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Numerical Investigation on Heat Sink Material for Temperature Control of Electronics

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Abstract. This article reports a numerical investigation on advanced heat sink material for thermal management of electronics. We investigated heat transfer enhancement using different heat sink materials. The cooling medium used for analysis is water. Forced water convection in copper alloy and aluminum alloy Al6060, Al6063 material micro-channel heat sinks cooling was studied numerically using Ansys Fluent. The heat sink is an essential element in a PC. The total efficiency, price, and size of the electronic device depend on the heat sink material. The heat transfer rate is a direct function of heat sink material. The simulation used three different velocities, 3, 5, and 7 m/s; the constant heat flux value taken is 8×10^5 W/m^2. The parameters considered for heat sink material are thermal conductivity, thermal expansion coefficient, density, and cost. The ceramic materials have a low thermal expansion coefficient and higher thermal conductivity hence used as a substrate. Results show that aluminum alloys are suitable materials for heat sinks because of their cost, weight, and ease of machinability.

Keywords: Heat sink material, Temperature control, Electronic cooling.

1. Introduction

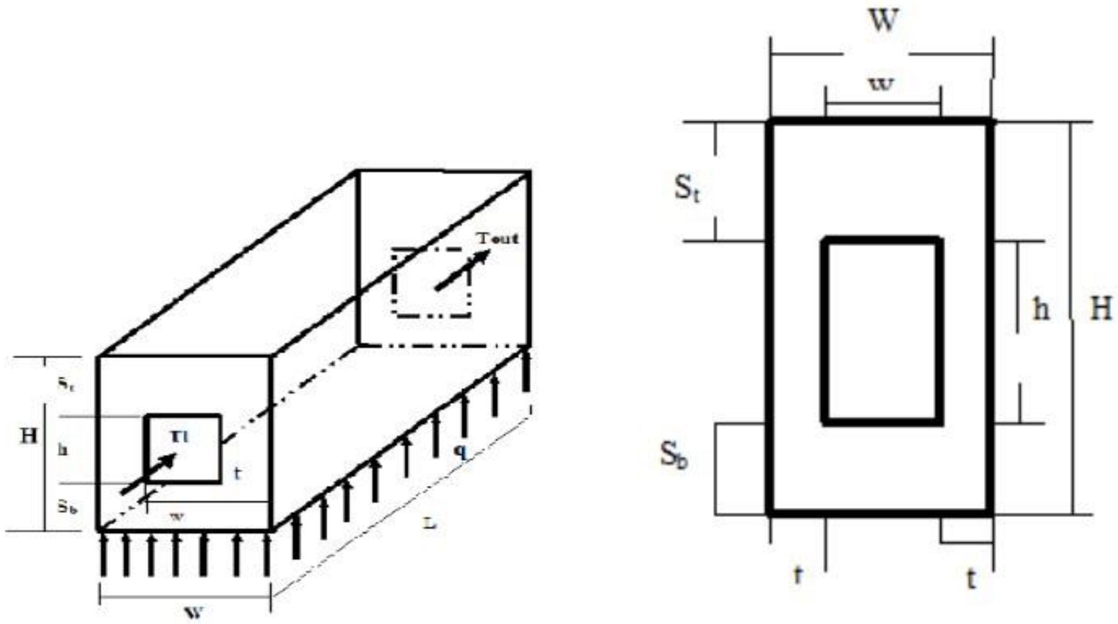
Power electronics applications always demand high efficiency, power density, and frequency. It is always preferable to include passive devices and semiconductor control circuits in one bunch. Therefore, an electronic package is a driving force for the inclusion of a power electronic system. Several researchers worldwide have been working on the developments in microchannel heat sink in the past few decades. However, it continues to reinforce the design and improve performance by new research in modeling and analytical techniques. The development of many conductor designs and different geometries has modernized the heat sink industry. Recently many works reported to optimize and characterize the performance of fanned heat sinks, amongst others. The exclusive properties of a heat sink are the thermal expansion coefficient and thermal conductivity. The main aim of this work is to predict suitable heat sink material for better thermal performance. Gaikwad et al. [1] have conducted experiments to check the dimensional accuracy of MCHS using tetra-methyl-ammonium hydroxide and LASER machining methods. The authors found better thermal performance at higher flow rates. Zhao and Lu [2] have analysed heat transfer performance from microchannel heat sink (MCHS). They found better results in turbulent flow compared to laminar counterpart. Hung et al. [3] have numerically studied cooling of heated modules under forced convection and found enhanced heat transfer as a result. Ng and Poh [4] have numerically studied manifold MCHS to transport high heat fluxes. They found heat transfer from MCHS was greatly dependent on the flow rate. Several investigators [5, 6, 7] have studied transport modeling in MCHS of different types to analyse their suitability and to figure out performance from theoretical aspects. Several authors [8, 9, 10] have worked on the most critical scenarios of MCHS material to study the effects of thermal conductivity and the thermal expansion for heat transfer.

