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Prediction and Measurement of Pressure Drop of Water Flowing in a Rectangular Microchannel

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Abstract

This paper presents experimental results of pressure drop measurement and prediction of water flowing through a copper rectangular microchannel with a hydraulic diameter of 437 µm. The aim of this work is to identify discrepancies between experimental data and macrochannel theory. An inlet temperature of 60^{o}C was kept constant at the channel entrance and the experiments were performed with Reynolds numbers (based on the mean velocity and hydraulic diameter) ranging up to 4500.

The results show that the pressure drop prediction agrees with the theory. However, the trend of Poiseuille number with the Reynolds number was not constant for laminar flow. This could be due to the entrance effect. Moreover, the friction factor theory could predict the experimental data for turbulent flow. Thus, in this experiment, the theory for flow in macro passages is still applicable.

Keywords: microchannel, pressure drop, friction factor, Poiseuille number

1. Introduction

Microchannels have become more significant interests in recent years due to their potency for removing high heat fluxes. They have been used in practical applications, scientific research and industrial sectors. Commonly, a microchannel is applied as a micro reactor, micro mixer, and micro heat exchanger. As a micro reactor, the microchannel is used for reacting two or more substances to produce a substance which has required characteristics. As a micro mixer, it is used for mixing or combining two or more fluid without a reaction. Micro heat exchanger usually is employed for transferring heat from one fluid to another fluid or from solid to fluid and vice versa. In another sector, microchannel is widely utilized in cooling systems for micro processors, electronics, laser diode, gas turbine blades, bearing and cutting tools.

Mudawar (2001) classified applications of the microchannel, based on the amount of cooling requirements, into two groups; a high and an ultra-high heat fluxes. A high heat flux with cooling requirements in the order of 1–10 MW/m^2 is encountered in high performance supercomputers, power devices, electric vehicles and advanced military avionics, whilst an ultra-high heat flux with cooling requirements of 10– 10^3 MW/m^2 is found in applications such as fusion reactors, laser and radar devices and microwave weapon.

A number of researchers have studied pressure drop of flow in microchannels for laminar and turbulent. Some authors concluded that the single-phase friction factors in microchannels complied with the laws of theory and correlation; whilst other researchers claimed that the friction factors were lower or higher than the theory. Several papers below indicate contradictory results. Yue et al. (2004) studied pressure drops of single and two-phase flows through a T-type microchannel mixer. They used the channel with hydraulic diameters of 528 and 333 µm. Water or Nitrogen was used as the working fluid for single phase flow experiment and Nitrogen-Water was used for two phase flow experiment. They performed the experiments with Reynolds numbers ranging from 20 to 500 (still in laminar flow). With considering the experimental uncertainty, the results agreed with the theory. The Poiseuille number found for laminar flow in their experiment was 57.3. Papautsky et al. (1999) investigated water flow in rectangular metallic pipette arrays. Each array consisted of 5 or 7 pipettes, 50 to 600 mm in width and

