Experimental Study in Measuring Pressure Loss at Micro Channel

J Hendrarsakti1,*, R M Huda1 and E Junianto2

1Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia
2Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences, Bandung 40135, Indonesia

*jooned@ftdm.itb.ac.id

Abstract. The objective of study was to conduct experimental study in measuring the pressure loss due to the major and minor loss in fluid flow at straight and bent micro channel. Test channel had circular cross-sections with hydraulic diameters of 118 µm to 1203 µm for straight and 348 to 1203 for bent micro channels. The results showed that losses for larger diameter of straight channel were well predicted. The bent channel showed that the loss coefficient values were higher if the Reynolds number got smaller.

Keywords: Micro channel, pressure drop, friction factor, bend loss coefficient

1. Introduction

Research on pressure drop in an internal flow has long been conducted. In the early nineteenth century, H Darcy [1] conducted experiments on the pressure drop of the flow in pipes with various materials and roughness. He introduced the concept of relative roughness especially for turbulent flow regime. Darcy found that the type of flow would depend on the roughness of the pipe, the diameter of the section, and also the slope of the pipe. Nearly 30 years later, J T Fanning [2] then proposed a correlation for pressure drop as a function of surface diameter and roughness. The quantification of the effect of surface roughness on pressure drop was first introduced by J Nikuradse [3], who proposed grain coarseness (ε) as relative roughness, equivalent to the diameter of sand particles used in his experiment as the main parameter affecting friction factors in laminar and turbulent flows. Variation in diameter and roughness was done for the first time 6 years after that. C F Colebrook [4] varied the pipe cross-sectional diameter (101.6 to 1524 mm) and surface roughness (0.043 to 0.254 mm) to see their effect on pressure drop. The pipes are tested with water flow in transition and turbulent regime. It was found that the friction factor decreases with increasing water velocity, but once the speed reaches a fully developed condition, the friction factor will remain constant for higher speeds. Then L F Moody [5] characterized the friction factor that had been studied by Darcy (fDarcy) as a function of fluid velocity and channel cross-sectional diameter. Moody’s diagram combined the results of Colebrook [4] and Nikuradse’s [3] research to determine the pressure drop (∆p) and the relative roughness ε.
With the development of technology from macro to micro size, it requires accurate pressure loss calculations for smaller diameter channel. As the channel size becomes smaller, conventional theories for fluid and heat transfer at macro scale might need to be revisited to ensure these theories are applicable at smaller scale. Additional forces such as capillary and adhesion might contribute more at the micro channel. Other fundamental elements such as in modeling the flow of fluid flow in small diameter channels may arise as a result of uncertainty about the application of empirical factors derived from experiments conducted on a larger scale, such as the loss coefficient due to angles in pipe bends or friction factors in pipes. The objective of current study was to conduct experimental study in measuring the pressure loss due to the major and minor loss in fluid flow at straight and bent micro channel with variety of pipe length and diameter at micro scale channel.

Peiyi and Little [6] conducted one of the preliminary investigations of fluid flow characteristics in microchannels. The study was conducted using variations of hydraulic diameter with variations of 45.46 to 83.08 μm. The fluid used for research is a gas and also varies, namely H2, N2 and Ar. The conclusion of this study was that the effect of surface roughness still affects the value of the friction factor even under laminar flow conditions. The rougher the surface, the faster the transition flow conditions were formed. For ducts with untreated glass material, the transition conditions were achieved at a Reynolds number of about 350. The friction factor for bends (angle 90° and 135°) were also found with respect to Reynolds number.

Mala & Li, [7] investigated the characteristics of water flow in micro channels with two different materials, fused silica and stainless steel. For fused silica lines the hydraulic diameter varies from 50 to 250 μm, while for stainless steel it is between 63.5 and 254 μm. Experiments were carried out with various Reynolds numbers up to 2300. Each channel with the same diameter had two different channel lengths, so that there were two pressure drop values for a long channel and a short channel for one type of diameter. The difference in pressure drop for each type of diameter was divided by the difference in length of the channel to produce a pressure gradient which was then plotted on the ΔP/Δl vs Re curve. The resulting pressure gradient value in the experiment was higher than the prediction using conventional theory.

Pfund [8] studied friction factors at laminar flow for water with high aspect ratio channels using depths varied from 128 to 521 μm and Reynolds numbers were between 60 and 3,450. By omitting the pressure loss at entrance and outlet, measurement was focused at the channel. Measurement uncertainty was calculated and propagated into the estimated friction constant. The study results showed the significant differences remained between the results and classical theory.

Qu and Mudawar [9] conducted research of pressure drop on heat sinks with micro channels both experimentally and numerically. The channel cross-section is a rectangle with dimensions of 231 μm × 713 μm. The test was carried out with two variations of heat flux, namely 100 W/cm² with Reynolds numbers ranging from 139 to 1672 and 200 W/cm² with Reynolds numbers ranging from 385 to 1289. The test results show that the slope change in pressure drop to Reynolds’s number can be related to the viscosity of water is temperature dependent. Based on this research, fluid flow with a hydraulic diameter greater than 350 μm and a Reynolds number below 1700 can still follow the conventional Navier-Stokes equation. Wu and Cheng [10] investigated the laminar pressure drop of water in 13 different trapezoidal silicon microchannels. Based on 168 experimental data points, dimensionless correlations for the apparent friction constant are obtained for the flow of water in trapezoidal microchannels having different geometric parameters, surface roughnesses and surface hydrophilic properties.