MCHS absorbs excessive heat generated by electronic equipment and dissipates it to the liquid or air used as a coolant to maintain the optimum temperature of the device. Aluminum and copper alloys are most preferred materials for MCHS. The commonly used alloys for MCHS are 6060, 6061, and 6063 for different applications as their extrusions are comparatively simple. Copper Molybdenum (CuMo) having k = 215 W/m K and its composition Mo60Cu40 has copper weight by 40%. Copper Tungsten having k = 175 W/m K are preferred for heat sinks with composition of W 90%, and Cu 10%. This work aims to find thermal materials that may be important to the production of a heat sink. This study also focused on the use of heat sink materials to show their effects on heat transfer. The main objectives of the work are:

1. To study the single MCHS for various velocities numerically.
2. Predict temperature and pressure profiles for constant heat flux at different velocities.
3. To define Nusselt number and average heat transfer coefficient for different velocities and materials at constant heat flux.

2. The model materials and methods

Fig. 1 shows a rectangular micro-channel with its specific dimensions of length, L = 8 mm, depth, h = 150 μm, width w = 45 μm, and 35 μm thickness. The heat flux was applied to the bottom of the heat sink.



(a) (b)

Figure 1. (a) Heat sink model and (b) Details of channel.

This geometrical model with the entirely developed laminar flow analysed heat dissipation in an MCSH for various velocities and materials. Table 1 show the dimensions of MCSH.

Table 1. Dimensions of MCHS

L	W	w	H	h	S_t	S_b	t
8	80	45	700	150	340	210	17.5

†All dimensions are in μm

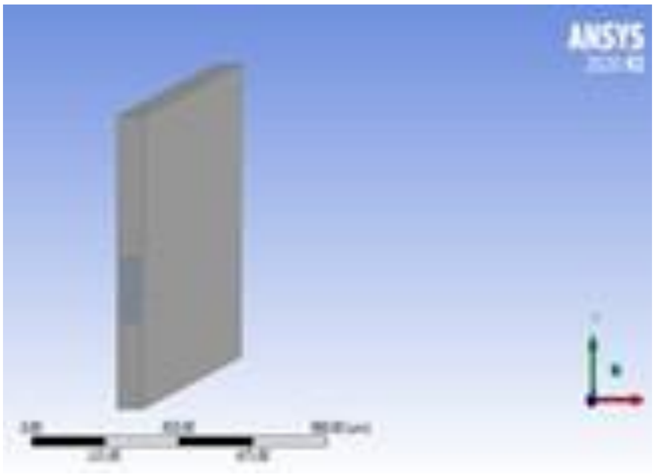


Figure 2. CAD model

2.1. *Meshing and grid responsive study*

The Ansys Fluent software is used for simulations. The geometry, and mesh was generated using the software. The boundary conditions for laminar flow module, and the materials are selected from Ansys fluent. The grid responsive test is considered to a model for suitable to the domain. The grid responsive study was performed with 160300, 170450, 180555, 190265, and 195400 number of cells. The number of grids above and below 180555 has no significant difference in the simulated temperatures.

