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EXPERIMENTAL INVESTIGATIONS ON FLUID FLOW CHARACTERISTICS OF SINGLE PHASE LIQUID FLOW THROUGH CIRCULAR MICROCHANNELS

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ABSTRACT
Microchannels which are light in weight, smaller in size, handle low amount of coolants and provide higher surface area to volume ratio give higher heat transfer coefficients are efficient cooling devices for various modern electronic systems where higher heat fluxes are encountered**.** In this connection an experimental investigation has been carried out on the laminar flow and convective heat transfer of deionized water in circular microchannels. To explore the the validity of classical correlations of friction factor based on conventional sized channels for predicting the fluid behavior of single phase liquid flow of water through circular microchannels experiments were conducted with deionized water with Reynolds number ranging from 71 to 1495. The copper microchannels used in the experiment have the hydraulic diameter of 279 µm and 45 mm length. Pressure drop and flow rates were measured to analyze the flow characteristics. The results show good agreement between the classical correlations of friction factor and the experimentally measured data.

Keywords*:* Microchannels, Reynolds numbers; Friction factor

INTRODUCTION
Miniaturization of Microfluidic devices has led to development of high heat fluxes during operation of these devices. We are in the era of developing Micro and Nano devices leading tremendous increase in power density which arises significant thermal management problems. One of the solutions proposed is to enhance heat transfer by using microchannels. In a microchannel a fluid is used to carry away heat from the small hot surface by forcing it through passages having hydraulic diameters ranging from 10 µm to 200 µm [1]. As a microchannel has higher heat transfer surface area to fluid volume ratio, so it provides high heat transfer coefficient for convective heat transfer. However this small channel experiences a considerable pressure drop.

The pioneer work in the field of heat transfer using microchannel heat sink for electronic cooling was first time demonstrated by Tuckerman and Pease [2] by achieving high heat flux removal capacity of up to 800 W/cm2 with microchannels in single-phase and two-phase flows. They noted that as the hydraulic diameter of the channel decreases, the heat transfer coefficient increases. This landmark work paved the door for further research in the area of microchannel heat transfer. However it has been reported by various researchers that phenomena in microgeometry may differ from those in macroscopic counterparts and great differences still exist between the available measured data of Nusselt number and friction factor. One of the important factor for variations in reported data may be differences in channel roughness [3].The review conducted by Steinke and Kandlikar [4] on the results of single-phase liquid friction factors in microchannels concluded that conventional Stokes and Poiseuille flow theories could apply for single–phase liquid flow in microchannel flows. Mala and Li [5] conducted experiments on flow of water through microtubes with inner diameters from (50 µm to 254 µm) made of fused silica and stainless steel. For higher values of Reynolds number, they found a noticeable increase in friction factor, compared to the predictions based on conventional Poiseuille flow theory. They also observed the material dependence of flow behavior, for similar flow and hydraulic diameter; fused silica microtubes exhibited higher friction factor than stainless- steel microtubes. But for larger microtubes, as well as for lower Reynolds number flows , the experimental data were in agreement with the conventional theory. The most salient feature of their work was the attribution of these deviations of microscale flow characteristics to the effects of surface roughness of the microtubes. Choi et al. [6] conducted experiments in circular silica microtubes with inside diameters 3, 7, 10,53 and 81.2 μm having length 24 to 52 mm with nitrogen as working fluid for evaluating heat transfer and pressure drop characteristics.They observed that for both laminar and turbulent flows Nusselt number depends on Reynolds number in a different manner as compared to macroscale theory. Based on the measurements they found the critical Reynolds number 2000, which is concurrent with microtubes. Qu et al.[7] conducted experiments to investigate the flow behavior of water through trapezoidal silicon microchannels ($51\ \mu m \leq D \geq 169\ \mu m$) and apply the roughness viscocity model to explain the experimentally obtained higher values of friction factor. Pfund et al. [8] experimentally investigated the water flow characteristics through high-aspect-ratio smooth and rough rectangular microchannels ($128\ \mu m \leq D \geq 521\ \mu m$) for Reynolds number ranging 60 to 3450, and concluded that the laminar flow friction was considerably higher than the classical value for the rougher microchannels. Wu and Cheng [9] in their experimental study found that for channels having similar geometry, the friction factor obtained was higher for the channel having the greater surface roughness and it was in accordance with the majority of the works highlighting the effects of surface roughness on microflow characteristics.

