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Full Length Research paper

Analysis on friction factor and temperature profiles of liquid stream in circular microchannels

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Heat dissipation in electronic components becomes an important issue in efficiency promotion and stable operation. Microchannel heat exchanger plays the major role for heat dissipation from such high heat generating electronic components. In this connection an experimental investigation was conducted to explore the validity of classical correlations of friction factor based on conventional sized channels for predicting the fluid behavior in single-phase water flow through circular microchannels. The microchannels under investigation have the hydraulic diameter of 279 µm and 45 mm long. Test piece was made of stainless steel and the test section contained a total of seventy nine microchannels arranged in circumferential manner. The experiments were conducted with deionized water of Reynolds number ranging from approximately 300 to 3000. 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. The temperature profiles along as well as across the channels shows that channel length and channel diameter play the major role on its behavior.

Key words: Microchannels, friction factor, temperature profiles.

INTRODUCTION

The development of micro heat exchanger becomes an important area of interest in many fields of developing technology that requires compact high heat energy removal such as micro miniature refrigerators, micro heat pipe spreader, microelectronics, biomedical, fuel processing and aerospace etc. It is necessary to study not only the theoretical aspects but also experimental investigation of fluid flow and heat transfer in micro channel heat sink. In the beginning of the 1980s, Tuckerman and Pease (1981) conducted initial experiments on water flow and heat transfer characteristics in microchannel heat sinks that demonstrate the cooling of electronic components by the use of forced convective flow of fluid through microchannels. This opened a wide area in the field of electronics cooling and heat transfer in microscale geometries. The first study concerning circular microtube configurations was reported by Choi et al. (1991). They conducted experiments for evaluating the heat transfer and pressure drop characteristic of circular silica microtubes with inside diameters 3, 7, 10, 53 and 81.2 µm, and length 24 to 52 mm using nitrogen gas as a working fluid. They found that the Nusselt number in both laminar and turbulent flow depends on Reynolds Number in a different manner compared to macroscale theory. Based on their measurements the critical Reynolds number equals to 2000, which is concurrent with microtubes.

Yu et al. (1995) conducted experiments with liquid water flowing in circular tubes having inner diameters 19.2, 52.1 and 102 µm, measuring the heat transfer coefficient. They found that the heat transfer data at low Reynolds number agreed with those for microtubes, and diverged as Reynolds number increased. Adams et al. (1998,1999) investigated the heat transfer coefficient of turbulent water flowing in circular channels with inner diameters 0.76 and 1.09 mm, and found that the Nusselt number for these channels were higher than those for

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microchannels. Mala and Li (1999) experimentally tested water flow through microtubes with inner diameter from 50 to 254 µm. Their results show that the deviation from the macro scale theory increases as the Reynolds number increases, and diameter decreases. They also concluded that there is an earlier transition from laminar to turbulent flow in microchannels. Celata et al. (2000) experimentally investigated liquid R114 flowing through six parallel tubes with inner diameter 30 µm and the length 90 mm. The transition from laminar to turbulent flow was reported in the range $1881<Re<2479$, and they found a large discrepancy between the experimental heat transfer coefficient in microchannels and those predicted by classical correlations, particularly at high Reynolds numbers. Experimental analysis of the flow and heat transfer characteristics of water flowing through the microchannel made of stainless steel was done by Peng et al. (1994) and their fluid flow results were found to deviate from the values of classical correlation and the transition was observed to occur at the Reynolds number in the range of 200 to 700. These results were contradicted by Xu et al. (2000). Chein and Chuang (2007) experimentally studied the performance of microchannel heat sink using nanofluids. They found that nanofluid cooled microchannel heat sink could absorb more energy than water-cooled microchannel heat sink when the flow rate is low. For high flow rates, the heat transfer was dominated by the volume flow rate and nanoparticles did not contribute to the extra heat absorption. Their measured microchannel heat sink wall temperature variations agreed with the theoretical prediction for low flow rate.

For high flow rate, the measured microchannel heat sink wall temperatures did not completely agree with the theoretical prediction due to the particle agglomeration and deposition. It was concluded that the literature is inconclusive concerning prediction about heat transfer and fluid flow in microchannels. Therefore carefully designed experiments are necessary before final conclusions can be drawn. The objective of this work is to investigate experimentally the characteristics of water flow and heat transfer in microchannels and attempt to explain the obtained results.

EXPERIMENTAL SETUP AND PROCEDURES

A schematic diagram of 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. Deionized water from a holding tank is driven through the flow pump, which provided smooth and steady flow over a wide range of flow rates that corresponds to a Reynolds number ranging from 300 to 3000. The fluid then passes through a 0.1 µm filter before entering the microchannel 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 (Type-T) 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 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 attends this temperature, open the valve of water tank and motor is switch 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 304 to 2997.

