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An Experimental Study on Alcohol Flow in Micro-Channels

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ABSTRACT

Experiments were performed to study the flow characteristics of ethanol and methanol flow in rectangular micro-channels using test models 1 and 2 (TM1, TM2). The TM1 and TM2 used were of 47 and 50 micro-channels in rectangular cross-section of equivalent diameters of 387 and 327 μm respectively. The channel length of 192 mm were fabricated on a 304 stainless steel substrate (230 mm x 160 mm x 1.6 mm) by photo chemical etching process. Covering the top with another plate of 0.5 mm thickness formed the channels by vacuum brazing. The pressure drop and flow rate data were measured and used as raw data to evaluate friction factors in micro-channel. Analysis of friction factor *vs* Reynolds number relation indicates that friction factor for liquid flow is same as that of normal channels in the laminar region. Transition region lies in Re > 500 and transition set off at lower Re ~ 500 in comparison to normal channel. Further it may be possible to identify transition as the deviation of NDPD values from laminar region.

Keywords: *Experiments, laminar, transition, friction factor, NDPD and micro-channels.*

Nomenclature

C	constant
d	diameter (m)
D_{eq}	equivalent diameter (m)
H	channel height (m)
L	channel length (m)
NDPD	non-dimensional pressure drop
Re	Reynolds number ($=\rho v d/\mu$)
v	velocity (m/s)
W	channel width (m)

Greek Letters

Δ	differential
μ	dynamic viscosity, (N s/m^2 or Pa s)
ρ	fluid density (kg/m^3)

Subscripts

eq	equivalent
1	test module 1
2	test module 2

1. INTRODUCTION

Many researchers have studied flow in small channels over the years. Schlichting [1] documents theories and experimental data from the pioneering works. Rapid development of micro-mechanics stimulated during the past decades numerous investigations in the field of fluid mechanics of micro-devices [2]. The problems of micro-hydrodynamics were considered in different contexts. The drag in micro-channels with hydraulic diameters from 10^{-6} m to 10^{-3} m considered at laminar heat transfer of liquid and gas flows. The studies performed in these directions encompass a vast class of problems related to fluids in micro-channels. The discoveries of special micro-effects caused these problems are extensively discussed [3]. Kohl *et al.* [4] measured the local pressure of water flow at different points along the length of rectangular channels (D_{eq}:25-100 μm) with Reynolds number range of 5-2068. Experimental results and the analytical laminar flow solution including minor losses and entry region effects are compared and found to be in good agreement. Caney *et al* [5] investigated single phase flow in a 1000 μm square mini channel of 420 mm long, etched on aluminium. The Reynolds number was varied from 310-7780 covering the laminar and turbulent regimes. The friction factor results show a good agreement with classical correlations for conventional channels. Jung and Kwak [6] have studied fluid flow in rectangular micro-channels 100, 150 and 200 μm wide respectively, all 100 μm high and 150 mm long. They obtained the friction factor constant C (= fRe) values between 53.7 and 60.4, and concluded, that are close to the theoretical value from a correlation for macroscopic dimension, 56.9 for D_{eq} = 100 μm. An experimental investigation was performed in the direction on flow characterisation of the above said test modules and those are detailed in the subsequent sections. Kalaivanan and Rathnasamy [7, 8] investigated heat transfer characteristics in test modules wherein, they used ethanol, methanol and mixture of former liquids in laminar region to propose correlation.

2. MICRO-CHANNELS FABRICATION

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. The substrate overall dimensions are of 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. TM1 and TM2 were manufactured first by photo chemical etching process as shown in Fig. 1. Subsequent to etching of channel the channel header portions were deepened by EDM in order to have negligible pressure loss. TM1 and TM2 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.

2.1 Surface Roughness Measurement

The surface roughness (ε) measurement of TM1 and TM2 was done to check the uniformity of the channel. The average surface roughness of the surfaces in contact with the fluid was measured using a surface profilometer (Rank Taylor Hobson) using a diamond stylus tip of radius of 2.5 μm. The details of surface roughness measurement are given in the Table 1. Figure 2 illustrates the typical surface profile of an EDM machined micro-channel (TM1) surface.