Hsieh et al. [11] carried study the pressure drop using deionized water inside a channel with hydraulic diameter of 146 μm. Using Reynolds numbers of 50,100, 470, and 900, mass flow rate and the pressure drop between inlet and outlet of the channel were measured. The results also showed the flow visualization of the micro flow at the mid channel in order to obtain the hydrodynamic entry length correlation for both laminar and turbulent flows.

Xiong and Chung [12] conducted an identical study as [7] did, namely examining the pressure gradient in a channel with the same hydraulic diameter. The test was carried out on three channels
with a hydraulic diameter of 209µm, 395µm and 549µm. The transition flow conditions occurred earlier than the macro channel theory, namely the Reynolds numbers ranging from 1500 to 1700. The bend loss coefficients have been calculated and it had three characteristics.

Qureshi et al. [13] conducted numerical simulation of blood flow and pressure drop in the pulmonary arterial and venous circulation. They studied the effects on flow and pressure associated with three classes of pulmonary hypertension expressed via stiffening of larger and smaller vessels, and vascular rarefaction. The results of simulating these pathological conditions were in agreement with clinical observations.

Y Liu et al. [14] conducted a test regarding the effect of the relative roughness of the micro channel with air as a fluid. The effect of relative roughness on airflow has an impact on the difference in friction factor and is compared with conventional theory. The channel used is a micro channel with a hydraulic diameter of 400 µm with a relative roughness variation of 0.58% to 1.26% and tested at Reynolds numbers between 200 and 2100. The results of this study are that the resistance of flow increases with the proportion of roughness relatively.

Dirker et al. [15] conducted an experimental investigation of pressure drop in the rectangle microchannels. It was determined that critical Reynolds number were between 1800 and 2000 for sudden contraction inlet type, and adiabatic friction factor was well predicted by laminar correlation formulated for rectangle macro channel.

2. Experimental Apparatus
The variations of the micro channel diameters in this study were 118 µm, 144 µm, 348 µm, and 1203 µm for straight micro channels. For bent micro channels, it only used the 348 µm, and 1203 µm. The sizes were picked randomly from available micro channel in the market. Angle variation for bent micro channel can be seen in Table 1. Measurement of the channel cross-sectional diameter was carried out using a Meiji Techno America microscope connected to a computer display.

| Diameter (µm) | Angle (°) |
|--------------|-----------|
| 1203         | 90, 120, 135 |
| 348          | 90, 120, 135 |

For channel measurements with very small cross-sections of 118 µm, 144 µm and 348 µm there were no obstacles when determining the length of the channel diameter, but when measuring the cross-sectional diameter of the channel above 1000 µm, the microscope had difficulty capturing the entire image with focus, so the resulting image was less than perfect. Especially for the channel with the largest cross-section, the image that can be captured is only about a quarter of the total image and it was decided to estimate the diameter by equation (1). The scheme for estimating the length of the diameter can be seen in Figure 1 with description of $W$, $H$ and $R$ as the measurement parameters.

$$R = \frac{W^2+H^2}{2H}$$

The variable that has been determined in this study is the volume of water flowing in the micro channel that is 60 ml for variations in diameters 1203 µm and 348 µm. Meanwhile, for the diameters of 144 µm and 118 µm, 10 ml of water were used. Determination of the volume of water injected into the micro channel triggered a difference in mass flow rate in data collection for each test. The selection of control variables was based on the length of time to collect data and the limitations of the syringe. Meanwhile, the dependent variable in this study was the value of pressure drop or the difference in pressure at the entry and exit of the test channel as measured on the micro channel.
Pressure measurement on the test line used two pressure transducers with different measuring ranges. In testing channels with a diameter of 348 µm to 1860 µm and a low Reynolds number, pressure transducer with a range of 0-5 psi was used for the inlet and a range of 0-15 psi pressure transducer for the outlet was used and vice versa for testing high Reynolds numbers. Meanwhile, for channels with a diameter of 118 µm and 144 µm, a pressure transducer with a range of 0-60 psi was used for high Reynolds numbers. This is because the smaller the diameter, even with a lower Reynolds number when compared to a larger diameter channel, will result in a greater pressure, thus requiring a sensor with a large range for measurement. The static pressures were measured at the diameter of micro channel respectively.

Pressure transducers calibration was carried out on using a pressure gauge with the same range. The pressure gauge firstly was calibrated, then pressure transducers were validated by using Pascal Law. The calibration was conducted by making a simple instrument that is able to suppress fluid in a closed channel with a pressure gauge and pressure transducer attached to the ends and sides. Validation was conducted manually by pushing the instrument and recording the results of the pressure transducer for every 1 psi increase. From the results collected, a calibration graph and a regression equation was generated.