20 to 30 mm in height. The experimental data obtained showed an increase in the Darcy friction factor, especially at the lower Reynolds number. Jang et al. (1995) examined micro fluid flow in microchannels with circular, rectangular, trapezoidal and trapezium shapes. They made the microchannel (for non circular) using anisotropic etching process. The microchannel used was made of silicon, 400 µm in height and 25 µm, 50 µm, 100 µm in widths (47, 88.89 and 160 µm in hydraulic diameters). The conclusion had been made that the linear line pressure drop was found, however, they elucidated that the friction factor obeyed the theory. In contrast, Jiang et al. (2008) studied fluid flow and heat transfer characteristics in rectangular microchannels with a length, width and depth of 80 mm, 900 µm and 350 µm. They found that the friction factor was lower than that of the theory. It was only 20% to 30% of the theoretical value. Also, the critical Reynolds number found was 1100 which was lower than that of flow in conventional conduits. Wilding et al. (1994) performed an experiment on flow of biological fluids including blood, serum and water. They applied straight glass-capped silicon microchannels, 40 to 150 µm wide and 20 to 40 µm deep. The channel used was a trapezoidal channel. They compared their results in pressure drop with the theory in the form of pressure drop versus flow rates (ml/min). The pressure drops found were higher than the theory, especially at high flow rates. However, they concluded that the results agreed with the theory because the discrepancy was due to inertial losses and entrance length effects. Silverio and Moreira (2008) conducted an investigation of pressure drop and heat convection in single-phase fully developed flows (laminar flows) in microchannels of diverse cross section. They used water and HFE7100 as the working fluids. The channel was made of borosilicate glass with hydraulic diameters of 200 to 500 µm. The Reynolds numbers run were up to 800. They found that the friction factor did not deviate from the theory. Pfund et al. (2000) investigated pressure drops in microchannels with heights ranging from 128 to 521 µm and a width of 10 mm. The channels were formed in a sandwich structure which consisted of polycarbonate, spacer/gasket, and 0.05-in thick polyimide (DuPont CIRLEX film). They used water as the working fluid with Reynolds numbers ranging from 60 to 3450. Although the experimental uncertainty and systematic error were already included in the analysis, the deviation from the theory remained significant. An experimental investigation of flow friction for liquid flow in microchannels was conducted by Xu et al. (2000). The microchannels were made of aluminium with hydraulic diameters of 30 µm and 344 µm and aspect ratios of 0.041 and 1.716. The Reynolds numbers tested ranged from 20 to 4000. Water was used as the working fluid. They revealed that deviations with the theory were not observed.

The Poiseuille number (Po = *fRe*) often used for assessing the pressure drop for laminar flow. Based on the Poiseuille number, experimental data of pressure drop in microchannel can be used for revealing whether the flow in microchannel still obeys the theory. The following papers show the different Poiseuille numbers found by researchers. Recently, Judy et al. (2002) investigated the characteristics of friction factor for liquid flows through microchannels. They used circular and square microchannels made of fused silica. The nominal hydraulic diameters used were 50 µm, 75 µm and 100 µm. The lengths of the test section ranged from 80 to 130 mm (for 50 µm hydraulic diameter), 110 to 300 mm (for the second hydraulic diameter) and 180 to 300 mm (for the rest hydraulic diameter). The Reynolds numbers applied ranged from 61 to 1723. They concluded that the Navier-Stokes equation was applicable for such microchannel. Akbari et al. (2009) studied experimentally pressure drop in rectangular microchannels with aspect ratios (height/width) of 0.13 and 0.76. The microchannels were fabricated from polydimethylsiloxane with 390 µm and 67 µm in widths and 55 µm and 51.5 µm in depths. The length of microchannels was 50 mm. The Reynolds number tested varied from 1 to 35. They used distilled water as the working fluid. They also investigated the effect of developing region, minor flow contraction-expansion, on the Poiseuille number. They concluded that the Poiseuille number found was to be only a function of microchannel geometry and aspect ratio in the range of Reynolds number tested. However, they claimed that the experimental results agreed with the theory. Costaschuk et al. (2007) investigated axial static pressure measurements of water flow in an aluminum rectangular microchannel with a hydraulic diameter of 169.3 µm. The working fluid used was water and the Reynolds number tested ranged from 230 to 4740. Pressure measurements were simultaneously acquired at eight different axial locations within the channel. The average Poiseuille number for laminar flows was 86.4, which agreed with the theoretical value of 86.9. The average critical Reynolds number was found to be 2370. Furthermore, they also examined the effect of entrance length and some minor loses. Due to those effects, the Poiseuille numbers were not in agreement with the theory, however, they claimed that this deviation was due to a function of the inlet geometry and pressure recovery in the microchannel rather than a microscale effects. Baviere et al. (2004) investigated micromachined strain gauges for the determination of liquid flow friction coefficient in microchannels. The microchannel was made of silicon, 23 µm deep, 500 µm wide, and 20.5 mm and 36.5 mm long. The working fluid was water which was flowed with Reynolds numbers ranging up to 300. The pressures were measured using Cu-Ni strain gauges micromachined on different sorts of silicon nitride (Si_3N_4) membrane. The Poiseuille number found was 23.44, which confirmed the conventional theory.