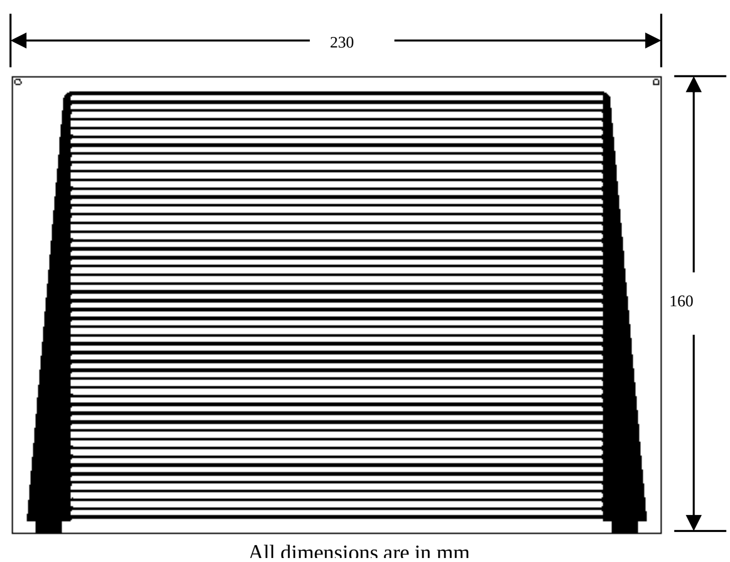

Fig. 1. Layout of the rectangular parallel micro-channel

Table 1. Surface roughness details (μm)

Specimen	RMS	Average	Peak to valley	Remarks
TM1	3.4295-5.7915	4.22-6.90	12.80-8.93	EDM portion
TM2	0.8679-1.2141	1.11-1.52	4.11-5.64	Etched channel

Cover plate (SS)	0.2453-0.1560	0.19-0.34	0.88-1.32	Non-machined

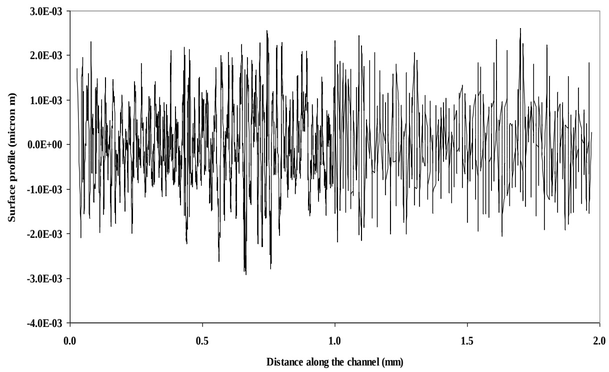

Fig. 2. Typical surface profile of TM1 machined (EDM)

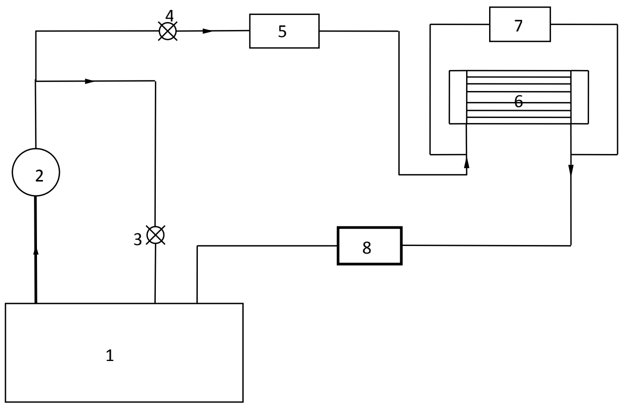

Fig. 3. Schematic experimental set-up

Legend: 1 Sump 2 Pump 3 By-pass control valve 4 Flow control valve 5 Micro-filter 6 Test section 7 Differential pressure transducer 8 Flow meter.

3. EXPERIMENTAL SET-UP

The set-up of the liquid flow experiments is shown in Fig. 3. It consists of liquid reservoir/sump (capacity ~20 lit) to supply fluid to the test section. A diaphragm operated pump is used to pump fluid to the test section through a micro-filter (~50 micron) built-in in the main line to avoid any dirt that may enter into the test section causing data error. Further the test set-up is provided with by-pass line and control valves to establish the required flow rate in the test section and as well the pressure drop. The pressure drop was measured with the aid of differential pressure transducer. Flow rate through the test section was measured by using the flow meter (make: DIGMESA, magnetic turbine flow meter). However, the flow meter was calibrated besides measuring known volume of methanol manually with a maximum absolute deviation 4% over the measuring range 0.03- 8.00 $L \cdot min^{-1}$. A reassessment with other liquids was done also. The calibration curve is shown in Fig. 4. The details of experiments conducted with liquids are given in Table 2.

