International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol. 2, Issue. 5, Sept.-Oct. 2012 pp-2964-2968 ISSN: 2249-6645

Pressure Drop Measurements in Rectangular Micro-Channel Using Gas Flow

R. Kalaivanan[1] and R. Rathnasamy[2]

[1] *Associate professor, Mechanical Engineering, Annamalai University, India*

[2] *Professor, Mechanical Engineering, Annamalai University, India*

Abstract: *Due to the need for practical cooling technologies which could dissipate high heat fluxes, an experimental study of pressure drop in micro-channel was performed. In this work, laminar flow friction factors were determined using gas (air) as flow medium. Pressure drop vs flow rate data were used to evaluate friction factors in two parallel micro-channels, namely MCP1 and MCP2 (1.0 mm deep x 0.240 mm width and 0.9 mm deep x 0.2 mm width, respectively). Each channel of length 192 mm fabricated on a 304 Stainless Steel substrate by chemical milling Reynolds number was covered between 24 – 5398 for MCP1 and 26 – 6233 for MCP2. Transient pressure drops measured within the channel itself to exclude entrance and exit losses. Friction factor – Reynolds number analyses show that the friction constant are identical as normal channels for gas flow in the laminar region. Transition region lies in Re > 500 and transition set off at lower Re ~ 500 in comparison to normal channel. The discontinuity in f – Re data identified as transition. Further, it may be possible to identify transition (from laminar region) as the deviation of non-dimensional pressure drop (NDPD) values.*

Keywords: *Experiments, friction factor, gas, micro-channels, NDPD.*

I. Introduction

Rapid advances in microelectronics during the past three decades have brought about a surge of interest in identifying means to reject heat from small surfaces. Heat fluxes in excess of 100 W/cm^2 are often required and in some instance rates that are an order of magnitude higher and desirable. A number of studies have been performed on this topic where the authors concluded that single-phase micro-channel cooling can be used as an effective means of heat rejection [1]. Friction factors measured in laminar and in turbulent flow of gas by [2], using silicon and abraded into glass. It is reported that the friction factors be greater than the classical values, by comparison to the Moody chart for flow in round pipes, not to corresponding charts for rectangular channels. Several investigations ensued which dealt with flow of gases [3]. Fluid flow and heat transfer experiments conducted in rectangular micro-channels by and offered a friction factor correlation ($f=56.9/Re_{Deq}$) close to theoretical value [4]. Based on previous studies and current experimental work was performed to establish transition from f-Re characterisation. In addition, NDPD method is adopted to characterise the same.

II. Fabrication of MCP1 and MCP2

For the present experiments, two test sections were prepared having common features; each channel of length 192 mm were fabricated on a 304 stainless steel substrate of overall dimensions 230 mm x 160 mm x 1.6 mm. This size is chosen to be comparable to the size of a double *Euro* PCB so that eventually the results of the study can be applied therein. The two test sections MCP1 and MCP2 were manufactured first by photo chemical etching process as shown in Figure 1. Subsequent to etching of channel the channel header portions were deepened by EDM in order to have negligible pressure loss. MCP1 and MCP2 have 47 and 50 micro-channels of rectangular cross-section 1000 by 240 µm and 900 by 200 µm in width and depth, respectively. Both ends of channels are provided with common header for uniform flow distribution through each channel [5]. These header portions were deepened after etching by EDM in order to have negligible pressure. The channel top covered with another plate of 0.5 mm by vacuum brazing.

III. Experimental set-up and procedure

Figure 2 shows the set-up for the gaseous flow experiments. The experimental set-up for gas flow consists of compressed gas source and a storage reservoir to supply gas to the test section. A pressure regulator is mounted between the gas source and the reservoir to avoid over pressurisation in the circuit under any circumstance. The storage reservoir has capacity of 0.0564 m^3 (56.4 litre). The compressed gas was admitted through the pressure regulator into the storage reservoir to build up a known pressure of about 5 bar. A solenoid valve is connected between the reservoir and test section and it was closed while charging the reservoir. The charged reservoir was allowed to discharge by opening this valve resulting in decrease of the gas pressure in the reservoir. Transient pressure measurements were conducted at a time interval of 5 seconds for both MCP1 and MCP2 at room temperature (~30^{o}C). The reservoir pressure and the pressure drop through the channels between each instant are recorded using differential pressure transducers (make: KELLER Druckmesstechnik; piezoresistive pressure transmitter, PD-23/ 5 bar / 8666.1). The experiment details are given in Table 1.

