Effect of Heat Flux Variation on Thermal Performance of Circular Mini Channel

Bhavsar Twinkal[1] and Chhotani Paresh[2]

Chhotubhai Gopalbhai Patel Institute of Technology, Bardoli, India
twinkal7107@gmail.com, paresh.c.chhotani@gmail.com

Abstract. This paper presents a numerical simulation of a mini channel to investigate the temperature distribution obtained by solid domain using boundary conditions. A uniform heat flux is applied to the bottom surface of the mini channel, top surface is assumed to be adiabatic and remaining two surfaces are assumed to be symmetric. The variation of maximum temperature of the periphery of the mini channel with the different values of the flux is illustrated in this study. Various solid materials were considered for analysis: aluminium, lead, brass, tin, bronze and constantan. The methodology was validated with published results and they were found to be in good agreement. The analysis was extended for two nano-fluids (Cu-water and Al-water) and the results achieved have been discussed in the present work.

Keywords: Mini channel, Numerical simulation, Nano-fluids.

1 Introduction

Two most important issues, which are very concerned since few decades, are energy and environment. Therefore production and proper utilization of energy is the key to sustainable cost-effective development and also useful for future purpose. Among all energy sources the most important form of energy is heat, which is widely used in power generation, automotive and HVAC industries, nuclear industries, aerospace application, space research, marine and mining applications, chemical processing, petroleum and many other areas[1]. Thus heat transfer is an important phenomenon in various applications in energy conversion, transmission and consumption. Special instruments are manufactured to obtain effective heat transfer. Heat exchangers are the devices that exchange heat energy between two or more fluids at different temperatures and in thermal contact in order to remove or to add heat as quickly as possible. In many heat exchangers, two fluids are separated by a wall through which the heat transfer occurs. Heat transfer can be defined as the transport of thermal energy from a hotter object to a cooler object. Some of the examples of heat exchangers include cooling towers, evaporators, condensers, car radiators and pre-heaters.

Classifications of heat exchangers are based on the working principles, geometry of construction, heat transfer mechanisms and fluid flow arrangements. They can also be classified based on size and surface area to volume ratio. Based on channel dimensions,especially the characteristic length or hydraulic diameter, two main classification schemes are available (as shown in table 1 and 2).

Table 1. Channel classification according to Mehendale [2]

Type	**Size**
Microchannels	1 – 100 μ m
Meso-channel	100 μ m – 1mm
Compact passages	1 – 6 mm
Conventional passages	< 6 mm

Table 2. Channel classification according to Kandlinkar [2]

Type	**Size**
Conventional passages	< 3 mm
Minichannels	3 mm $\geq$ D < 200 μ m
Microchannels	200 μ m $\geq D <$ 10 μ m
Transitional Microchannels	10 μ m $\geq$ D < 1 μ m
Transitional Nanochannels	1 μ m $\geq$ D < 0.1 μ m
Nanochannels	0.1 μ m $\geq$ D

Channels are of different cross sections such as circular, triangular, rectangular and trapezoidal. The channel, considered in the present study, is of circular shape (as shown in figure 1). The block containing micro-channels is of rectangular shape and holes are placed in this rectangular block and mini channels are placed inside the holes of this rectangular block. There is no gap in between adjacent channels for fluid interaction. Flat surfaces at the top and the bottom of each mini-channel offer the fluid flow an excellent contact with the heating surfaces that leads to elevated heat transfer over the conventional heat exchangers of isolated tube rows. Figures 1 and 2 illustrate the difference between tubes and monolithic channels structures inside heat exchanger core.

In many specialized areas such as microelectronics, robotics, aerospace, biomedical, and automotive applications, miniature heat exchangers with different fluids are widely used.

Minichannel heat exchangers are becoming popular in engineering and industrial applications because of its enhanced heat transfer flux, light weight, larger heat transfer area density, less energy consumption and increased reliability when compared to other traditional methods of heat exchange.

A wide range of studies have reported about heat transfer and fluid flow in meso-channel, mini-channel and micro-channel heat exchangers or heat sinks with experimental and numerical simulation results. Although literature for non-circular cross-section in narrow size heat exchangers or heat sinks is available, the study of a full-size heat exchanger with circular channels in multi-port flat slabs is rare. Many researchers have studied different heat transfer and fluid flow characteristics through narrow channel heat exchangers and compared with conventional ones in recent years.

