Experimental and Numerical Investigation of Forced Convection Heat Transfer in Rectangular Microchannels

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ABSTRACT

Experimental and numerical analysis were performed to evaluate heat transfer characteristics of water through five sets of rectangular microchannels. Microchannels of hydraulic diameter of 222 μm, 267 μm, 323 μm, 330 μm and 343 μm respectively for Re number between 2.1 to 48 were analysed. Numerical analysis and experiments were conducted under a input heat of 10 W to 100 W, inlet fluid temperature 29ºC and mass flow rates of 0.0167 kg/sec to 0.116 kg/sec. Nusselt number tends to be linear increasing as Reynolds number increases. Besides high temperature gradient exist in the region between inlet and exit of flow microchannel. For hydraulic diameter 222 μm, heat transfer coefficient seems to be higher as compare to other configurations of hydraulic diameters. Numerical results showed reasonably good agreement within 4-5% with experimental results.

Keywords: heat transfer, pressure drop, heat transfer coefficient, forced convection.

NOMENCLATURE

a	Height of channel (μm)
b	Width of cannel (μm)
D_h	Hydraulic diameter (μm)
fRe	Poiseuilles number
h	Heat transfer coefficient (W/m²K)
Lc	Length of channel (m)
m	Mass flow rate (kg/s)
n	Number of microchannels
Nu	Nusselt number
Pr	Prandtl number
q	Heat input (W)
Re	Reynolds number of channel
s	Spacing between channel (μm)
U_m	Mean flow velocity (m/s)
ΔP	Pressure drop in microchannel (N/m²)
Δ	Difference

GREEK SYMBOLS

α	Aspect Ratio
ρ	Density of water (kg/m³)

1. INTRODUCTION

Micro heat exchangers are becoming an important area of interest in many fields of developing technology that requires high heat energy removal solutions. Fields such as MEMS, microelectronics, biomedical, fuel processing, and aerospace are all pushing the limits of thermal control and finding ways to make smaller devices with higher heat flux removal potential. This high heat removal requirement are more efficiently serves through smaller heat exchangers which works as a key working components for cooling applications for high heat removal.

2. LITERATURE REVIEW

Tuckerman and Peace[1] in 1980s described the use of microchannel cooling for high power densities. They demonstrated cooling of 790 W/cm^2 with a temperature increase of 71 °C for a flow rate of 0.00832 kg/sec with pressure drop of 2.14 bar where 0.3 mm deep channels were fabricated on opposite side of 0.4mm thick wafer from 1 × 1 cm thin film resistor plate. However the coolers could not fabricated and pressure drops where very high. Given the cost of high performance processor chip it is not practical to form the microchannels directly on back surface of the chip. Nilson et al[2] studied microchannel using analytical and numerical solution for evaporating flow in rectangular microchannel for uniform width. The evaporating cooling capability of rectangular microchannels are presented in terms of flow on channels dimensions, also they investigated flow pattern within microchannel. Rin Yun et al[3] conducted experimentation for effect of oil concentration on gas cooling for heat transfer and pressure drop characteristics of oil mixture. The effect of oil concentration on convective gas cooling heat transfer and pressure drops for micro channel tubes are experimentally confirmed to be significant. Welin Qu et al[4] investigated friction factor correlation for water as working media for micro channels. Analyses of optimum heat transfer for rectangular aluminum micro channels are done with friction factor consideration. By analyzing microchannels for six friction factor correlations with own experimental data, they investigated new friction factor correlation. Proposed friction factor correlation is suggested by verifying available correlation for friction factor from literature. Melanie Derby et.al.[5] analyzed microchannel with zigzag, curvy, step microchannels and this various shape microchannels are compared with straight and wavy channels by numerical method. Hydraulic diameter 340μm with length of 10cm considered for analysis. For same cross-section of microchannel temperature and heat transfer coefficient of zigzag shape is least and greatest among various channel shape. Numerical prediction result shows that Zig-zag microchannel is best in thermal and hydraulic performance as compared to straight microchannel. P.Gunnasegaran et.al.[6] investigated effect of geometrical parameters on water flow and heat transfer characteristics in microchannels numerically for Reynolds number range of 100–1000. Investigation is for three-dimensional steady, laminar flow and heat transfer governing equations solved by using finite volume method. Rectangular, trapezoidal, and triangular shape considered for analysis. The water flow field and heat transfer phenomena inside each shape of heated microchannels are examined with three different geometrical dimensions. In their investigation it is found that better uniformities in heat transfer coefficient and temperature can be obtained in heat sinks having the smallest hydraulic diameter, also smallest hydraulic diameter has better performance in terms of pressure drop and friction factor. Ali Kosar et. al. [7] numerically analyzed heat and fluid flow in microchannels of size 200 μm × 200 μm, 5 cm long of different substrate thicknesses 100 μm to 1000 μm and different microchannel materials Polyimide, Silica Glass, Quartz, Steel, Silicon was studied. The effects of thermal conductivity and substrate thickness on convective heat transfer in laminar internal flows analyzed by cosmol multiphysics-3.4 software. They proposed general Nusselt number correlation for fully developed laminar flow which is function of two dimensionless parameters, namely Biot number and relative conductivity. In literature review it is found that work is carried out for silicon material. In this paper copper as a microchannel material considered with water as a cooling medium with variation in flow rate and heat input to the microchannel.