Table 1. Details of experiments

Fluid	No. of experiments		Re range	
	MCP 1	MCP 2	MCP1	MCP2
Air	16	13	24-5398	26-6233

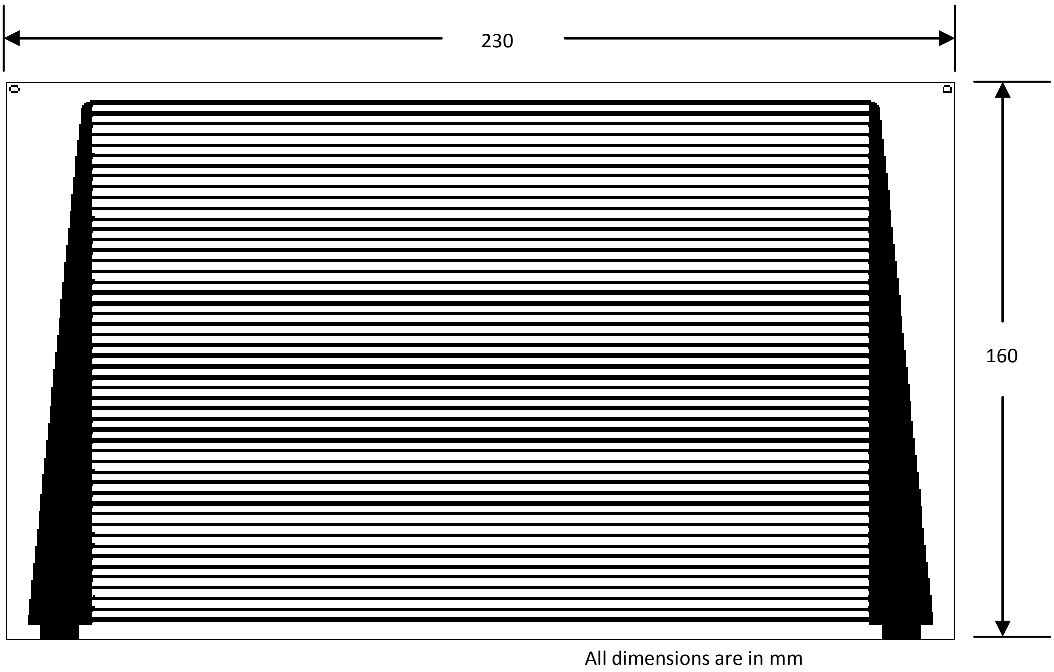

Fig.1 Layout of the parallel type rectangular micro-channel

3.1 Primary data for gas flow

Experiments were conducted for flow of gas as described. The data recorded in the current experimental program are presented graphically. Typical transient pressure curves for gas flow through MCP1 and MCP2 are shown in Figs. 3 and 4 respectively. The transient cylinder pressure and the pressure drop across the test section form the primary data.

IV. Gas flow - Data reduction/analysis

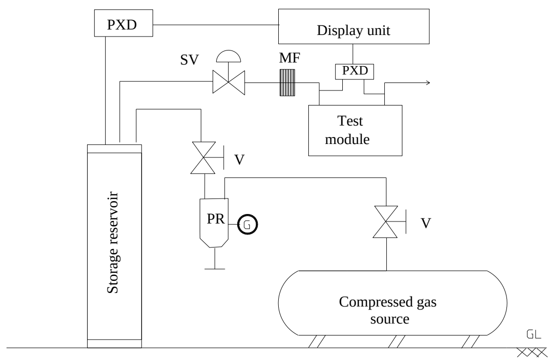

Fig. 2 Gas flow experimental set-up schematic Legend: G-Pressure gauge; MF-Micro filter; PR-Pressure regulator; PXD-Pressure transducer, SV- Solenoid valve V-Valve

The mass flow rate was calculated by numerical differentiation of the reservoir pressure transient. By differentiating the perfect gas relation,

$$pV=m_gRT \qquad (1)$$

and the mass flow rate can be calculated as

$$dm_g/d\tau = (dp/d\tau)\ V/RT \qquad (2)$$

The use of perfect gas relation is valid as the compressibility effects under the conditions of experiments are negligible (compressibility factor is almost 1.0).