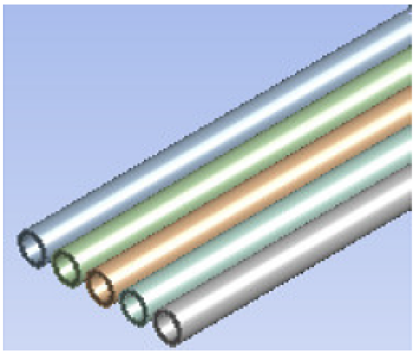

Fig. 1. Circular mini channels

Amador M. Guzman et al.[3] have investigated the numerical simulation of flow and heat transfer characteristics in mini and micro pressure driven communicating channel. S.-A.B. Al Omari[4] has investigated about the enhancement of heat transfer from hot water by co-flowing it with mercury in a mini-channel. Mostafa Keshavarz Moraveji et al.[5] have investigated about the CFD investigation of nano-fluid effects (cooling performance and pressure drop) in mini-channel heat sink. Nano-fluid as an innovative heat-transfer fluid was used in mini-channel heat sink. G. Hetsroni et al.[6] have compared the experimental results with theoretical and numerical results. They have considered the problem of heat transfer in the frame of a continuum model, corresponding to small Knudsen number. Circular shape of micro-channel has been selected for study. Pramod Kumar and M. R. Nagraj[7] have investigated about the computational fluid dynamics analysis of fluid flow and heat transfer in two phase flow microchannel.

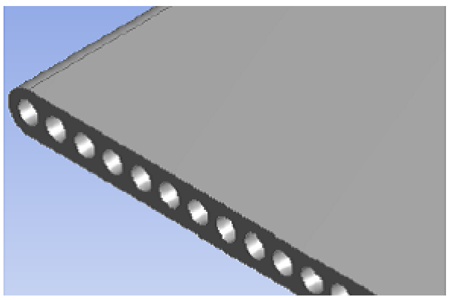

Fig. 2. Circular channels inside solid domain

Fluid flow inside channels is at the heart of many natural and man-made systems. Heat and mass transfer is accomplished across the channel walls in biological systems such as the brain, lungs, kidneys, intestines, blood vessels as well as in many man-made systems such as heat exchangers, nuclear reactors, desalination units, air separation units. In mini channel heat sink, the surface of the slab gets heated and the hot surface exchanges heat from hot surface to the cold fluid passing through the mini-channels. Thus the fluid gets heated and as the fluid carries the heat along with it, the surface temperature is controlled.

The rate of the heat transfer process and transport process depends on the surface area that varies with the diameter D for a circular tube. As diameter increases surface area increases, whereas the flow rate depends on the cross-sectional area which varies linearly with D2. Thus the tube surface area to volume ratio varies as 1/D which means as the diameter decreases, surface area to volume ratio increases.

Multiport minichannel and microchannel tube heat exchangers are used in various industrial applications and are produced in large quantities with many different geometries and lengths and therefore they are relatively inexpensive. Minichannel and microchannel tubes are ideal for use in compact and light weight heat exchangers.

Because of increasing use of these channels widely, it is required to make progress towards fast development of mini-micro channel heat sink design and for their applications as cooling systems for devices in which high heat flux is exposed. The mini/micro scale heat sink is widely used in electronics cooling, space thermal management, MEMS devices for biological and chemical analysis. Special characteristics of the mini channel are as discussed below:

High surface area per unit volume and high heat transfer coefficient.

The ratio of area cross-section of the solid substrate to that of the fluid domain is quite small. As a result of high heat transfer coefficient with high conductive material, the conduction resistance of the substrate is comparable to the convective resistance.

Considering a single cell from many parallel cells forming the minichannel heat sink, the heat is supplied to one side of the substrate (at the bottom side) while the other three sides are considered as adiabatic surface (assuming the channel is cut from two sides and the top side is assumed to have negligible heat losses). The result of this arrangement dictates that the mini/micro channel has variable heat flux around the channel perimeter.

In the present study, the effect of variation in the magnitude of heat flux on maximum peripheral temperature is analyzed. Different solid substrate materials are used: Copper, silicon, stainless steel, aluminium, lead, brass, tin, bronze and constantan. The analysis is performed with various cooling fluids: Water, mercury, engine oil, Cu-water and Al-water.

2 METHODOLOGY

For investigation about the phenomenon of heat transfer in mini channel heat sink, the geometrical configuration of the mini channel heat sink used is shown in figure 3.

It is a plate of length L, width W and height H having number of channels from which the fluid flows. All the channels are of same diameter and distance between two channels is also same for all.