3. CO-RELATIONS USED FOR THEROTICAL ANALYSIS OF MICROCHANNEL GEOMETRY

All these correlations referred for analysis of Microchannel heat sink are taken from S. Kandilkar, S.Garimella textbook of "Heat transfer and fluid flow in mini-channels and microchannels" 2006

Aspect Ratio,

$$\alpha = \left(\frac{b}{a}\right) \qquad \alpha = \left(\frac{b}{a}\right) \tag{1}$$

$$No\ of\ channels\ 'N' = \frac{Microchannel\ Width}{Finwidth + Channel\ Width}$$

Cross- Sectional area of single microchannel

$$A_{single} = a \times b \tag{2}$$

Hydraulic diameter D_h

$$D_h = \left(\frac{2ab}{a+b}\right) \tag{3}$$

Heat transfer due to conduction is given as,

$$q = K\,c \times As \times dT/\mathrm{L} \tag{4}$$

Base Surface Area of microchannel

$$A_s = \mathrm{L} \times B \tag{5}$$

Temperature difference between Base surface and wall, *dt*

$$dT = (q \times \mathrm{L}) / \frac{q \times \mathrm{L}}{K_c \times A_s} \tag{6}$$

$$dT = T_s - T_w \tag{7}$$

The average temperature between wall and fluid at inlet is,

$$\mathrm{Tavg.} = \frac{T_w + T_{wi}}{2} \tag{8}$$

4. NUMERICAL ANALYSIS OF RECTANGULAR MICROCHANNELS

Numerical analysis was carried out using available literature based governing equations by developing C language code. Microchannels were tested for 50 mm, 70 mm and 90 mm length respectively. Width of microchannel test section consists of 25 mm and 4 mm thickness. Geometrical parameters of five sets of microchannel with length are described in table 1.

Table 1. Geometrical parameter of five sets of microchannels l = 50 mm, l = 70 mm, l = 90 mm

Configurations	1	2	3	4	5
a(μm)	200	300	200	300	350
b(μm)	400	400	250	350	400
s(μm)	500	500	500	500	300
Hd(μm)	222	267	323	330	343

5. NUSSELT NUMBER VS REYNOLDS NUMBER

Figure 1, Figure 2 and Figure 3 describes variation of Nusselt number verses Reynolds number for hydraulics diameter of 222 µm, 267 µm 323 µm 330 µm 343 µm respectively with variation of length 50mm, 70mm and 90mm respectively. For length 50mm the Nu number maximum for Hd- 222 µm

