Testing Conjugate Conduction in Stainless Steel Micro Heat Sink

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Abstract. In this paper the microchannel setup to study longitudinal conduction phenomenon was developed and tested. Circular microchannels, 18 in number (hydraulic diameter ≈ 400±9μm, Length=40±0.4 mm) were manufactured using EDM process in square piece made of stainless steel material to study forced convection using water and ethanol as coolant. The setup was tested under uniform heat flux conditions for the identification of backward conduction phenomenon. The test rig was also able to reproduce the data. The temporal variations observed in coolant temperatures during transient conditions at various locations provided encouraging results. Rise in the temperature of the coolant at the inlet location for various experimental conditions was observed. Higher degree of axial conduction was observed in ethanol relative to water.

Nomenclature

Abbreviations and Symbols

| Symbol | Description |
|--------|-------------|
| A      | Area of cross section (m²) |
| D      | Hydraulic Diameter (m) |
| k      | Thermal conductivity (W/mK) |
| μ      | Dynamic viscosity (Ns/m²) |
| L      | Length (m) |
| Ṽ      | Velocity (m/s) |
| q      | Heat transfer rate (W) |
| ID     | Inner Diameter |
| OD     | Outer Diameter |

Non Dimensional Number

| Symbol | Description |
|--------|-------------|
| Re     | Reynolds Number |
| M      | Maranzana Number |
| Pr     | Prandtl Number |
| Gz     | Greatz Number |
| Br     | Brinkmann Number |

Subscript

| Symbol | Description |
|--------|-------------|
| h      | Hydraulic |
| f      | Fluid |
| L      | Length |
| in     | Inlet |
| wall   | Wall |
| m      | Mean |

1. Introduction

Microdevices (Ink printers, cell phones, I pads) are now a technological reality. All such devices contain multiple passages of typically micron range at their origin. Practical implementation of micro channels for dissipating high heat fluxes was demonstrated at first by Tuckerman and Pease [1] but research revolution began when additional effects observed at lower dimensions were systematically observed as scaling effects with respect to models developed for conventional systems by Herwig [2].
Good and updated reviews about various scaling effects noticed at lower dimensions are available in literature [3-5]. Entrance effects, Viscous heating, Conjugate heat transfer was observed as major scaling effects for liquid flows through microchannels due to greater influence of surface forces. Due to compact characteristics, flow lengths in micro systems are small; accordingly entrance region is extensive portion of the total length. Viscous dissipation is the heating of the fluid due to work done against the viscous forces and is imperative for flows having $Re > 100$. In normal channels, the channel thickness is negligible relative to the hydraulic diameter. However, at microscales, the thickness is of the similar order of magnitude of the flow region i.e. the heat transfer via conduction in the wall cannot be neglected for convective liquid flows and the heat transfer phenomenon becomes conjugate. The effect of axial conduction at the wall for the micro-channel heat sinks for parallel plate [6] and circular [7] channel geometries was studied by Maranzana et al.[6] and Kroeker et al. [7]. Axial conduction effects were observed to be negligible by Maranzana et al. [6] for water flow in a parallel plate channel of 100μm diameter, when ratio of axially conducted to convected heat is less than 0.01. Heat transfer characteristics during single phase flow in a square channel etched in aluminum substrate was experimentally conducted by Caney et. al [8]. Results show that experimental temperatures correspond to calculated ones situated at 50 μm from the wall. The phenomenon of axial conduction in rectangular channel geometry for $Re$ ranging 100 to 2000 was analyzed by Kosar [9]. The effects of various parameters like wall thickness and wall material on heat transfer mechanism were reported. Conduction effects were observed to be significant for higher thickness and conductivity of the substrate. On the contrary, conjugate effects were found to be dominant at low Reynolds numbers ($Re < 100$) [10, 11]. Thus to study conjugate phenomenon at microscales the experimental facility was developed and tested. The details of the facility developed to study conjugate phenomenon are discussed. The testing of the setup for the identification of longitudinal conduction produced positive results.