Li et al.[10-11] in their experimental study for laminar flow of deionized water through glass, silicon and stainless steel microtubes ($79.9\ \mu m \leq D \geq 166.3\ \mu m$) and obtained the Poiseuille number relatively higher for rougher stainless steel microtubes than for smoother glass and silica microtubes. Further they found that for rough stainless steel microtubes ($373\ \mu m \leq D \geq 1570\ \mu m$) the friction factor was not only higher than the predicted by conventional theory but increased further as relative roughness increased. However experimental values of friction factor found in agreement with the values predicted by conventional theory for water flows through relatively smooth fused silica microtubes ($50\ \mu m \leq D \geq 100\ \mu m$). They also concluded that classical theory successfully addressed the frictional characteristics for flows in microtubes with relative surface roughness less than about 1.5 %. Most of the experimental studies conducted have reveled deviations in the values of friction factor from classical conventional theory the reasons asserted are by various researchers are experimental uncertainty, surface roughness.

From the review of literature it has been observed that there is a large scatter in the data measured for friction factor and reasons suggested by various studies are contradictory. Meanwhile recent papers have shown that conventional theory is applicable by careful evaluation of geometry or by considering other effects. In this present work an attempt is made to investigate friction factor experimentally and then comparing with theory.

EXPERIMENTAL SETUP

The Experimental setup used in this investigation for measurements of pressure and temperature difference at inlet and outlet of the test section is shown in Figure 1. A flow pump is used to drive the Deionized water from a water holding tank; the flow pump provides smooth and steady flow over a wide range of flow rates that corresponds to a Reynolds number ranging from 50 to 1500. In order to avoid blockage of the microchannels , a submicron filter of 0.1μm was installed between outlet of pump and inlet of test section . The test section was enveloped by the heated oil in the oil bath. Details of the microchannel test section are shown in Figure 2. The test section consists of total seventy nine stainless steel tubes having the inner diameter 279 and 45 mm long arrange in the circumferential manner. Three copper-constantan (T-Type) thermocouples were used to measure the temperatures at the inlet and outlet of the test section as well as of the oil of the oil bath and hand operated digital RS232 manometer (has a pressure range of 0 to 100 Psi with an accuracy of ±0.3% of its full scale at 25°C) was used to measure the differential pressure between the inlet and outlet of the test section as shown in Figure 2. HJ-123 heater of 500 W was placed in the oil bath to heat the oil and the connection of this heater through the blind temperature controller (BTC) which cut the electric supply of the heater when the temperature of the oil reaches the desired temperature. The first step in conducting the experiment was to fill the water tank with Deionized water and note down the initial as well as final reading of measuring scale of water tank before and after filling. This gives the

