Int. J. Mech. Eng. & Rob. Res. 2014

International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 3, No. 3, July 2014

Research Paper

FLOW AND HEAT TRANSFER SIMULATION IN MINI CHANNEL

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This paper presents the a numerical simulation of a front side of mini channel (for z = 0 surface) to investigate the temperature distribution obtained by solid domain using boundary conditions . Here uniform heat flux is applied to the bottom side of the mini channel top surface is assumed to be adiabatic and remaining two surfaces are selected 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. Here thermal characteristics of the mini channel is represented by maximum temperature obtained by the periphery of the mini channel. In order to obtain the behaviour of thermal conductivity of the material in heat transfer characteristics of the mini channel three different solid material is used one is copper which has highest thermal conductivity second one is stainless steel which is lower thermal conductive material and third one is silicon whose thermal conductivity ranges between the thermal conductivity of the other two solid materials copper and stainless steel. For the cooling purpose of the mini channel three different cooling fluids are taken into analysis water, engine oil and mercury. And also comparing the results of the best fluid and solid to that of the results obtained by researchers.

Keywords: laminar flow, Mini channel, Fluent, Mercury, Water, Engine oil

INTRODUCTION

Mini Channel Heat Exchanger

Classification of heat exchangers are based on the working principles, geometry of construction, heat transfer mechanisms, fluid flow arrangements, and transfer processes. They can also be classified based on sizes and surface area to volume ratio. Based on channel dimensions, especially the characteristic length or hydraulic diameter, two main classification schemes are available in open the literature which is shown in table below.

Channels are of different cross sections may be its circular, triangular, rectangular, trapezoidal, etc. Channel used for the current

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study is the circular shape mini channel. Circular channels are most likely as shown in Figure 1. The MICHX used in the current study is of rectangular shape and holes are placed in this rectangular space of different materials and mini channels are placed inside the holes of this rectangular block. There is no gap in between adjacent channels for fluid interaction. Flat heat transfer surfaces at the top and the bottom faces of each holes offer the fluid flow an excellent contact with the heating surfaces, which leads to elevated heat transfer over the conventional heat exchangers of isolated tube rows. Flow, in a cross-flow orientation, over tubes in inline or staggered arrangement, which is widely used in many conventional heat exchangers applications forms a wake region at the rear of each tube when fluid is flowing in the tube. Figures 1 and 2 illustrate the differences between tubes and monolithic channels structures inside heat exchanger core.

Figure 1: Circular Shapes Mini Channel Flow Passage

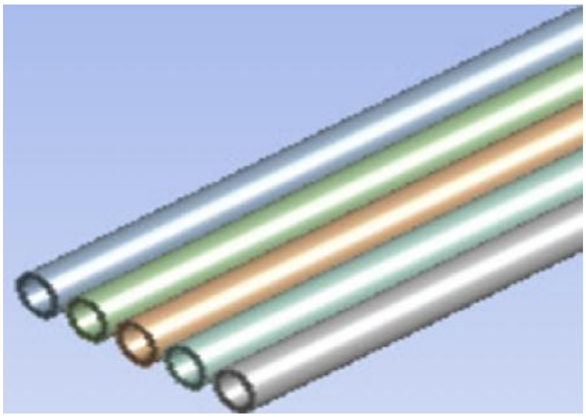
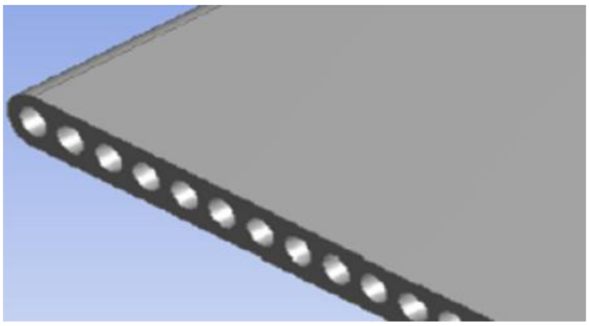


Figure 2: Circular Channels Inside Solid Domain



Why to Choose Smaller Flow Passages?