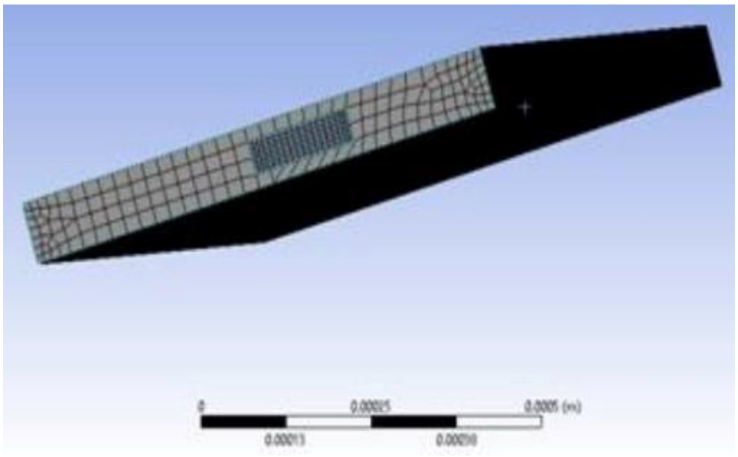


Figure 3. Expanded view of the mesh

Therefore, the mesh with 180555 number of grids was used for the entire simulation study. The mesh sensitivity study was administered for MCHS of specifications as shown in Table 1. The pressure-based steady-state solver is used from the simulation software.

The viscous k - ε laminar flow model is considered from the Ansys CFD software. The fluid domain used is water, and the solid Domains are copper alloy and aluminum alloys. Fig. 3 shows the expanded view of the mesh used in the study. The thermo-physical properties that influence the heat transfer from fluid and solids are given in Table 2 and 3, respectively.

2.2. *Boundary conditions and assumptions*

Boundary conditions are u = v = w = 0 (No slip condition, for all other stationary walls except bottom wall) at inlet: x = 0, T = T_∞ = 298 K, and u_0 = 3, 5, and 7 m/s.

at outlet: x = L, p = p_∞ (atm. pressure).

Following are the assumptions made in the simulation study:

1. Negligible radiation heat transfer
2. Constant thermophysical Properties
3. The flow is laminar and incompressible

5. Bottom Wall Boundary Condition: Constant Wall heat flux 8×10^{5} W/m^2

2.3. Governing Equations

Eqs. 1 - 5 are continuity equation, momentum equations in x, y, z direction for fluid and energy equation for solid solve coupling between fluid and solid region. Eq. 6 - 9 describes the hydraulic diameter, Reynolds number, heat transfer coefficient, and the Nusselt number. Transport equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

x - mom equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

y - mom equation

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right] \tag{3}$$

z - mom equation

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \tag{4}$$

Heat rate equation,

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right] \tag{5}$$

The hydraulic diameter,

$$D_h=\frac{4A}{P}=\frac{4hw}{2(h+w)} \tag{6}$$

Reynolds number,

$$Re=\frac{\rho vL}{\mu} \tag{7}$$

Heat transfer coefficient,

$$h=\frac{\Delta T}{q} \tag{8}$$

Average Nusselt number

$$Nu = \frac{hD}{k_f} \tag{9}$$

Table 2. Properties of fluid

Fluid	ρf, kg m−3	kf, W m−1 K −1	μf, kg m−1 s−1	Cp, J kg−1 K−1	T, K
Water	999.3	0.70	0.001004	4182	298

Table 3. Properties of Solids

Solids	ρs, kg m−3	ks, W m−1K−1	Cp, J kg−1 K−1
Al6060	2700	210	890
Al6063	2690	200	900
CuMo	9680	215	300

3. Results and Discussion

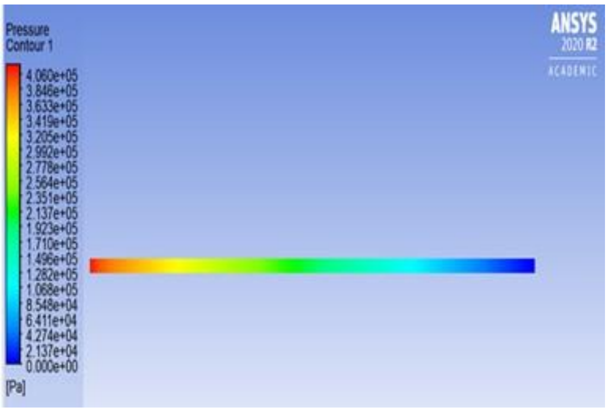
Numerical simulations have been performed using Ansys Fluent. The temperature and pressure contours are obtained from the simulation study, and the consequence at average heat transfer coefficient, temperature distribution in MCHS. The solid figure is progressive to resolve flow, conjugate heat transit within the micro channel placed conductor for electronics cooling applications.