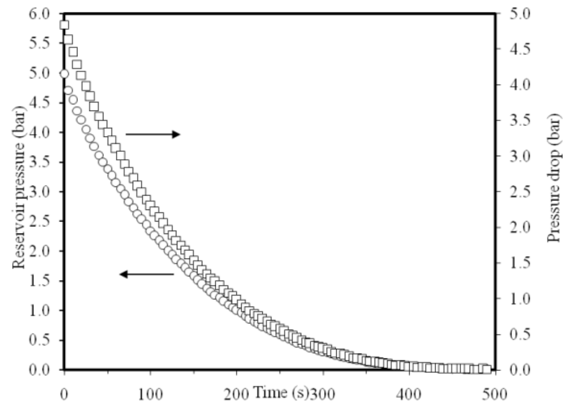

Fig. 3 Transient pressure data for air flow in MCP1

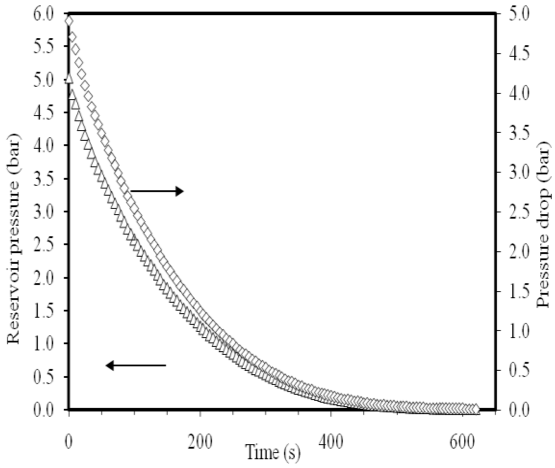

Fig. 4 Transient pressure data for air flow in MCP2

It is assumed that the temperature is constant. The Reynolds number is defined in the conventional way ($\rho v D_{eq}/\mu$) based on cross-sectionally averaged velocity (v) (evaluated using the mass flow rate) and hydraulic equivalent diameter (D_{eq}) which is defined for non-circular duct as follows:

$$D_{eq} = 4WH/(2W + 2H) \qquad (3)$$

For the present experiment with gas, Re can be written as follows:

$$\mathrm{Re} = 2V(dp/d\tau)/[\mu RT(W+H)] \qquad (4)$$

The values of viscosity used [6] is 1.82×10^{-5} Pa·s, for air. The pressure drop across the channel for any time step was taken as the average value at the two instants. The Darcy-Weisbach formula was used for calculating the friction factor as below

$$\Delta p/\rho = f\,(L/D_{eq})\,(v^2/2) \qquad (5)$$

where, Δp is the pressure drop, ρ is the density, f is the friction factor, L/D_{eq} is length to diameter ratio and v is the velocity. Equation (5) can be rewritten as follows:

$$f = \Delta p \left[\frac{2WH}{W+H}\right]^3 \left(\frac{2\rho}{\mu^2}\right) \frac{\mathrm{Re}^{-2}}{L} \qquad (6)$$

The density used in the above equation was evaluated at the average pressure between the inlet and outlet of the channel.

V. Gas flow results

The values of friction factor (f) obtained in the present flow experiments are plotted as f *vs* Re and the line $f = C_{theo}/\mathrm{Re}$ have also been drawn in for reference. The C_{theo} is the theoretical value for fully developed laminar flow in a straight channel. It is evident, that there is a deviation between C_{theo} for normal channel assumption and to the present micro-channel. The value of C_{theo}, which depends on the aspect ratio, had been calculated for MCP1 and MCP2 using the data given in F.M.White.

5.1 Friction data

Figures 5 and 6 shows the friction factor *vs* Reynolds number plots for MCP1 and MCP2 respectively. The laminar flow data were fitted using the following relation,

$$f = C_1/\mathrm{Re} \qquad (7)$$

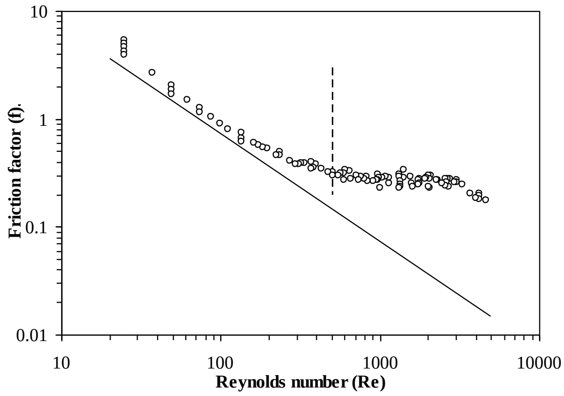

Fig. 5. Plot of f *vs* Re for flow in MCP1

Legend: O - Experimental, Solid line- Theory, Dashed line-Transition

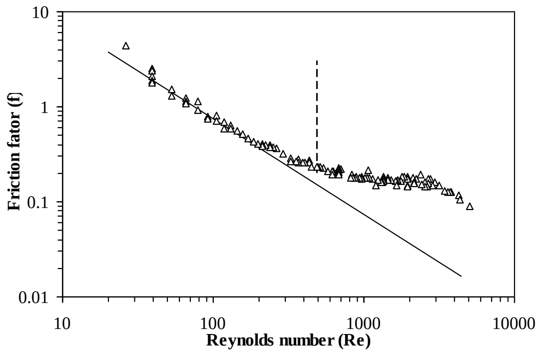

Fig. 6. Plot of f *vs* Re for flow in MCP2

Legend: Δ - Experimental, Solid line- Theory, Dashed line-Transition

Table 2. Values of C_1 in eq. (7)