3.1 Primary data

The pressure drop and the flow rate form the *raw data* and are used to obtain the friction factor in the present study. Figure 5 depicts some typical primary data consisting of flow rate *vs* pressure drop for ethanol flow with the TM1 and TM2. Corresponding typical data are shown in Fig. 6 for methanol flow.

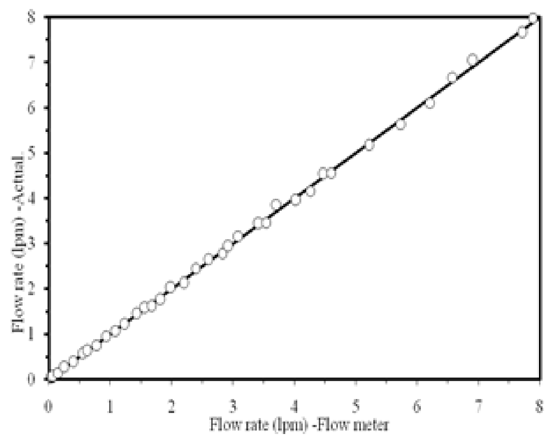

Fig. 4. Calibration data for flow meter

Table 2. Details of experiments conducted with liquids

Fluid	No. of experiments		Range of Reynolds number covered	
	TM1	TM2	TM1	TM2
Ethanol	6	4	14-1033	13-921
Methanol	5	5	29-2104	26-1812

4. DATA REDUCTION

The primary data obtained from the liquid flow experiments are used to deduce various parameters pertaining to fluid flow in micro-channels. The objective is to obtain the friction factor *versus* Reynolds number relation.

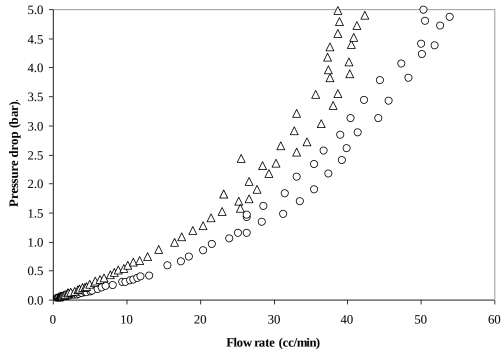

Fig. 5. Typical pressure drop *vs* flow rate data for ethanol flow

Legend: O - TM1, Δ- TM2

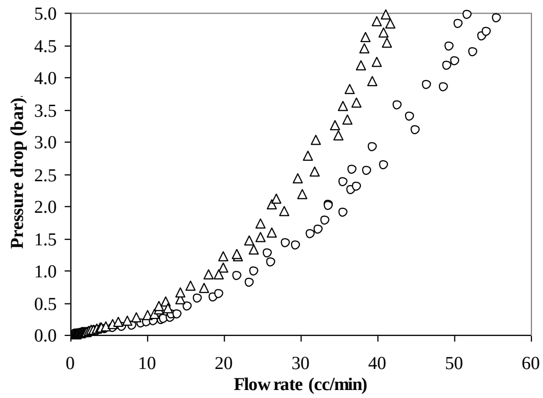

Fig. 6. Typical pressure drop *vs* flow rate data for methanol flow

Legend: O - TM1, Δ- TM2

The friction factor 'f' is deduced from the raw data using Darcy-Weisbach formula.

$$\Delta p/\rho = f\,(L/D_{eq})\,(V^2/2) \qquad (1)$$

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. 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:

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

Equation (1) can be rewritten as follows:

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

For data reduction and evaluation, pure liquid thermo-physical property data at 25°C were taken from Beaton and Hewitt [9].

5. FRICTION DATA

The friction factor *vs* Reynolds number plots are shown in Figs. 7 to 10 for the liquids studied with TM1 and TM2. The laminar flow data were fitted using the following relation,

$$f = C_1/Re \qquad (4)$$

and the values of C_1 are given in the Table 3 for TM1 and TM2. The solid line drawn in figures 7 to 10 represents theoretical value C_{theo} (i.e; Column 2 in Table 3).

