International Journal of Research in Advent Technology, Vol.2, No.8, August 2014
E-ISSN: 2321-9637

Heat Transfer Simulation of Impinging Jet with Finned Heat Sink

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Abstract- This study examines numerically details of the flow and temperature fields of heat sinks with short plate fins cooled by impinging jet. The main focus is on the effect of fin spacing, fin material and jet velocities on the heat sink performance. Conjugate heat transfer between airflow convection and conduction inside the fin and base is considered. Three different fin spacing (2 mm, 3 mm, 4 mm), fin material (Aluminum, copper and steel) and jet velocity of (5 m/s,10 m/s and 15 m/s) are the parameters under study. Detailed temperature contours, velocity vector, pressure drop are presented and compared. In this current work the effect of fin material is observed that heat transfer rate varies in accordance with thermal conductivity of fin material. For the considered geometry there was increase of 0.2 W and 0.7804 W heat transfer rate for copper fin material, when it is compared to Aluminum and steel respectively for 15 m/s jet velocity. The effect of fin spacing on rate of heat transfer rate for the considered geometry it is observed that there is increase of 19% and 48% heat transfer rate for decrease of fin spacing of 2 mm and 3 mm respectively at 15 m/s jet velocity. Pressure drop is also sensitive to fin spacing in all the combinations, as fin spacing decreases pressure drop increases. For the considered geometry it is observed that pressure drop of 100 Pa, 120Pa and 140Pa for 4 mm, 3 mm, and 2 mm fin spacing respectively for jet velocity of 15 m/s. In overall pressure drop and heat transfer rate are contradicting with respect to fin spacing. However use of copper material makes heat sink heavier and expensive. Hence it can be concluded that for considered geometry of fin spacing 2 mm at 15 m/s of jet velocity for Aluminum fin material the numerical result was found to be optimum. The results of this can help in design of heat sinks with jet impingement, which are commonly used in electronic cooling systems.

Index Terms: Jet impingement, heat sink, plate fin.

1. INTRODUCTION

The relentless trend of ever increasing integrated circuit chip functionality and decreasing chip dimensions for miniaturization of products have led to the need to develop new thermal management techniques to handle intense heat generation rate in IC chips. The need for effective cooling of chips at an acceptable cost is an urgent issue Extended surfaces (fins) and impinging jets have commonly been used to enhance heat transfer in many applications, for example, electronic cooling and gas turbine cooling. In electronic thermal management, heat sinks are designed to take advantage of the combined effect of fins and jet impingement such as jets impinging on an array of pin fins or plate fins. Significant studies have been focused on the thermal resistance, pressure drop, and the parametric effect of Reynolds number, fin thickness, density and height. Different correlations based on one-dimensional heat conduction and experimental data are developed to predict the heat sink performance. Efforts to optimize the heat sink design have also been made by using both experimental and numerical methods.

2. CURRENT STUDY

This study applies numerical simulation to examine the details of flow and temperature fields of plate fin heat sinks with jet impingement. Based on the literature review few studies have been done on the effect of fin spacing, fin material and jet velocity. Therefore, the main focus of this study is on the effect of fin spacing of (2 mm, 3 mm and 4 mm), fin material Aluminum, copper and steel, jet velocity of (5 m/s, 10 m/s and 15 m/s) on the heat sink performance. The characteristics of 3D temperature field inside the fins and solid base are also explored. It is observed that the fin spacing affects largely both the heat transfer and pressure drop, fin material and jet velocity effects on heat transfer rate especially of the short fin cases .The results of this paper can help in design of heat sinks with jet impingement.

2.1 Objectives:

1. This concerns the familiarization with the methods and materials. This involves literature reviews on the different methods of cooling employed in electronic equipment’s.
2. This involves choosing the parameter on which analysis should be carried out. In this work the parameters selected are fin material (Aluminum, copper and steel), fin spacing (2 mm, 3 mm, 4 mm), and velocity of jet (5 m/s, 10 m/s and 15 m/s).
3. The selection of geometry for the CAD model was selected from literature [10] and the physical

arrangement of fin is modeled using hyper mesh V10 software.