The assumptions made are as follows:

- The fluid is Newtonian and incompressible with constant physical properties in steady state heat transfer problem.
- Negligible viscous heat dissipation.
- The flow is laminar[1].
- Hydrodynamically and thermally developing flow.
- Body force is neglected and no external force is applied.
- The radiation heat transfer is neglected.
- Thermal conductivity of the solid substrate is constant.
- No heat generation

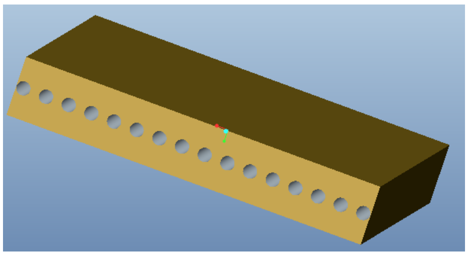

Fig. 3. Geometrical configuration of heat sink

Only a single channel is considered for the analysis of temperature distribution as shown in figure 4 which is attributed to the symmetrical design of the mini channel heat sink.

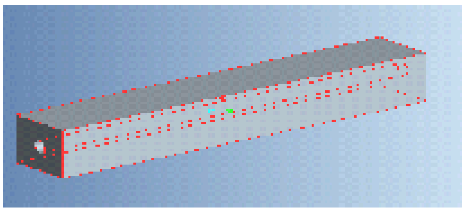

Fig. 4. Geometrical configuration of domain for a single channel

Uniform heat flux is supplied to the bottom side of the substrate, the top side of the substrate is assumed to be adiabatic (negligible heat loss) and the other two sides are considered as symmetry boundary conditions.

Dimensions of the domain are:
Length L = 8.13 mm
Width W = 8.13 mm
Depth D = 50 mm
Diameter of circular hole d = 1.91 mm

3 RESULTS AND DISCUSSION

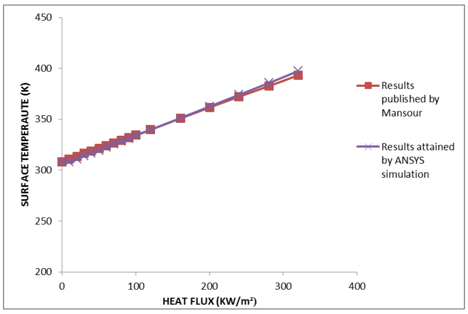

Fig. 5. Verification of results of average bottom surface temperature (Tsav) for combination of copper and mercury

For verification of methodology, the material of solid and fluid are selected same as taken by M. Khamis Mansour[8]. The results achieved by numerical simulation for those materials and fluids are compared with the same published by M. Khamis Mansour[8]. The results were found in good agreement with them as shown in figure 5, figure 6 and figure 7.

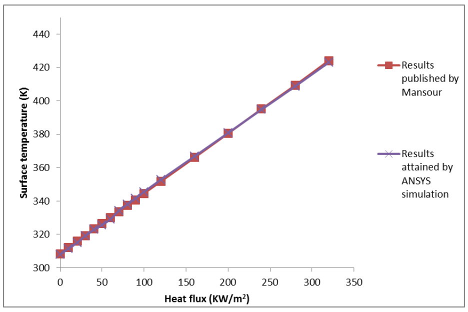

Fig. 6. Verification of results of average bottom surface temperature (Tsav) for combination of copper and water

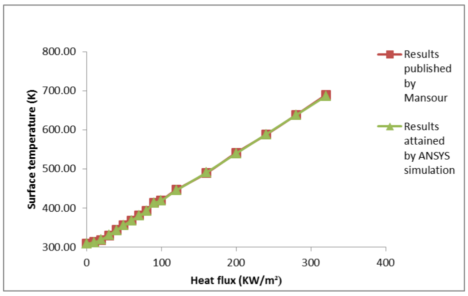

Fig. 7. Verification of results of average bottom surface temperature (Tsav) for combination of copper and engine oil

As mercury demonstrated good results compared to other fluids water and engine oil, it is used as reference. Figure 8 and 9 show graph of variation of average bottom surface temperature and average heat transfer coefficient of mini channel when mercury is used as coolant fluid respectively. The various solid materials used are: aluminium, lead, brass, tin, bronze, constantan, silicon.

It is observed from the figure 8 and 9 that tin as solid material gives highest average heat transfer coefficient and silicon as solid material gives lowest average bottom surface temperature for different values of heat flux.

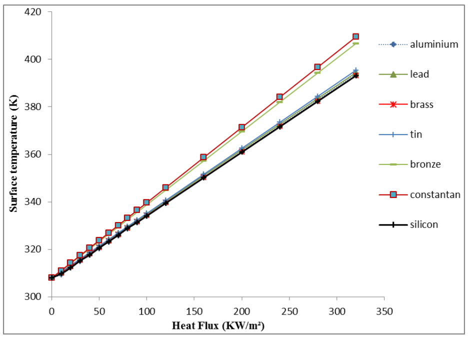

Fig. 8. Average bottom surface temperature using mercury with different solid materials

For heat flux value of 320 kW/m2, value of highest hav for tin as solid material is 2429.58 W/m2.C and for silicon it is 2369.69 W/m2.C. For silicon, value of Tsav for same heat flux value is 393.14 K and for tin, it is 395.43 K which is nearly same. Aluminium, brass and lead also illustrated nearly same results for Tsav when mercury is used as coolant fluid.