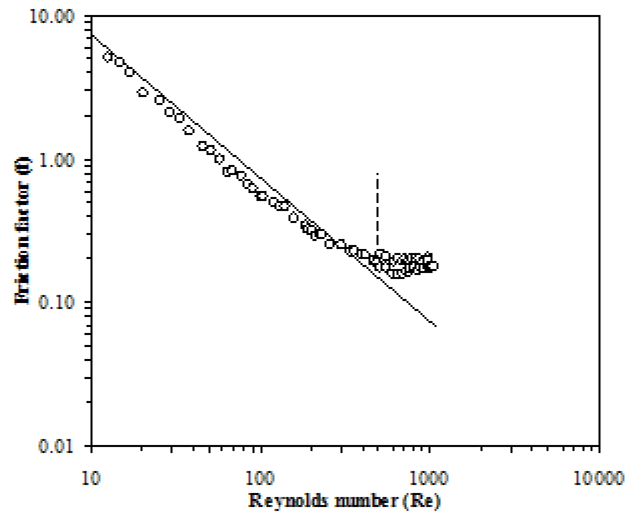

Fig. 7. Plot of f *vs* Re for ethanol flow in TM1

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

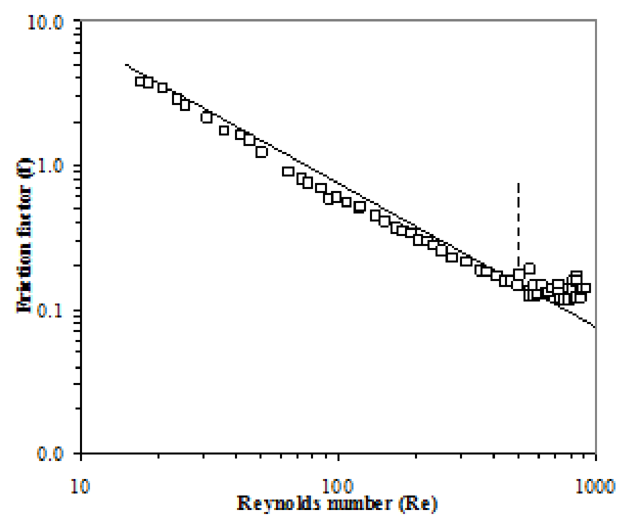

Fig. 8. Plot of f *vs* Re for ethanol flow in TM2

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

6. NON - DIMENSIONAL PRESSURE DROP (NDPD)

An alternative way of presenting friction data is to give a relation between non-dimensional pressure drop (NDPD=2 Δp [(ρ D_{eq}^3)/(μ^2L)]) and Re. Equation (4) re-written becomes