RESULTS AND DISCUSSION

Friction factor

Yang et al. (2003) measured the friction factors of water flow in tubes with diameter ranging from 0.5 to 4.0 mm. They found that there is no significant discrepancy for water flow in these tubes in comparison with large tubes. Phillips (2008) studied the fluid flow and heat transfer characteristic in rectangular microchannels having the hydraulic diameter 234 µm using water as the working fluid. Their results agree well with the conventional correlations in the laminar region. The present study measured experimentally the friction factors of Deionized water flows in microchannels having the hydraulic diameter 279 µm and 45 mm long shown in Figure 3. The results of experimental data are plotted and shown in Figure 3. It was found that the experimental data agree very well with the developing laminar flow equation and Churchill Equation (13) in laminar and turbulent flow regime, respectively.

Developing laminar flow equation:

$$f_{lam,\,dev} = \frac{16}{\mathrm{RE}} + \frac{1.28 D_2 \mathrm{RE}}{4L} x 10^{-9}$$

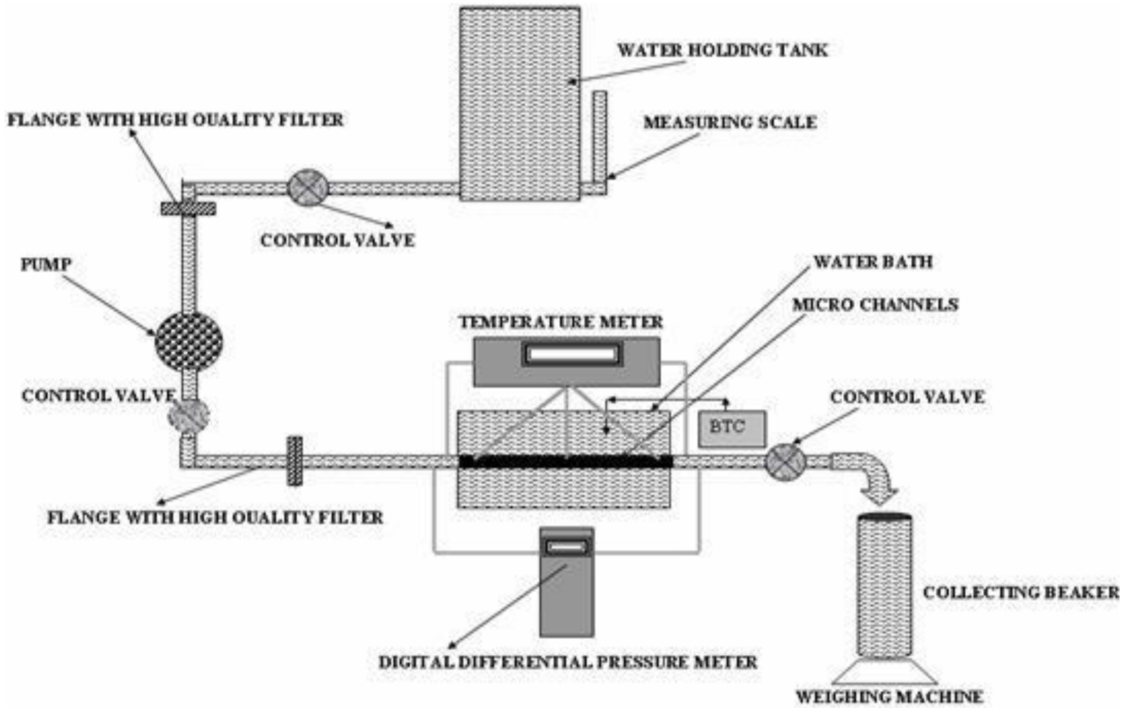

Figure 1. Schematic of the experimental system.

