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Experimental Investigation of Low Flow Rate, Low Pressure Drop and Heat Transfer in Micro-Channel

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ABSTRACT

The objective of the current experimental program is to generate data for liquid flow through micro-channels. The channel dimensions are 0.9 mm deep x 0.5 mm width. Rectangular seven micro-channels each of 70 mm long were cut on a stainless steel substrate (100 mm x 100 mm x 10 mm) by Electro Discharge Machining (EDM) technique. Covering the top with another plate formed the channels. The liquids used were ethanol and methanol as flow media. Pressure drop and flow rate data were measured and used as raw data to evaluate friction factors in the micro-channels. Transitions occur at lower Reynolds number (Re ~1200) than that in normal channels. Transition region lies in the range 1200 < Re < 2500. Transition was identified as the discontinuity in friction factor-Reynolds number data. Analysis of friction factor *vs* Reynolds number relation indicates those friction factors is same in the laminar region and lower than that in the turbulent region of normal channels. Temperature data were used to evaluate Nusselt number only with methanol flow. In the absence of enough data, that generalised conclusion is not stated about the dependency of channel dimension and flow media on friction factor and Nusselt number.

Keywords: *experiments, laminar, turbulent, friction factor, Nusselt number and micro-channels*

NOMENCLATURE

C	empirical constant {no units}
c_p	specific heat, J/kg-K
d	diameter, m
f	friction factor, {no units}
H	height of the channel, m
h	heat transfer coefficient, W/m^2-K
k	thermal conductivity, W/m-K
l	length of the channel, m
m	mass flow rate, kg/s
Nu	Nusselt number, {no units}
P	pressure drop, Pa
Pr	Prandtl number, {no units}
Q	heat transfer rate, W
q"	heat flux, W/m^2
Re	Reynolds number, {no units}
T	temperature, °C
v	velocity, m/s
W	width of the channel, m
z	no of channels

Greek Letters

Δ	difference
μ	viscosity, Pa s
ρ	density, kg/m^3

Subscripts

eq	equivalent
fi	fluid inlet
fo	fluid outlet
fm	fluid mean
wm	wall mean

1. INTRODUCTION

Fluid flow through micro-scale flow geometries is encountered in numerous engineering systems such as cooling of electronic devices and compact heat exchangers. Micro-channel flows have been used for liquid dosing and flow measurement [1]. The literature sources are more recent to the extent that micro-scale flow passages are concerned. Tuckermann & Pease [2, 3] were, perhaps, the first to conduct a systematic research into micro-scale flow and heat transfer. Several investigations ensued which dealt with flow of gases [4,5] and liquids [6,7,8,9] through micro-geometries. Issues pertaining to micro-channel heat exchangers were dealt with by [10,11,12]. Theoretical approaches to fluid flow and heat transfer were also reported [13,14]. Water, methanol and n-propanol were used as liquid media and nitrogen, helium, argon and hydrogen as gaseous media for experiments. The test section geometries varied from a fraction of a µm to a few 100s of *µm.* There had been only one study with mixtures of fluids [15]. The substrates used were silicon, glass, copper and stainless steel. These studies provide substantial evidence to prove that flow and heat transfer in micro-channels need to be addressed differently compared to conventional channels. It appears that, firstly, the transition from laminar to turbulent flow takes place at a low Reynolds number and secondly, friction factor and heat transfer cannot be described by the empirical relations used for normal geometries. There is a need for more experimental data on a variety of fluids and flow geometries so that some generalized conclusions can be evolved.

2. FABRICATION OF MICRO-CHANNEL

Micro-components are mostly fabricated using etching, deposition and photo-lithographic techniques. There are numerous techniques available and also being innovated to meet the requirements of specific formations on various substrates. Non-circular geometries are often adopted because of their relative simplicity in fabrication as compared to circular channels. The conventional techniques, which have been administered for the fabrication of heat sinks and heat exchangers, include a) precision sawing or cutting and b) micro machining. The latter is an offshoot of bulk and surface chemical machining processes widely used in microelectronics industry. Other techniques for producing micro-channels include [16]: i) spark erosion or EDM ii) laser machining iii) stereo lithography and iv) LIGA (Lithography, Galvanoformung, Abformung) electroforming, a process developed initially in Germany [17]. It was reported that with a precision EDM dimensional tolerances up to 0.5 µm could be obtained. In the present case, a channel of 0.9 mm deep and 0.5 mm width was cut by using EDM on a 100 mm x 100 mm x 10 mm stainless steel plate. Figure 1 shows the micro-channel dimensions typical (29 channels). The surface roughness measurement of test section was done to check the uniformity of the channel. The flow passage is formed by the machined plate and another stainless steel plate of thickness 10 mm on top. The inlet and outlet conduits were attached and brazed together with the two plates.

