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Enhancement of Heat Transfer Rate from Fin Using Thermal Analysis Through Geometrical Optimization

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Abstract
Thermal analysis has been performed in this work on a different designs of fin in order to investigate the temperature distribution, heat flux, and thermal stresses using ANSYS workbench. For this work total nine designs of fin have been created such as rectangular plate fin, rectangular plate fin with hole, rectangular perforated fin, rectangular plate fin with slot, rectangular plate with pin inserted fin, rectangular plate inserted pin with hole fin, triangular plate fin, triangular plate with perforated fin & triangular plate fin with slot. Aluminum 1060 is used as a material for all designs of fin, The 13 W of heat supply at the bottom of the fin have been applied which is equal to the power supply at ambient temperature of 22 ºC. Results show that the 48.76 ºC is the lowest temperature for the rectangular plate inserted pin with hole fin which is 8.9% lower than the plane rectangular plate fin and the 51.67 ºC is the lowest temperature for the rectangular plate fin with hole which is 5.5% lower than the plane rectangular plate fin while the 0.0378 W/mm² is the lowest temperature for the triangular plate fin with slot which is 3.5 times greater than the plane rectangular plate fin. The 7.3 degree is the highest temperature difference for the rectangular perforated fin which is 4.2 times higher than the plane rectangular plate fin and the 0.0276 MPa is the lowest thermal stress for the rectangular plate fin with hole & triangular plate with perforated fin which is 5.74 times lower than the plane rectangular plate fin. Hence the rectangular plate inserted pin with hole fin is suggested for better heat transfer.

I. INTRODUCTION:

The Heat transfer rate depends on several factors of geometrical, Material properties and environmental conditions of an object such as thermal conductivity, surface area, temperature difference, and convective coefficient. This heat transfer rate can be optimized by improving them. Out of these, the object's design limits the base surface area, and the temperature difference is dependent on the process and is subject to process constraints. The convective heat transfer coefficient seems to be the only option, and this cannot be raised above a particular point. As a result, adding extended surfaces, often known as fins, to the base may be an alternative.

Fins are used when the surface area of the object is found inadequate to transfer required heat with existing temperature difference and coefficient of heat transfer. The direction of heat transfer for fins by convection is perpendicular to the direction of conduction heat flow. Some of examples of the use of extended surfaces are in cylinder heads of air-cooled engines and compressors and on electric motor bodies. In radiators and air conditioners, tubes with circumferential fins are normally used to rise the heat flow. An electronic circuit chip cannot function without dissipating generated heat, so requirement fins are necessary for that kind of compact component where packaging space is limited. The surface area of the fin and the surface area of the fin tip, as indicated in the figure, determine how much heat is transferred from the fin. Typically, this fraction of the overall fin area is minimal.

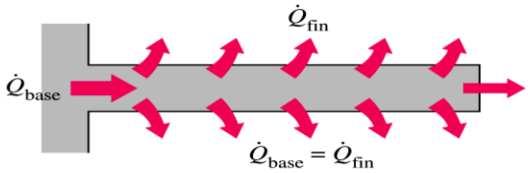


Figure 01: Concept of heat transfer from the exposed surfaces of the fin [33]

The objective of our study is to increase the heat transfer rate from the fin by creating different designs of the three-dimensional CAD model for thermal analysis in order to investigate the temperature distribution, heat flux and thermal stress and compare the results obtained from the thermal analysis and suggest better fin with optimized design

Altaf (2022) conducted numerical and experimental thermal and hydraulic analyses of slotted plate fns heat sinks; Wu (2022) performed optimization analyses of passive fin-concrete heat sinks for thermal environment control; Rajat (2022) conducted static thermal analyses of fins models using ANSYS; Song (2021) conducted an investigation into the heat-dissipation performance of a cylindrical heat sink with perforated fins; and Jafferson (2021) conducted an investigation into and thermal analysis of novel heat-sink fins for FDM 3D printer liquefier. *Ahmadian* (2021) A comprehensive study on parametric optimization of the pin-fin heat sink to improve its thermal and hydraulic characteristics, *Lee* (2021) Worked on thermal optimization of the pin-fin heat sink with variable fin density cooled by natural convection, *Jasim* (2020) Worked on heat transfer enhancement from heat sources using optimal design of combined fins heat-sinks, *Wang* (2020) Numerical investigation on hydraulic and thermal characteristics of micro latticed pin fin in the heat sink, *Hussain* (2019) Numerical investigation of heat transfer enhancement in plate-fin heat sinks *Hosseinirad* (2019) Study the effects of splitter shape on thermal-hydraulic characteristics of plate-pin-fin heat sink, *Gonzalez* (2019) Worked on practical approaches to assess thermal performance of a finned heat sink prototype for low concentration photovoltaic systems, *Yazici* (2019) Study the combined effects of inclination angle and fin number on thermal performance of a PCM-based heat sink, *Luo* (2019) Study and experimental investigation on the heat dissipation performance of flared-fin heat sinks, *Sathe* (2019) Thermal analysis of an inclined heat sink with finned PCM container for solar applications, *Arshad* (2018) Study and experimental investigation of PCM based round pin-fin heat sinks for thermal management of electronics, *Tijani* (2018) Thermal analysis of perforated pin-fins heat sink under forced convection condition, *Oguntala* (2018) Worked on improved thermal management of computer microprocessors using cylindrical-coordinate micro-fin heat sink with artificial surface roughness, *Kwon* (2018) Analytic approach to thermal optimization of horizontally oriented radial plate-fin heat sinks in natural convection, *Ambreen* (2018) Study the effect of fin shape on the thermal performance of nanofluid-cooled micro pin-fin heat sinks, *Chiu* (2017) Worked on the heat transfer characteristics of liquid cooling heat sink with micro pin fins, *Al* (2017) A numerical investigation of the thermal-hydraulic characteristics of perforated plate fin heat sinks, *Li* (2016) Study the heat transfer characteristics of pin-fin heat sinks cooled by dual piezoelectric fans, *Ali* (2015) Thermal performance investigation of staggered and inline pin fin heat sinks, *Jeong* (2015) Worked on optimal thermal design of a horizontal fin heat sink with a modified-opening model mounted on an LED module, *Ma* (2015) Worked on mechanism of enhancement of heat transfer for plate-fin heat sinks with dual piezoelectric fans &*Kim* (2014) Worked on thermal optimization of branched-fin heat sinks subject to a parallel flow.