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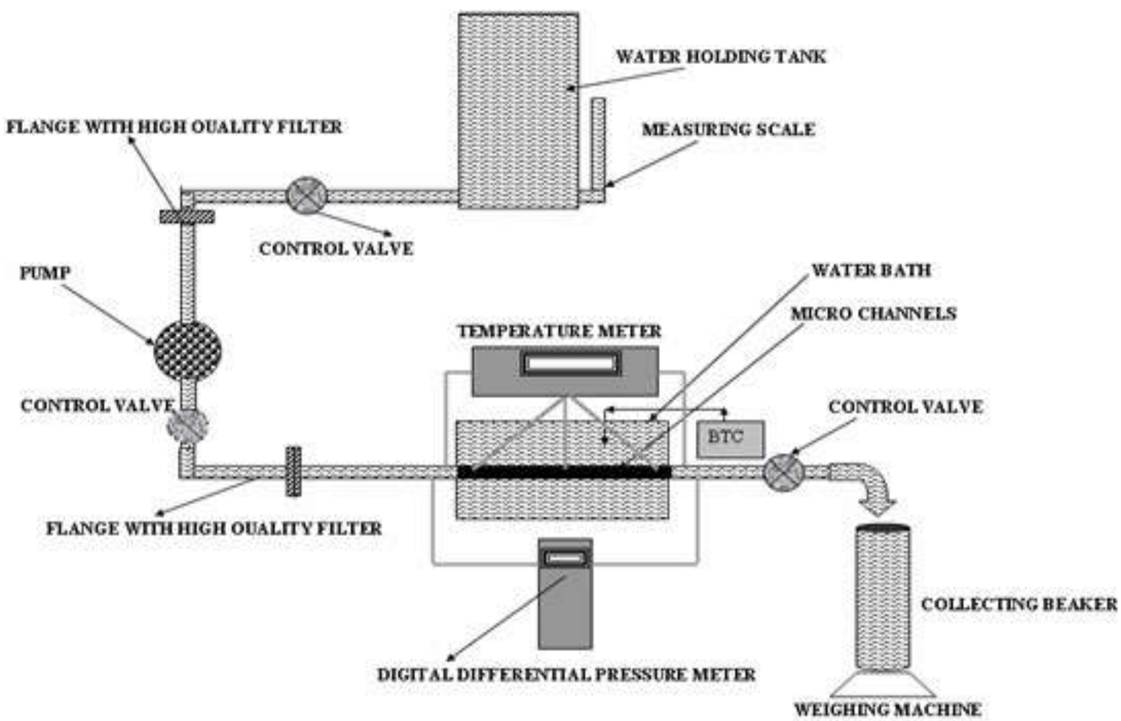
volume of water contained in the water tank. Once the water was filled, heater is turned on the heater and wait until the temperature of the oil reaches the desired temperature. Once the oil in the oil bath beaker attains this temperature, open the valve of water tank and motor is switched on. This allowed water to flow through the Microchannel Heat Exchanger. A set flow rate was established with the help of controlled valves by monitoring the digital manometer and setting the valve at a position where a predetermined pressure was measured on the digital manometer. After a steady state was reached, temperatures of water at inlet and outlet of the test section were recorded from the monitor of temperature indicator keeping in mind that the temperature of the oil in the oil bath remained constant with time during measurement. Once the temperature measurements were completed, water is collected in the volumetric beaker from the exit section for predetermined period of time and measured the flow rate. This procedure was repeated for several times for various differential pressure readings. The experiments cover the Reynolds numbers from 71 to 1495.

Figure: **1**



Schematic diagram of Experimental setup

In conventional channels, internal laminar flow and heat transfer the surface irregularities are considered negligible for laminar flow, and the Nusselt number for thermally fully developed flow is dependent on the cross sectional shape of the channel.

Data Reduction

In this Experimental study, Reynolds number is defined by

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$$\mathrm{Re} = \frac{\rho\, V\, D}{\mu} \tag{1}$$

Where ρ is density of the fluid flowing through microchannel and V is the mean velocity of the flowing fluid, μ is the viscosity of fluid and D is the hydraulic diameter defined by

$$D = \frac{4\,A}{P} \tag{2}$$

Where A is the area of cross section and P is the wetted perimeter of the microchannel.

The Experimental friction factor based on the pressure drop measurements in microchannel flow are represented by Darcy friction factor which is given as

$$fe = \frac{2\Delta p D}{\rho V\hat{}2L} \tag{3}$$

Where Δp is the pressure drop acroos the length of the microchannel, L is the length of the microchannel, D is the Hydraulic diameter of the channel, ρ is the density of fluid flowing through microchannel and V is the mean velocity of the flowing fluid. The experimental friction factor is compared with theoretical frction factor for fully developed laminar flow in circular pipes based on classical macroscale theory given as

$$f_{th} = 64/Re \tag{4}$$

In microchannel flow analysis, hydrodynamically developed flow is very important because of short length of microchannel [4]. Kays and Crawford [12] suggested a good approximation for development flow length as given by relation (x+ = x/ReD),and fully developed flow is assumed valid above the value of x+ =0.05 [12].