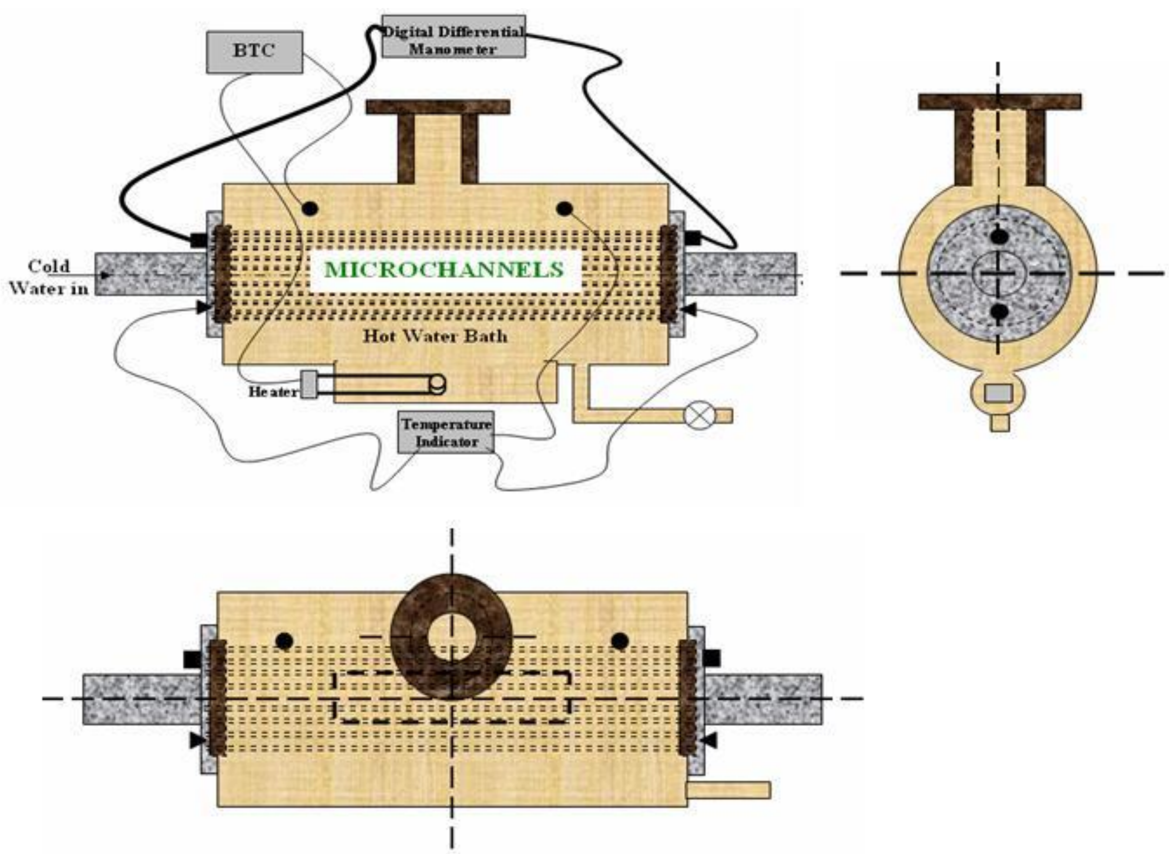

Figure 2. Detail of heat exchanger system.

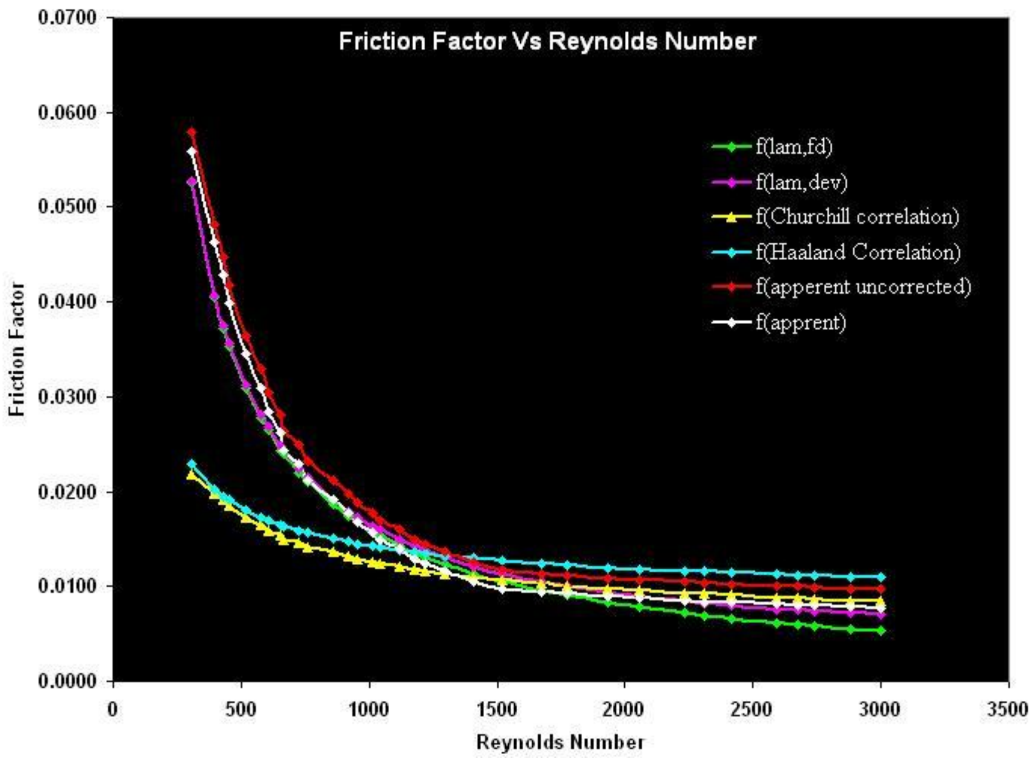

Figure 3. Comparative plots of friction factor with the experimental results.

