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Flow characteristics of ethanol-methanol mixture through a parallel micro-channels

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Abstract: *The present work investigates is to study the flow characteristics of ethanol and methanol mixture flow in rectangular micro-channels using test specimens 1 and 2 (TS1, TS2). The TS1 and TS2 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 friction factor is estimated from the measured pressure drop along the whole channel of TS1 and TS2. Analysis of friction factor vs Reynolds number relation indicates that friction factor for mixture 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, friction factor, NDPD and micro-channels.*

Nomenclature

C	*constant*
d	*diameter (m)*
Deq	*equivalent diameter (m)*
H	*channel height (m)*
L	*channel length (m)*
NDPD	*non-dimensional pressure drop*
Re	*Reynolds number (=ρvd/μ)*
v	*velocity (m/s)*
W	*channel width (m)*
Greek Letters	
Δ	*Differential*
μ	*dynamic viscosity, (N s/m2 or Pa s)*
ρ	*fluid density (kg/m3)*
Subscripts	
eq	*equivalent*
1	*test specimen 1*
2	*test specimen 2*

I. Introduction

After the publication of Tuckerman and Pease's pioneering work [1], there has been a great deal of interest in studying fluid flow and heat transfer characteristics in micro-channels for electronic cooling applications. However, only few studies have been carried out for a mixture flow through micro-channels as required in practical applications. With increasing miniaturization of electronic chips and increasingly larger heat dissipation rates, better designs of cooling system are needed. Harley et al.[2], and Pfahler [3] conducted a series of experimental investigations to measure the friction factor in micro-channels with liquids (silicone oil, iso-propanol and alcohol. They correlated their data by a relation of the form given as:

C=F*Re

The value of C is found to be generally smaller than the theoretical value in normal channels at lower Re values. At large Re values, C or C* $(=C_{exp}/C_{theo})$ appeared to be independent of Re. They further noted that increase in the channel depth significantly increases friction factor. They also observed both fluid species and channel size influence the flow in micro-channels and that the deviations from normal channels increase with diminishing channel dimensions.

Fu et al [4] did experiments of two-phase flow pattern and pressure drop in the converging and diverging, silicon based micro-channels with mean hydraulic diameter of 128μm and CO_2 bubbles produced by chemical reaction of sulphuric acid and sodium bicarbonate. They reported that the increase of inlet concentration of reactants does not increase the pressure drop in the diverging micro-channel. Huiying et al. [5] investigated on the flow friction and convective heat transfer characteristics of ethanol-water solution flowing through trapezoidal silicon micro-channels having hydraulic diameters of 141.7μm to 268.6μm. It was found that the cross sectional geometric parameters like entrance effect, volume concentrations had great effect. Xie et al. [6] studied the characteristics of single phase flow and forced convection heat transfer in rectangular micro-channels with an application to avionics. Two liquid coolants used were; one 30% of ethanol-water solution and another fluid FC-72. Six test sections were fabricated with micro-channels having equivalent diameters from 332 to 540 μm. Correlations were proposed for each coolant in different regions:

f = 6298.65 Re-0.938 (Deq/L)1.0314 (H/W)0.1013 for 50<Re<220

f =0.004743 Re-0.9553 (Deq/L)-1.5349 (H/W)-0.09793 for 300<Re<750

For the ethanol-water solution and FC-72 respectively. Transition flow region (Re_{Tr} ~750-1250) occurred in rectangular micro-channels were stated to be lower than Re_{cr} =2200 in normally sized rectangular channels and given the turbulent friction factor relationship,

f =0.6833 Re-0.6678 for 1250<Re<3000

Steinke and Kandlikar [7] based on their review of about 150 papers specifically addressing the topic of fluid flow and heat transfer in micro-channels generated a database of over 5000 data points. An explanation for the deviation in data, as consequence of inlet, outlet, developing region, experimental uncertainties and also surface roughness are emphasized. Their experiments include range of 0.002<Re<5000 and 8<Deq<990 μm and those corrected data shows good preliminary agreement in value and trend with the conventional theory for laminar fluid flow.