Figure 9 shows variation of values of average heat transfer coefficient with different values of heat flux ranging from 0 to 320 kW/m. It is seen from figure 9 that when mini channel is subjected to lower value of heat flux of about 0 to 120 kW/m, value of heat transfer coefficient is nearly same for all materials, but when the value of heat flux increases from 120 kW/m to 320 kW/m, minor variation is observed in values of average heat transfer coefficient for different solid materials as shown in figure 9.

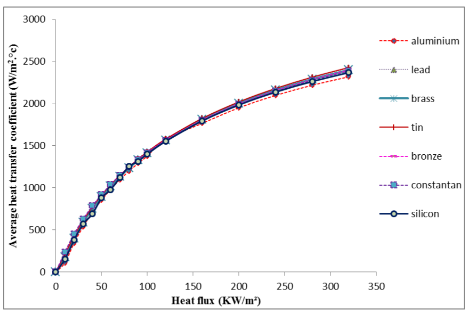

Fig. 9. Average heat transfer coefficient using mercury with different solid materials

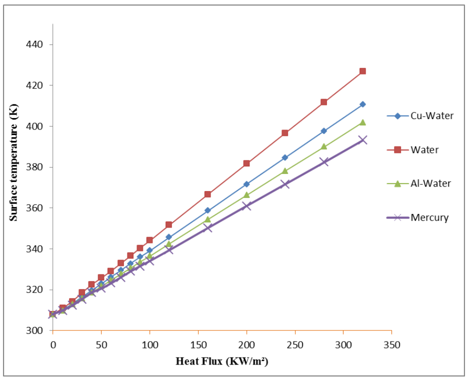

Fig. 10. Average bottom surface temperature using silicon with different coolant fluids

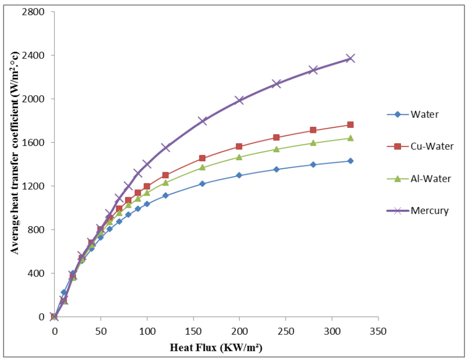

Fig. 11. Average heat transfer coefficient using silicon with different coolant fluids

Figures 10 and 11 discuss the variation of average bottom surface temperature and average heat transfer coefficient, when nano-fluids are considered as fluids and silicon is taken as solid material. The two nano-fluids used for simulation are: aluminium oxide and copper oxide. Both nano-fluids present lower values of average bottom surface temperature as compared to water but possess higher values of average bottom surface temperature as compared to mercury. When mini channel is exposed to higher value of heat flux (320 kW/m), the average bottom surface temperature is 410.64 K for Cu-water (copper oxide), 426.76 K for water, 401.82 K for Al-water (Aluminium oxide) and 393.44 K for mercury (solid material is silicon).

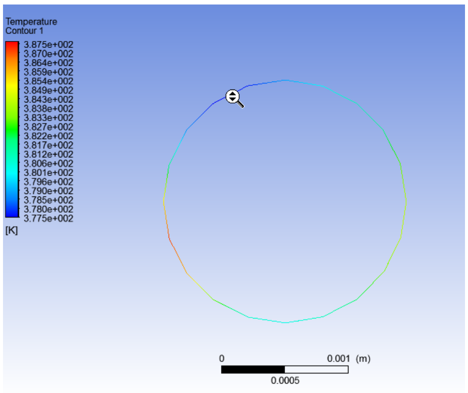

Fig. 12. Peripheral temperature distribution of mid-plane of mini-channel (in Z direction) using Al-water as a coolant fluid

As shown in figure 11, for lower values of heat flux, the average heat transfer coefficient remains nearly same for both the nano-fluids, but as the value of heat flux increases behaviour of nano-fluids changes. At higher value of heat flux, average heat transfer coefficient value are: mercury - 2369.69 W/m2.C, Cu-water - 1762.2 W/m2.C, Al-water - 1640.33 W/m2.C and water - 1431.19 W/m2.C.