Churchill equation:

$$f_{ch} = 8\left[\frac{1}{\left[\left(\frac{8}{Re}\right)^{10} + \left(\frac{Re}{36500}\right)^{20}\right]^{1/2}} + \left(2.21 \ln \frac{Re}{7}\right)^{10}\right]^{-1/5}$$

Figure 3 shows that for Reynolds number greater than 2000, the experimental data follow the Churchill equation more exactly and in the range of 500<Re<1000, the experimental friction factor is close to developing laminar flow equation. This indicates that the in range 1000<Re<2000 flow is in the transition region. This early transition from laminar to turbulent seen in the microchannels tested here is due to the reason of inlet condition at the entrance and hydrodynamic entrance length. Figure 3 also shows the comparison of theoretical friction factor with the experimental friction factor. The plots show that there is no single equation that agrees well with the experimental as well as theoretical data over the entire range of Reynolds number under study. Using curve fitting method the best equation that describes the whole range of experimental data is $f = 2.336\ Re^{-0.6886}$ and Figure 4 shows the comparison of proposed equation for friction factor with the experimental results.

The results show that the proposed equation of friction factor gives very close results with the experimental data. Therefore this equation help to predict the friction factor with the variation of Reynolds number ranging of this study without performing the experiment.

Temperature profiles

Experiments were conducted for single-phase water flow on the same experimental setup in order to find out the characteristics of temperature profiles in microchannels. The thermocouples inserted at the inlet and exit section of the test piece gives the inlet and exit temperature of water at different flow rates. The total heat applied to the working fluid to all the channels is given by

$$q_{tot} = \dot{m}\, c_p \left(T_{out} - T_{in}\right)$$

where the mass flow rate, $\dot{m}$, was measured from the volume of water collected from the outlet of the channels over a specified period of time. The mass flow rate in term of measured quantities of experiment is reduce as $\rho\ c\ avg$. It is noted that the boundary condition of the experiment was that of a constant surface temperature for the walls of the microchannels. Under this assumption, the temperature profiles are plotted w.r.t. Reynolds number as shown in Figure 5. Figure 5 shows that in the low Reynolds number range exit temperature as well as difference of exit to inlet temperature decreases more rapidly than in the high Reynolds temperature range and this might be due to that in low Reynolds number range fluid in the microchannels get more time for gaining more heat as compared to in high Reynolds temperature range. Figure 5 also indicates that all the temperature profiles are more

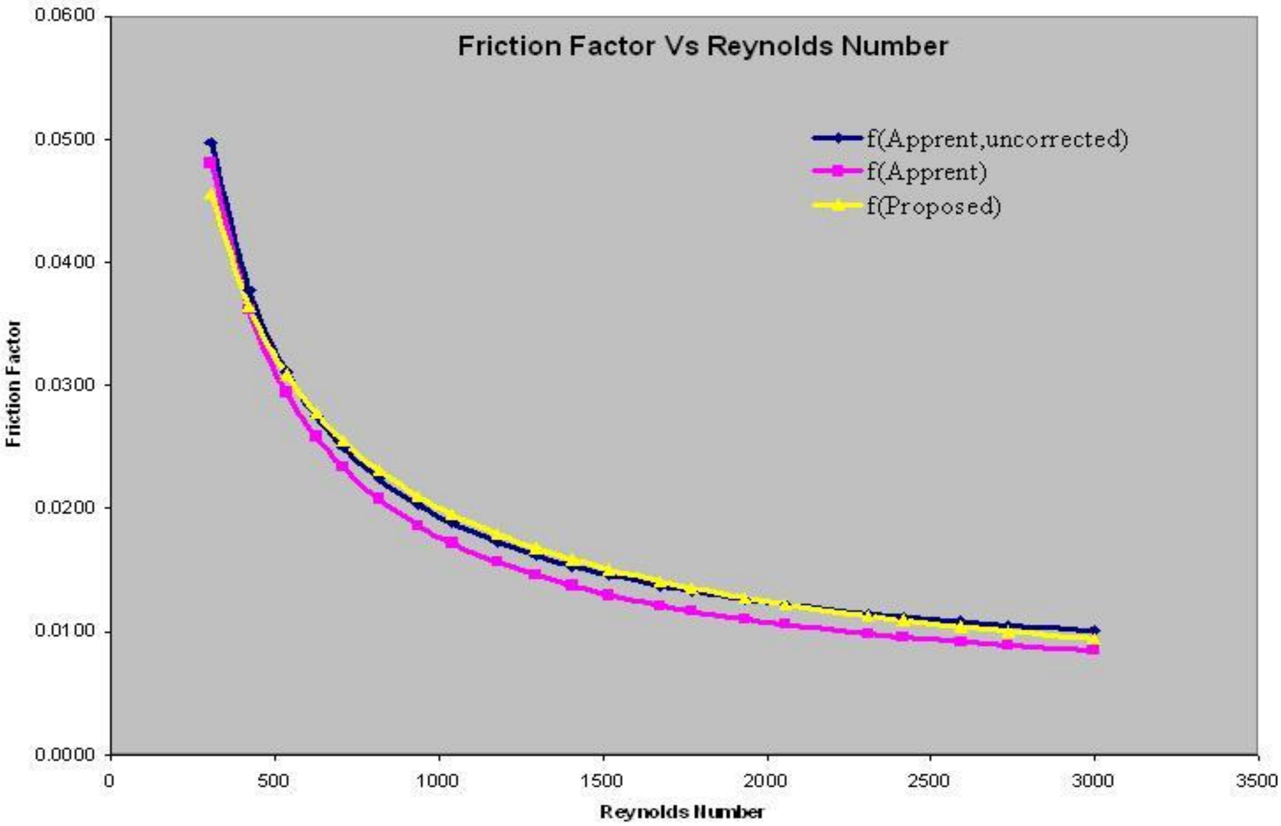

Figure 4. Comparative plots of experimental friction factor with proposed equation.