Fluid flow inside channels is at the heart of many natural systems. Heat and mass transfer is accomplished across the channel walls in biological systems as well as in many man-made systems. In general, in mini channel transportation of heat occurs through the solid region and fluid is passing through the fluid region means through holes of the block. As some surface of the slab is heated so much so that the need of cooling this plate or slab is necessary so for that this mini channels are used block is placed on that heated surface and cold fluid is passing through this holes as the fluid is passing through this holes hot surfaces exchanges heat from hot surface to the cold fluid so the fluid get heated and then this fluid is removed and new fluid is inserted again and again.

A channel serves to accomplish two objectives:

1. Bring a fluid into intimate contact with the channel walls; and
2. Bring fresh fluid to the walls and remove fluid away from the walls as the transport process is accomplished.

Classification of Channels

A classification of the channels is described in given table:

Table 1: Channel Classification According to Mehendale

Microchannels	1-100 μm
Meso-channel	100 μm-1 mm
Compact passages	1-6 mm
Conventional	passages > 6 mm

Table 2: Channel Classification According to Kandlinkar

Conventional Passages	> 3 mm
Minichannels	3 mm ≥ D > 200 μm
Microchannels	200 μm ≥ D > 10 μm
Transitional Microchannels	10 μm ≥ D > 1 μm
Transitional Nanochannels	1 μm ≥ D > 0.1 μm
Nanochannels	0.1 μm ≥ D

Special characteristics of the mini channel are a s 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. And 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 sided while the topside is assumed to have a negligible heat losses). The result of this arrangement dictates the mini/micro channel to have variable heat flux around the channel perimeter.

All the above mentioned concerns imposes that the heat transfer condition which the fluid actually experiences at the solid-fluid interface significantly deviates from the conventional uniform heat flux or uniform wall temperature heat transfer problem heat transfer problem.

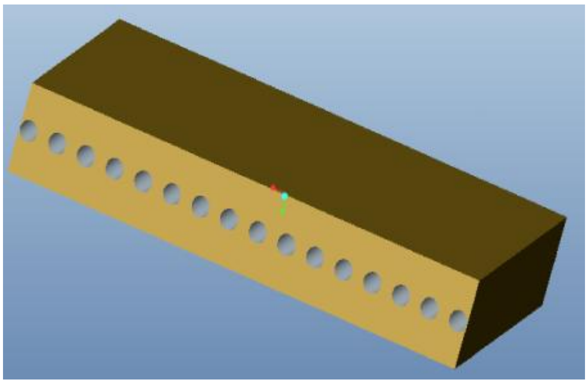
Here in this study addressing the effect of heat flux magnitude which is applied on one of the surface of the mini channel, on the heat transfer characteristics. and for this representation discussion effect of heat flux values are compared with maximum peripheral temperature. Here analysis is performed with the help of three solid substrate materials copper, silicon and stainless still. The analysis is performed with three different cooling liquids mercury, water and engine oil.

MATHEMATICAL MODELLING

For investigation about the heat transfer in mini channel heat sink, the geometrical configuration of the mini channel heat sink is as shown in Figure 3.

It is a plate of length L, width W and height H in which number of cells are there from which fluid is flowing and all the cells are of same diameter and distance between two cells is also same for all.

Figure 3: Geometrical Configuration of the Two Different Heat Sink



The assumptions which have been taken into account are as follows:

1. The fluid is newtonian and incompressible with constant physical properties in steady state heat transfer problem.
2. Negligible viscous heat dissipation.
3. The flow is laminar.
4. Hydrodynamic and thermal developing flow.
5. Body force is neglected and no external force is applied.
6. The radiation heat transfer is neglected.
7. Thermal conductivity of the solid substrate is constant.
8. No heat generation.