Mokrani et al [8] investigated the design, construction and instrumentation of an experimental micro-channel, with a rectangular cross-section and large aspect ratio, to characterize the flow and convective heat transfer. As the wall thermal conditions inside the micro-channel cannot be measured directly, they followed the temperature measurements in the wall thickness and an inverse heat conduction method. The thermal and hydrodynamic results obtained by varying the hydraulic diameter between 1 mm and 100 μm do not deviate from the theory or empirical correlations for macro-scale channels. They substantiate that for smooth walls the continuum mechanics laws for convection and fluid mechanics remain valid in micro-channels of hydraulic diameter greater than or equal to 100 μm.

Kalaivanan , Kalaivanan and Rathnasamy [9,10] investigated flow and heat transfer characteristics in test modules wherein, they used ethanol, methanol and mixture of former liquids in laminar region to propose correlation.

II. 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. TS1 and TS2 were manufactured first by photo chemical etching process. Subsequent to etching of channel the channel header portions were deepened by EDM in order to have negligible pressure loss. TS1 and TS2 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 1 illustrates the typical surface profile of an EDM machined micro-channel (TS1) surface.

Table 1. Surface roughness details (μm)

Specimen	RMS	Average	Peak to valley	Remarks
TS1	3.4295-5.7915	4.22-6.90	12.80-8.93	EDM portion
TS2	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

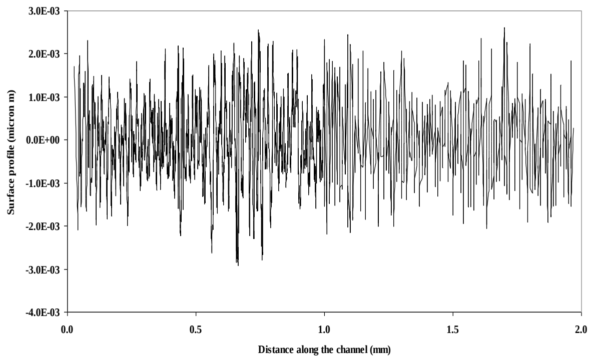

Fig. 1. Typical surface profile of TS1 machined (EDM)

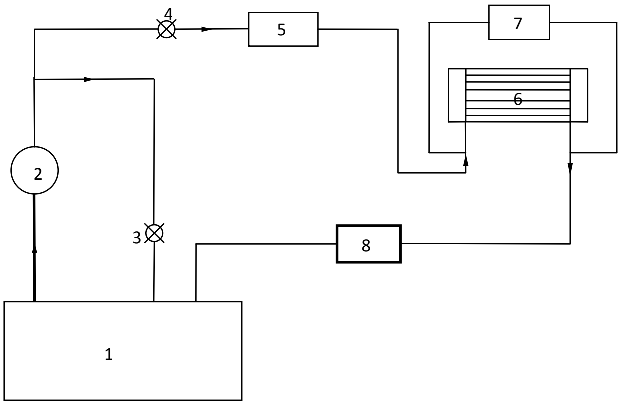

Fig. 2. Schematic experimental set-up

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

III. Experimental set-up

The set-up of the liquid flow experiments is shown in Fig. 2. 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 (make: KELLER Druckmesstechnik; piezoresistive pressure transmitter, PD-23/ 5 bar /8666.1). 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·min-1. A reassessment with other liquids was done also. The calibration curve is shown in Fig.3. 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 4 depicts some typical primary data consisting of flow rate vs pressure drop for mixture flow with the TS1 and TS2.

Table 2. Details of experiments conducted with liquids

Fluid	No. of experiments		Range of Reynolds number covered	
	TS1	TS2	TS1	TS2
50%E-50%M	5	5	17-1781	18-1650

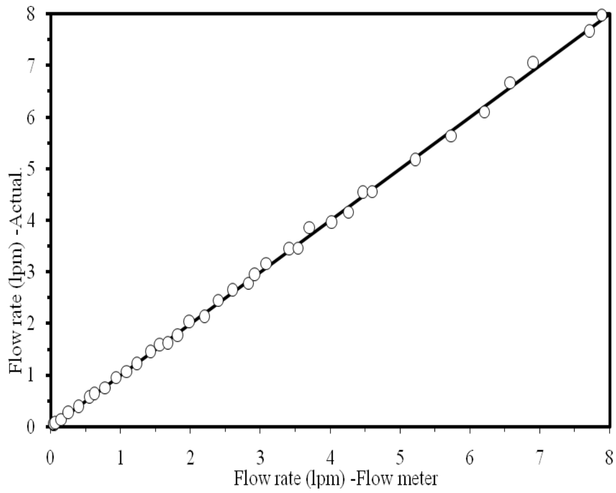

Fig. 3. Calibration data for flow meter

IV. Studies with liquid mixture

The experimental investigation on flow in micro-channels with mixture was performed using 50% E-50% M by volume (ie; 0.53E- 0.47M by mole fraction). Both laminar and turbulent regimes are covered with TS1 and TS2.