$$NDPD = Re\, C_1 \quad (5)$$

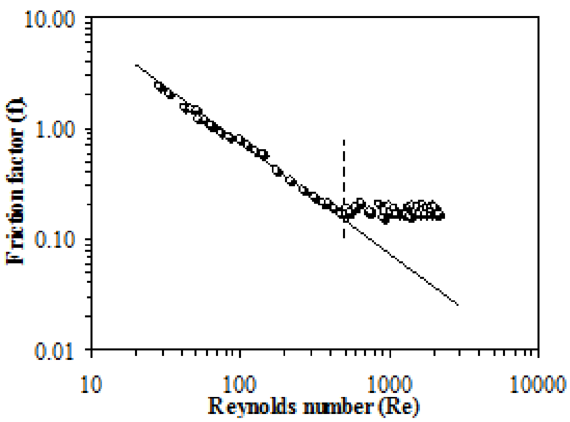

Fig. 9. Plot of f *vs* Re for methanol flow in TM1

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

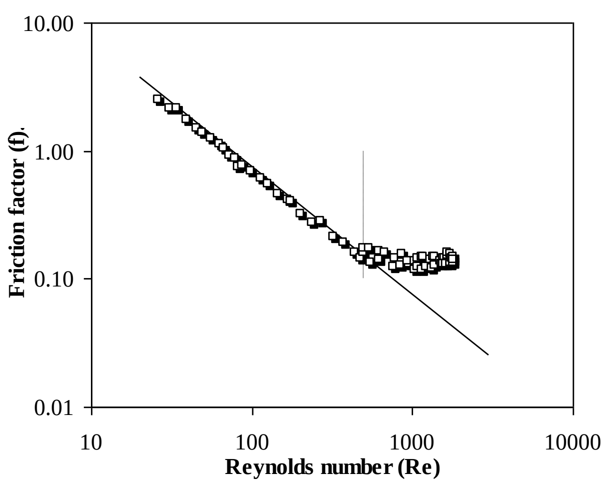

Fig. 10. Plot of *vs* Re for methanol flow in TM2

Legend: Shadow □ - Experimental, Solid line- Theory, Dashed line- Transition

From the flow measurement data, experimental NDPD was evaluated. Figures 11 to 14 show the NDPD variation with Re for liquid flow in TM1 and TM2. The solid lines drawn in Figs. 11 to 14 represent the theoretical value of NDPD (i.e; Re C_{theo} or C_1=C_{theo} in eq. (4) in laminar fully developed flow in normal straight channels. The dashed lines correspond to average values of C_1 (i.e; Column 3 of Table 3 for each liquid and channel) determined from the present experimental data. As for the channels TM1 and TM2 the friction factors are lower in the case of liquid flow (Table 3).

7. 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 Gerlach [10]. 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 [10] 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 TM1 and TM2 is also evident. These Reynolds numbers in the present analysis are termed as transition Reynolds numbers (Re_{Tr}). This change in slope appears to be like the characteristic transition to turbulence observed in pipe and channel flows. The transitions in liquid flow are identified in the f *vs* Re or NDPD *vs* Re plots. The liquid flow data show the transition point(s) clearly. Flow of liquids show one transition Reynolds number: ~500. The derived or identified transition point is marked in Figs. 7 to 10 with vertical dashed line. The upper transition Reynolds number believed to be the final transition to turbulence is not observed. These early transitions are possibly caused by the flow behavior in micro-channels.

Table 3. Values of C_1 in eq. (4)

Fluid	C_{theo}[11]	Avge.	min.	max.	Std Devn.	Re_{Tr}^t	Remarks on eq. (4)
TM1:	73.56						

Ethanol (E)		65.33	61.33	69.10	3.10	~500	Re<500
Methanol (M)		65.19	62.40	66.19	0.62	~500	Re<500
TM2:	74.73						
Ethanol (E)		66.84	64.59	69.66	2.22	~500	Re<500
Methanol (M)		64.48	63.28	67.36	1.70	~500	Re<500

[t]Note: Only perceived data are presented.