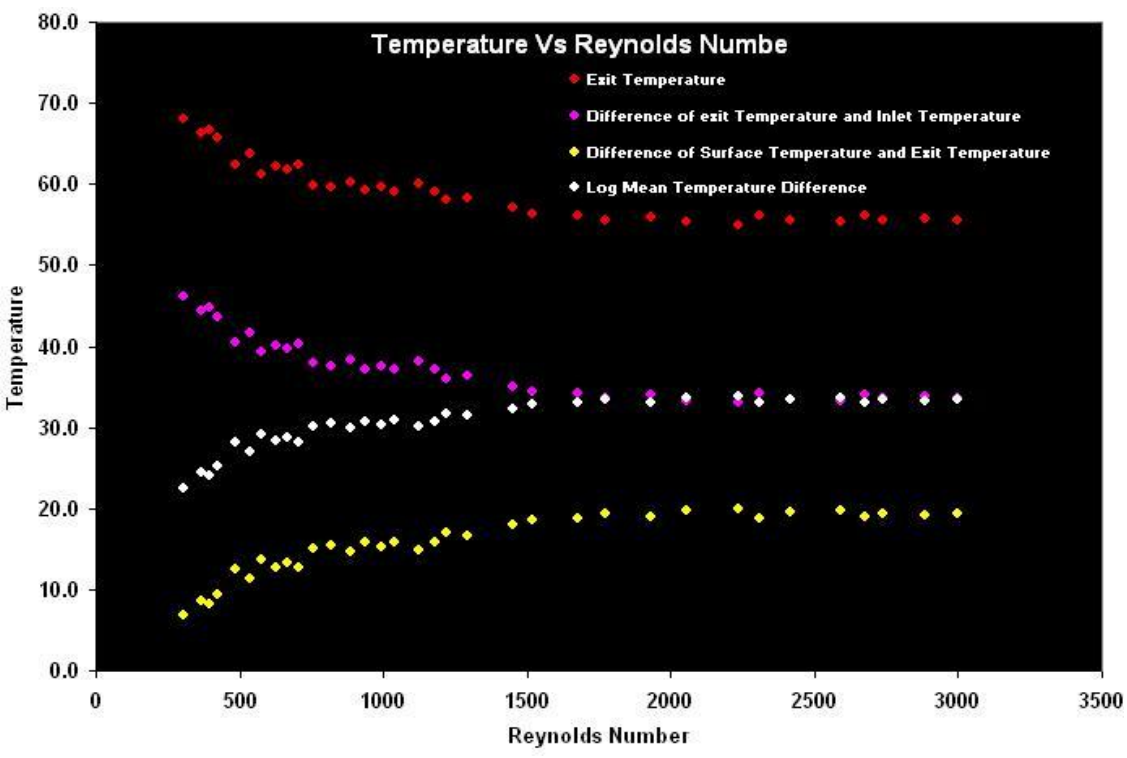

Figure 5. Temperature profiles of w.r.t. Reynolds number.