Here this problem of heat transfer in mini channel, conjugate heat transfer problem is consisting of the flowing fluid and the channel wall is governed by the respective energy equations in 3D form. Here, we are selecting one cell for the calculation of temperature distribution in solid region as show in Figure 4. This is attributed to the symmetrical design of the many cells forming the mini channel heat sink.

Here, Heat 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 condition.

Figure 4: Geometrical Configuration of Domain for the Unit Cell

The governing equations for the conservation of mass, momentum and energy in the solid and liquid regions in circular mini channels are as follows:

Governing Equation for Fluid Domain

$$\frac{\partial V}{\partial r} + \frac{1}{r} V_r + \frac{1}{r}\frac{\partial V_\theta}{\partial \theta} + \frac{\partial V_z}{\partial z} = 0 \qquad ...(1)$$

$$V_r \frac{\partial V}{\partial r} + \frac{V_\theta}{r}\frac{\partial V}{\partial \theta} + V_z \frac{\partial V}{\partial z} - \frac{1}{r} V_\theta^2 - \frac{1}{\rho_f}\frac{\partial P}{\partial r}$$

$$+\nu \left[\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V}{\partial z^2} - \frac{V}{r^2} - \frac{2}{r^2}\frac{\partial V_\theta}{\partial \theta} \right] \qquad ...(2)$$

$$V_r \frac{\partial V_\theta}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_\theta}{\partial \theta} + V_z \frac{\partial V_\theta}{\partial z} - V_r \frac{V_\theta}{r} = -\frac{1}{\rho_f}\frac{\partial P}{r\partial \theta}$$

$$+\nu \left[\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial V_\theta}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V_\theta}{\partial z^2} - \frac{V_\theta}{r^2} - \frac{2}{r^2}\frac{\partial V_r}{\partial \theta} \right] \qquad ...(3)$$

$$V_r \frac{\partial V_z}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_z}{\partial \theta} + V_z \frac{\partial V_z}{\partial z} = -\frac{1}{\rho_f}\frac{\partial P}{\partial z}$$

$$+\nu \left[\frac{\partial^2 V_z}{\partial r^2} + \frac{1}{r}\frac{\partial V_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V_z}{\partial z^2} + \frac{\partial^2 V}{\partial z^2} \right] \qquad ...(4)$$

$$V_r \frac{\partial T_f}{\partial r} + \frac{V_\theta}{r}\frac{\partial T_f}{\partial \theta} + V_z \frac{\partial T_f}{\partial z}$$

$$= \alpha \left[\frac{\partial^2 T_f}{\partial r^2} + \frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T_f}{\partial \theta^2} + \frac{\partial^2 T_f}{\partial \theta^2} \right] \qquad ...(5)$$

Solid Domain

Now for solid domain, assuming steady state conditions and constant properties of the wall, the energy equation for this region is as follows:

$$\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} + \frac{\partial^2 T_s}{\partial z^2} = 0 \qquad ...(6)$$

Since it is a mini channel simulation problem we have to use cylindrical coordinate system to simulate the model convection within the circular channel while the cartesian coordinate system is used to simulate the conduction within the solid substrate domain.

Boundary Conditions

At Inlet Section

At the inlet section of the fluid domain,

- Velocity and temperature are considered as uniform,
- For the solid domain velocity is zero, and
- Wall is adiabatic.