4. Mesh generation of the modeled geometry was carried out using hyper mesh V10 software.
5. The boundary conditions for the fluid flow analysis were imposed and the solution was obtained through the analysis software FLUENT 6.3.26.
6. The analysis was carried out to obtain heat transfer rate, pressure drop and contours of temperature, Velocity vector are drawn

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3. PROBLEM UNDER CONSIDERATION

There are generally two types of heat sinks with jet impingement. One is with parallel plate fins, and the other is with pin fins. In this study the plate fin heat sink is considered. Figure 1 shows the geometric schemes of this type of heat sink. The slot jet impinges from the top to the plate fins and exits from two sides into the surroundings. The sink base is connected to the electronic modules to dissipate the heat to the cooling airflow. The top can be either open or confined, which is considered as confined in this study. The performance depends on the jet velocity, fin height, fin width, number of fins, and the base thickness. In practice, there usually is a small gap between the fin tip and jet plate

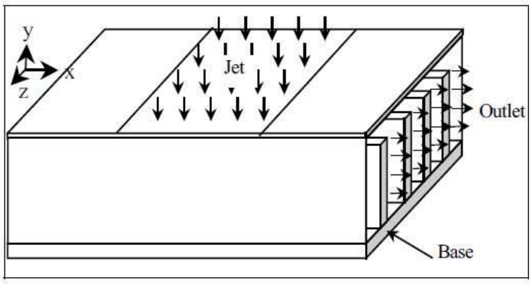


Fig 1 Geometric scheme of a heat sink of parallel plate fins cooled by an impinging jet

The heat sink in Fig 1 is symmetric in both the x- and z directions unless the flow or thermal boundary conditions are applied differently. Figure 2 shows the symbolic dimension of the cases under study. The fin shape considered is rectangular fins. All the fins share the same height and base width, which leads to a slightly different surface area and thus different volume or weight. The total height in the y-direction is H, and heights for the fin and base are h_1 and h_2, respectively. The fin has a thickness of b, and the distance between the fins is B_1.The the impinging slot jet has a width of(l_1) and the rest of the top surface is the confined wall (l_2).In this study, the air jet with constant properties impinges on the heat sink vertically with a uniform inlet velocity and temperature. Constant temperature is applied to the heat sink bottom surface for simplification. The considered dimensions and thermal Properties of fin materials are presented in table 1 and 2 respectively.

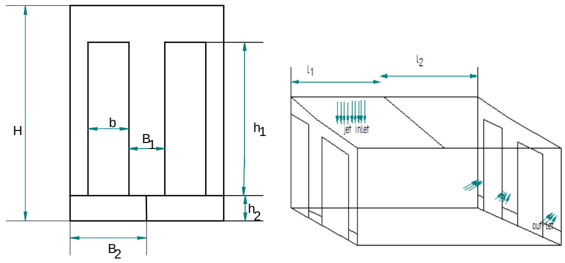


Fig. 2 shows the symbolic dimension of the cases under study

Table 1 Dimensions of Fin geometry

Fin height(h_1)	0.006 m
Base height(h_2)	0.002 m
Total height (H)	0.01 m
Fin width (b)	0.002 m
Distance between the fins(B_1)	0.002 m, 0.003 m and 0.004 m
Jet width(l_1)	0.01 m
Confined wall length(l_2)	0.015 m

Table 2 Thermal properties Fin materials

Material	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (J/kg-K)
Copper	8978	387.6	381
Aluminum	2719	202.4	871
Steel	8030	16.3	502.5

4. NUMERICAL METHADOLOGY

In CFD calculations, there are three main steps.

- Pre-Processing
- Solver Execution
- Post-Processing

Pre-Processing is the step where the modeling goals are determined and computational grid is created. In the second step numerical models and boundary conditions are set to start up the solver. Solver runs until the convergence is reached. When solver is terminated, the results are examined which is the post -processing.