2. Experimental facility

The schematic of the closed loop experimental setup developed is shown in Figure 1. It consists of peristaltic pump, test section, air cooled radiator and collector tank. The peristaltic pump, Acuflow D 100 was used to supply steady flow rates of working fluid at various speeds of the rollers. Weight and time method was used to determine mass flow rate using electronic balance AND GR 200. The test

![Figure 1. Schematic of the Experimental Facility](image)
section made of stainless steel consisted of heat sink (Figure 2) having 18 circular microchannels with headers for common entry and exit of coolant. The channels in heat sink were placed in 2 layers with each row consisting of 9 channels to obtain staggered configuration between them. Hydraulic diameter of each channel, \( D_h = 400\pm 9\mu m \), was measured through microscope under 225x magnification. A plate type heater (52x30 mm\(^2\)), coupled to AC power source was placed above the heat sink to provide constant wall heat flux conditions as shown in Figure 3. T-type thermocouples (calibrated to ± 0.2 K) were used to measure the coolant temperatures at the common inlet and exit of the heat sink. Similarly T-type thermocouples were placed along the length on lower surface for measuring the axial variation in the temperature. A cover of insulation was then provided uniformly from all sides of the test section to restrict the heat losses. A composite pack consisting of different thickness of Bakelite (25mm), Glass wool (5mm), Asbestos (5mm) and Wood (10mm) were placed in series from heat sink to outer environment. Figure 4 demonstrates the composite insulation pack made of various materials placed in series.

To ensure proper working of the closed loop system convective heat taken by the coolant has to be extracted. Thus air cooled radiator designed to work in 35°C was placed following the test section. Copper tubing of \( ID = 5mm \) and 0.5 mm thickness was used to manufacture the air cooled condenser. 15 Aluminum fins (\( OD = 27mm \)) per 10cm of tube length was used for cooling the coolant.
3. Testing of the Experimental setup

3.1 Identification of Axial Conduction in Heat sink

The heat sink developed in this work was first tested for the presence of possible axial conduction effects. A prior evaluation for the presence of micro effects in the setup, indicated by Morini and Yang [12], was conducted. To evaluate axial conduction through wall, a parameter proposed by Maranzana et.al [6], \( M = \frac{k_w}{k_f} \frac{\Delta u}{\Delta f} \frac{1}{Re Pr} \) was used. According to their study axial conduction effects were proved to be significant for \( M > 0.01 \). On the other hand, other scaling effects namely viscous dissipation, tested by Brinkmann number \( Br = \frac{\mu_f \varepsilon m^2}{q_L} \), and entrance effects, tested by Greatz Number, \( Gz = \frac{(RePrD_h)}{L} \), should remain negligible. Viscous dissipation and Entrance effects become appreciable for \( Br > 0.005 \) [4] and \( Gz > 10 \) [10] respectively.

![Figure 5. Variation between M with Re for Stainless Steel heat sink](image)

The variation between \( M \) and \( Re \) for steel heat sink with coolants namely, water and ethanol is shown in Figure 5. For the range of experimental conditions, extreme values of \( Br \) and \( Gz \) were calculated as \( Br = 5 \times 10^{-8} \) (< 0.005) and \( Gz = 5.44 \) (< 10) hence viscous and entrance effects were considered negligible. However the \( M \) parameter remained greater than 0.01 indicating considerable amount of conduction phenomenon. Moreover degree of longitudinal conduction in case of ethanol was expected to be higher than that of water.

3.2 Confirmation of Axial Conduction during experimentation

A set of experiment with highest value of \( M \) (= 0.0713) is conceived in steel heat sink with water as coolant. The experiment was performed with water flow rate of 0.032g/s and heat input of 7.15 W. The variation in the fluid temperatures with time at inlet \( (T_{in}) \), outlet \( (T_{out}) \) and ambient \( (T_{amb}) \) is plotted in Figure 6. along with the temperature of the fluid in the collector tank \( (T_{set}) \). Initially all the thermocouples were at the same temperature. During experimentation, gradual increase in temperature at every location, finally reaching a steady state was observed. Careful study of Figure 6. reveal that the inlet temperature of the coolant also increased with time and reached a steady state value higher than \( T_{set} \). This is due to continuous conduction of heat in longitudinal direction from the exit to inlet, opposite to the flow direction of coolant. In this the net heat input is distributed as convection heat carried by coolant and backward axial conduction heat through the coolant channel.
4. Results