RESULTS AND DISCUSSIONS

In this experimental study the inlet and outlet plenums were incorporated to induce a uniform flow distribution in microchannels and total pressure drop between the inlet and outlet plenums is measured. The flow rate was varied from 54 mL/min to 1367 ml/min and steady-state laminar flow was assumed, the flow velocity in microchannels varied from 0.19 m/s for lowest Reynolds number 71 to 4.72 m/s for highest Reynolds number 1495 as sown in Fig.2. It can be seen from Fig.3 that the pressure drop is linearly proportional to Reynolds number for a given microchannel dimension and the fluid flow is laminar without any transient effects as predicted by classical theory of fluid dynamics. The values of friction factors obtained from experimental pressure drop data are shown in Fig. 4. Each curve shows that experimental values are very close and consistent with the values predicted by the theory of fully developed flow as shown in fig.5. Steinke and Kandlikar [4] compared their experimental results with previous researchers data and suggested that the entrance effects caused by developing flows was very important and should be taken into consideration in microchannel flow. Our experimental results show the flow in michrochannels to be fully-developed as all of the x+ values (0.11-2.26) obtained are bigger than 0.05[12] and our experimental results are in good agreement with classical theory. Further the values of fexp /fth obtained by assuming fully-developed flow were between 0.79 and 1.23 except one value of 1.4 having (average 1.03) which shows that the flow in microchannels can be well predicted by applying conventional friction factor theory and the flow inside the microchannels is fully-developed.

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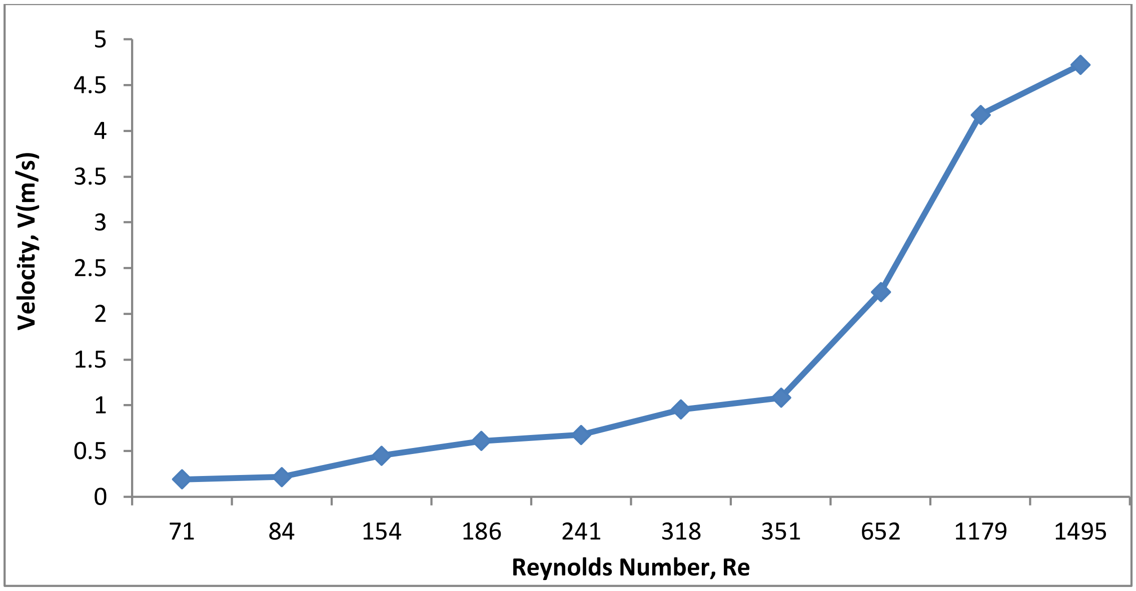
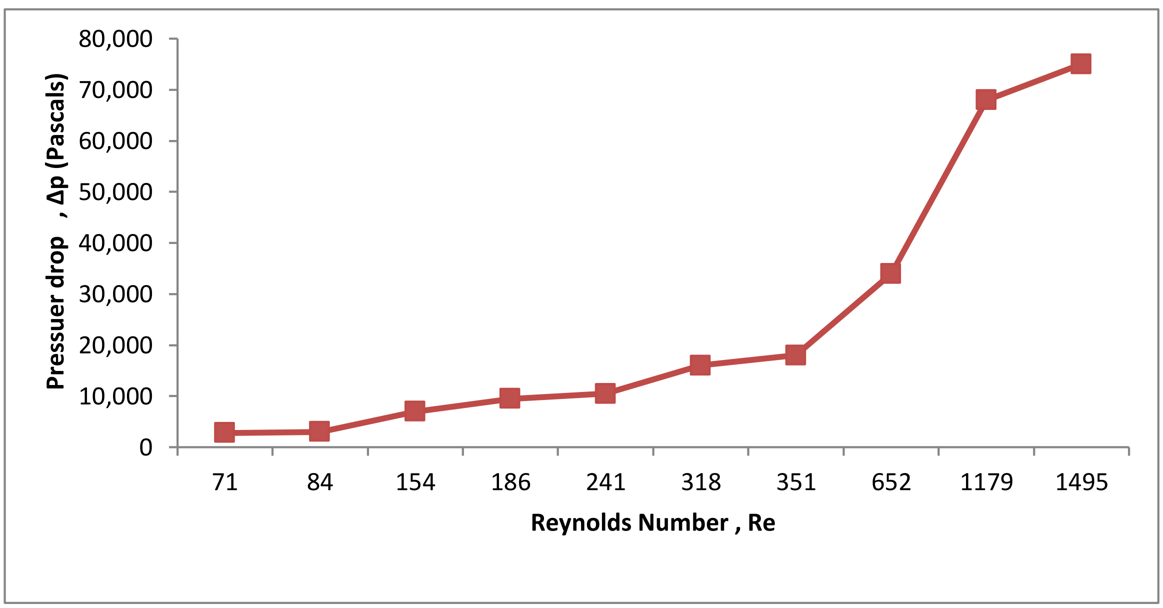
Figure: 2