4.1 Pre-Processing

In this study, the aim is to investigate the cooling characteristics of different fins. So, an adequate numerical model is to be created. Pre-processing is the most time consuming and least knowledge requiring part. There are two important points here. The first one is the size of the domain, and the second one is the density and quality of the computational grid. Model size is the computational domain where the solution is done. It is important to build it as small as possible to prevent the model to be computationally expensive. On the other hand it should be large enough to resolve all the fluid and energy flow affecting the heat transfer around the Fin. In this problem, domain is selected to be the two fins

The model of the present problem is created using hyper mesh 10 software major commands used for creation are nodes; line .The obtained model is meshed using the HYPERMESH 10 software. In meshing first 2D meshing is done using the quad elements it is because the model is in regular shape as shown in Fig 3 to Fig 5.

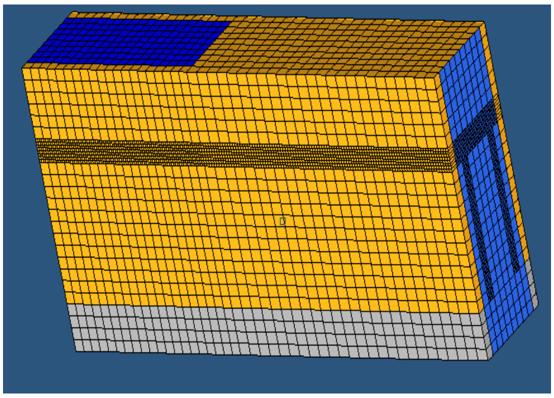


Fig. 3 Meshed diagram of 2mm spacing

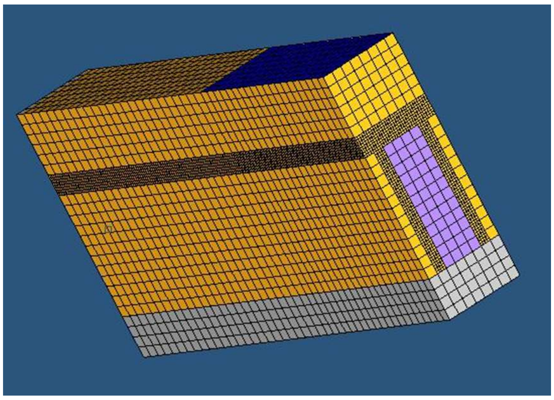
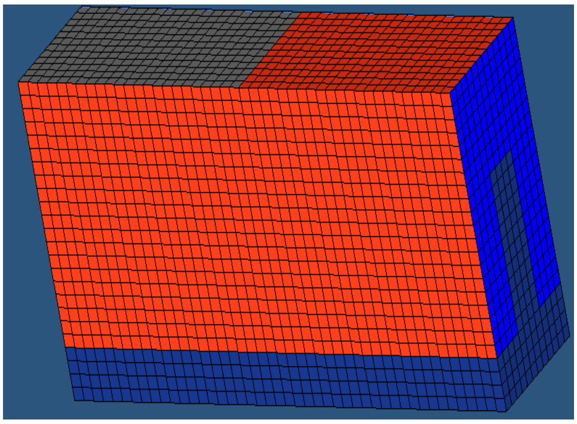


Fig 4 Meshed diagram of 3mm spacing



. Fig 5 Meshed diagram of 4mm spacing

4.2 Symmetry Condition

Symmetry boundary conditions are used when the physical geometry of interest, and the expected pattern of the flow/thermal solution, has mirror symmetry. These can also be used to model zero-shear slip walls in viscous flows. In the present case single fin is considered and applying symmetry boundary condition at one face it can obtain two fins. The symmetry grid display is shown in Fig 6.

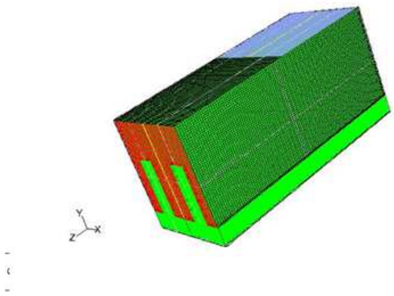


Fig 6 symmetry grid display

5. SOLVER SET UP

The solver set up is very important in any of the fluid flow problem; the solver setting indicates the method and also a procedure for solving (analysis) the problem. The flow analysis has studied using ANSYS FLUENT (6.3.26) [17]

5.1 Turbulence Modeling

The turbulence model used for this work is standard k-epsilon. The 3D space pressure based solver is used and implicit formulation is used for solution scheme. Solution controls uses flow and turbulence equations. The simple algorithm is used for pressure velocity coupling and for discretization second order scheme is used [9]. The convergence criteria for all case studies are taken as 0.001.