Entrance region, geometry configuration, wall roughness, uncertainty and compressibility may be factors in the discrepancy between experimental results and the conventional theory. Jiang et al. (2001) conducted an experiment on frictional losses in a rectangular microchannel with a hydraulic diameter of 300 µm. The microchannel was made of copper plate. Water was the working fluid. The average value of non-uniform relative roughness was measured by using an electron microscope and was found to be 12%. The measured friction factor was larger than the theory. This result was attributed to the channel wall roughness and the short length of the microchannels. The authors suggested that the effect of hydrodynamic entrance region should not be neglected. The transitional flow found started at the Reynolds number of 600 which was lower than the transitional Reynolds number of conventional channel. Kohl et al. (2005) investigated the discrepancy in previously published data, by using straight channel test section with integrated miniature pressure sensors along the flow direction. The hydraulic diameters used ranged from 25 µm to 100 µm under incompressible flow condition and the Reynolds numbers tested ranged from 4.9 to 2068. This technique allowed them to consider the entrance effect and hydrodynamic developing flow for pressure drop calculation. The results showed that the friction factor for microchannels could be accurately determined from data for standard large channels. The author explained that the large inconsistency in previous research might be due to the instrumentation errors and compressibility effects. In addition, the pressure drop inside the channel associated with the developing flow was found to be as large as 17%. Qu and Mala (2000) performed an experimental study of pressure drop in trapezoidal silicon microchannels with hydraulic diameters ranging from 51 µm to 169 µm. A high ratio of channel length to diameter $180 < (L/D_h) < 600$ determines fully developed laminar flow regime in which the calculated friction factor was found to be higher, by 8% to 38% than the expected value. The author justified the deviation as being the results of the high relative roughness (3.5% to 5.7%). An experimental investigation on the Poiseuille number for deionized water flow through deep rectangular microchannels with a hydraulics diameter of 401 µm made of silicon substrate was conducted by Harms et al. (1999). They used water as the working fluid with Reynolds numbers ranging from 173-12900. They concluded that in laminar flow the friction factor was reasonably well predicted by the conventional theory. In addition, they found that the transitional flow happened at the Reynolds number of about 1500 which was lower than that of conventional theory. In turbulent flow, the experimental friction factor agreed with the theory.

2. Experimental Apparatus and Method

All tests were done at the boiler temperature of 102°C which corresponded to the saturation pressure in the order of 110 kPa. The test loop is shown schematically in Fig. 1, which consists of several components: a main boiler with reflux and auxiliary condensers, subcooler, filter, pump, Coriolis flowmeter, pre-heater, and test section. The working fluid, de-ionized water, was circulated from the main boiler through the entire loop using a gear pump model O/C GA-T23 PFSB (serial no. 1315225).

The fluid flowing from boiler was cooled by means of a subcooler. Before coming into the pump inlet, the fluid was filtered via a mesh filter with mesh holes approximately 1 mm^2. The pump speed could be adjusted with the micro pump speed regulator "ISMATEC REGLO ZS digital drive", so that the desired mass flow rate of working fluid could be achieved. After leaving the pump, the fluid was also filtered by a 1-micron filter, which had a hole of approximately 1 μm^2. The fluid then flowed through a Coriolis meter (model Elite MF010 micro motion) which was used for measuring the mass flow rates. All measurements signal were sent to the NI DAQ and converted suitable variables using the LABVIEW program. Before entering the inlet plenum of the test section, the fluid flowed through pre-heaters to get the temperature rising up to a certain required degree. From the test section, the fluid then flowed to an auxiliary condenser and then back to the boiler. In the schematic diagram of the experimental facility, several equipments (sensors) are not drawn to make the schematic clearly, and to show the main parts which correlate to this experimentation.