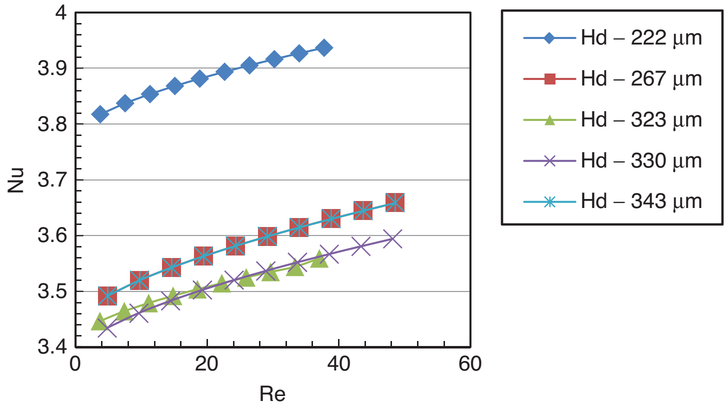

Figure 1. Nu number Vs Re number for L = 50 mm

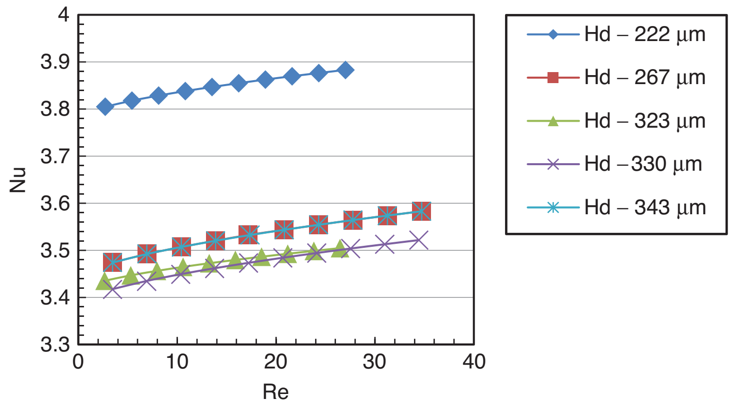

Figure 2. Nu number Vs Re number for L = 70 mm

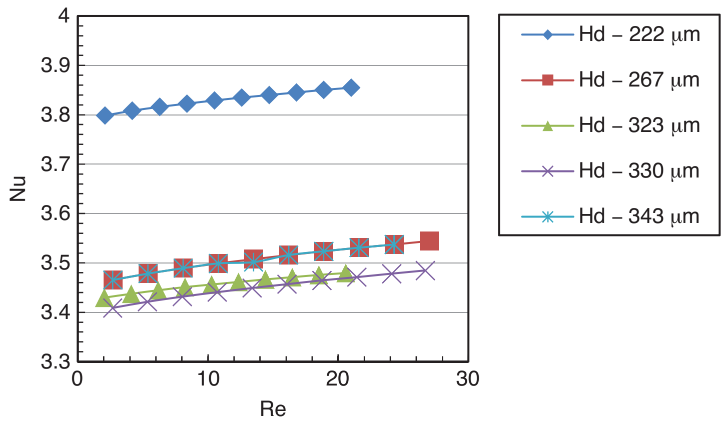

Figure 3. Nu number Vs Re number for L = 90 mm

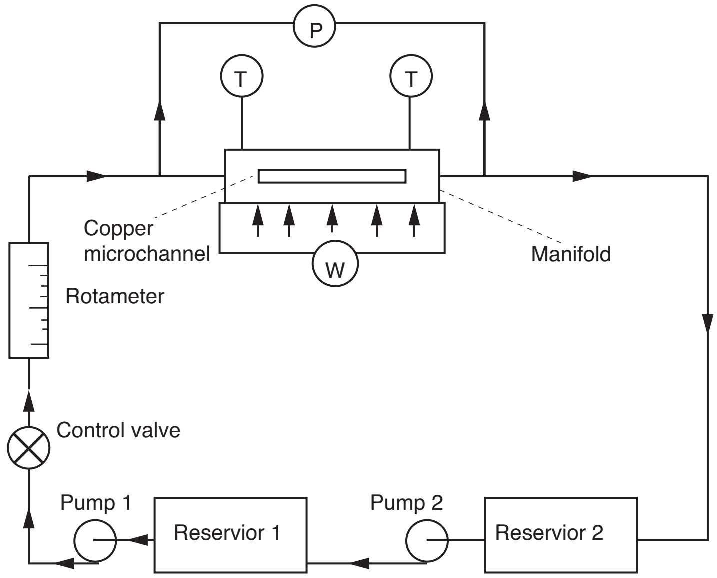

Figure 4. Flow loop of Experimental Test set up

where for other configuration the Nu number is in between 3.4 to 3.6 for a Re number of 5 to 60 respectively. For length of 70mm the Nu number is maximum of 3.9 for Hd- 222 μm where for other configuration the Nu number is in between 3.4 to 3.7 for a Re number of 5 to 50 respectively.