5.2 Governing Equations to be solved

Time independent flow equations with turbulence are to be solved. The viscous dissipation term will be omitted. Therefore the governing equations for the fluid flow, Above Equation are modified as follows:

Mass $\nabla.(\rho\vec{V}) = 0$

X momentum $\nabla.(\rho u\vec{V}) = \frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+S_{Mx}$

Ymomentum: $\nabla.(\rho v\vec{V}) = \frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+S_{My}$

Zmomentum: $\nabla.(\rho w\vec{V}) = \frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+S_{Mz}$

Energy: $\nabla.(\rho h_0\vec{V}) = -p\nabla.\vec{V}+\nabla.(k\nabla T)+S_h$

Equation of state: $p=\rho RT$

5.3. BOUNDARY CONDITIONS

The boundary conditions are the important values for the mathematical model. The boundary condition is applied to different zones. There are different kinds of boundary conditions for the fluid flow to enter and exit the domain. The boundary condition is depending on type of fluid use for the analysis. The fluid used for this analysis is incompressible hence velocity inlet condition applies. Inlet velocity profile was assumed, slip condition assigned to all surfaces. The boundary conditions used for the analysis are listed in table 3

Table 3 Boundary conditions used in CFD analysis.

Sl no	Quantities	Condition/value
1	Working fluid	Air
2	Gauge pressure	0 Pa
3	Inlet velocity	5m/s,10m/s and 15m/s
4	Fin material	Aluminum, copper and steel

6. RESULTS AND DISCUSSION

In this study two rectangular fin geometry is considered. The parameters like fin material (Aluminum, copper and steel) are considered and fin spacing varied as (2 mm, 3 mm, 4 mm) and jet velocity of (5 m/s, 10 m/s and 15 m/s) are considered. The detailed effect of these parameters are analysed as shown below Simulation technique is used in the present work which involves selection of geometry from the literature, modeling and meshing of the geometry was performed using HYPERMESH10 software. The physical boundary conditions were applied to meshed model by importing meshed model to FLUENT 6.3.26 and analysis is carried out using CFD solver. The different graphs of heat transfer rate, pressure drop and temperature distribution, velocity vectors for varied combinations of fin material, fin spacing and jet velocity (27 combinations) were analyzed in detail.

6.1 Convergence

Only a well converged simulation can give reliable results. Convergence is determined by the order of magnitude residuals drop the convergence of simulation is required to get the parameters of the fin. It also gives accurate value of parameters for the requirement of heat transfer rate, pressure drop. Continuity, X-velocity, Y-velocity, Z-velocity, energy, k, epsilon are the part of scaled residual which have to converge in a specific region. For the continuity residuals set are 10^{-3}, X velocity, Y velocity, Z-velocity, k, epsilon should be less than 10^{-5} and the energy should be less than 10^{-6}. If all values in same manner then solution will be converged. For the considered problem convergence is obtained at 500 iterations.

6.2 Heat transfer rate in impinging jet with finned heat sink:

Heat transfer rate is defined as the amount heat transferred from the fin and base to the surrounding fluid. The effect of velocity and fin material is examined and tabulated in table 4, table 5 and table 6 for 2 mm, 3 mm and 4 mm fin spacing respectively.

Table 4 Heat transfer rates for 2mm spacing between the fins.