Variety of experimental tests was carried out to observe the phenomenon of axial conduction developed in microchannel system. Experiments under different flow rates ranging between 0.032g/s to 0.147g/s (corresponding $Re$ values indicated) were conducted. Ethanol and water were employed as coolants under various heat inputs in heat sink made of stainless steel material. Figure 7. and Figure 8. shows the rise in the temperature at the inlet ($T_{in} - T_{set}$) observed at various experimental conditions under steady state conditions. In Figure 7, heat input was varied from 3.3 W to 14.7 W by maintaining the flow rate constant. The coolant temperatures at the inlet location were observed to be much higher than the set temperatures. Higher amount of temperature rise was observed in ethanol relative to water. This rise in temperature was observed to increase with increase in heat input. This is attributed to the increase in the contribution of heat flowing backward towards the inlet. This raises the temperature of the coolant at the inlet as the heat input is increased. Similar observation of increase in the amount of backward conduction with increase in heat input was communicated by Caney and Bigot [8].

It is important to note that $Re$ will also have an influence on axial conduction and hence it is necessary to study the effect of $Re$ on the axial conduction phenomenon. In Figure 8, the rise in temperature at inlet was observed with variation in the flow rate ($6 > Re > 40$) for constant heat input.
A drop in the increased temperature at inlet location was observed as Re increases. This clearly indicates that the rise or drop in the temperature is occurring due to the presence of the phenomenon of axial conduction. The decrease in the amount of axial conduction with increase in the Re was in agreement with the results reported by Maranzana et al. [6] and Huang et al. [11].

![Figure 8. Rise in Temperature at Inlet with Re](image)

5. Conclusions
In this study, design, fabrication and testing of experimental apparatus to study conjugate heat transfer phenomenon at microscales was discussed. A multi microchannel heat sink containing 18 circular microchannels was fabricated in substrate of stainless steel material. The substrate was heated from the top surface to provide uniform heat flux at outer surface of the channel walls. A prior evaluation for the presence of micro effects in the setup provided positive results for longitudinal conduction. Higher degree of backward conduction was observed in ethanol relative to water. Under steady state conditions, with increase in heat input greater rise in coolant temperature at inlet location was observed. However, a drop in same temperature rise was recorded at relatively higher values of Re which may be attributed to the influence of convective contribution. This clearly indicates that the setup is able to demonstrate the phenomenon of axial conduction in the wall.

References
[1] Tuckerman D M and Pease R F W 1981 High performance heat sinking for VLSI IEEE Electron Device Lett. 2 126–129
[2] Herwig H 2002 Flow and heat transfer in micro systems: is everything different or just smaller? Z. Angew. Math. Mech. 82 579 – 586
[3] Guo Z Y and Li Z X, 2003 Size effect on microscale single – phase flow and heat transfer Int. J Heat Mass Transfer 46 149 – 159
[4] Rosa P, Karayiannis T G and Collins M W 2009 Single phase heat transfer in microchannels: The importance of scaling effects Applied Thermal Engineering 29 3447 – 3468
[5] Hetsroni G, Mosyak A, Pogrebnyak E and Yarin L P 2005 Heat transfer in microchannels: comparison of experiments with theory and numerical results Int. J Heat Mass Transfer 48 5580 – 5601
[6] Maranzana G, Perry I and Maillet D 2004 Mini and Microchannels: influence of axial conduction in the walls Int. J. Heat Mass Transfer 47 3993-4004
[7] Kroeker C J, Soliman H M and Ormiston S J, 2004 Three-dimensional thermal analysis of heat sinks with circular cooling micro-channels Int. J. Heat Mass Transfer 47 4733–4744
[8] Caney N, Marty P and Bigot J 2007 Friction losses and heat transfer of single phase flow in a mini channel Applied Thermal Engineering 27 1715 – 1721
[9] Kosar A 2010 Effect of substrate thickness and material on heat transfer in microchannel heat sinks Int. J Thermal Science 49 635 – 642
[10] Celata G P 2008 Single and two phase flow heat transfer in micropipes 5th European Thermal-Sciences Conference (accessed June 2016) http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.458.2539&rep=rep1&type=pdf
[11] Huang C Y, Wu C M and Liou T M 2014 The experimental investigation of axial heat conduction effect on the heat transfer analysis in microchannel flow Int. J Heat Mass Transfer 70 169 – 173
[12] Morini G L and Yang Y 2013 Guidelines for the determination of single phase forced convection coefficients in microchannels ASME J Heat transfer 135 101004