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EXPERIMENTAL INVESTIGATION OF FORCED CONVECTIVE HEAT TRANSFER IN RECTANGULAR MICRO-CHANNELS

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ABSTRACT

This paper investigates the experimental program on the study of heat transfer characteristics in micro-channels. The two test sections used are of 47 and 50 micro-channels in rectangular cross-section of equivalent diameters 387 and 327 µm, respectively. Each channel of length 192 mm is 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 forms the channels by vacuum brazing. Experiments cover laminar region using the fluids ethanol, methanol and an ethanol-methanol mixture. The heat transfer coefficient is evaluated based on the heat carried away by the coolant and an average wall to mean fluid temperature difference. The Nusselt number is correlated through empirical correlations involving Reynolds number and Prandtl number with length parameter, the hydraulic diameter.

Keywords: heat transfer, micro-channels, alcohols, alcohol mixture, forced convection, laminar.

Nomenclature

Symbols

a	index
c_p	specific heat (J/kg K)
C	constant
d	diameter (m)
D_{eq}	equivalent diameter (m)
H	heat transfer coefficient (W/m^2 K)
H	channel height (m)
L	channel length (m)
M	mass flow rate (kg/s)
n	Prandtl index
q	heat transfer rate (W)
q_{epi}	electrical power input (W)
q	heat flux (W/m^2)
Re	Reynolds number (=ρvd/µ)
t	temperature (^{o}C)
v	velocity (m/s)
W	channel width (m)
x	mass fraction
y	mole fraction

Greek letters

Δ	differential
λ	thermal conductivity (W/m K)
µ	dynamic viscosity, (N s/m^2 or Pa s)
ρ	fluid density (kg/m^3)

Subscripts

eq	equivalent
f	fluid
i	inlet
m	mean
mix	mixture
o	outlet
w	wall conditions
1	component 1
2	component 2

1. INTRODUCTION

The systematic research into micro-scale flow and heat transfer studies were in vogue for the past three decades, started by initiation of Tuckermann and Pease [1,2] on the thermal management of high heat dissipating electronic components both covering chip and board levels. As far as micro-scale flow passages are concerned, the literature sources are not more recent. The emergence of micro-electro-mechanical systems (MEMS) has generated significant interest in the area of micro scale heat transfer. Several investigations ensued those dealt with flow of gases [3] and liquids [4] through micro-geometries. 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 [5]. Non-circular geometries are often adopted because of their relative simplicity in fabrication as compared to circular channels. Issues pertaining to micro-channel heat exchangers were dealt with by Peterson [6] and Ravigururajan *et al*., [7]. Theoretical approaches to fluid flow and heat transfer as well were reported [8]. The substrates used were silicon, glass, copper and stainless steel. The test section geometries varied from a fraction of a µm to a few 100s of µm. There had been limited study with mixtures of fluids [9] and Rathnasamy *et al*., [10] investigated flow of alcohols and its mixtures in long serpentine micro-channels. Steinke and Kandlikar [11] reviewed previous studies on the topic of fluid flow and heat transfer and tried to explain the deviation in data by conducting experiments. It is concluded that deviations came from the measurement uncertainty of micro-channel dimension in conjunction, with inlet and exit losses. Fluid flow and heat transfer experiments were conducted in rectangular micro-channels by Jung and Kwak [12]. There is general agreement in the literature that the high relative roughness of micro-channels reduces the critical Reynolds number for transition to turbulent flow. It is well known that

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roughness influences the transition to turbulent in Schlichting [13].

These studies provide substantial evidence to prove that flow and heat transfer in micro-channels need to be addressed differently compared to conventional channels. Wang *et al*., [14] have attempted to provide some possible explanation to peculiarities of micro-channel heat transfer. It appears that the results quite good agreement with experimental data. Moreover Jung-Yeul Jung *et al*., [15] have reported that the Nusselt number increases with increasing Reynolds number in laminar regime by doing experiments with nano fluids. There is a need for more experimental data on a variety of fluids and flow geometries (i.e. channel dimensions and relative roughness) so that some generalized conclusions can be evolved.

2. TEST SECTION

Micro-components are mostly fabricated using etching, deposition and photo-lithographic techniques. The EDM is considered to be a non-conventional machining technique. It was reported that with a precision EDM dimensional tolerances up to 0.5 μm could be obtained.