3. EXPERIMENTS IN MICRO-CHANNEL

Normally as a consequence, it is expected from experiments on micro-channels are, the prediction of (i) the zone of transition between the laminar and turbulent regimes (ii) the magnitude of friction factor and (iii) the magnitude of heat transfer rate. The objective of the current experimental program is to generate data on the friction and heat transfer characteristics in rectangular micro-channels.

The schematic experimental setup is shown in figure 2. It consists of liquid reservoir/sump (capacity ~ 10 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 (~ 100 micron) built-in in the main line to avoid any dirt that may enter into the test section. In the absence of micro-filter poor measurement data could be resulted due blockage of the channels to the flowing fluid. It 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, measured with the aid of U-tube differential mercury manometer.

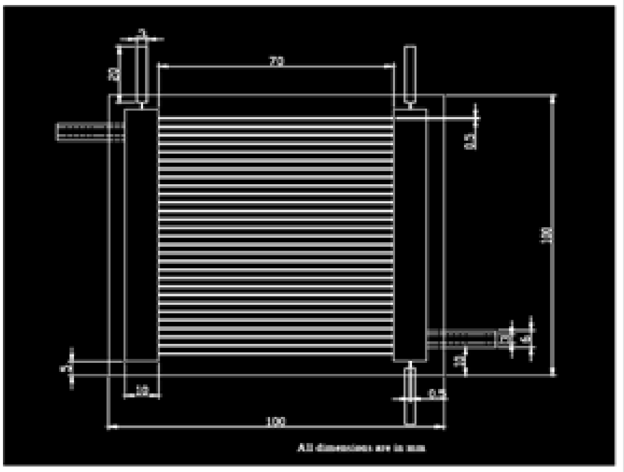

Figure 1. Typical micro-channel test section

The flow medium used to test was filled in the reservoir. To start the experiment all the required precautions were taken into consideration. The pump is switched on while keeping the by-pass valve in open position and control valves to test section closed. The required discharge flow rate of the pump is obtained through stroke adjustment in the pump system. Control valve was somewhat opened allowing the flow to take place in the test section. Further, the control valve was tuned to set the required pressure drop indicated by the U-tube manometer. Corresponding to a pressure drop, flow rate through the test section was measured by collecting either known volume of liquid or a known period of time. Several trials were carried out and the average value is taken to evaluate flow rate in terms of cc/min basis. The average value of flow rate was taken from several run to reduce the measurement uncertainty. However, it may be noted that flow rate was based on manual measurement, as the flow meter put in the setup does not have instrument (display unit). The manometer system accuracy is about ±0.25 mm. The experiment was repeated for various values of pressure drops (range ~ 1 to 250 mm of Hg). The time intervals for flow rate measurement are carried out depending on the flow rate. Experiments were conducted at room temperature (~ 30°C). Figure 3 shows plot of pressure drop *vs* flow rate data.

In case of heat transfer experiments, fluid and wall temperatures are measured using thermocouples located at appropriate places in the test section (see Fig. 2) in addition to the above flow rate and pressure drop data. Electrical foil heaters mounted on either side heated equally the test section. This entire assembly of the test section is insulated on all sides to minimize heat loss to the surroundings. The wall temperatures were measured at locations 10 mm 35 mm and 60 mm from inlet of the channel.

Legend: 1-Sump 2-Pump 3-By-pass control valve 4-Micro-filter 5-Flow control valve 6-Test section 7-Differential pressure gage 8-Flow meter 9-Return line to sump. T_w- Thermocouple location on wall and $T_{fi/o}$-Thermocouple location for fluid inlet/outlet.