For length of 90mm the Nu number is maximum of 3.8- 3.9 for Hd- 222 μm where for other configuration the Nu number is in between 3.4 to 3.6 for a Re number of 5 to 40 respectively. For for hydraulics diameter of 267 μm 323 μm 330 μm 343 μm the Nu number is in range of 3.4 – 3.6 for different length consideration of 50mm, 70mm and 90mm respectively.

6. EXPERIMENTAL SETUP

Experimental test piece consists of Copper block having dimensions of width 30mm, thickness 4mm with variation of lengths 50mm, 70mm and 90mm respectively. On this block triangular microchannel are formed on one side. The test set up has microchannel provided with cartridge heater on back side of the copper chip, two tanks for storage of water, rotameter for measuring flow rate of water, two pumps for circulation of water over microchannel, acrylic enclosure. Water is used as a working fluid. The acrylic manifold has two ports, one at the inlet and other at the outlet. On the rear face, two K- type thermocouples one on the right and other on the left side at inlet and outlet ports are installed for measuring temperatures of water at respective points. Microchannel is press fitted in the acrylic manifold as shown figure 5A and 5B and its base surface is heated by cartridge micro heater by supplying power through dimmerstat from 10 W to 100 W and measured by digital wattmeter. Flow loop of experimental setup is described in figure 4. The supplied heat to the microchannel walls was adjusted to achieve the steady stable using electric heaters. Water from first reservoir is pumped by the first pump passes through piping via rotameter which is used to control the flow rate of water. Pumped water passes through the acrylic manifold, where it absorbs heat from the heated microchannel piece which causes its temperature to rise. This heated water exits the acrylic manifold and is then circulated towards second reservoir, from this second tank the water is pumped back again to the first tank in order to maintain a constant head in the first reservoir. Thus inlet and outlet temperature of water is noted from the temperature indicator with the help of K thermocouples.

Microchannel specimens were manufactured with EDM technology with copper as a material. Microchannels of five different configurations were tested under constant wall temperature case consideration.