In the present case, two test sections herein after designated as MCP1 and MCP2 having common features; each channel of length 192 mm were fabricated on a 304 stainless steel substrate (230 mm x 160 mm x 1.6 mm) by photo chemical etching process as shown in Figure-1. MCP1 and MCP2 have 47 and 50 micro-channels of rectangular cross-section 1000 by 240 μm and 900 by 200 μm in width and depth, respectively. The channel header portions were deepened after etching by EDM in order to have negligible pressure loss. The surface roughness (ε) of MCP1 and MCP2 was done to check the uniformity of the channel using a surface profilometer (Rank Taylor Hobson). The surface roughness measured have shown rms values of the order 1.11-6.90 μm for machined surface and 0.19-0.34 μm for cover plate. The flow passage is formed by vacuum brazing the machined plate, covering with another stainless steel plate of thickness 0.5 mm on top. Inlet and out conduits were attached together with the two plates and brazed in a vacuum furnace at 10^{-5} *torr* and about 1000^{o}C. The mating surfaces were coated with some plating technique to assist brazing.

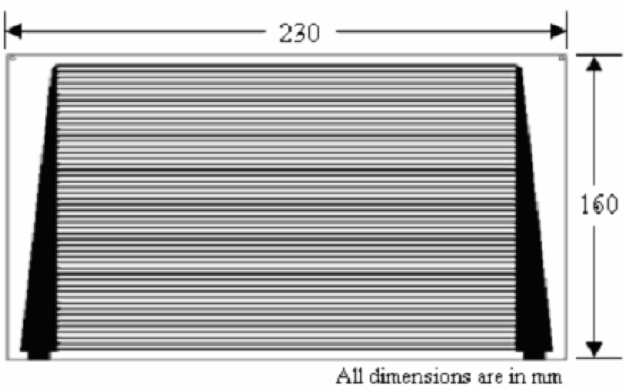

Figure-1. Details of micro-channel test section.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental set-up, shown in Figure-2, consists of a liquid reservoir (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. In the absence of micro-filter poor measurement data could be resulted due to blockage of the channels to the flowing fluid.

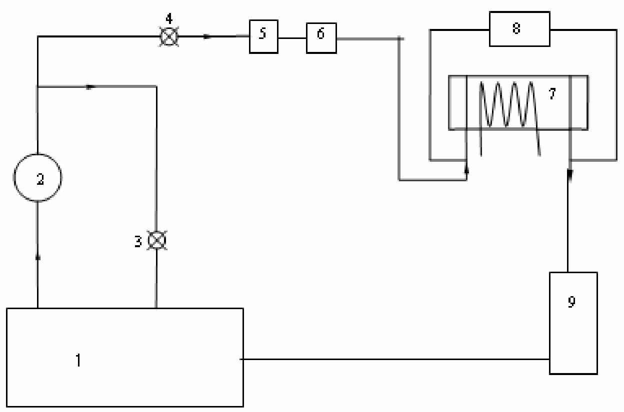

Figure-2. Schematic of experimental setup.

Legend: 1 Sump; 2 Pump; 3 By-pass control valve; 4 Flow control valve; 5 Micro-filter; 6 Flow meter; 7 Test section; 8 Differential pressure transducer; 9 Temperature bath.

Experiments were conducted with liquids ethanol, methanol and a mixture 50%E-50%M by volume (i.e. 0.53E-0.47M by mole fraction). Further the test setup 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 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 by measuring known volume of methanol manually with a maximum absolute deviation 4% over the measuring range 0.03- 8.00 lpm. Nichrome ribbon heaters wound on a mica sheet and encapsulated between a pair of mica sheets were used as heat sources. Two identical heaters were mounted on either side of the test section. This enabled application of equal heat inputs from both sides of the test module. The entire test section was adequately insulated with 2-mm thick asbestos sheet followed by 75-mm thick glass wool and 20-mm thick polystyrene foam on each side and at the edges. The fluid coming out of the channel was passed through a cooling coil and then in to the sump. The cooling coil was submerged in a temperature bath. The flow rates were varied with a corresponding variation of heat inputs. Thermocouples (T-type) and few Platinum resistance thermometers were affixed to the surface at 15 designated locations on the each side of the test section. A few

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thermocouples were used for measuring the inlet and outlet temperatures of conduits of the micro-channel test section. A digital display unit is used with a resolution of 0.1°C in the measurement.