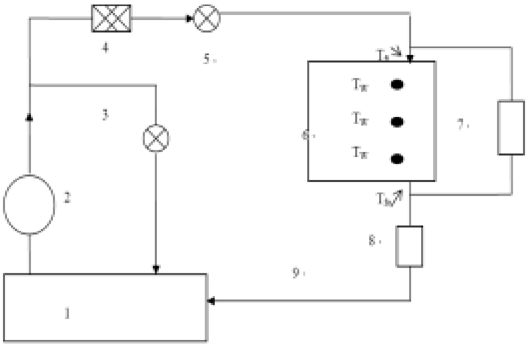

Figure 2. Schematic experimental setup fluid flow and heat transfer.

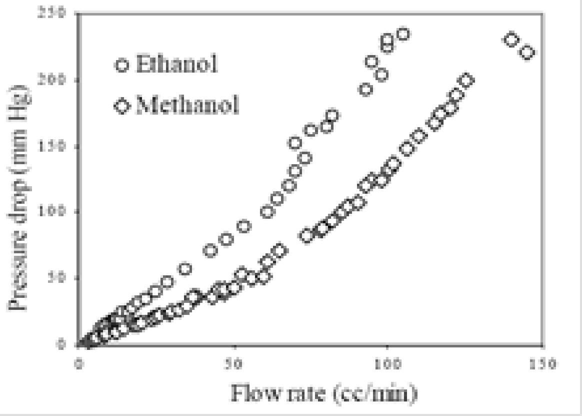

Figure 3. Plot of pressure drop *vs* flow rate data

4. FLUID FLOW DATA REDUCTION

The primary objective of this flow experiment is to obtain the friction factor *versus* Reynolds number relation. The friction factor T is deduced from the raw data using Darcy-Weisbach formula [18] given below:

$$\frac{\Delta p}{\rho} = f \left(\frac{l}{d}\right) \frac{v^2}{2} \qquad (1)$$

where, Δp is the pressure drop, ρ is the density, f is the friction factor, l / *d* is length to diameter ratio and v is the velocity. The Reynolds number is defined in the conventional way Re = *ρvd/μ.* The velocity v (average) is calculated from flow rate based on the cross-sectional area of the channel. For non-circular ducts, diameter d is replaced by equivalent diameter defined as, d_{eq}= 2 WH/(W+H) where W and H are width and height of the channel respectively. The thermophysical properties [19] were evaluated at inlet temperature of the test fluid neglecting the viscous heating effect in the channel.

4.1 RESULTS AND DISCUSSION

The friction factor data obtained from the present experiments for the test section is shown in figure 4, as plot of friction factor *vs* Reynolds number (f-Re). Normally, the flow experiment results give an initiative to identify flow regimes (laminar, turbulent and zone of transition). Further, friction factor dependence on Reynolds number could be established. The experimental values are compared with conventional theory and earlier correlations. The thick solid line characterizes the 'f' theoretical value in laminar regime.

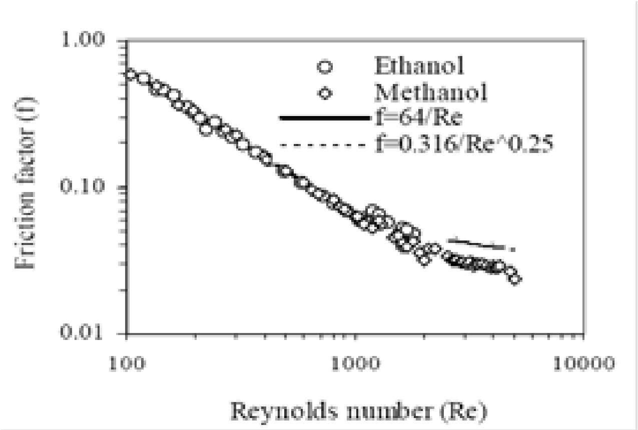

Figure 4: Plot of friction factor *vs* Reynolds number.