Fluid velocity variation with Reynolds number

Figure: 3



Total pressure drop variation with Reynolds number

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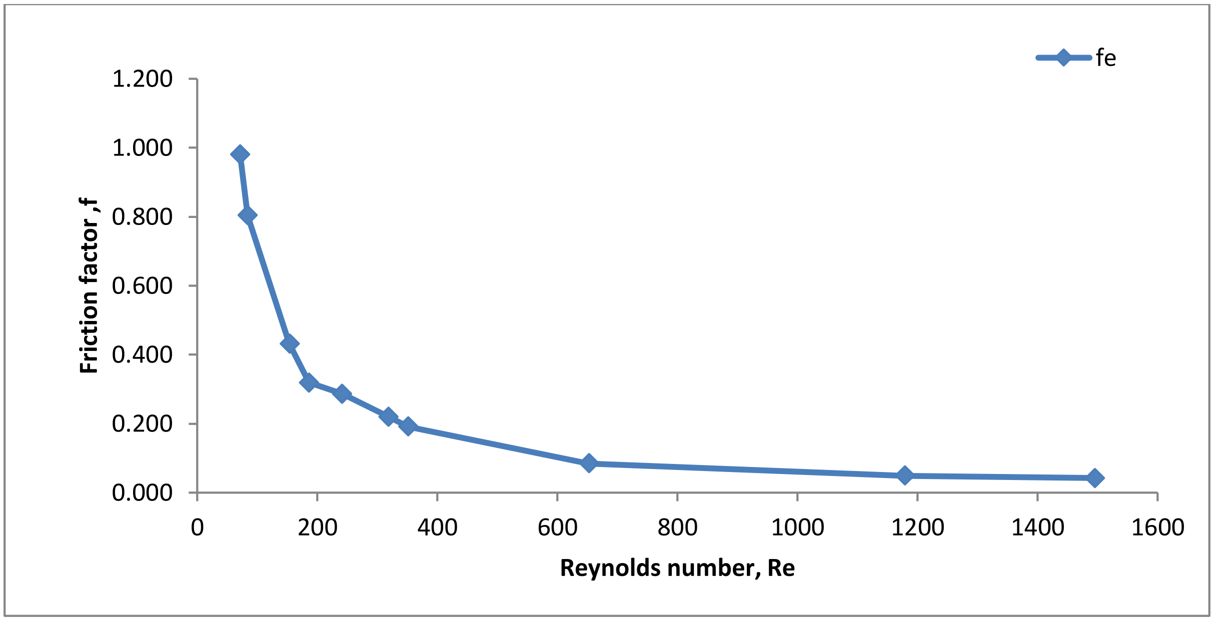
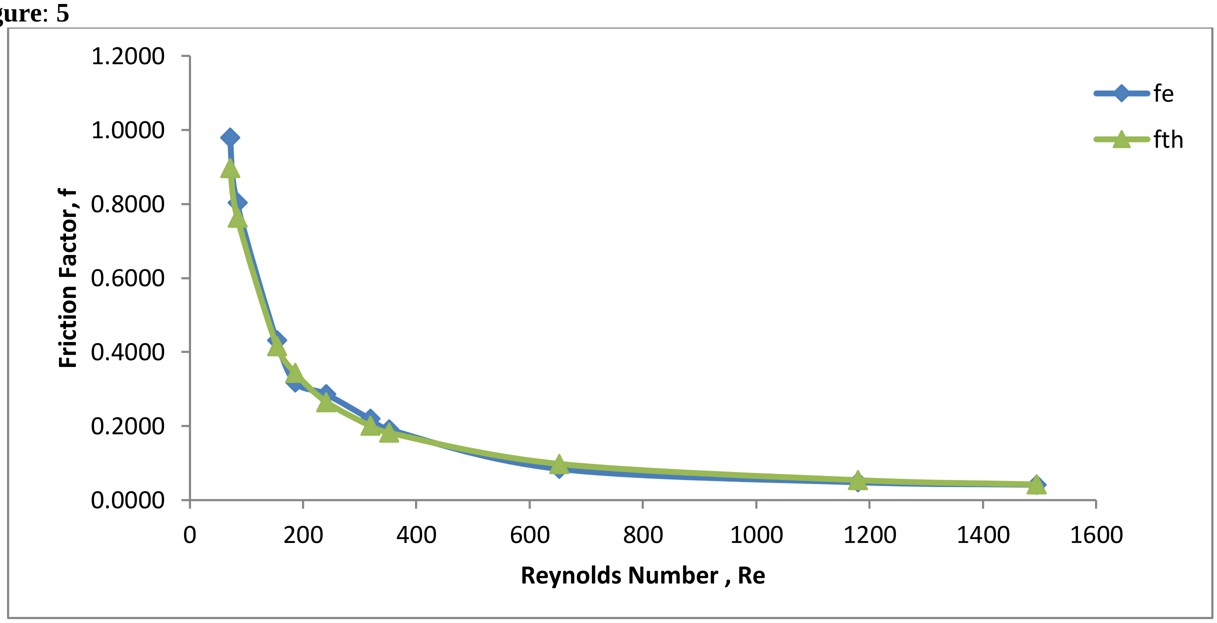
Figure: 4



Friction factor variation with Reynolds number

Figure: 5



Friction factor (Experimental & Theoretical) variation with Reynolds number

CONCLUSIONS

Experimental investigations have been carried out for friction factors in single phase liquid flow inside circular microchannels. The experimental results obtained showed good agreement with conventional hydraulic theory and also suggested that the flow inside the microchannels was fully developed laminar flow in the range of experiments

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conducted (71 < Re > 1493) inside the circular microchannels having hydraulic diameter of 279 µm and 45 mm length. The flow in microchannels can be well predicted by applying conventional friction factor theory and the flow inside the microchannels is fully-developed.

NOMENCLATURE

Re	Reynolds Number	Δp	Experimental pressure drop
Nu	Nusselt Number	L	Length of microchannel
D	Microchannel hydraulic diameter	x^+	Hydraulic entance length
MEMS	Micro-Electro Mechanical Systems	ρ	Density of fluid
f	Friction factor	µ	Viscosity of fluid
V	Mean flow velocity	f_{th}	Theoretical Friction factor
A	Microchannel cross section area	fe	Experimental friction factor

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