The flow medium used to test is filled in the reservoir. To start the experiment all the required precautions are 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 is somewhat opened allowing the flow to take place in the test section. Later, the control valve is tuned to set the required flow rate indicated by the display unit connected. Pressure drop at the test section for the corresponding flow rate indicated by the display unit is noted. The steady value of flow rate is taken to reduce the measurement uncertainty. Several trials are carried out and the average value is taken to evaluate flow rate in terms of cc/min basis. The primary data were heat flux, flow rate, pressure drop, and temperatures at various locations on the test section. Each experiment is continued till the steady state conditions had stabilized, which took about one hour after the commencement of a test. The experiment was continued for a further period of 10-15 minutes before switching to the next run. In the present case of heat transfer experiments the Reynolds number covered the laminar region (30 ≤ Re ≤ 500). All tests were conducted with the test section in a horizontal plane.

4. DATA REDUCTION

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. The velocity is evaluated using the mass flow arte and the equivalent diameter (D_{eq}= 2 WH/ (W+H)). The mass flow arte was evaluated based on the density at inlet condition.

4.1 Property evaluation

Thermo physical properties require d for the heat transfer calculations were evaluated at the mean fluid temperature, defined as

$$t_{fm} = \frac{(t_{fi} + t_{fo})}{2} \quad (1)$$

The linear mixing rules for specific volume were used for evaluating the density, specific heat and thermal conductivity of the mixtures. The logarithmic mixing rule was used for viscosity of liquid mixed mixtures [16]. Temperature-dependent pure property data used were taken from reference [17].

4.2 Heat transfer coefficient

There is an uncertainty over the amount of heat transferred to the fluid. Because of the inevitable losses from the test section, all the electrical power given to the heaters is not transferred to the fluid. Thus, the actual heat transferred to the fluid was calculated from the enthalpy change. The heat flux was calculated based on energy balance of the fluid.

$$q = \dot{m} c_p (t_{fo} - t_{fi}) \quad (2)$$

$$q''_m = \frac{q}{2L(W + H)} \quad (3)$$

The average heat transfer coefficient is defined as

$$h_m = \frac{q''_m}{\Delta t_m} \quad (4)$$

where,

$$\Delta t_m = (t_{wm} - t_{fm}) \quad (5)$$

The mean wall temperature (t_{wm}) was based on the measurements at 15 locations. The Nusselt number is correspondingly defined as

$$Nu = \frac{h_m D_{eq}}{\lambda_{fm}} \quad (6)$$

This is procedure is similar to the one used by other researchers also [18, 19]. Table-1 shows the electrical heat input, velocity, fluid inlet and outlet temperatures, mean wall temperature and heat transfer rate for ethanol flow in MCP1. The last column indicates the percent of heat transfer to the fluid with respect to electrical power supplied to the heater. Similar data for experiments with methanol and one liquid mixture were generated for both channels. It is seen that about 10% of the input power is lost to the ambient in experiments.

5. RESULTS AND DISCUSSIONS

The Nusselt number data obtained from previous section are shown in Figure-3 as a plot of Nusselt number versus Reynolds number. These include all the experiments with liquids. These data show a perceptible fluid species dependence. Several researchers [8, 19, 20, 21] have brought out that the transition to turbulent regime occurs at lower Reynolds numbers in micro-channels than in normal channels. These transitions have been identified in the present fluid flow work were communicated [22]. The experimental data from the present work had been fitted to relation as in Figure-4 with the following relation:

$$Nu = C \, Re^{a} \, Pr^{n} \quad (7)$$

The values in eq. (7) for correlation coefficient 'C' and indices a and n are obtained.

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Table-1. Raw data for ethanol flow in micro-channel.