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Heat transfer rate in watts		
1	Copper	1.4189	2.2440	2.9054
2	Aluminum	1.3076	2.0990	2.7054
3	Steel	1.1969	1.7456	2.1250

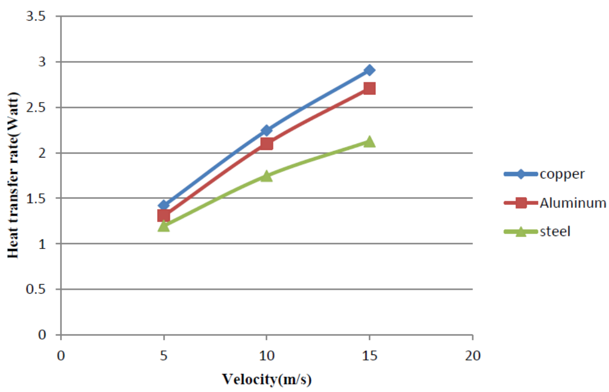


Fig 7 variation of heat transfer rate at 2mm spacing

Table 5 Heat transfer rates for 3mm spacing between the fins

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Heat transfer rate in watts		
1	Copper	1.3351	2.124	2.7084
2	Aluminum	1.3224	2.005	2.6615

3	steel	1.1674	1.6225	1.9434

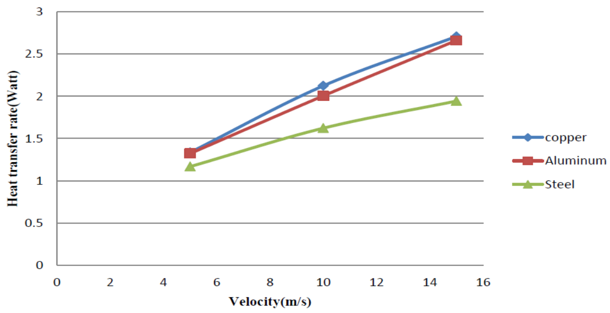


Fig 8 variation of heat transfer rate at 3mm spacing

Table 6 Heat transfer rates for 4mm spacing between the fins

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Heat transfer rate in watts		
1	Copper	1.2927	1.9200	2.4190
2	Aluminum	1.1999	1.8050	2.3900
3	steel	1.1307	1.5928	1.785

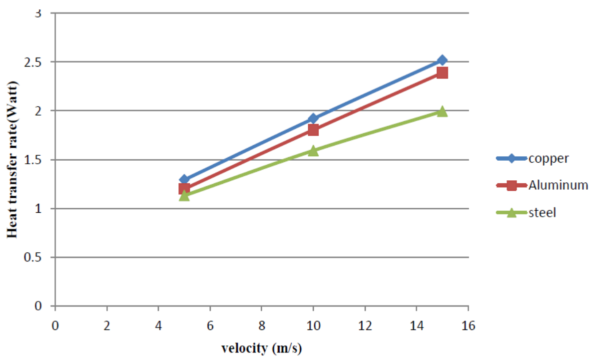


Fig 9 variation of heat transfer rate at 4mm spacing

Heat transfer rate is the important parameter to judge performance of a fin. The variation of heat transfer rate for Aluminum, copper and steel is tabulated and variation is plotted in Fig 7, Fig 8 and Fig 9. In all these cases heat transfer rate is increasing as the velocity increases and also heat transfer rate is high for the copper, than Aluminum and lowest for the steel .The variation of heat transfer rate depend on fin material, jet velocity and fin spacing. Heat transfer rate increases with increase in thermal conductivity of fin material and also with increase in jet velocity. But increase in fin spacing there was decrease in heat transfer rate for all the cases of fin material and jet velocity. For 2 mm spacing of copper material at 15m/s there was increase of 0.4864 W of heat transfer rate when compared to 4 mm spacing at 15 m/s jet velocity. It is due to decrease in fin spacing, velocity loss will be less and also volume flow rate of fluid particles will be higher between the two fins. Due to which there is increase in heat transfer rate at 2 mm fin spacing.