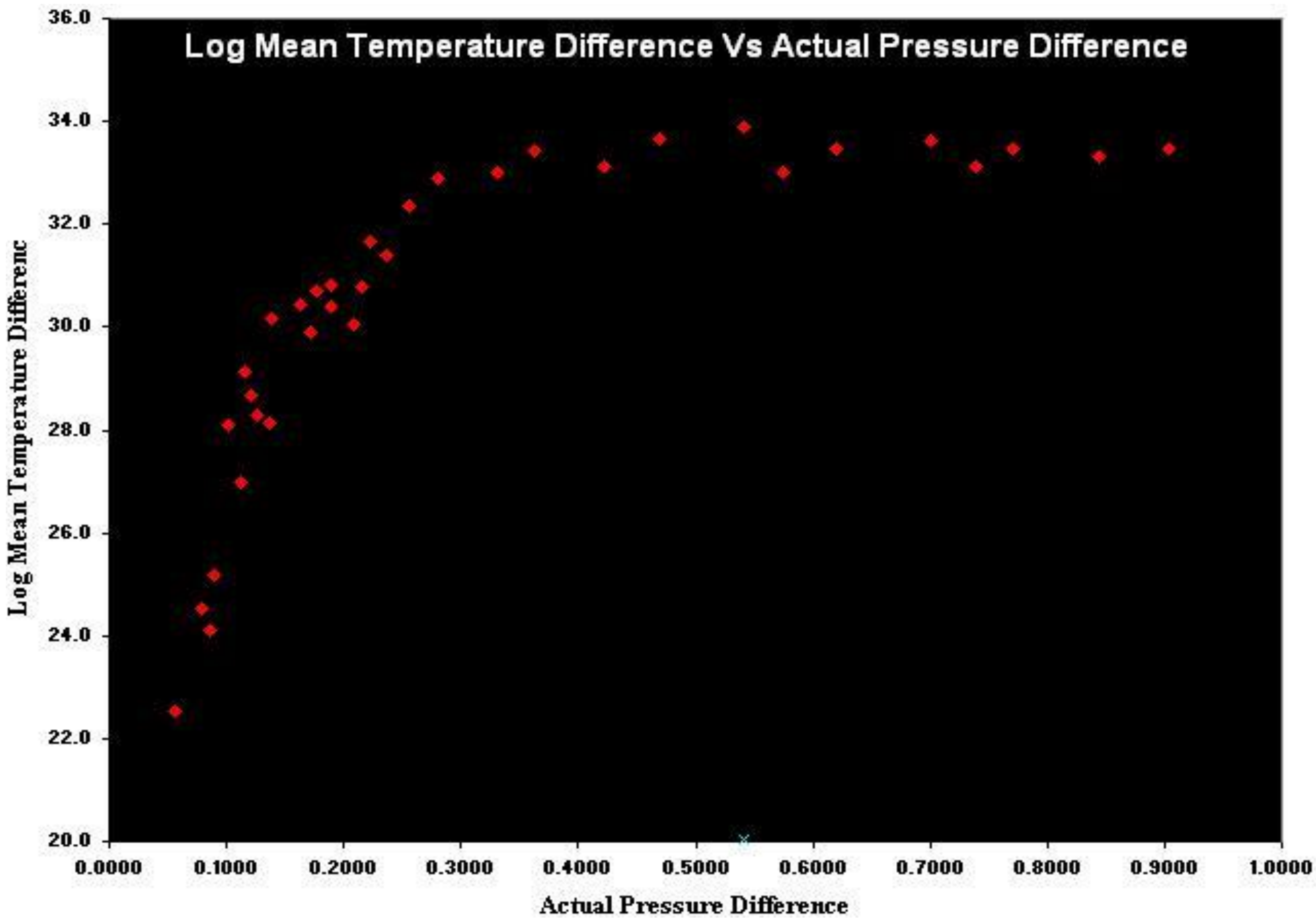

Figure 6. Temperature profile of "log mean temperature difference" w.r.t. Reynolds number.

or less constant with increase of Reynolds number for Reynolds number greater that 2000, this also indicates that for high Reynolds number range the heat gain by the working fluid is constant.

Figure 6 is the plot between log mean temperature difference (LMTD) Vs pressure difference at the inlet and exit section of the test piece. This figure indicates that as the pressure difference across the channels increases "log mean temperature difference" also increases but it achieves it constant value after the particular value of pressure difference. Again the vertical rise of "log mean temperature difference" at low values of pressure difference is due to more heat gain by the working fluid. Figures 5 and 6 represents the temperature profiles with respect to the Reynolds number and pressure difference respectively here it is not clear what sort of profile of working fluid along as well as across the channel for a particular Reynolds number. So in order to find out the temperature profiles along as well as across the channels curves are plotted as shown in Figures 7 and 8. Figure 7 is the plot of temperature profile of the working fluid along the channel length for various Reynolds number without varying the channel diameter. Figure 7 indicates that for the particular channel length the temperature of the working fluid increases with decrease of Reynolds number and this results match with Figure 5. Also for the particular Reynolds number the temperature of the working fluid increases with increase of channel length but the rate of this increase of temperature decreases with the channel length that is in the last portion of the channel the temperature of working fluid is more or less constant. Figure 8 is the plot between the temperature profiles of the working fluid across the channel that is these plots shows the temperature variation of the working fluid in the radial direction. Figure 8 also indicates the same results as in case of Figures 7 and 5 that is the temperature of the working fluid increases with decrease of Reynolds number.

It is also clear from this figure that for a particular value of Reynolds number, the major portion of the temperature of the working fluid is constant in radial direction except that part, which is very close to the channel walls.