(i.e.; f = 64/Re) and dashed line stands for smooth pipe turbulent regime by Blasius relation [18],

$$f = \frac{0.316}{Re^{0.25}} \qquad (2)$$

It is customary in pipe flow; the laminar flow regime is identified as friction factor T varies inversely to Reynolds number (typically as f = 64/Re for tubes). The laminar flow is continued up to Re ~1200. The transition is identified as discontinuity in f vs Re relation (see fig. 4). At Reynolds number greater than these critical values the fluctuation in friction factor cannot be observed and this region is identified as turbulent (i.e; Re>2500). The upper and lower bounds of transition are not identical with flow of ethanol and methanol in the test section in view of the limitation constrained by the differential pressure gauge (maximum 250 mm Hg) used. Consequently, the experimental data for the laminar region fitted in the friction factor relation of the form f = C/Re, yielded the constant C values 64.8 and 63.5 respectively for ethanol and methanol with regression coefficient (R2) of 0.98. The turbulent experimental data was fitted yielding a constant 0.276 instead of 0.316 in the form of equation (2) with regression coefficient (R2) of 0.90. In the turbulent case lower friction factor is observed as in figure 4. Therefore it appears that these micro-channels are preferred at low pumping power with high heat flux rate applications such as electronic cooling.

5. HEAT TRANSFERDATA REDUCTION

From the measured flow rate and temperatures various parameters are evaluated to obtain heat transfer rate and Nusselt number. The total heat transfer rate is obtained from energy balance of the fluid between inlet and outlet in the micro-channels as heat gained,

$$Q = mc_p (T_{fo} - T_{fi}) \tag{3}$$

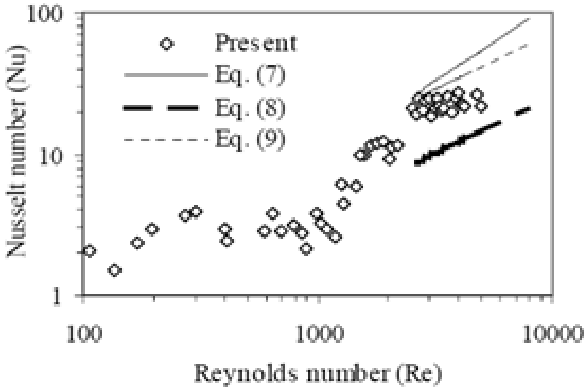

Figure 5. Plot of Nusselt number *vs* Reynolds number

The heat flux q" and heat transfer coefficient 'h' are calculated from the total heat transfer rate Q as

$$q'' = \frac{Q}{2L(W+H)} \tag{4}$$

$$h = \frac{q''}{(T_{wm} - T_{fm})} \tag{5}$$

The average Nusselt number is evaluated as,

$$Nu = \frac{hd_{eq}}{k} \tag{6}$$

5.1 Results and Discussion

The experimental average Nusselt number variation in the present experiment is depicted in figure 5 as a plot of Nusselt number vs Reynolds number. In general the data distribution is complex. However, for Re>2500 the experimental data is compared in the turbulent region with correlation available from literature [4, 6],

$$Nu = 0.00222\ Pr^{0.4}\ Re^{1.09} \tag{7}$$

$$Nu = 0.00805\ Re^{4/5}\ Pr^{1/3} \tag{8}$$

It is seen that the empirical relations given by equations (7) and (8) have not fit to the present data but be placed on either side. However, the conventional channel heat transfer correlation for fully developed turbulent flow,

$$Nu = 0.023\ Re^{4/5}\ Pr^{1/3} \tag{9}$$

Dittus-Boelter's equation is also compared in figure 5. In view of the less experimental data available, at present it is not possible to either evolve a correlation or any supposition on heat transfer in micro-channel.

6. CONCLUSIONS

Experimental investigation was carried in a test section with micro-channel dimensions 0.9 mm deep x 0.5 mm width having each 70 mm long seven parallel channels. From fluid flow results it appears that transition occurs at lower Reynolds numbers than that of conventional channels. Laminar data indicates that behaviour in micro-channel is as normally sized channels and while in turbulent region micro-channel behaves with less pressure drop than that of smooth conventional tube flow. Heat transfer data shows that there is an intricate and disparity in mechanism of heat transfer. In general it is concluded that there is a need for more experimental data on micro-channel flow and heat transfer.

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