4.1 Data reduction

The primary data obtained from the mixture 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.

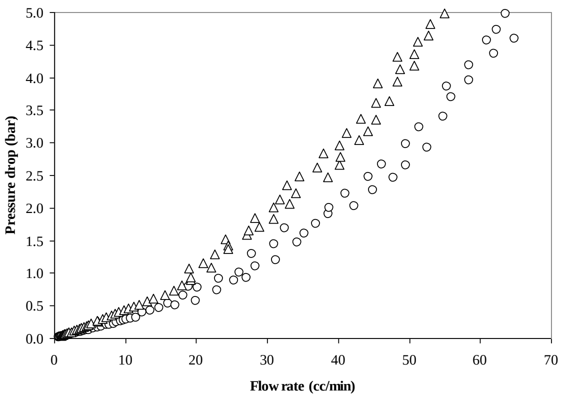

Fig 4. Typical pressure drop vs flow rate data for mixture (53%E-47%M) flow Legend: O - TS1, Δ- TS2

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 (Deq) 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^{o}C were taken from Beaton and Hewitt [9].

4.2 Property evaluation

For data reduction and evaluation, pure liquid thermo physical property data at 25°C were taken from Beaton and Hewitt [11]. In the case of mixture's appropriate mixing rules were used. The linear mixing rule for specific volumes was used for evaluating the mixture density as given below:

$$\frac{1}{\rho_{mix}} = \frac{x_1}{\rho_1} + \frac{x_2}{\rho_2} \qquad (4)$$

The logarithmic mixing rule for viscosity of liquid mixtures from Heide [12] was used as given under,

$$\ln\mu_{mix} = y_1 \ln\mu_1 + y_2 \ln\mu_2 \qquad (5)$$

V. Friction data for mixture flow in TS1and TS2

The friction factor vs Reynolds number plots are shown in Figs. 5 and 6 for the mixtures studied with TS1 and TS2. The laminar flow data were fitted using the following relation,

$$f = C_1 / Re \qquad (6)$$

And the values of C_1 are given in the Table 3 for TS1 and TS2. The solid line drawn in figures 5 and 6 represents theoretical value C_{theo} (i.e; Column 2 in Table 3).

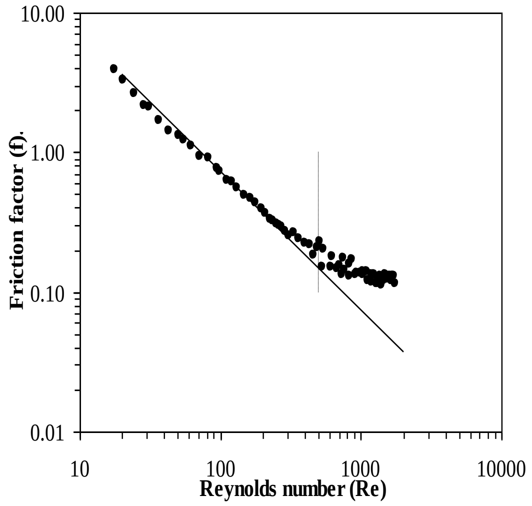

Fig 5. Plot of f vs Re for mixture (53%E-47%M) flow in TS1
Legend: Filled O - Experimental, Solid line- Theory, Dashed line- Transition

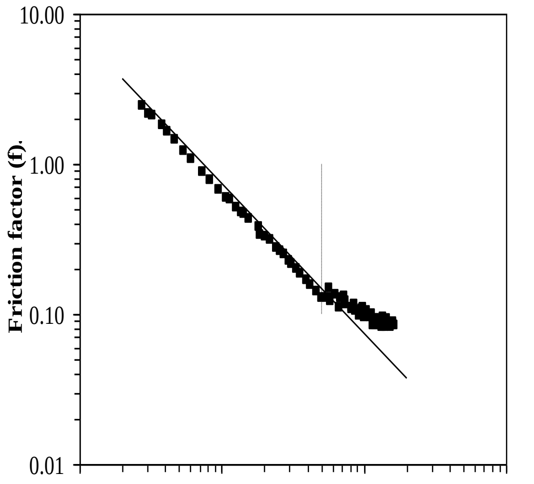

Fig 6. Plot of f vs Re for mixture (53%E-47%M) flow in TS2
Legend: Filled □ - Experimental, Solid line- Theory, Dashed line- Transition