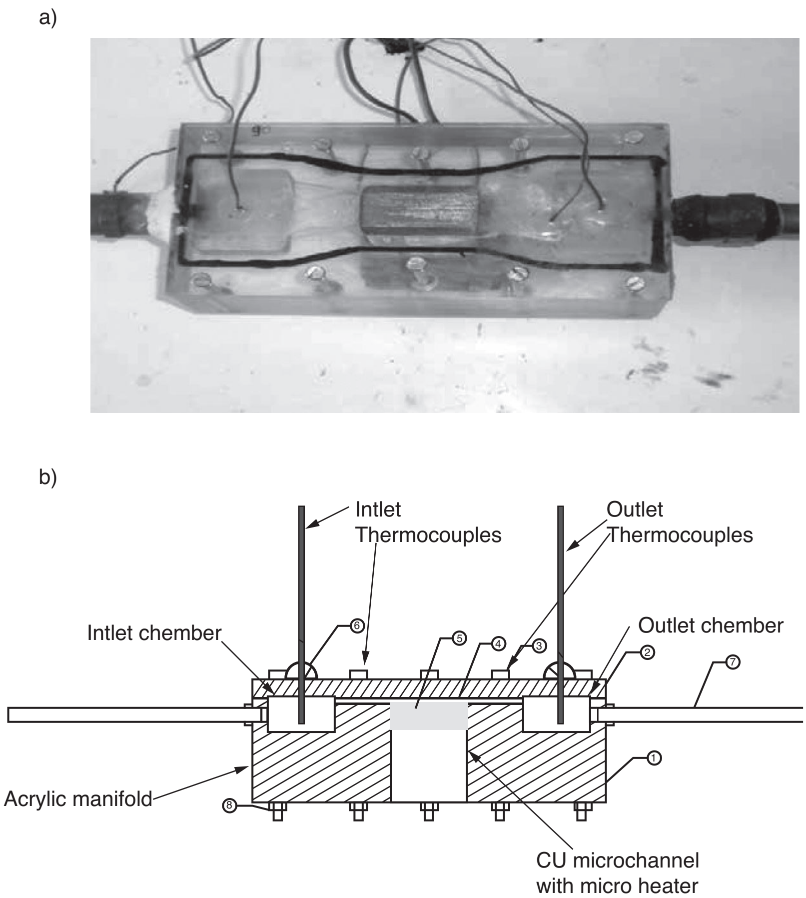

Figure 5. Microchannel test section manifold

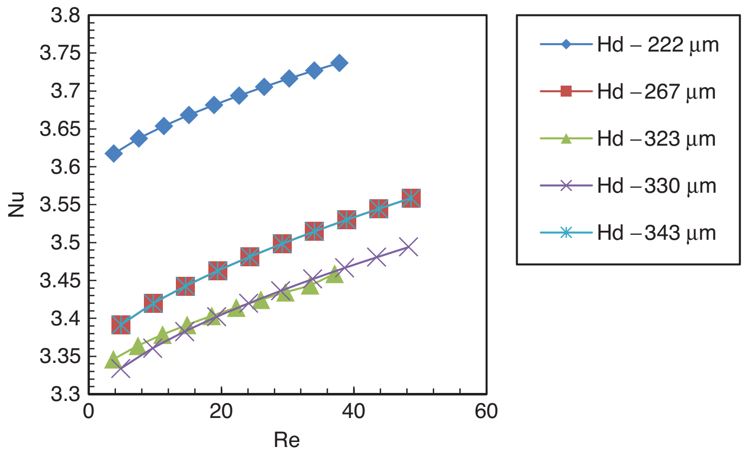

Figure 6. Nu number Vs Re number for L = 50 mm

7. EXPERIMENTAL RESULTS

7.1. Nusselt number Vs Reynolds number

For 50 mm length and different flow rate condition the Nu number is in range of 3.6 to 3.75 for hydraulic diameter 222 μm. As for hydraulic diameter of 343 μm the Nu number is in range of 3.3 to 3.45. As hydraulic diameter increases the Nu number increases with Re number but as the hydraulic diameter decreases the with variation Nu number decreases this tends as crossection area of triangular microchannel decreases this tends to viscous forces in the liquid particles, instead of increasing heat transfer it tends to decrease the heat transfer across the microchannel length. Nu number with variation of hydraulic diameter with Re number is described in Figure 7 to Figure 9 for a length of 50 mm, 70 mm and 90 mm respectively. Nusselt number tends to be linear increasing as Reynolds number increases. Besides high temperature gradient exist in the region between inlet and exit of flow microchannel. Numerical results showed reasonably good agreement within 3-5% with experimental results.

7.2. TEMPERATURE DIFFERNCE VS HEAT INPUT

Experimental results of temperature variation with heat input are described in figure 9 to figure 11 for a 50 mm length microchannel results.