Experiment	q_{epi} (W)	v (m/s)	t_{fi} (°C)	t_{fo} (°C)	t_{wm} (°C)	q (W)	q/q_{epi} (%)
1	2.00	0.136	24.1	52.0	41.7	1.83	91.4
2	2.50	0.165	24.5	53.0	42.0	2.28	91.1
3	2.70	0.185	24.3	52.0	42.4	2.47	91.4
4	3.20	0.208	24.1	54.2	44.2	3.03	94.8
5	3.80	0.232	24.3	57.0	46.9	3.69	97.0
6	4.00	0.248	24.3	54.7	45.0	3.66	91.5
7	4.50	0.278	24.3	54.6	46.3	4.07	90.6
8	5.25	0.324	24.8	56.2	48.8	4.93	93.9
9	5.50	0.306	24.8	58.5	49.1	5.03	91.4
10	5.80	0.377	25.2	54.4	49.7	5.33	91.9
11	6.00	0.428	25.0	52.0	47.0	5.58	93.1
12	6.60	0.467	25.0	53.3	48.3	6.39	96.8
13	7.00	0.443	24.2	54.5	49.2	6.49	92.8
14	7.50	0.502	24.0	54.0	51.2	7.29	97.1
15	8.00	0.829	24.6	43.5	48.1	7.30	91.3
16	8.50	0.916	25.1	43.5	47.1	8.07	94.9
17	9.00	0.798	24.8	46.4	50.1	8.17	90.8
18	10.00	0.572	25.0	57.9	55.2	9.18	91.8
19	10.00	0.689	25.2	53.4	54.0	9.39	93.9
20	10.00	0.730	24.2	51.2	51.9	9.49	94.9
21	10.20	0.764	24.2	49.1	51.1	9.13	89.5
22	11.00	0.660	25.2	58.0	55.5	10.56	96.0
23	11.00	1.086	25.3	44.8	49.8	10.01	91.0
24	12.00	1.210	25.1	44.8	50.4	11.15	92.9
25	12.00	1.507	25.3	42.0	52.2	11.82	98.5
26	12.40	1.285	25.2	43.7	51.0	11.16	90.0
27	12.50	1.420	25.1	42.5	51.6	11.47	91.7
28	14.20	1.831	25.2	41.0	54.0	13.47	94.8
29	14.50	1.754	25.5	42.0	53.4	13.76	94.9
30	14.60	1.670	25.2	43.0	52.8	13.91	95.3

6. CONCLUSIONS

An experimental setup was devised to study the characteristics of single phase forced convective heat transfer in micro-channels. The two test sections MCP1 and MCP2 employed has equivalent diameter of 387 and 327 µm on 230 x 160 mm^2 steel plate. The flow media studied were alcohols and their mixture. The measured flow rate and temperatures data were used to evaluate the Nusselt number. An empirical correlation is obtained for Nusselt number in terms of Reynolds number and Prandtl number for laminar region as below:

$$Nu = 0.949 \ Re^{0.06} \ Pr^{0.4} \quad (8)$$

More experiments on different channel dimensions, surface roughness and fluids are needed to evolve a generalised correlation for heat transfer at micro-scale length. These experimental data could set off the ongoing efforts on micro-channel studies. The dependence of Nusselt number on Reynolds number and Prandtl number in micro-channel is quite different from that of normal channels.