3.1. Simulation of Single Micro-channel

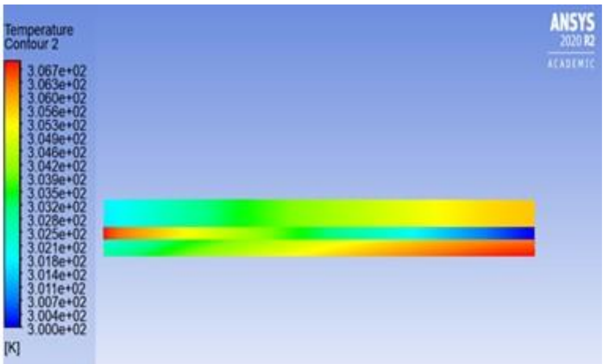
Simulated the single microchannel, and results of temperature contours plot, pressure contours plot, average Nusselt number, average heat transfer coefficient inequality besides the flow, and the consequence of averaged heat flux at various microchannel walls presented.

3.2. Temperature and Pressure Contours for Copper Alloy at velocity 7 m/s

The fluid is entered through the micro-channel at inlet velocity 7 m/s with a constant inlet temperature 25 $^{\circ}C$ and the bottom wall of a heat sink is applied to constant heat flux q = 8×10^5 W/m^2. Fig. 4 shows the temperature and pressure contours inside the channel. The maximum pressure of 406000 Pa and the maximum temperature of 306 K has occurred for the copper alloy heat sink using a water flow velocity of 7 m/s.



(a)

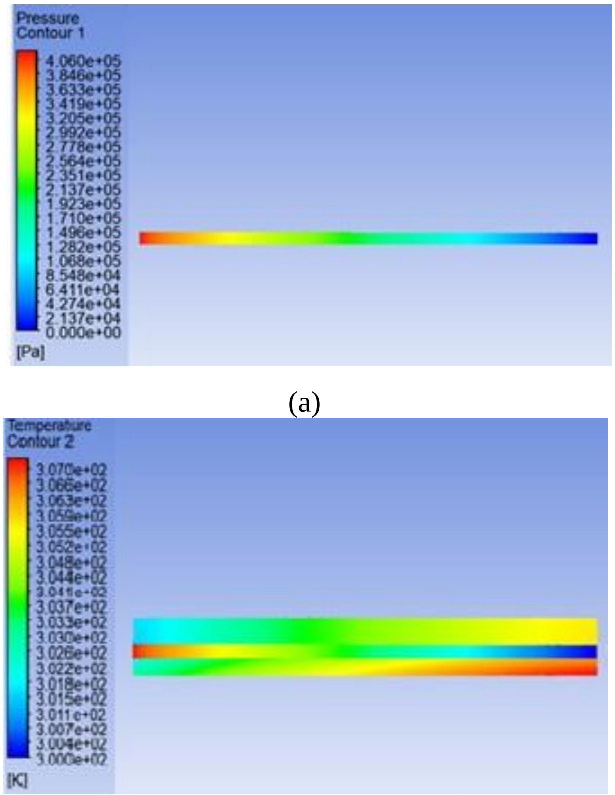


(b)

Figure 4. (a) Pressure and (b) temperature contours for copper alloy at velocity 7 m/s.

3.3. Temperature and pressure contours for aluminum alloy 6060 at velocity 7m/s

The simulation results obtained for pressure and temperature contours using aluminum alloy 6060 at 7 m/s velocity are shown in Fig. 5. The maximum pressure obtained for Al 6060 is 406000 Pa and the maximum temperature occurred was 307 K.