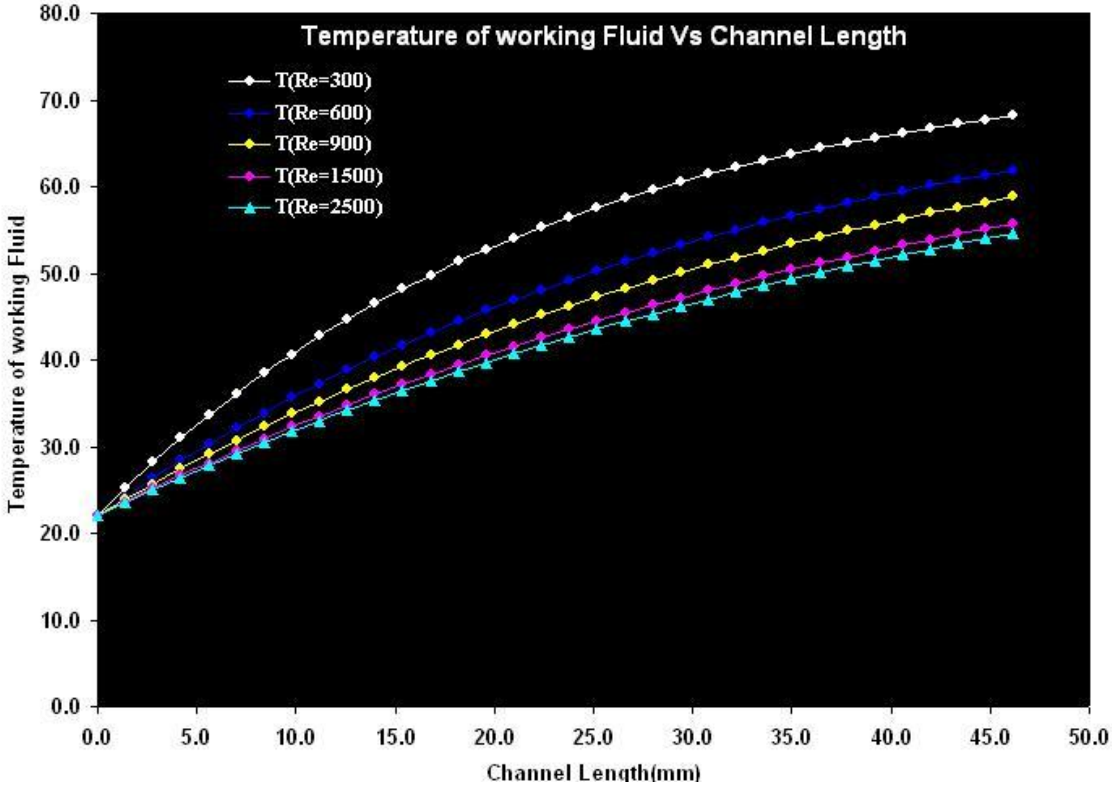

Figure 7. Temperature profile of working fluid along the channel length for different Reynolds number.

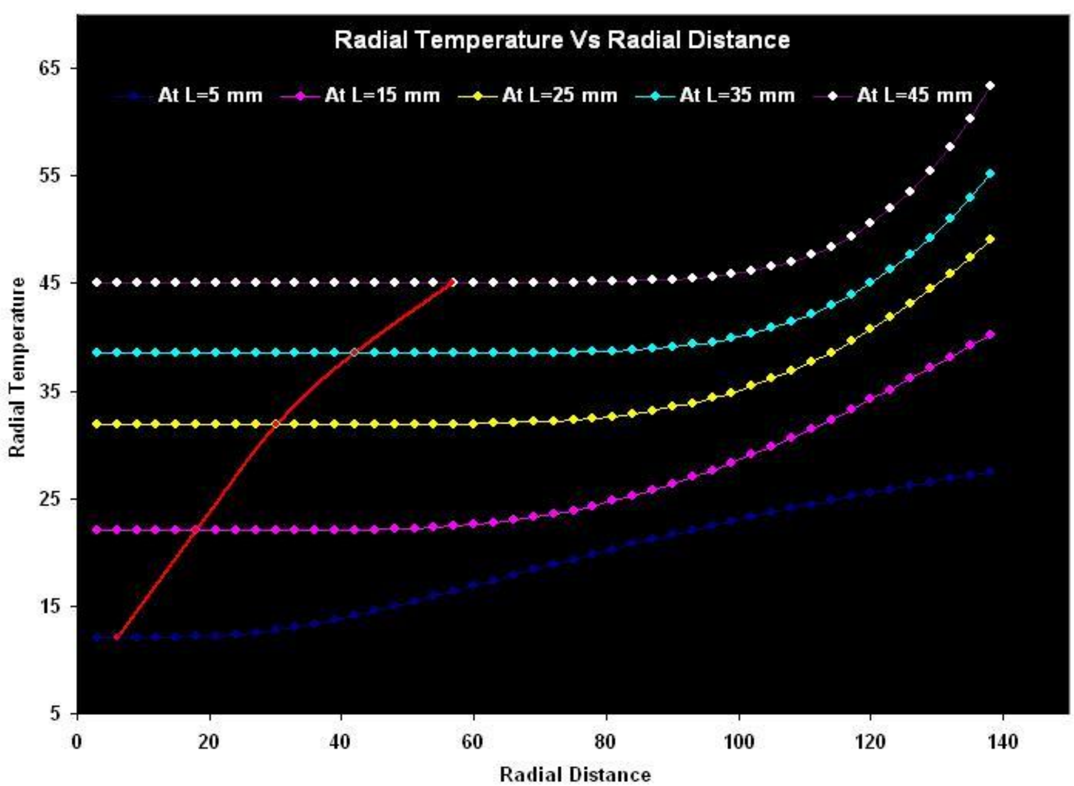

Figure 8. Temperature profile of working fluid along the channel diameter for different Reynolds number.