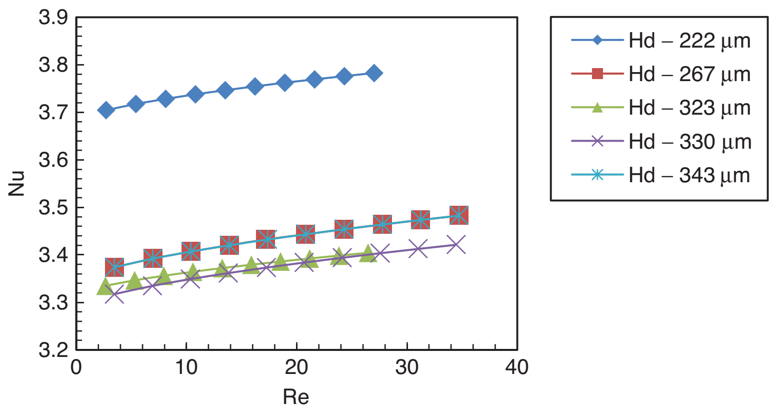

Figure 7. Nu number Vs Re number for L = 70 mm

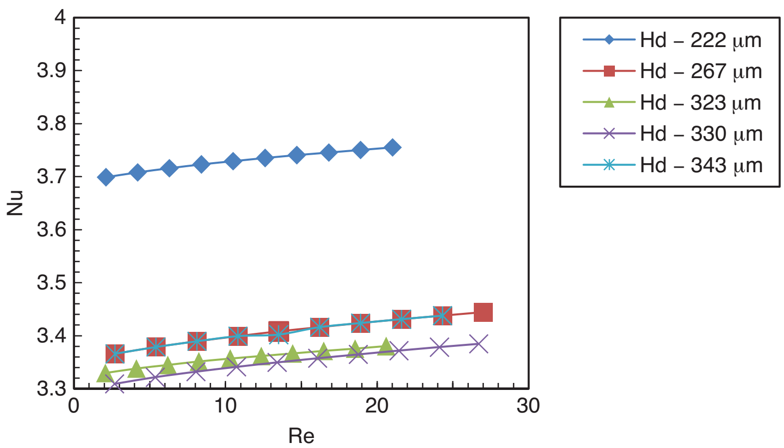

Figure 8. Nu number Vs Re number for L = 90 mm

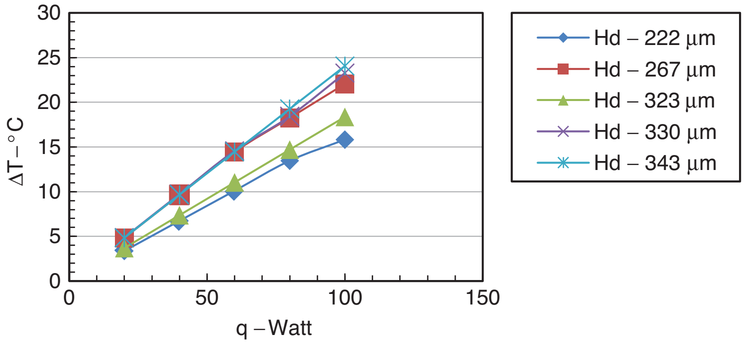

Figure 9. Temperature diff. Vs Heat input for flow rate of 0.0167 kg/sec, L = 50 mm

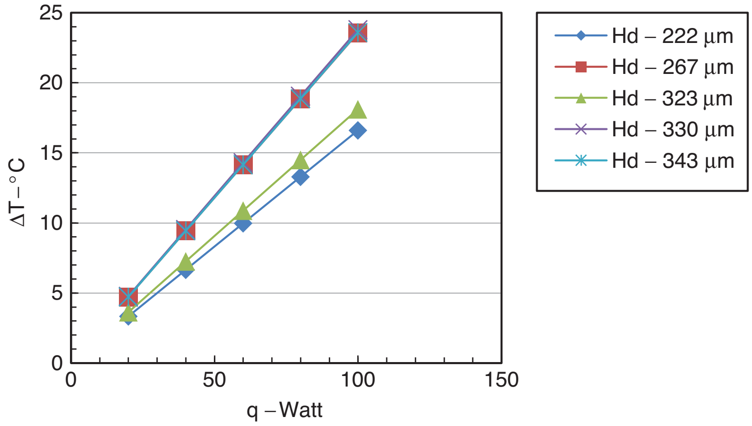

Figure 10. Temperature diff. Vs Heat input for flow rate of 0.067 kg/sec, L = 50 mm

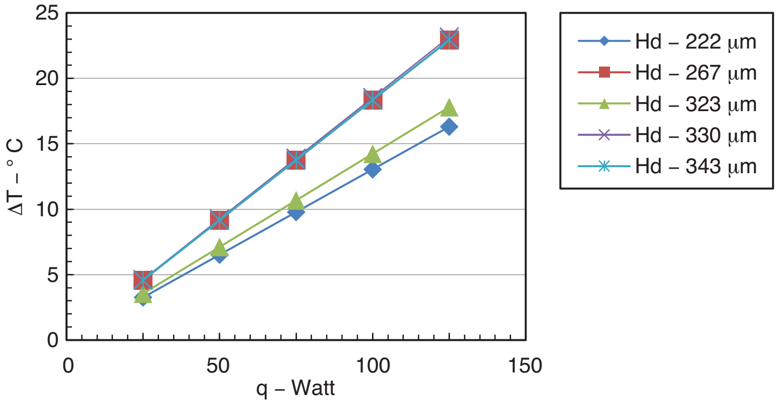

Figure 11. Temperature diff. Vs Heat input for flow rate of 0.167 kg/sec, L = 50 mm

For a heat input of 10 Watt-100 Watt the temperature rise is of 2ºC to 20ºC. For a hd- 222 μm temperature rise is upto 15ºC. For hydraulic diameter of 343 μm water temperature rise is remarkable upto 20 ºC. For a flow rate variation of 0.0167 kg/sec to 0.167 kg/sec. Experimental results of temperature variation with heat input are described in figure 12 to figure 14 for a 70mm length microchannel results.