From the CFD analyses the obtained graphs shows that when the steel is used as fin material there will be a drastic reduction in heat transfer rate for all the cases of fin spacing and jet velocity. When aluminum is used as fin material there was increase in heat transfer rate when compared to steel but slightly less when copper is used as fin material. For 2 mm spacing of aluminum material at 15 m/s there was 0.5804 W of heat transfer rate increase with respect to steel, but 0.2 W of heat transfer rate decrease when compared to copper fin material. From the above obtained graphs it can be concluded that for 2mm spacing at 15 m/s when copper is used as fin material heat transfer rate will be maximum for the considered geometry when compared to other materials and fin spacing

6.3 Temperature Distributions in Fins

For the considered geometry, the temperature distribution is mainly dependent on fin material used and inlet jet velocity, But it is invariant with fin spacing so temperature distribution is presented for fin material of copper ,aluminum and steel for varying inlet velocity 15 m/s for only 2 mm spacing. Fig 10, Fig 11 and Fig 12 shows temperature contour for copper, aluminum and steel at 15 m/s jet velocity

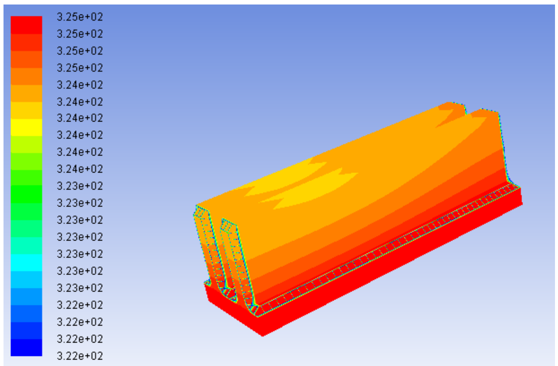


Fig 10 Temperature contour for copper 2 mm fin spacing @15 m/s

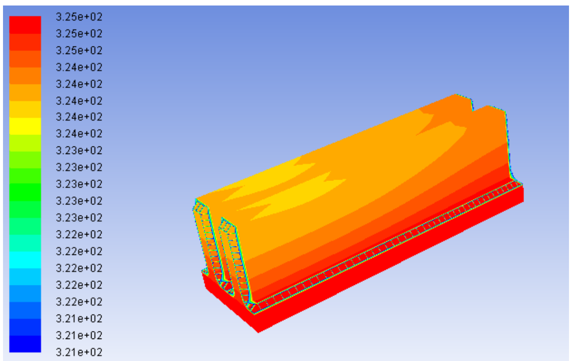


Fig 11 Temperature contour for Al 2 mm fin spacing @15 m/s

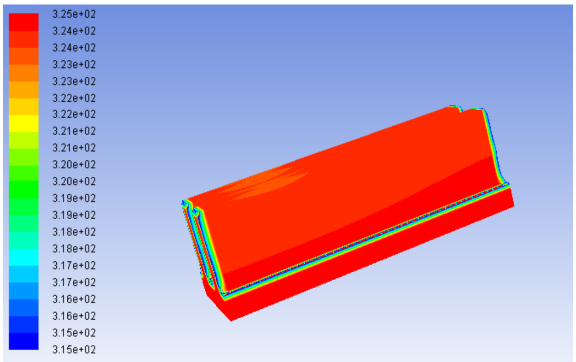


Fig 12 Temperature contour for steel 2mm fin spacing @ 15 m/s

It is reasonable to see that the temperature in the region close to the fin tip and jet inlet is lowest. It is observed that the temperature gradient for the fin base and tip of the fin for copper and aluminum is around 2 K to 3 K but for steel it is around 10 K it is because the Thermal conductivity for copper and aluminum is high as compared to steel. The conduction heat transfer takes place from bottom surface of the base to the top surface of the fin .The temperature in region close to the fin tip and jet inlet is lowest, because as the jet inlet velocity is maximum at the inlet and also heat transfer coefficient increases with increase in the Reynolds number due to which heat transfer rate is maximum at the inlet of the jet corresponding to fin tip. So it is observed that minimum temperature will be at the inlet of the jet.

From this there will be effective heat transfer takes place when the impinging jet technique is used for heat sink in an electronic cooling purpose.

6.5 Velocity Analysis

Velocity of jet around the fin and between the fins is predominant factor for rate of heat transfer by the heat sink. The variation of velocity from inlet to the outlet is presented by plotting velocity vectors since the velocity variation is mainly depends on inlet velocity of the jet and it is invariant with fin material so for the considered geometry velocity variation for copper material is presented. Fig 13, Fig14 and Fig15 shows the velocity variation for inlet jet velocity of 5m/s for copper material at 2 mm, 3 mm and 3 mm spacing respectively.

