it was difficult to obtain the same experimental condition like Re and temperature. Therefore, it is needed to develop a measurement device and a technique to investigate the effect of the developing flow in microtubes.

Viscous heating may change the properties of working fluid. For the evaluation of viscous dissipation, the methods by Xu et al. (2003) and Suryanarayana (Liu and Garimella, 2004) were adopted. Xu et al. (2003) proposed new dimensionless parameters for the viscous heating with their numerical results. Suryanarayana (Liu and Garimella, 2004) derived a relatively simple equation with proper assumptions from the energy equation. Figure 5 shows the calculated temperature rise using Xu et al. (2003) and Suryanarayana (Liu and Garimella, 2004) methods in each test tube. Two methods produced the almost same values for each flow condition and tube. Temperature increases linearly with mass flow rate (Re). From the results of the tube 1 and 2, temperature rise by viscous dissipation increases with tube length. It can be noticed that the effect of viscous dissipation increases with decreasing tube diameter by comparing the results of the tube 1 and 3. As the results show, viscous dissipation effect is very small and the temperature rise is difficult to detect with thermocouples. Moreover, it is very difficult to determine if temperature difference comes from viscous dissipation because of heat loss or addition between the test section and the environment. It seems that viscous dissipation has a little effect on pressure loss in microtubes. However, the effect of viscous heating cannot be negligible for the heat transfer and heat balance. Therefore, it is highly required to consider the viscous dissipation effect on the heat transfer in micro-channels.

Surface roughness induces early transition from laminar to turbulent and increases pressure loss in tubes. However, the effect of roughness can be negligible as the roughness height is lower than the thickness of laminar sublayer. Surface is treated as hydraulically smooth if Re_e does not exceed five. Re_e is defined as follows.

$$Re_e = \frac{e}{\mu}\sqrt{\frac{\rho D}{4}\frac{\Delta P}{\Delta z}} \tag{6}$$

From the definition of Re_e, roughness height corresponding to the Re_e is five can be calculated with the pressure loss per unit length at each Re. Figure 6 shows these calculated roughness heights with Re. If the roughness heights of test tubes were less than these calculated values at corresponding flow conditions, inner surface roughness could not affect the flow characteristics. At lower Re region, laminar sublayer is thicker than that of higher Re region. Therefore, higher surface roughness is needed to break the laminar sublayer. From the cross sectional figures of the test tubes, it is not believed that the test tubes had

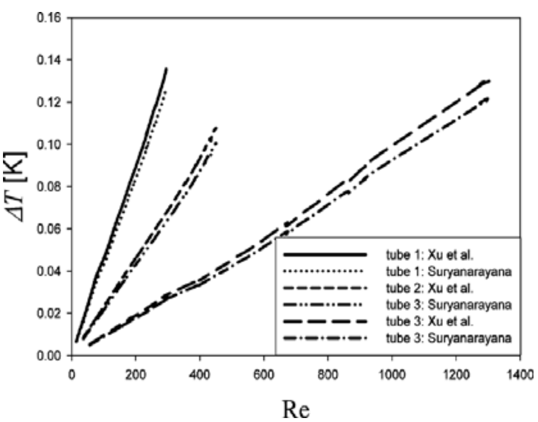

Fig. 5 Predicted temperature increase by viscous dissipation

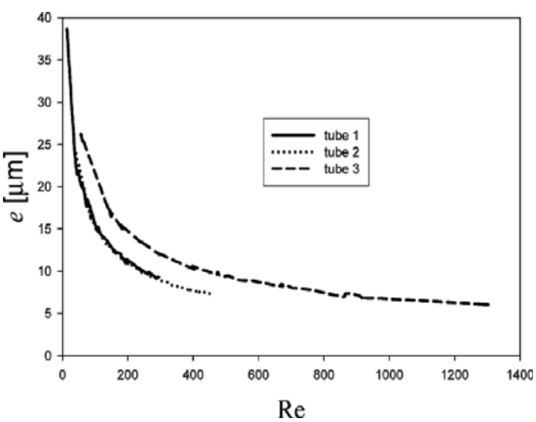

Fig. 6 Roughness height corresponding to Re_e 5

roughness height over 5 μm. Therefore, the surfaces of the test tubes can be treated as hydraulically smooth in this experimental study. If an early transition from laminar to turbulent flow was detected in experimental results or measured Po is higher than that of smooth tube in macro theory, it means that the surfaces of test tubes were rough enough to make turbulence or the approach with the macro concept is not applicable to the microfluidic systems.

Experimental Po with Re is shown in Fig. 7. Regardless of tube diameter, tube length, and Re, most of measured Po agree well with the macro theory within $\pm 10\%$. Figure 6 also shows that there is no early transition from laminar to turbulent flow within the test range. Xu et al. (2000) observed no early transition was detected up to Re 1500 in rectangular microchannels with diameter 30-344 μm. Liu and Garimella (2004) visualized the flow pattern with a dye technique and reported that there was no early transition in 244-974 μm hydraulic diameter rectangular tubes. Judy et al. (2002) tested 15-150 μm diameter circular fused silica and stainless steel tubes. Their results also showed that early transition to turbulent flow was not occurred like this study. Contrary to these researches, Mala and Li (1999) reported that early transition occurred at Re 300 to 900 in 51-169 μm diameter channels.