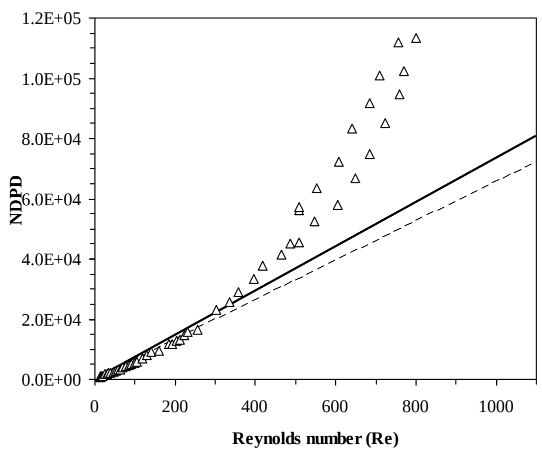

Fig. 11. Plot of NDPD *vs* Re for ethanol flow in TM1

Legend: Δ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

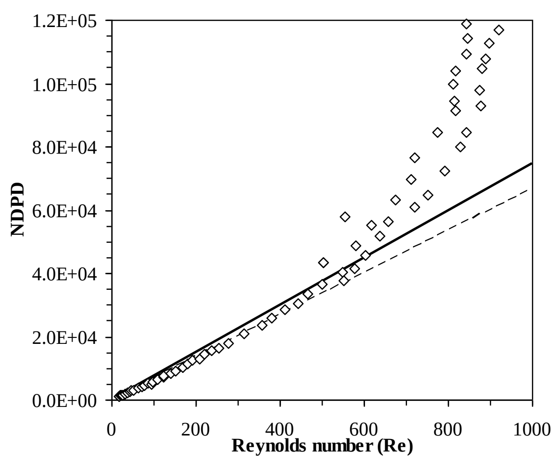

Fig. 12. Plot of NDPD *vs* Re for ethanol flow in TM2

Legend: ◊ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

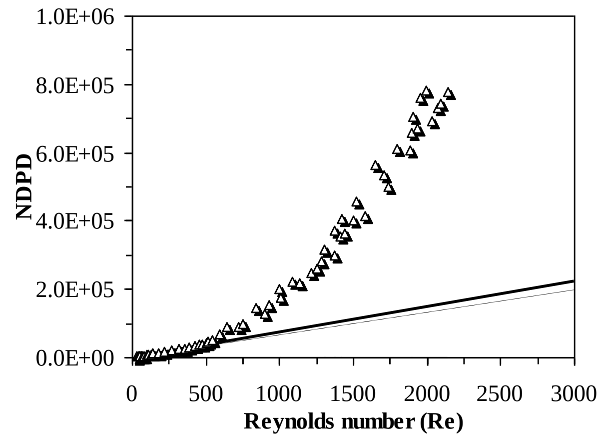

Fig. 13. Plot of NDPD *vs* Re for methanol flow in TM1

Legend: Shadow Δ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

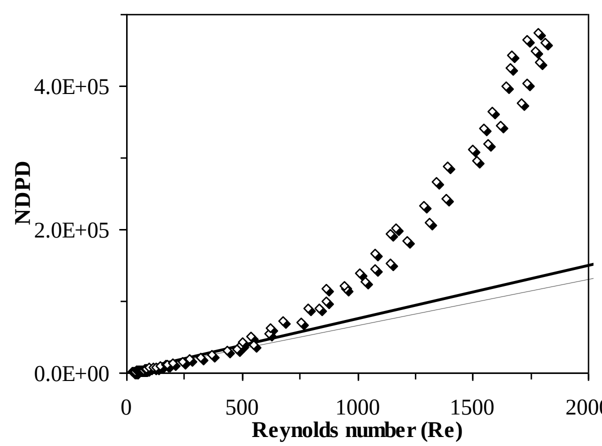

Fig. 14. Plot of NDPD *vs* Re for methanol flow in TM2

Legend: Shadow ◊ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

8. CONCLUSIONS

The following qualitative and quantitative conclusions emerge from the investigation on flow friction in micro-channels.

- The friction factor constant is lower than conventional channel (tube)

- The transition Reynolds number (Re_{Tr}) is not found to be channel geometry dependent.
- The transition region in micro-channel flow cannot be described distinctly as in the case of normal channels.
- Reynolds number alone is inadequate to explain the flow behavior in micro-channel.
- It may be possible to identify transition (from laminar region) as the deviation of NDPD values from change in slope.

The two channels TM1 and TM2 having same order of aspect ratio and fabrication methods, but with different relative roughness factor exhibited consistent friction factor results for liquids.

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REFERENCES

[1] Schlichting, H. 1979. *Boundary layer theory*, New York, Mc-Graw hill book company.

[2] Gad-el-Hak, M. 1999. The fluid mechanics of micro devices. Freeman lecture, *J. Fluid Engg*. 121: 5-33.

[3] Gad-el-Hak, M. 2003. Critical view on new results in micro-fluid mechanics. *Int. J. Heat Mass Transfer* 46: 3941-3945.

[4] Kohl, M. J., Abdel-Khalik, S. I., Jeter, S. M. and Sadowski, D. L. 2005. An experimental investigation of micro-channel flow with initial pressure measurements. *Int. J. Heat Mass Transfer* 48: 1518-1533.

[5] Caney, N., Marty, P. and Bigot, J. 2007. Friction losses and heat transfer of single-phase flow in a mini-channel. *Applied Thermal Engineering* 27: 1715-1721.

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

[7] Kalaivanan, R. 2010. Fluid flow and heat transfer studies in micro-channels. *Ph.D. Thesis*, Mechanical Engineering, Annamalai University, INDIA.

[8] Kaliavanan, R. and Rathnsamy, R. 2010. Experimental investigation of forced convective heat transfer in rectangular micro-channels. *ARPN Journal of Engineering and Applied Sciences* 5(5): 21-26.

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

[10] Gerlach, T. 1998. Microdiffusers as dynamic passive valves for micropump applications. *Sensors and Actuators*- A physical 69, 181-191.

[11] White, F. M. 1988. *Fluid Mechanics* 2nd ed. New York McGraw-Hill Book Co.