The test section was constructed from a copper block, the dimensions of which were 12 mm in width, 25 mm in height and 72 mm in length. The channel was grooved on the top of the copper block by using micro milling machine Bridgeport VMC 500X (accuracy of 10 µm) with the rotation speed of 4500 RPM, cut of depth of 380 µm and feed rates of 100 mm/min. The depth, width and length of the channel slot were 0.389 mm, 0.5 mm and 62 mm, respectively. The width was measured using SEM techniques with an accuracy of ±1µm, whilst the depth was measure using TSER V200 microscope with an accuracy of ±1µm and the length was measured using digital vernier calipers with a resolution of 10 µm. The test section and its construction can be seen in Fig. 2. The body of the first cover has 6 pressure holes to which the pressure connectors are attached, in order to measure the pressure distribution along the channel. The holes have an inter-axial distance of 12.4 mm each other.

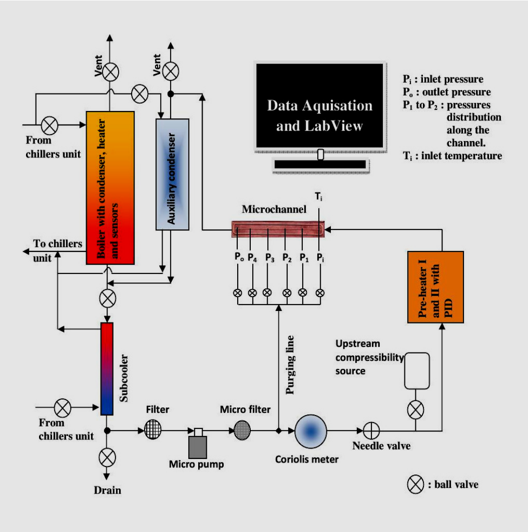

Figure 1: Schematic diagram of experimental apparatus, Mirmanto et al. (2012).

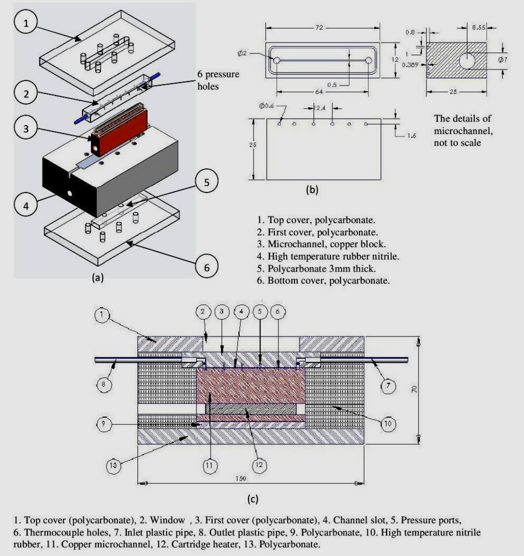

Figure 2. Test section schematics identifying main components; (a) exploded view, (b) the detail of microchannel dimension, (c) axial view of test section, Mirmanto et al. (2012).

Data reduction

The hydraulic diameter of microchannels is calculated using Eq. (1), whilst the aspect ratio is determined by applying Eq. (2). The friction factor is defined as the ratio of wall shear stress to dynamic pressure or the drop over the length of the channel divided by kinetic energy per unit volume over the diameter, and it is given in Eq. (3), taken from Mudawar (2001).

$$D_h = \frac{4WH}{2W + 2H} = \frac{2WH}{W + H} \tag{1}$$

$$\beta = \frac{W}{H} \tag{2}$$

$$f_F = \frac{\Delta p D_h}{2L\rho \overline{V}^2} \tag{3}$$

The current study uses the Fanning friction factor. According to the theory of flow for laminar regimes, the Poiseuille number, $\mathrm{Po} = f\,\mathrm{Re}$, is constant. For circular channel/pipe, $\mathrm{Po} = 16$ in the terms of Fanning friction theory, whilst for non-circular duct, Po depends on the aspect ratio of the channel. An empirical correlation can be used to calculate the Poiseuille number for fully developed flow in rectangular conduits, Shah and London (1969).