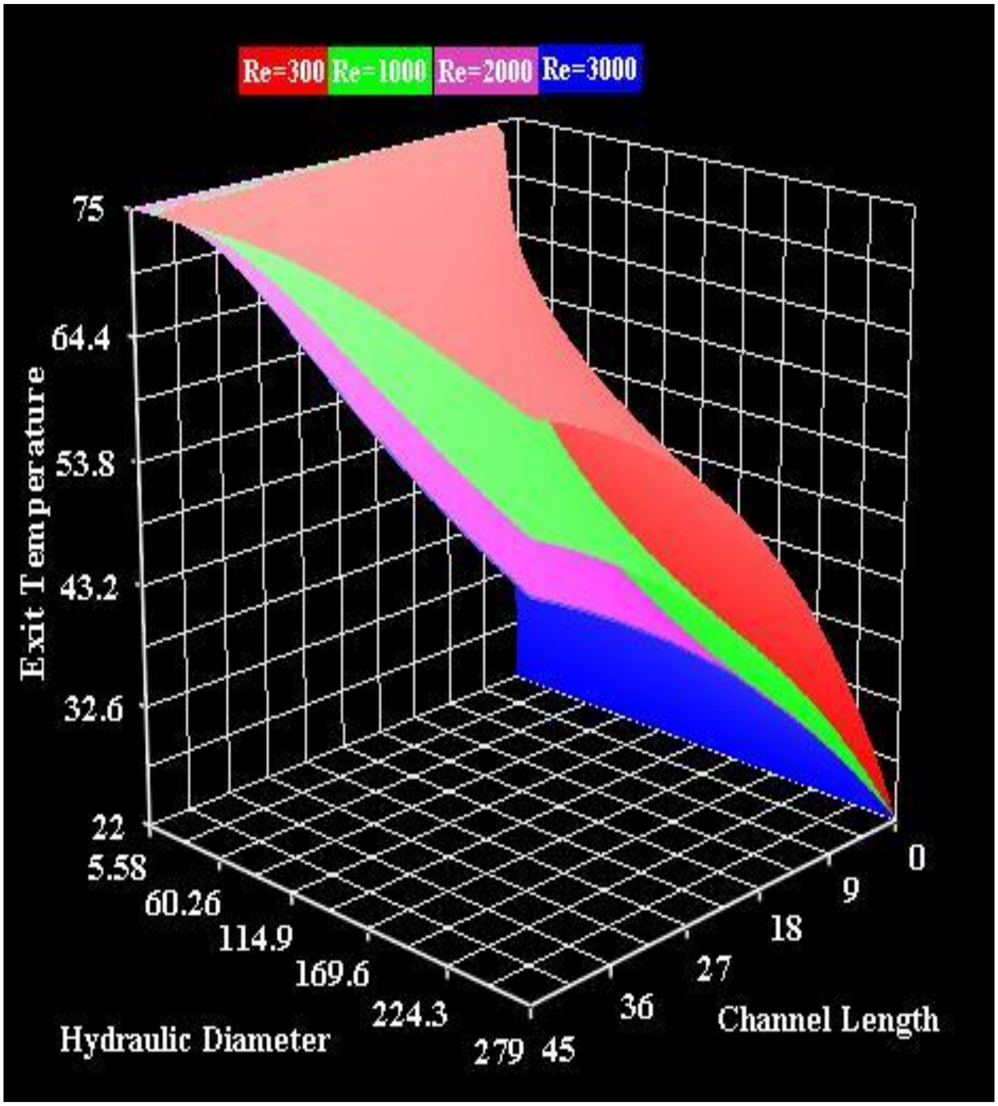

Figure 9. Surface plots of temperature profile of working fluid along as well as across the channel for different Reynolds number.

Figure 9 shows the combine effect of channel length as well as channel diameter on the temperature profiles of the working fluid.

Conclusion

Fluid flow and temperature variation in microchannels was investigated. Experiments were conducted on Microchannel Heat Exchanger. On the basis of certain measurements friction factor were calculated and temperature profiles are plotted for a Reynolds number range of 304 to 2997. Experimental friction factor matched reasonably well with the theoretical equations. On the basis of experimental data the correlation for friction factor was proposed in term of Reynolds number. The proposed correlation for friction factor agrees very well with the experimental data as well as existing correlations. As summary the proposed correlations for friction factor can be used for predicting the behavior of fluid flow in microchannels and temperature profile help to understand the variation of temperature along as well as across the channel.

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