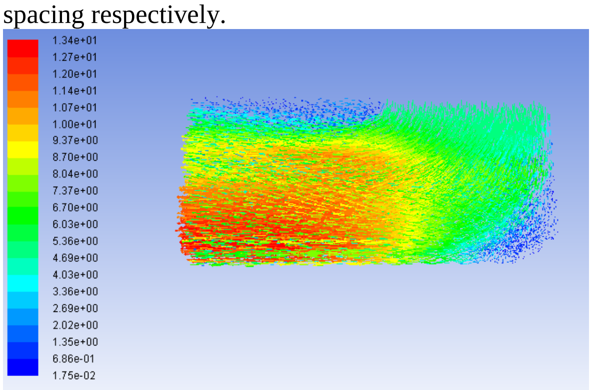


Fig 13 Velocity vector for cu at 5m/s for 2mm fin spacing

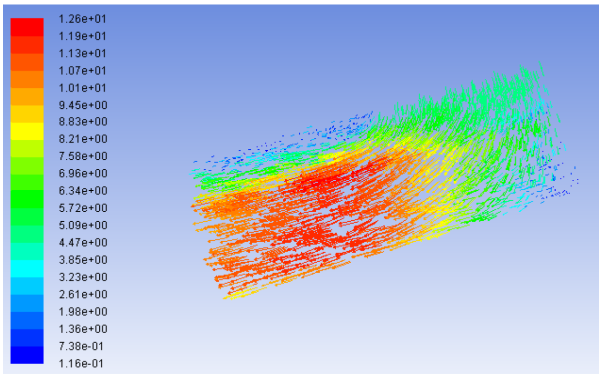


Fig 14 Velocity vector for cu at 5m/s for 3mm fin spacing

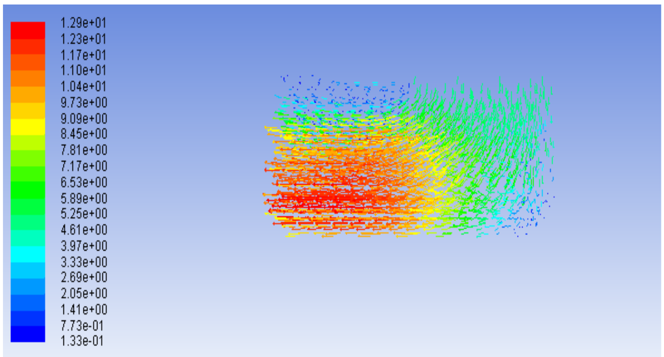


Fig 15 Velocity vector for cu at 5m/s for 4mm fin spacing

It is observed from velocity vectors for all the cases of varying inlet velocity the outlet velocity close to the base is higher due to the impinging effect. For the considered geometry for inlet velocity of 5 m/s, 10 m/s and 15 m/s the outlet velocity close to the base is around 13 m/s, 25 m/s and 38 m/s respectively.

For the decrease in fin spacing it is observed from velocity vectors there was increase in average channel velocity of jet. As the fin spacing decreases the pressure drop increases which results in increase of velocity. Since the velocity variation is mainly depends on fin spacing and inlet velocity but it is invariant of fin material so only for copper material velocity variation is presented in this work but velocity variation for aluminum and steel is also analyzed.

6.6 Pressure drop analysis

Pressure drop is the resistance to the air movement and it is related with flow cross sectional area, fin spacing and fin length. The heat sink should be designed so as to yield a smaller pressure drop than the static pressure of the fan. In general, the total heat sink pressure drop depends on four major factors the friction factors, the heat sink geometry, the approach velocity and the heat sink channel velocity. The friction factors arise from the airflow entering and exiting heat sink channel are known as the contraction loss coefficient and expansion loss coefficient respectively, whereas the friction factor that due to the transition of airflow from developing flow to fully developed flow is called the apparent friction. Pressure drop values were tabulated in table 7, table 8 and table 9 for 2mm, 3mm and 4mm fin spacing respectively.