From figure 10 and 11, it is seen that behaviour of nano-fluids is better than water, but poorer than mercury. Thermal properties of nano-fluids used for simulation is for volume fraction of 5%.

Figure 12 and 13 show peripheral temperature distribution at mid plane of mini channel (in z-direction) for heat flux value of 320 kW/m for nano-fluids. Maximum peripheral temperature difference for nano-fluids is around 10 K.

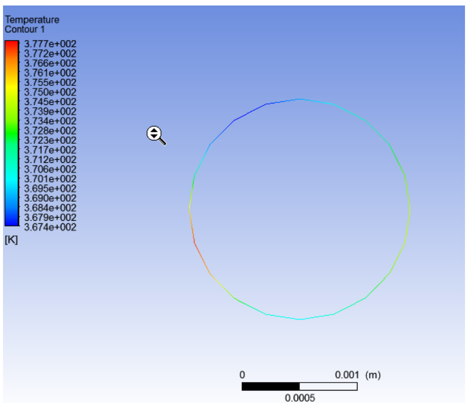

Fig. 13. Peripheral temperature distribution of mid-plane of mini-channel (in Z direction) using Cu-water as a coolant fluid

4 CONCLUSION

In the present study, the bottom surface of the mini channel is heated by applying heat flux and other three sides are considered as adiabatic wall. The effect of heat flux variation on heat transfer characteristics for the mini channel is investigated. Six solid materials are implemented to highlight the effect of variation of heat flux on the performance of mini channel, when mercury is used as coolant fluid. Two nano-fluids have been implemented for the comparison with the combination of water-silicon and mercury-silicon.

The conclusions obtained from the study are summarized below:

– For lower heat flux applications ($<$ 120 kW/m2), all six materials (aluminium, lead, brass, tin, bronze and constantan) present the similar average heat transfer coefficient for mercury being used as fluid.
– For higher heat flux applications ($>$ 120 kW/m2 and $<$ 320 kW/m2), tin illustrates the lower average bottom surface temperature and higher average heat transfer coefficient.
– The nano-fluids used (Al-water and Cu-water) definitely demonstrate better thermal behavior than water, but thermal behavior of mercury was better than nano-fluids used in the study.

References

1. Zhanying Zheng, David F Fletcher, Brian S Haynes. Laminar heat transfer simulations for periodic zigzag semi-circular channels: Chaotic advection and geometric effects. International Journal of Heat and Mass Transfer 2013; 62: 391401.
2. Satish G Kandlikar, Srinivas Garimella, Dongqing Li, Stphane Colin and Michael R King. Heat transfer and fluid flow in mini channel and micro channel. Elsevier (ISBN: 978-0-08-044527-4) 2007; 1-136.
3. Amador M Guzman, Maximiliano P Beiza, Andres J Diaz, Paul F Fischer, Juan C Ramos. Flow and heat transfer characteristics in micro and mini communicating pressure driven channel flows by numerical simulations. International Journal of Heat and Mass Transfer 2013; 58: 568577.
4. S-AB Al Omari. Enhancement of heat transfer from hot water by co-flowing it with mercury in a mini-channel. International Communications in Heat and Mass Transfer 2011; 38: 10731079.
5. Mostafa Keshavarz Moraveji, Reza Mohammadi Ardehali, Ali Ijam. CFD investigation of nanofluid effects (cooling performance and pressure drop) in mini-channel heat sink. International Communications in Heat and Mass Transfer 2013; 40: 5866.
6. G Hetsroni, A Mosyak, E Pogrebnyak, L P Yarin. Heat transfer in micro-channels: Comparison of experiments with theory and numerical results. International Journal of Heat and Mass Transfer 2005; 48: 55805601.
7. Pramod Kumar and M R Nagraj. CFD Analysis of Fluid Flow and Heat Transfer in Two Phase Flow Microchannels. International Journal of Engineering Research & Technology 2013; Vol. 2 Issue 8: 2132-2143.
8. M Khamis Mansour. Numerical analysis of conjugate heat transfer for circular liquid mini channel. JP journal of Heat and Mass transfer 2013; Vol. 7 Number 1: 85-111.

About Authors

Working as assistant professor in sigma institute of engineering, Vadodara since 1st July,2014, as a assistant professor.

Mr. Paresh Chandrakant Chhotani had worked as an Assistant Professor in Mechanical engineering department at Chhotubhai Gopalbhai Patel institute of Technology till 31st December, 2016. During the tenure, he had been involved in the teaching of Analytical Methods in Heat Transfer, Engineering Mathematics for Problem Solving and Computational Fluid Dynamics subjects to the Post Graduate students.