Table 3 Values of C_1 in eq. (6) for mixture flow

Fluid	C_{theo}	Avge.	min.	max.	Std Devn.	Re_{Trt}	Remarks on eq. (6)
TS1:	73.56						
50%E-50%M		65.44	63.23	67.11	1.50	~500	Re<500
TS2:	74.73						
50%E-50%M		65.31	63.23	67.52	1.79	~500	Re<500

ŧNote: Only perceived data are presented.

VI. Non-dimensional pressure drop (NDPD)-mixtures

From figures 7 and 8 shows the NDPD variation with Re for mixture flow in TS1 and TS2. The solid lines drawn in Figs. 7 and 8 represent the theoretical value of NDPD (i.e; Re C_{theo} or C_1=C_{theo} in eq. (6)) 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 mixture and channel) determined from the present experimental data. As for the channels TS1 and TS2 the friction factors are higher than the corresponding theoretical values.

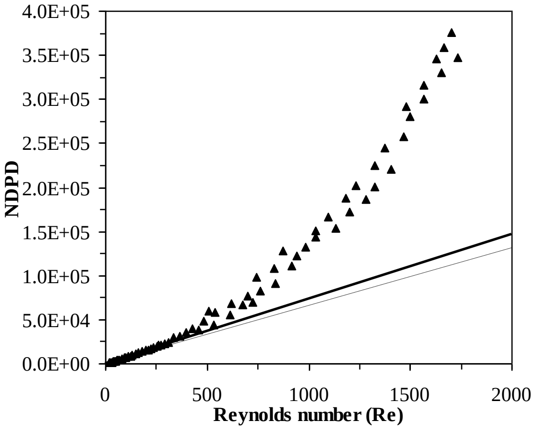

Fig 7. Plot of NDPD vs Re for mixture (53%E-47%M) flow in TS1
Legend: Filled Δ - Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

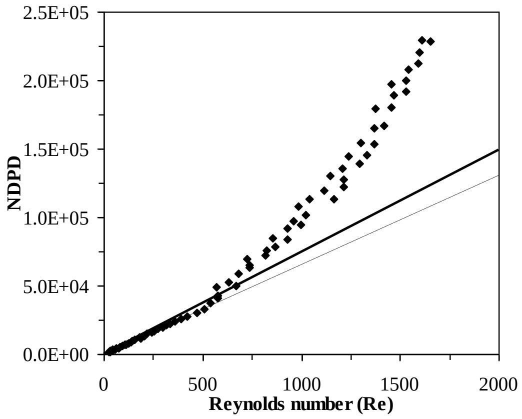

Fig 8. Plot of NDPD vs Re for (53%E-47%M) flow in TS2
Legend: Filled ◊- Experimental, Solid line- C_{theo}, Dashed line- C_1 (exp)

4.4.2 Transition Reynolds number (Re_{Tr}) in liquid flow

The transitions in mixture flow are identified in the f vs Re or NDPD vs Re plots. The mixture flow data also show the transition point(s) clearly. Flow of mixture shows one transition Reynolds number: ~500. The derived or identified transition point is marked in Figs. 5 and 6 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 behaviour in channels.

VII. Conclusions

The main results derived from the experimental investigation of in micro-channels using a mixture of 50%E-50%M by volume (ie; 0.53E-0.47M by mole fraction) are detailed below.

Pressure drops were measured and friction factors were calculated for mixture flow in both micro-channels (TS1, TS2). The surface roughness of each channel was measured over large areas using a surface profilometer (Rank Taylor Hobson). Pressure drops were evaluated using entrance and exit of channels. Confidence intervals were determined for each of the measurements made during the experiments and the propagation of uncertainties to the derived results was determined. Uncertainties in the measured friction factor make it impossible to conclude with confidence that either channel geometry or channel roughness are played important factors in determining the friction factors for laminar flow in micro-channels. Further the Reynolds number alone is inadequate to explain the flow behavior in micro-channels. Reynolds number relation indicates that friction factor for mixture 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.

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