Fluid	C_{theo}	Avg e.	mi n.	max .	Std Dev n.	Re_{Tr}[t]	Remarks on eq. (7)
MCP 1:	73.56						
Air		90.38	81.69	98.77	5.12	~500	Re<500
MCP 2:	74.73						
Air		91.29	86.47	95.28	2.89	~500	Re<500

[t]Note: Only perceived data are presented.

and the values of C_1 are given in the Table 2. Also Table 2 (Column 2) gives the theoretical values for the two channels. Although, the aspect ratios for MCP1and MCP2 are of same order, the values of friction constant for MCP1 and MCP2 are more than C_{theo} and are about 22% higher. Comparing the values of MCP1 and MCP2, it is seen that there is a deviation of about 1%.

VI. Non-dimensional pressure drop (NDPD)

An alternative way of presenting friction data is to give a relation between non-dimensional pressure drop (NDPD=2 $\Delta p [(\rho D_{eq}^3)/(\mu^2 L)]$) and Re. Equation (7) re-written becomes

$$NDPD = Re\ C_1 \qquad (8)$$

From the flow measurement data, experimental NDPD was evaluated. Figures 7 and 8 show the plots of NDPD *vs* Reynolds number for flow of gas in MCP1 and MCP2 respectively. At low Reynolds number values a linear relationship between the NDPD and Reynolds number is evident, wherein experimental NDPD data fall along the solid line (in Fig. 7 for MCP1 and Fig. 8 for MCP2). The solid lines drawn in Figs. 7 and 8 represent the theoretical value of NDPD for laminar flow in straight macro-channels. The dashed lines drawn (in Figs. 7 and 8) represent the experimental value of NDPD based on the average value of C_1 for air (Column 3 in Table 2).

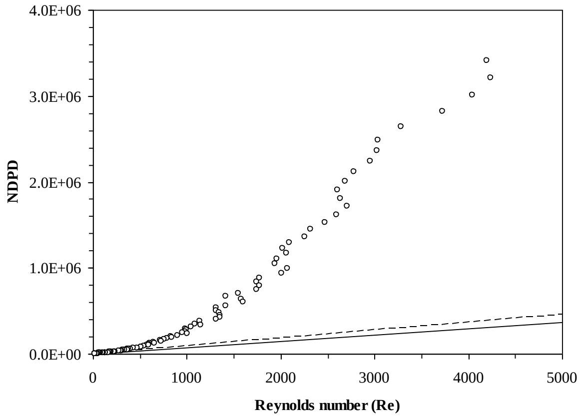

Fig. 7 Plot of NDPD *vs* Re for flow in MCP1
Legend: O - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

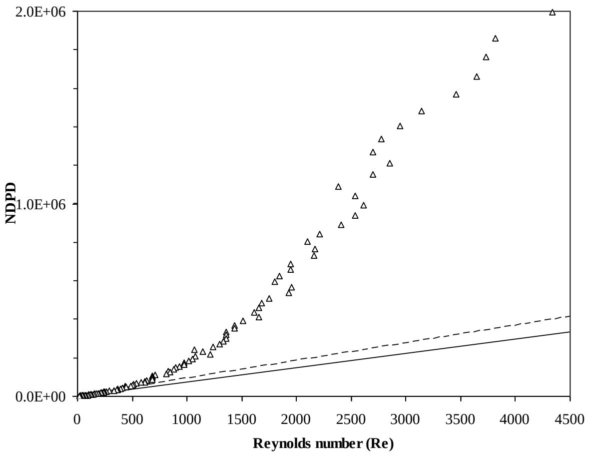

Fig. 8 Plot of NDPD *vs* Re for flow in MCP2
Legend: Δ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

Both from the f-Re and NDPD-Re plots, it is clear that in each of the two channels at low Re the pressure drop varies linearly with velocity as would be expected for laminar flow. However, the friction factor is higher than the respective theoretical values for MCP1 and MCP2 (Figs. 5 and 6). It may be mentioned here that other experiments in micro-channels have shown both higher [2] and lower [8] values of friction factor than those obtained in macro-channels. Further, the Figs. 5 to 8 shown are for one set of experimental data for each fluid and channel.