The method used was by measuring all channels in order to obtain the gross pressure drop value which was then reduced by the theoretical equation for pressure drop. Measurements were made using a pressure transducer that was placed on the connection between the tube from the injection and the micro channel. Figure 2 shows the experimental research scheme used to investigate the pressure drop of a water flow in a micro channel.
Figure 3. The experimental set up.

The overall research scheme can be seen in figure 3. This test used a custom syringe pump as a fluid booster. The stepper motor was connected to the syringe pump system and then controlled by the control program. The syringe was connected by a hose to the tee connector for input, one to the pressure transducer and the other to the test line. The test line connected to the tee output connector to the pressure transducer and the hose with atmospheric pressure (open system). The stepper motor used was a unipolar type with 6 pins, an input voltage of 12V, and a strong current of 0.8A. The stepper motor was connected to the TB6560 Driver before connecting to the control program. The voltage source to drive the motor used an adapter with an output voltage of 12V and a strong current of 1A. The speed of the stepper motor was controlled using the Arduino program.

Pressures were measured with pressure transducer before and after the test line, so the effect of the fluid at the entrance and exit cannot be neglected. The pressure transducer has a calibrated reading range of 0-5 psi, 0-15 psi and 0-60 psi. The reading and data acquisition of measured pressure values were also performed using the Arduino software.

3. Experimental Result and Discussion

Figure 5 shows the effect of Reynolds number over pressure drop per unit length (bar/cm) in microchannel, which has five diameter variations. All pressure drop tests were assumed in adiabatic conditions. The experimental results are compared to the theoretical calculation of Poiseuille equation as shown in equation 2.

$$\Delta p = \frac{128\mu LQ}{\pi D^4}$$

Where \( P \) is pressure, \( D \) is diameter, \( L \) is length, \( Q \) is discharge, and \( \mu \) is viscosity. As expected, the pressure drop per unit length increases as the Reynolds number increases. This is because the friction force increases with the increase in the average velocity of the fluid and the shear stress on the surface. As it can be seen, for channels with diameter 348 \( \mu \)m, 1203 \( \mu \)m and 1860 \( \mu \)m, pressure drop per length from the test results is almost similar to the Poiseuille theoretical calculation. This condition is exactly the same as the conventional diameter tube, at least in this study up to a channel with a diameter of 118 \( \mu \)m. Unlike three previous diameters, the two channels with the smallest diameter in this study, 144 \( \mu \)m and 118 \( \mu \)m, have a large gap between the test results and conventional theory. The
experimental results of both are smaller than Poiseuille theoretical calculation; even so, the resulting trends are actually quite identical.

**Figure 4.** Comparison between theoretical and experimental ΔP with respect to Re

All the experimental data were also plotted in correlation of Reynolds number over friction factor in figure 5. The graph shows all measured data for all five channels. From the overall data it can be seen that the channels with larger diameters, i.e. 0.348 µm, and 1203 µm, the data agree well with laminar friction factor theoretical relation (f = 64/Reynolds number). The micro channel with a diameter of 144 µm has the same graph trend as conventional theory even though there is a sizable gap between them. The discrepancy between the experimental and theoretical results might due to the existing of other forces acting on the channel surface such interfacial tension and capillarity effect.

**Figure 5.** Comparison between theoretical and experimental f with respect to Re
Figure 6. Relationship between the bent loss coefficient and the Reynolds number.

For the minor loss due to the bent channel, the results are presented in figure 6. The bent loss coefficients ($k_b$) for two diameter channel (348 and 1203) and three different angles ($90^\circ$, $120^\circ$, $135^\circ$) with Reynolds number from 500 to 9000 are presented. It is similar conclusion with Yamashita et al. [15] and Xiong and Chung [12] that the bent loss coefficient in laminar regime (according to macroscale theory) is larger than in turbulent regime. The results show that $k_b$ is dependent of Reynolds number and decreases as Reynolds number increase, which is also different with turbulent flow. For macro channel turbulent flow at larger Reynolds number, $K_b$ almost would not change with the increasing of Reynolds number. When Reynolds number is larger than some value in 1000, $K_b$ almost keeps constant and changes in the range of $\pm 10\%-15\%$.

4. Conclusion

In this paper, the experimental study of pressure drop on straight and bent microchannel were carried out. The microchannel had circular cross-sections with diameter 118 $\mu$m, 144 $\mu$m, 348 $\mu$m, and 1203 $\mu$m for straight and 348 $\mu$m, and 1203 $\mu$m for bent. The test has been carried out using a custom syringe pump and the fluid velocity is controlled using the Arduino software. Data acquisition is done by taking data for every second. From this study, following conclusion can be drawn.

- For straight microchannels, the $\Delta P/L$ experimental show agreement with conventional theory especially on larger diameter channels, however on channels of smaller diameter, there is a large enough gap. Friction factor for microchannels also shows agreement to the standard theory except for the channel with the smallest diameter, which actually have the same trend despite having a much larger gap.
- The bend loss coefficients for every test almost keeps constant and changes in the range of $\pm 10\%-15\%$ when $Re > 1000$, but increased significantly when $Re$ goes to a smaller number.

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