At $z = 0, 0 \le r < \frac{d}{2}, V_r = 0, V_{-} = 0, V_{z_{in}} = V_{f_{in}}, T_f = T_{f_{in}}$

At $z = 0, r \ge \frac{d}{2}, 0 < x < W, 0 < y < H,$

$$V_x = V_y = V_z = 0, \frac{\partial T_s}{\partial z} = 0$$

At Outlet Section

Flow is assumed to be a fully developed at the channel outlet and the outlet boundaries for the solid domain are same as that of the inlet section:

At $z = L, 0 \le r < \frac{d}{2}, \frac{\partial V_r}{\partial r} = \frac{\partial V_{-}}{\partial \overline{\ }} = \frac{\partial V_z}{\partial z} = 0, \frac{\partial^2 T_f}{\partial z^2} = 0$

At $z = L, r \ge \frac{d}{2}, 0 < x < W, 0 < y < H,$

$$V_x = V_y = V_z = 0, \frac{\partial T_s}{\partial z} = 0$$

At Solid-Fluid Interface

No slip condition is assumed at the wall interface between the solid and fluid domain:

At $0 \le z \le L, r = \frac{d}{2}, V_r = V_1 = V_z = 0,$

$$T_f = T_s, K_f \frac{\partial T_f}{\partial r} = K_s \frac{\partial T_s}{\partial r}$$

At Solid Walls

Adiabatic boundary conditions are applied to all the boundaries of the solid region except the heat sink bottom wall , where a constant heat flux is assumed:

At $x = 0, 0 \le y \le H, 0 \le z \le L,$

$$\frac{\partial T_s}{\partial y} = \frac{\partial T_s}{\partial z} = 0, V_x = V_y = V_z = 0$$

At $x = W, 0 \le y \le H, 0 \le z \le L,$

$$\frac{\partial T_s}{\partial y} = \frac{\partial T_s}{\partial z} = 0, V_x = V_y = V_z = 0$$

At $0 \le x \le W, y = 0, 0 \le z \le L$

$$-K_s \frac{\partial T_s}{\partial x} = -K_s \frac{\partial T_s}{\partial z} = q, V_x = V_y = V_z = 0$$

At $0 \le x \le W, y = H, 0 \le z \le L$

$$\frac{\partial T_s}{\partial x} = \frac{\partial T_s}{\partial z} = 0, V_x = V_y = V_z = 0$$

RESULTS AND DISCUSION

The numerical analysis and simulation using ANSYS software is discussed in previous chapter. Now here discussion is taken out for the thermal characteristics of the mini channel in terms of temperature distribution. Here different fluids and different solid materials are taken one by one to each other for the simulation. Water as cooling liquid and silicon as a substrate material are selected as the base operating condition for mini channel heat sink with the variation of heat flux. Two fluid selection is taken out with the help of thermal property of the fluid. Here mercury is selected due to its high thermal property with respect to water and other fluid engine oil acts as coolant which has poorer thermal properties as compared to water. And in solid material selection of material is done with respect to thermal conductivity. Copper has higher thermal conductivity with respect to silicon and steel has lower thermal conductivity as compared to silicon. So behaviour of thermal property (temperature distribution) is discussed in this section by changing flux values. Surface temperature is calculated from the outlet temperature of the fluid domain.

At higher heat flux value, it is interesting to note that surface temperature of periphery of the mini channel for coolant engine oil is higher as compared to other liquid coolant water and mercury which we have used.

Figure 5 shows the surface temperature of mini channel periphery for copper as substrate material used for solid domain, with changes in value of heat flux. It is seen from the figure that engine oil has highest value of periphery temperature as respect to other fluids water and mercury. When fluid is water or mercury peripheral temperature of mini channel is almost same for both fluids when solid material is copper. Figure 6 shows the surface temperature of mini channel periphery for stainless steel as substrate material used for solid domain, with changes in value of heat flux. It is seen from the figure that engine oil has highest value of periphery temperature as respect to other fluids water and mercury. When fluid is water or mercury peripheral