6.1 Transition Reynolds number (Re_{Tr})

The transition from laminar to turbulent regime is traditionally visualized as a discontinuity in the f *vs* Re relation. These change(s) of slope as construed to be points of transition as suggested by [7]. Unlike in the conventional flow geometries where one can expect a discontinuity in f *vs* Re relation, in the case of micro-channels such a sharp discontinuity is absent. Gerlach [7] proposed identification of these mild discontinuities through a plot of normalized pressure drop ($\Delta p D_{eq}^2 \rho/\mu^2$) against Re. This is also analogous to NDPD *vs* Re (or f *vs* Re) which has been adopted in the present analysis.

` It can be noticed from the f-Re and NDPD-Re plots, for each of the two channels at low Re the pressure drop varies linearly with velocity as would be expected for laminar flow. This feature is the change(s) in slope of NDPD at certain Reynolds number(s) for MCP1 and MCP2 is also evident. These Reynolds numbers in the present analysis are termed as transition Reynolds numbers (Re_{Tr}). For MCP1 and MCP2, large changes in slope occur at Re ≈500. This change in slope appears to be like the characteristic transition to turbulence observed in pipe and channel flows. The derived or identified transition point is marked in Figs. 5 and 6 with vertical dashed line. Further study is required to relate the deviations in the friction curve with different fluids and geometries. However, it is clear that accurate data of friction is required for design of micro-channels.

Three important conclusions arise out of the experiments with gas, namely

i) The friction factors in MCP1 and MCP2 are the same.
ii) The friction factors in MCP1 and MCP2 are higher than theory for laminar region.
iii) The transition was observed in MCP1 and MCP2 at $Re_{Tr} \approx 500$.

VII. Conclusion

Pressure drop, friction factor were measured and calculated for gas flow in rectangular micro-channels. The gas flow experiments have been conducted in MCP1 and MCP2 with Reynolds number range of the order of 24 – 6233, covering laminar and transition flow regimes. The following conclusions emerge from the investigation

1. The transition region in micro-channel flow cannot be described distinctly as in the case of normal channels.
2. Reynolds number alone is inadequate to explain the flow behaviour in micro-channels.
3. To identify the transition, as the deviation of NDPD values or from change in slope.
4. The friction factor values are comparable to conventional tube flow in laminar region.
5. To obtain a generalised correlation for friction factor there is a need for more experiments on various geometries and different gases.

Acknowledgements

The test modules used in this paper are financially supported by Department of Mechanical Engineering, Indian Institute of Science (IISc), Bangalore from Centre for Air Borne Systems project. The authors are grateful to Liquid Propulsion Systems Centre, Indian Space Research Organisation, Bangalore for deploying their expertise in the fabrication of test sections.

References

[1] M.B. Kleiner, S.A. Kuhn, and K. Haberger, High performance forced air cooling scheme employing micro-channel heat exchangers. *IEEE. Trans. On Components, Packaging and Manufacturing Technology*. Part A *18(4)*, 1995, 795.

[2] P. Wu and W.A. Little, Measurement of friction factors for the flow of gases in very fine channels used for Micro-miniature Joule-Thomson Refrigerators. *J. Cryogenics. 23,* 1983, 273.

[3] G. Hetsroni A. Mosyak, E. Pogrebnyak and L.P. Yarin, Fluid flow in micro-channels. Int. *J. Heat and Mass Transfer, 52*, 2005, 1982-1998.

[4] J.Y. Jung and H.Y. Kwak, Fluid flow and heat transfer in micro-channels with rectangular cross section. *J. Heat and Mass Transfer*, *44*, 2008, 1041-1049.

[5] R.H. Perry, D. W. Green, and Maloney, *Perry's chemical engineer's hand book*, 6th edition, *McGraw-Hill Book Company*. 1984.

[6] C. F. Beaton, and G. F. Hewitt, *Physical property data for the design engineers*. New York Hemisphere publishers, 1989.

[7] T. Gerlach, Micro-diffusers as dynamic passive valves for micro-pump applications. *Sensors and Actuators,* - A physical *69*, 1998, 181-191.

[8] D. Yu, R. Warrington, R. Barron, and T. Ameel, An experimental and theoretical investigation of fluid flow and heat transfer in micro-tubes. *ASME/ JSME Thermal Engineering Conf. 1,* 1995, 523-530.