For a heat input of 10 Watt-100 Watt the temperature rise is of 2ºC to 20ºC. For a hd- 222 μm temperature rise is upto 12ºC. For hydraulic diameter of 343 μm water temperature rise is remarkable upto 20 ºC. For a flow rate variation of 0.0167 kg/sec to 0.167 kg/sec.

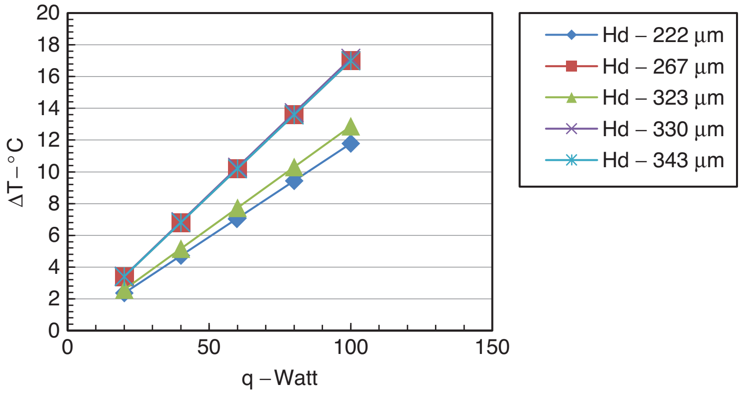

Figure 12. Temperature diff. Vs Heat input for flow rate of 0.0167 kg/sec, L = 50 mm

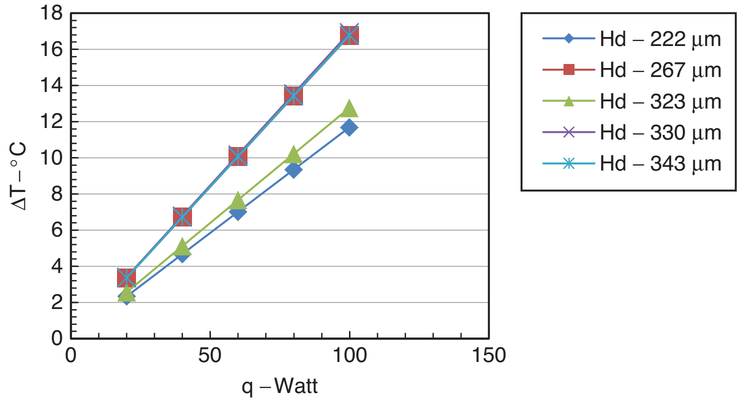

Figure 13. Temperature diff. Vs Heat input for flow rate of 0.067 kg/sec, L = 70 mm

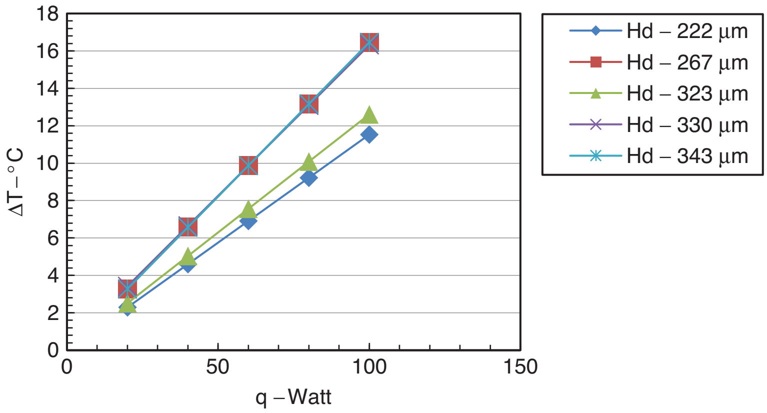

Figure 14. Temperature diff. Vs Heat input for flow rate of 0.167 kg/sec, L = 70 mm

Experimental results of temperature variation with heat input are described in figure 15 to figure 17 for a 90mm length microchannel results. For a heat input of 10 Watt-100 Watt the temperature rise is of 2ºC to14ºC. For a hd- 222 μm temperature rise is upto 8ºC. For hydraulic diameter of 343 μm water temperature rise is remarkable up to 14 ºC. For a flow rate variation of 0.0167 kg/sec to 0.167 kg/sec.