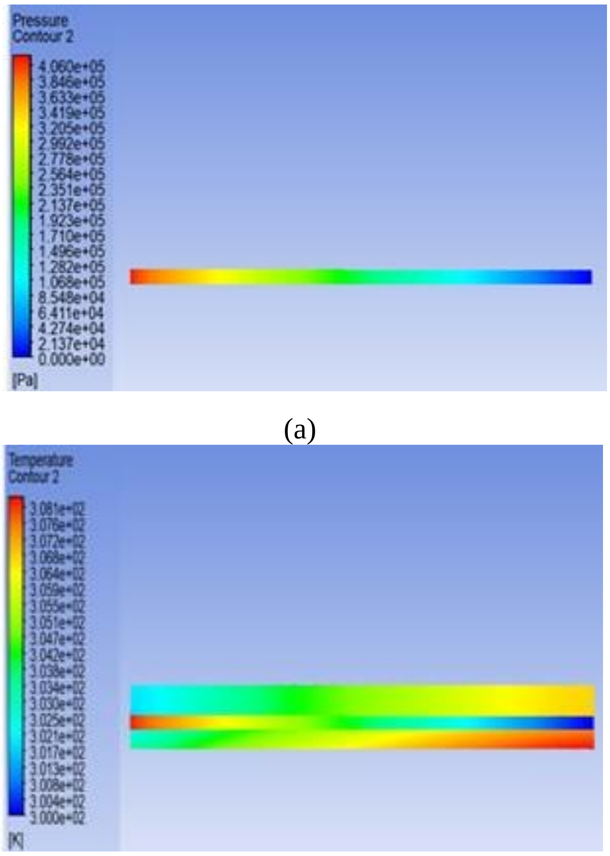
(a)

(b)

Figure 5. (a) Pressure and (b) temperature contours for aluminum alloy 6060 at velocity 7 m/s.

3.4. Temperature and Pressure Contours for Aluminum Alloy 6063 at velocity 7 m/s

Fig. 6 shows temperature and pressure Contours for aluminum alloy 6063 at velocity 7 m/s. The maximum pressure obtained was 406000 Pa, and the maximum temperature occurred was 308 K. The maximum pressure contours show almost the same values. The temperature values in the case of copper alloys are minimum, and that for Al 6063 is maximum using 7 m/s of flow velocity.



(a)

(b)

Figure 6. (a) Pressure and (b) temperature contours for aluminum alloy 6063 at velocity 7 m/s.

3.5. Effect of velocity and thermal conductivity of fluid on heat transfer

Effect of various fluid velocities used in the study, thermal conductivity of heat sink materials viz. Al6060, Al6063, copper alloy (CuMo) is shown in Fig. 7. The heat transfer characteristics were obtained by supported dimensional analysis and closely associated with the surface heat transfer properties. At an inlet water flow velocity of 3 m/s, the Nusselt number value for copper alloy is 4.6 and that for both aluminum alloys was about 3.4. Whereas, at water inlet velocity of 5 m/s the value of Nu for copper alloy is 6.2. In the case of Al 6063 the Nu value is 5.6 and that for Al 6060 was 5.3. Moreover, at inlet water velocity of 7 m/s, value of Nu for copper alloy is 7.6 that is highest compared with all the cases studied. It is interesting to see that the Al 6060 has Nu value of 6.8 that is higher compared with Nu value of 6.2 for Al 6063. The Nu values are higher for all compositions of copper alloy than aluminum alloys. It is observed that Nusselt number significantly increases with increasing fluid flow velocity or Reynolds number. It is also found that using copper alloy as heat sink material values of Nusselt number for higher velocities are higher than aluminum alloy Al6060, Al6063. It is an indication of enhanced heat transfer in the case of copper alloy compared with aluminum alloys.