Figure 5: Peripheral Temperature Distribution for Copper as Substrate Material

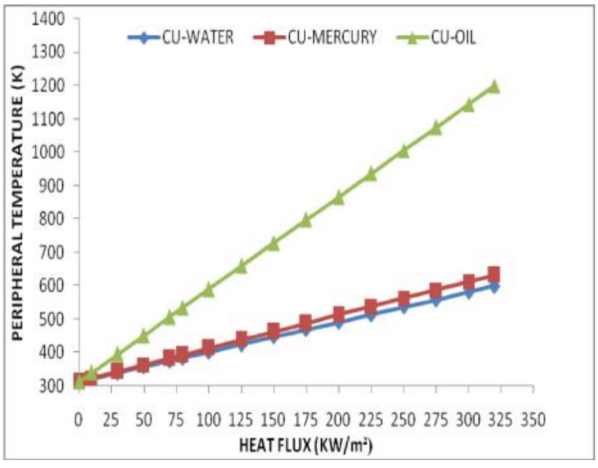


Figure 6: Peripheral Temperature Distribution for Steel as Substrate Material

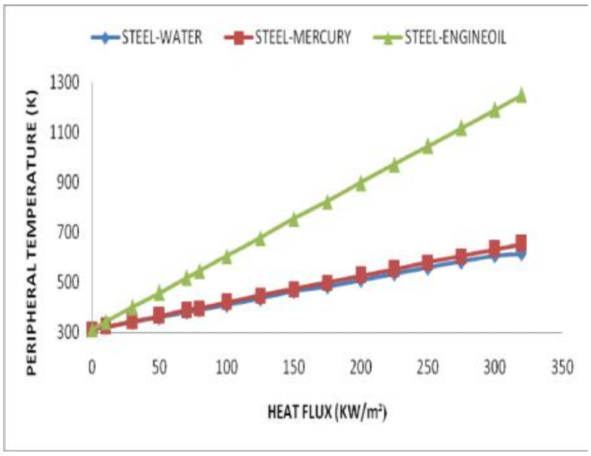
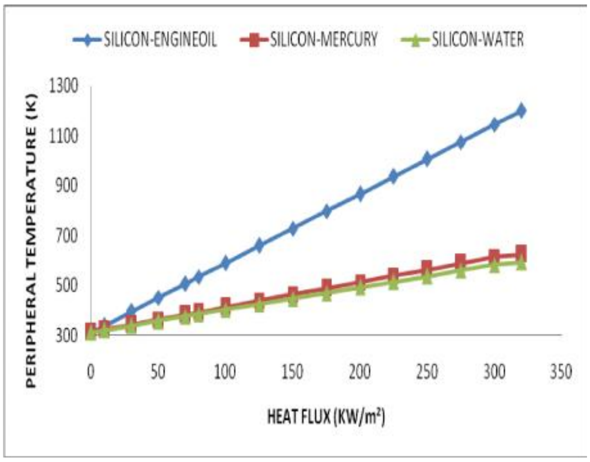


Figure 7: Peripheral Temperature Distribution for Silicon as Substrate Material



temperature of mini channel is almost same for both fluids when solid material is stainless steel. Figure 7 shows the surface temperature of mini channel periphery for silicon as substrate material used for solid domain, with changes in value of heat flux. It is seen from the figure that engine oil has highest value of periphery temperature as respect to other fluids water and mercury. When fluid is water or mercury peripheral temperature of mini channel is almost same for both fluids when solid material is silicon. Figure 8 shows the surface temperature of mini channel periphery for water used as fluid for fluid domain, with changes in value of heat flux. It is seen from the figure that stainless steel has highest value of periphery temperature as respect to other solid materials copper and silicon. When solid substrate material is copper or silicon peripheral temperature of mini channel is almost same for both solids when fluid used is water. Figure 9 shows the surface temperature of mini channel periphery for mercury used as fluid for fluid domain, with changes in value of heat flux. It is seen from the figure that stainless