$$f_F \mathrm{Re} = 24\begin{pmatrix} 1 - 1.3553\,\beta + 1.9467\,\beta^2 - 1.7012\,\beta^3 \\ + 0.9564\,\beta^4 - 0.2537\,\beta^5 \end{pmatrix} \tag{4}$$

The inverse is taken to use the Eq. 4 when the aspect ratio is greater than 1. Where *β* represents the aspect ratio, *Re* is the Reynolds number $\left(Re = \frac{\rho \overline{V} D_h}{\mu} = \dot{m}\, D_h / \mu A_c\right)$ and μ refers to the dynamic viscosity, $\dot{m}$ and A_c are the mass flow rates and the cross sectional area respectively. Due to the short length of the micro channel, the entrance length could play an important role for the pressure drop and friction factor. The entrance length can be expressed in Eq. (5), Potter and Wiggert (1984):

$$\frac{L_e}{D_h} = 0.065\mathrm{Re} \tag{5}$$

Equation (5) is based on the presumption that fluid entering the channel with a uniform velocity and the equation only relates to the laminar flow.

Experimental uncertainty

A careful analysis of the experimental uncertainty was carried out in this study and was crucial in order to interpret the experimental data and to explore any deviation from the theory. The uncertainty associated with a parameter as a function of other measured variables was calculated using error analysis, described in Coleman and Steel (2009). The uncertainty of pressure drop, Reynolds number, friction factor and Poiseuille number can be estimated as follows, Coleman and Steel (2009).

$$\Delta p = p_i - p_o \tag{6}$$

$$U_{\Delta p} = \sqrt{\left(U_{p_i}\right)^2 + \left(U_{p_o}\right)^2} \tag{7}$$

$$\frac{U_{\mathrm{Re}}}{\mathrm{Re}} = \sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{U_{D_h}}{D_h}\right)^2 + \left(\frac{U_{A_c}}{A_c}\right)^2} \tag{8}$$

$$\frac{U_{f_F}}{f_F} = \sqrt{\left(\frac{U_{\Delta p}}{\Delta p}\right)^2 + \left(\frac{U_{D_h}}{D_h}\right)^2 + \left(\frac{2U_{A_c}}{A_c}\right)^2 + \left(\frac{U_L}{L}\right)^2 + \left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2} \tag{9}$$

$$\frac{U_{Po}}{Po} = \sqrt{\left(\frac{U_{f_F}}{f_F}\right)^2 + \left(\frac{U_{\mathrm{Re}}}{\mathrm{Re}}\right)^2} \tag{10}$$

All thermocouple were calibrated using oil bath method against platinum resistance thermometer MK II with an accuracy of 0.01 K, and the uncertainties of them were ±0.2 K. The temperature difference between inlet temperature and outlet temperature was ±0.3 K. The local pressure transducers were calibrated against a druck differential pressure transducer and a water column manometer. Their uncertainties were ±0.2 kPa, and pressure drop uncertainty was ±0.3 kPa. The druck differential pressure transducer was calibrated against the deadweight tester. The dead weight tester had a resolution of 1 psi whilst the water manometer had resolution of 1 mm. The error propagation of the Reynolds number was 5.5%, and the uncertainties of friction factor and Poiseuille number were 10% and 11.4% respectively.