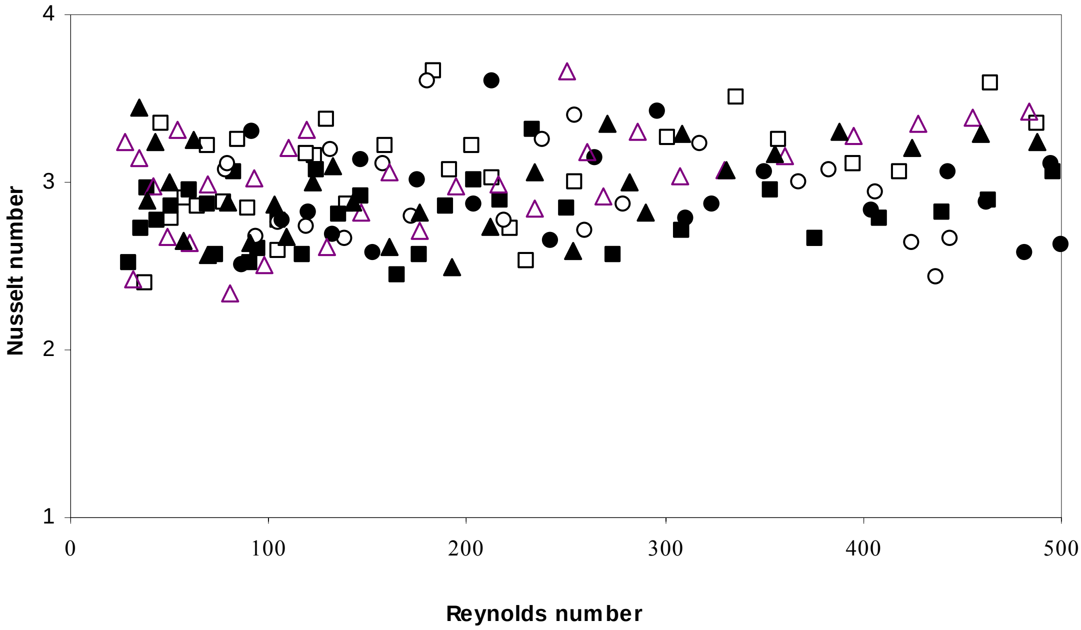

Figure-3. Nusselt number versus Reynolds plots for all liquids in micro-channels.

Legend: □ MCP1 ethanol; ■ MCP2 ethanol; ○ MCP1 methanol; ● MCP2 methanol; Δ MCP1 0.53E-0.47M mixture; ▲ MCP2 0.53E-0.47M mixture.

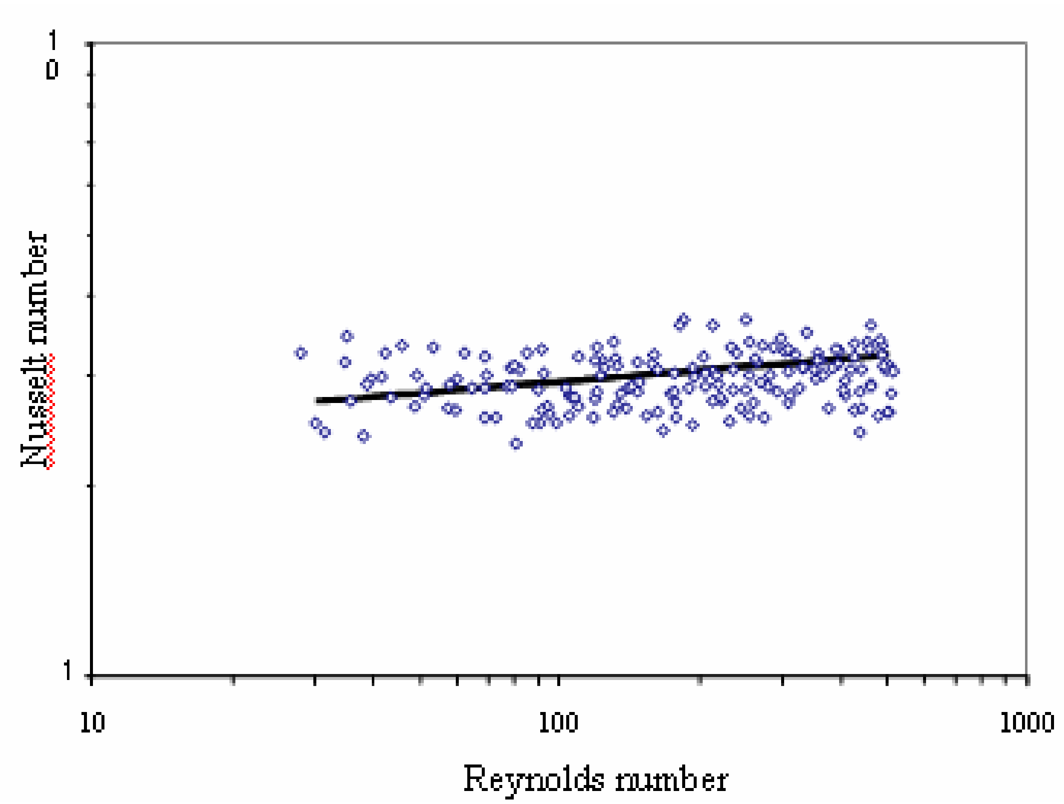

Figure-4. Nusselt number versus Reynolds number plot for all liquids in micro-channels with fit to equation (7) as solid line.

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