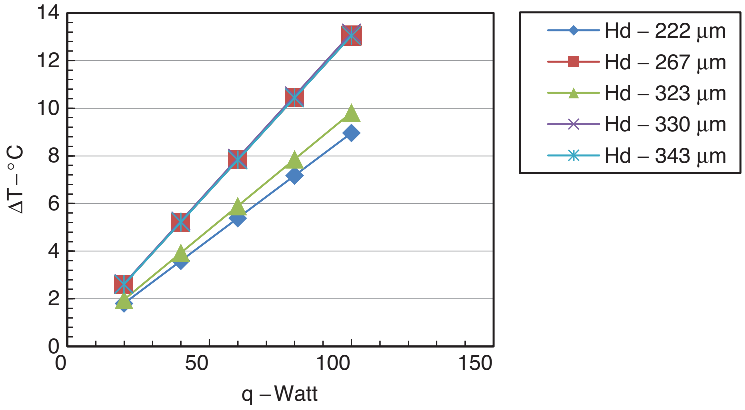

Figure 15. Temperature diff. Vs Heat input for flow rate of 0.0167 kg/sec, L = 90 mm

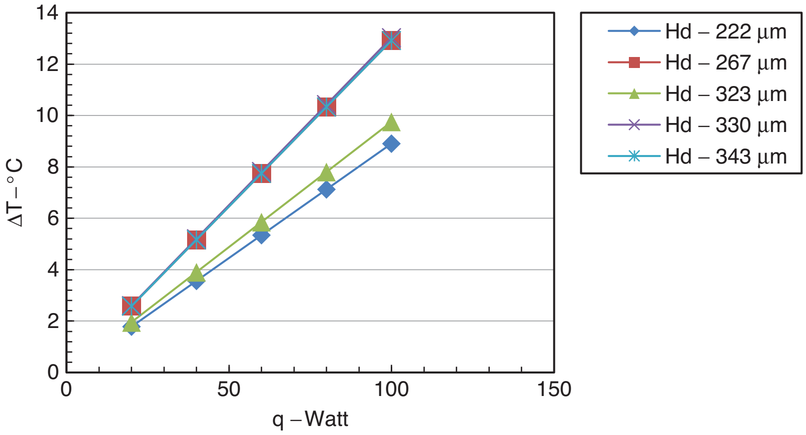

Figure 16. Temperature diff. Vs Heat input for flow rate of 0.067 kg/sec, L = 90 mm

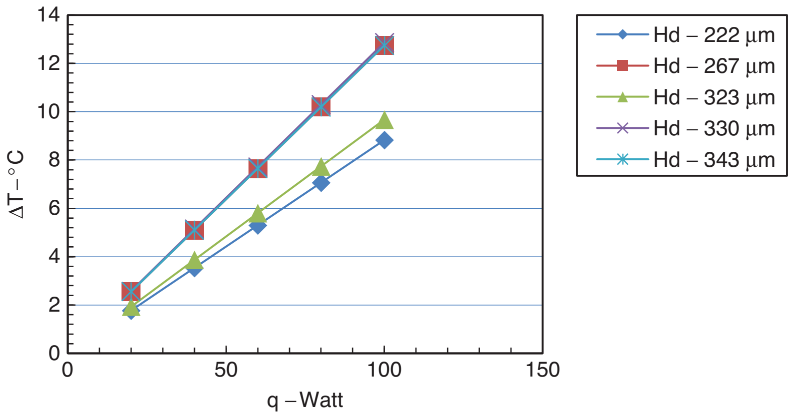

Figure 17. Temperature diff. Vs Heat input for flow rate of 0.167 kg/sec, L = 90 mm

8. CONCLUSIONS

Heat transfer coefficient varies from 8500 W/m^2 K to 11000 W/m^2 K for heat input of 10 W to 100 W under flow rate of 0.0167 kg/sec to 0.116 kg/sec. Nusselt number for configuration-1 is having higher in the range of 3.9 to 4.2 as compare to other configurations for Reynolds number of range 2.1 to 40 as described in figure 1. Temperature gradient of 17ºC to 20ºC exists in the regions between inlet and exit of flow microchannel for heat input of 100W. Nusselt number tends to be linear increasing as Reynolds number increases. Besides high temperature gradient exist in the region between inlet and exit of flow microchannel. Numerical results showed reasonably good agreement within 3-5% with experimental results.

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