3. Results and Discussion

From the literature review above, it can be interpreted that decreasing hydraulic diameter does not always affect the Poiseuille number of flow in microchannels. For example, hydraulic diameters used by Jiang et al. (1995), Wilding et al. (1994) and Qu et al. (2000) were smaller than those used by Pfund et al. (2000) and Jiang et al. (2001) but the Poiseuille numbers found by Jiang et al. (1995), Wilding et al. (1994) and Qu et al. (2000) agreed with the theory. Therefore, the effect of decreasing hydraulic diameter on the Poiseuille number has not been clear yet. It indicates that the applicability of the theory for macrochannels to predict the data of flow in microchannel is still questioned and this needs to be clarified.

Figure 3 shows the experimental pressure drop results and repeatability of pressure drop measurements at an inlet temperature of 60°C. As the Reynolds number was increased, the pressure drop increased. It means that the trend of pressure drop is the same as that in macrochannels. The inlet and outlet minor losses should be taken into account in calculating pressure drop predictions. As explained by Jiang et al. (2001), minor losses, e.g. elbow, sudden contraction and expansion, sharp entrance and exit, may give a great effect on experimental measurement of pressure drop. Let's consider that the measured pressure drop, Δp_{meas}, consists of pressure drop in inlet and outlet plenum (minor losses, min), $\Delta p_{\min}$, and pressure drop in the channel itself, $\Delta p_{channel}$.

$$\Delta p_{meas} = \Delta p_{\min} + \Delta p_{channel} \qquad (11)$$

The minor losses can be given by Eq. (12):

$$\Delta p_{\min} = k_l \rho \overline{V}^2 / 2 \qquad (12)$$

where k_l is the minor losses coefficient. For sharp entrance and exit, the minor losses coefficients are $k_l = 0.5$ and $k_l = 1$ respectively when the inlet and outlet plenum diameters are bigger than the hydraulic diameter of the conduit (*D*>>*D*$_h$ or $D_h / D \approx 0$). For sharp elbow, the minor losses coefficient is $k_l = 1.1$. The test section used in this experiment consists of sharp entrance and exit, but the hydraulic diameter of the channel compared to the inlet-outlet plenum diameters cannot be neglected because $D_h / D = 22\%$, as shown in Fig. 6. Thus the minor loses are more significant due to the effect of sharp elbow rather than sharp entrance and exit. In laminar flow, the friction factor for predicting the pressure drop is $f = 14.42 / \mathrm{Re}$, whilst in turbulent flow, where Re>2000, the friction factor used for predicting the pressure drop is $f = 0.079\,\mathrm{Re}^{-0.25}$. Using Eq. (11) and (12), the pressure drop of flow in this microchannel can be estimated as shown in Fig. 3. The measured and predicted pressure drops are almost the same with deviations between them of less than 5%.

Figure 5 describes the experimental and predicted friction factor versus Reynolds number. The experimental friction factor is higher than the theory for both laminar and turbulent. However, the experimental friction factor agrees with that predicted using Eq. (11) and (12). The higher friction factor than the theory is due to entrance length effect and minor loses. It is recommended that these two factors cannot be neglected when the measurements of pressure drop include the inlet and outlet plenum and the length of the channel is very short (without calm section).

In Fig. 5, the experimental Poiseuille number is not constant but it increases with an increas in Reynolds number. This indicates that the effect of entrance region and minor loses are significant for small channels. Compare to the theory of Poiseuille number in developing region, the experimental Poiseuille number is higher than the theory, this could be due to the effect of inlet and outlet plenum. Applying Eq. (11) and (12), the experimental Poiseuille number can be predicted very well. It can be concluded that the deviation between experimental data and the theory is owing to the entrance region and inlet-outlet plenum effects. Thus, the theory for flow in macrochannels is applicable for water flowing in microchannels with a hydraulic diameter of 437 µm.

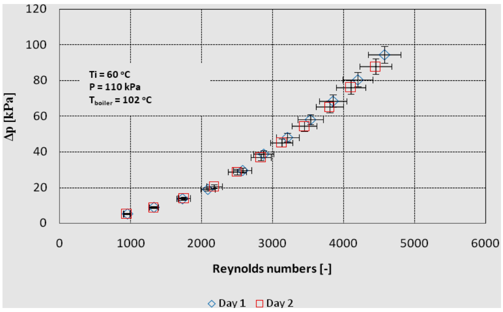

Figure 3: Pressure drop at inlet temperatures of 60°C.