Figure 8: Peripheral Temperature Distribution for Water as Coolant Medium

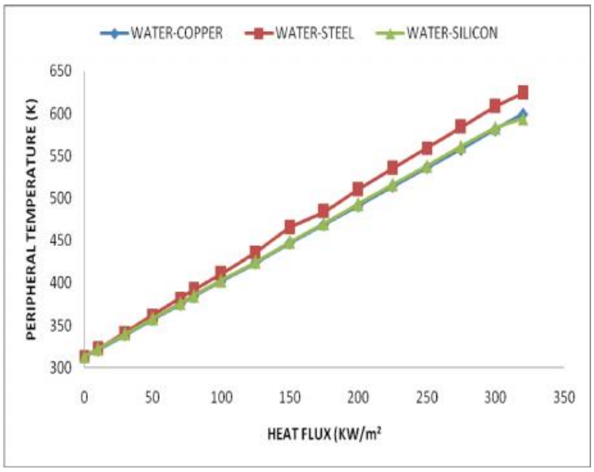


Figure 9: Peripheral Temperature Distribution for Mercury as Coolant Medium

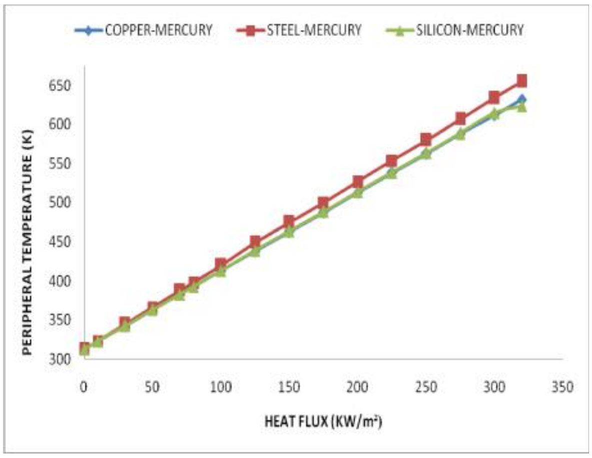
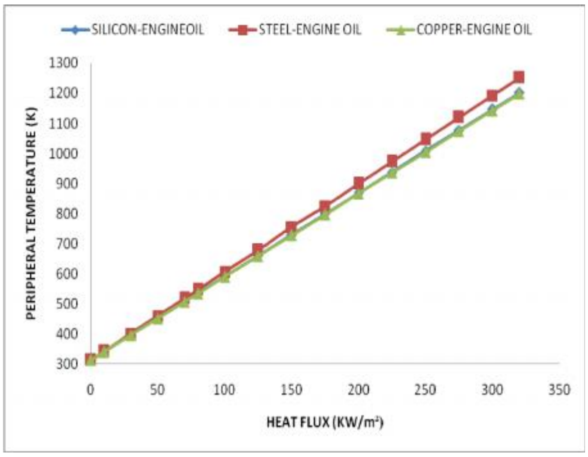


Figure 10: Peripheral Temperature Distribution for Engine Oil as Coolant Medium



steel has highest value of periphery temperature as respect to other solid materials copper and silicon. When solid substrate material is copper or silicon peripheral temperature of mini channel is almost same for both solids when fluid used is mercury. Figure 10 shows the surface temperature of mini channel periphery for engine oil used as fluid for fluid domain, with changes in value of heat flux. It is seen from the figure that stainless steel has highest value of periphery temperature as respect to other solid materials copper and silicon. When solid substrate material is copper or silicon peripheral temperature of mini channel is almost same for both solids when fluid used is engine oil. As shown in the graph whenever high thermal conductive material is used for solid domain (stainless steel) the peripheral temperature difference is higher as compared to the lower thermal conductive material. Copper as substrate material comes in the centre of the other two solid substrate material when using all fluids which is discussed earlier one by one as shown in the Figures 8-10. And the results of the copper material obtained by simulation is nearly same as that of silicon till the results of the silicon is so good as compared to other solid materials.