3.2 Numerical results

Numerical simulations were performed to investigate the applicability of conventional CFD software for the design of micro-fluidic systems. A general purpose finite volume based CFD software, STAR-CD was used for the calculation of pressure loss in the tube 2 and 3 with actual experimental condition like temperature and mass flow rate. The properties of distilled water were used. The working fluid was assumed incompressible and its properties were considered as constant. Pressure drops were calculated with an adiabatic boundary condition. Even though temperature variation along radius exists, its value is too small as can be expected in Fig. 5. Moreover, the length of the considered geometrical structure was short. Therefore, viscous dissipation effect can be neglected in this numerical study. The considered structure had a periodic inlet/outlet and a cyclic boundary to save computing time. 15% of total cross section in the tube 2 and 3 were considered for this simulation. With the periodic inlet/outlet boundaries, fully developed flow could be obtained. The mesh structure was presented in Fig. 8. Grid density was increased toward the wall. To check the grid density dependence, geometries were compared with increasing the number of total cells. Finally, structures with 213,084 and 236,760 cells were selected for the tube 2 and 3, respectively. The SIMPLE algorithm was adopted and convergence was declared as the normalized residual were less than 10^{-4}.

Typical pressure contour is shown in Fig. 8. As can be expected, pressure decreases gradually along flow path. Numerical results are shown in

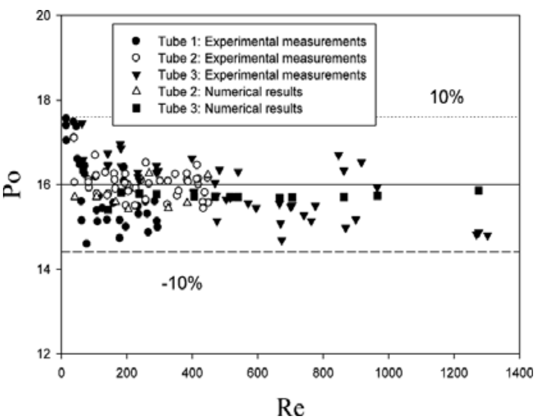

Fig. 7 Experimental and numerical Po with Re

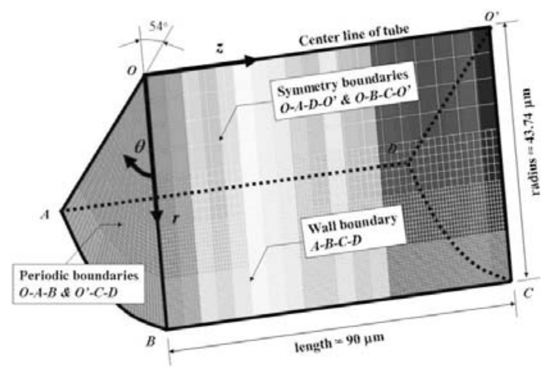

Fig. 8 Numerical structure and pressure contour of tube 2

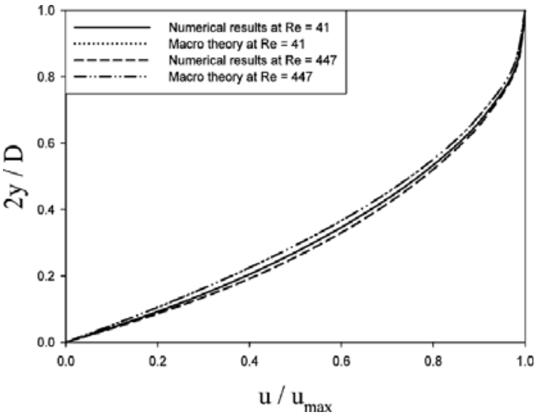

Fig. 9 Dimensionless velocity profile

Fig. 7 with the experimental results to compare the measurement and computational outputs. Experimental measurements and numerical calculations for pressure losses in microtubes matched well within 4% discrepancy. This discrepancy is lower than that of experimental uncertainty. Figure 9 shows the dimensionless velocity profiles of numerical results and the Hagen-Poiseuille for the tube 2. As it can be expected, the dimensionless velocity goes to zero at the tube wall and approaches to unity at the centerline of tube. Regardless of Re, the velocity profiles of numerical analysis agree well with that of macro theory (Hagen-Poiseuille). These results suggest that a conventional CFD can be used for the design of the microfluidic systems. Liu and Garimella (2004) also compared their own experimental measurements with numerical results using their commercial CFD software and their numerical tool, FLUENT was acceptable for the prediction of flow characteristics in rectangular microchannels.

4. Conclusions

Study on frictional pressure loss in polyetheretherketone circular microtubes with 87 and 118 μm diameter were performed through a numerical analysis and an experimental measurement. Viscous dissipation and roughness effects on the pressure loss were negligible in the test tubes. However, the effect of entrance length (developing flow region) should be considered especially for the high Re region. Experimental and numerical Po agreed well with the macro theory for all tubes in terms of uncertainties. No early transition from laminar to turbulent flow was detected in the experimental range. Conventional CFD software seems to be applicable to predict the flow characteristics in microtubes and be able to use for the design of microfluidic systems.

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