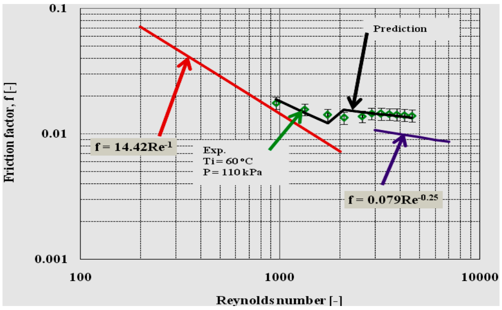

Figure 4: Friction factor at inlet temperature of 60°C compared with predictions.

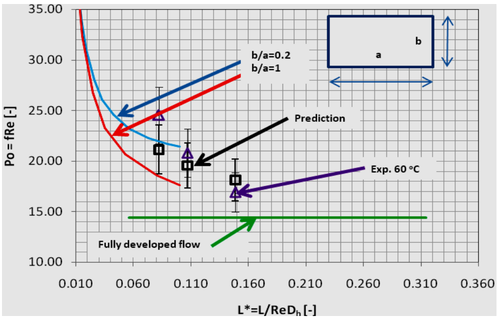

Figure 5: experimental, theretical and predicted Poiseuille numbers in laminar flow regimes, the lines with an aspect ratios of 0.2 and 1 were taken from Shah and London (1978)

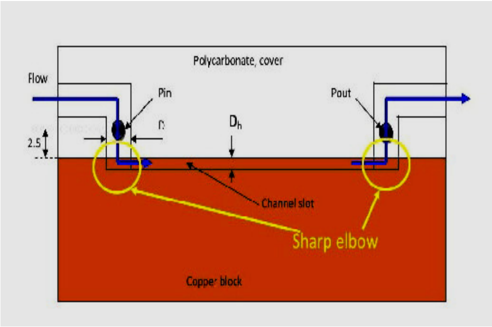

Figure 6: Minor loses caused by sharp elbow, $k_l = 1.1$

4. Conclusions

Prediction and measurement of pressure drop were carried out to validate the theory for macroscale. In laminar flow, the friction factor used was $f = 14.42/\mathrm{Re}$, whilst in turbulent flow, it was $f = 0.079\,\mathrm{Re}^{-0.25}$. It has been proved in this particular experiment the theory for macrochannels can be used for predicting the pressure drop, friction factor and Poiseuille number for flow in microchannels. Raw data show that the friction factor and Poiseuille number for both in laminar and in turbulent are higher than those of the theory, but when the minor loses are considered, those two experimental parameters agree with the theory.

Nomenclature

A_c : cross sectional area (m^2)
D_h : hydraulic diameter (m)
f : friction factor

$$\left(f = \frac{\Delta p D_h A_c^{\,2} \rho}{2L\dot{m}^2} \right)$$

G : mass flux (kg/m^{2}s)
H : channel height (m)
L : channel length (m)
L^* : dimensionless entrance length ($L/\mathrm{Re}\,D_h$)
Le : entrance length (m)
$\dot{m}$: mass flow rates (kg/s)
p : pressure (kPa)
Po : Poiseuille number ($f\,\mathrm{Re}$)
Re : Reynolds number ($\rho \bar{V} D_h/\mu$)
T : temperature (°C)
U : uncertainty
$\bar{V}$: average velocity (m/s)
W : channel width (m)

Subscript:

F : Fanning
i : inlet
o :outlet

Greek symbol:

β : aspect ratio (W/H)
Δp : pressure drop (Pa or kPa)
μ : dynamics viscosity (kg/ms)
ν : kinematics viscosity (m^2/s)
ρ : density (kg/m^3)

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