As the fluid is selected one by one for all solid substrate materials from the graph of different values of heat flux against the maximum peripheral temperature of the mini channel, the results of the mercury as fluid is selected as best since it gives highest heat

Figure 11: Peripheral Temperature Distribution of Silicon and Mercury

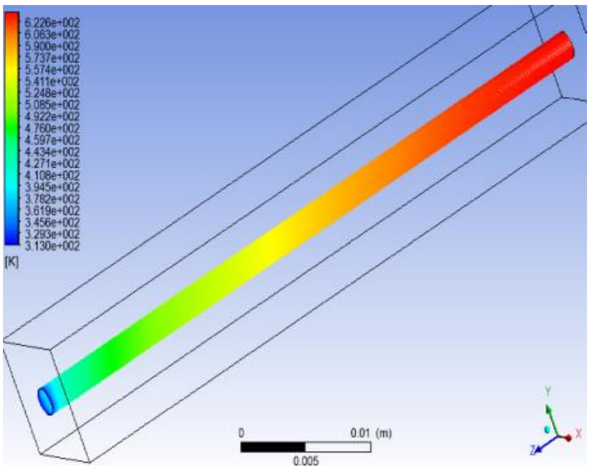
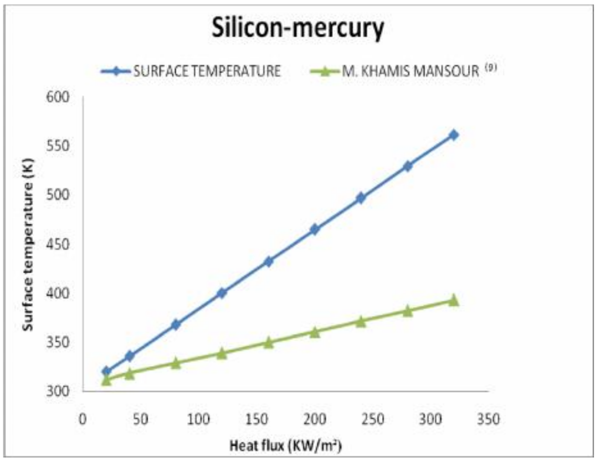


Figure 12: Average Bottom Surface Temp. for Silicon and Mercury as Solid and Fluid Material



transfer coefficient value as compared to other fluids. And also temperature distribution on the periphery of the mini channel is also lowest as shown in graph of mercury as fluid. So if the value of the maximum peripheral temperature of the mini channel and heat transfer coefficient is lower and higher respectively. Figure 11 shows the peripheral temperature distribution for copper as solid substrate material and mercury as fluid since it gives best results for cooling purpose. Figure12 shows the variation of average bottom surface temperature of the mini channel to that of the obtained by researcher M. Khamis Mansour. This Figure 11 shows that as the area of the solid substrate is increases the average bottom surface of the mini channel is also increases. as shown in Figure 12 there is about 168.6 K temperature difference obtained when area of the solid domain is increases from 3.3 × 4.0 mm to 8.13 × 8.13 mm. Since the area used by researcher M. Khamis Mansour is small as compared to the domain used in this study, average of temperature of bottom surface is obtained about 393.14 K and average of the bottom surface temperature of the domain used for the study is 561.75 K. So as the area of the solid domain increases heat transfer area also increases and therefore higher temperature obtained in this study. So, Whenever channel used for cooling purpose select lowest cross section as possible of the solid domain so that average surface temperature of the bottom surface is low and it cools the domain.

CONCLUSION

From the above study following conclusions may occur:

- The behaviour of the periphery of the mini channel is very different when domain is subjected to the higher heat flux value or when it is subjected to lower heat flux value.
- Temperature difference of the periphery of the mini channel is higher when the solid domain is of the higher thermal conductive material.
- At maximum value of the heat flux (320 KW/m^2) steel with engine oil has highest peripheral temperature and silicon and mercury has lowest peripheral temperature.
- With the increase in the area of the solid domain, average bottom surface temperature of the mini channel is also increases.

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