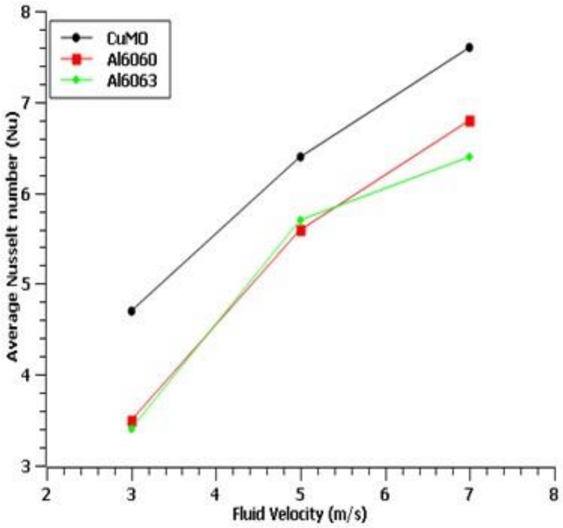


Figure 7. Effect of velocity and thermal conductivity of fluid on heat transfer

3.6. *Effect of Heat transfer coefficient on heat sink materials*

Fig. 8 shows the effect of heat transfer coefficient on various heat sink materials with the change of water flow velocity. Nusselt numbers and heat transfer coefficient are very closely associated with heat transfer rate. The heat transfer coefficient values for flow velocity of 7 m/s are higher compared with 3 and 5 m/s for all the cases. It is observed that for copper alloy heat sink the heat transfer coefficient are higher at all velocities of 3, 5, and 7 m/s. It is an indication that for all velocities studied Cu alloy are better than Al6060, Al6063. At inlet fluid velocity of 7 m/s, the higher values of Nusselt numbers are obtained. It is an indication of improvement in heat transfer coefficient.

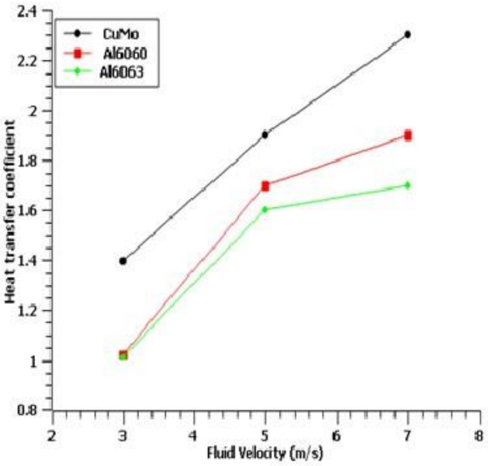


Figure 8. Effect of velocity and thermal conductivity of fluid on heat transfer

Table 4 compares of heat sink materials with their properties, cost, and their suitability as heat sink materials. The performance of copper alloy heat sink for all flow velocities is higher. But considering the weight, cost, and the machining processes aluminum alloys are preferred over copper alloys.

The popular methods for production of Al and Cu alloys MCHS are viz. extrusion, forging, rolling, milling, and soldering.

Table 4. Comparison of heat sink materials

Materials	Al6060	Al6063	CuMo Cu40Mo60	CuMo Cu50Mo50	$CuWO_4$ W90Cu90	Silicon
k	209	201	215	250	175	148
C_p	898	900	310	323	155	712
ρ	2700	2690	9680	9500	17000	2330
Cost INR/kg	250	170	720	8000	6800	825
Advantages	Low cost, Low weight, rust free	Low cost, Low weight, rust free	High thermal conductivity, Excellent hermeticity	High k, Excellent hermeticity	Low thermal Expansion, High arc resistant	Low thickness
Disadvantages	Tooling free, Hard to satisfy orders of small quantity	Tooling free, Hard to satisfy orders of small quantity	High weight and costlier	High weight and costlier	High weight and costlier	Low thermal conductivity

4. Conclusions

From the numerical investigation on advanced heat sink material for thermal management of electronics following are the conclusions:

1. Copper alloy (CuMo) give better heat transfer performance over Al 6060, and Al 6063 for all flow velocities studied. But it is difficult for machining, costlier and heavier compared with Al 6060 and Al 6063. Hence Aluminum alloys are the preferred choice as heat sink material.
2. Al 6060 results in better heat transfer performance at a flow velocity of 7 m/s. But Al 6063 at a flow velocity of 5 m/s give better thermal performance than Al 6060. At a flow velocity of 3 m/s, the aluminum alloys provide almost the same performance. Al 6063 is a lower cost than Al 6060, and Al 6063 is a better choice as heat sink material at a moderate velocity of 5 m/s.
3. Nusselt numbers and heat transfer coefficient are slightly decreases at inlet sections and gradually increases at outlet section for Cu alloy, Al6060, Al6063.
4. The heat transfer coefficient in the case of CuMo is maximum that for Al6060 is moderate and Al 6063 is lower, but the difference is not very significant. Therefore, Al6060 is the suitable material for heat sink due to its advantages of cost, weight, and machining processes.

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