Table 7 pressure drop for 2 mm spacing between the fins

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Pressure drop in (Pascal)		
1	Copper	140	520	1200
2	Aluminum	140	520	1200
3	Steel	140	520	1200

Table 8 pressure drop for 3 mm spacing between the fins

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Pressure drop in (Pascal)		
1	Copper	120	450	1000
2	Aluminum	120	450	1000
3	Steel	120	450	1000

Table 9 pressure drop for 4mm spacing between the fins

Sl no	Material	Velocity 5m/s	Velocity 10m/s	Velocity 15m/s
		Pressure drop in (Pascal)		
1	Copper	100	300	800
2	Aluminum	100	300	800
3	steel	100	300	800

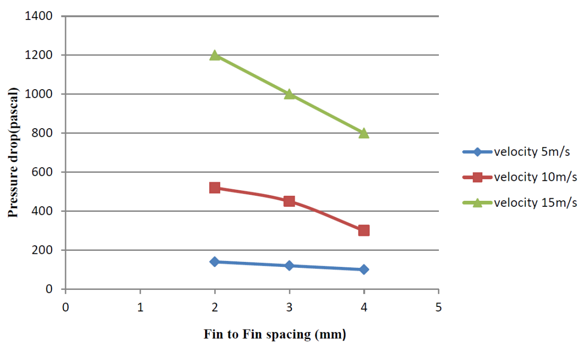


Fig 16 pressure drop variation with fin spacing

Since from the table 7 table 8 and table 9. It is observed that pressure drop is invariant with fin material so pressure drop along the fin is presented with the variation of fin spacing only. From Fig 16 It can be observed that as the fin spacing decreases pressure drop increases. With the decrease in fin spacing flow between the fin spacing is fully developed because due to high Reynolds number friction Factor will be very much greater for minimum fin spacing this affects heat transfer rate. Increase in pressure drop affects the fluid flow particles movement over the fin material.

Sometimes negative pressure will be developed at inlet with respect to exit. Due to which the flow will be reversed which affects performance of the heat sink. For the considered geometry it is observed increase in pressure drop as the decrease in fin spacing but not less than static pressure.

7. CONCLUSIONS

The analytical model is developed for high Reynolds number turbulent flow and heat transfer in inter fin channels of impingement flow plate fin heat sink. The simple model is suitable for heat sink parametric design study. From the obtained numerical results the following conclusions can be drawn.

1. From the obtained numerical analysis maximum heat transfer rate was for copper fin material at 2 mm spacing for 15 m/s jet velocity. The results shows that there was increase in 0.2 W and 0.7804 W heat transfer rate compared to aluminum and steel respectively at 2mm fin spacing and 15m/s.
   When aluminum is used as fin material and compared with respect to copper and steel. The rate of heat transfer was maximum compared to steel but there was slight reduction in rate of heat transfer compared to copper at all fin spacing (2 mm, 3 mm and 4mm) and at all jet velocity (5 m/s ,10 m/s).
   In overall copper fin material showed good results but the use of copper as fin material makes heat sink heavier and expensive so aluminum can be selected as fin material for thermal heat sink which gives optimum result compared to copper.
2. For all combinations it is observed as the fin spacing decreases there is an increase in heat transfer rate. For the considered geometry 2mm fin spacing gives optimum heat transfer.
3. Pressure drop plays vital role with respect to fin spacing. With decrease in fin spacing for the considered geometry pressure drop increases which affects the rate of heat transfer. But for considered geometry the effect of pressure drop is negligible. But when higher dimensions are considered with impinging jet the rate of heat transfer decreases with increase in pressure drop for the reduced fin spacing.
4. From the velocity vectors it was observed that there was an increase in jet velocity as the fluid flows from inlet to exit. It is because of the impinging effect and reduced fin spacing. This

results in increase of heat transfer rate when compared to parallel flow arrangement.

5. From the temperature contours it can be concluded that temperature close to the fin tip at inlet of the jet is observed minimum. This indicates maximum temperature difference resulting in high heat transfer rate at the inlet.
6. In overall for the considered geometry and boundary conditions it can be concluded that fin material of aluminum with 2 mm fin spacing at 15 m/s jet velocity gives the optimum result for electronic cooling systems.

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