It has been observed from the above literature survey that there are lot of work have been carried out and still going on various design of fins using different geometry, applications and medium using experimentally, numerically and with simulations. such as slotted plate fns, passive fin-concrete heat sinks, heat-dissipation performance of cylindrical heat sink, variable fin density, micro latticed pin fin, effect of flow direction and fillet profile, plate-pin-fin heat sink, performance of a PCM-based heat sink, inclined heat sink with finned PCM, Effect of pin-fin diameter, perforated pin-fins heat sink, horizontally oriented radial plate-fin heat sinks, nanofluid-cooled micro pin-fin heat sinks, natural convective micro-finned heat sinks etc.

II. METHODOLOGY:

From the figure 02 it is cleared that the heat flow direction is x, and the cross-sectional area of the fin is taken to be a function of x. Consider the small volume element of the fin of length dx. An energy balance is performed on this element in which it is assumed that the element is at a constant and uniform temperature of T.

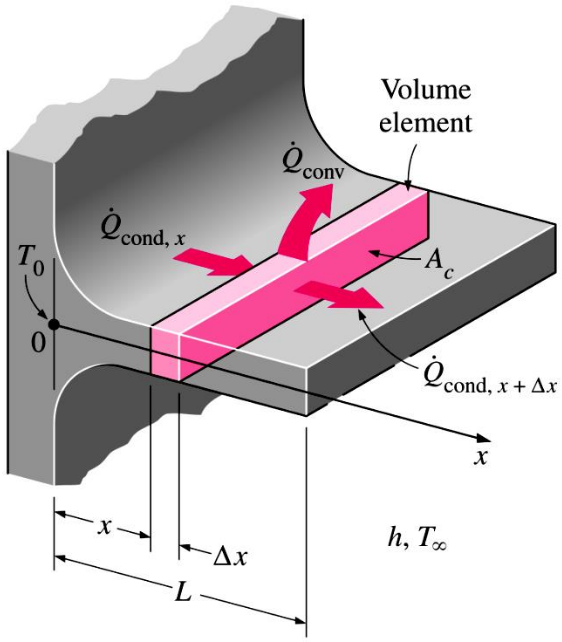


Figure 02: Volume element of fin geometry

Heat in to the left face = Heat out from the right face + Heat loss by convection

This yield

$$Q_x = Q_{x+\Delta x} + Q_{con} \quad (1)$$

Applying the Taylor series expansion of the first term on the right side of the Equation (1)

$$Q_{x+\Delta x} = Q_x + \frac{dQ_x}{dx}\cdot\Delta x + higher\ order\ terms$$

$$Q_{x+\Delta x} = Q_x + \frac{dQ_x}{dx}\cdot\Delta x\ neglecting\ the\ higher\ order\ terms$$

Substitute the above value of $Q_{x+\Delta x}$ in equation (1)

$$Q_x = Q_x + \frac{dQ_x}{dx}\cdot\Delta x + Q_{con}$$

$$\frac{dQ_x}{dx}\cdot\Delta x + Q_{con} = 0$$

Where

$$Q_x = -kA\frac{dT}{dx} \quad by\ Fourier's\ law$$

$$Q_{con} = hP\Delta x(T - T_\infty) \quad by\ Newton's law\ of\ cooling$$

$$\therefore -kA\frac{d^2T}{dx^2}\Delta x + hP\Delta x(T - T_\infty)$$

$$\frac{d^2T}{dx^2} - \frac{hP}{kA}(T - T_\infty) = 0 \quad (2)$$

Let

$$\theta = T - T_\infty$$

After differentiating

$$\frac{d^2\theta}{dx^2} = \frac{d^2T}{dx}$$

Let the composite parameter

$$\frac{hP}{kA} = m^2$$

Equation (2) becomes

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0 \qquad (3)$$

Equation (3) shows the temperature as the function of x and m. it is a second order, linear ordinary differential equation.

$$D^2\theta - m^2\theta = 0 \qquad \because \frac{d}{dx} = D, \quad \frac{d^2}{dx} = D^2$$

$$(D^2 - m^2)\theta = 0$$

$$D = \pm m$$

The general solution

$$\theta = C_1 e^{-mx} + C_2 e^{mx} \qquad (4)$$

Where C_1 and C_2 are constant that can be determined from the boundary conditions.

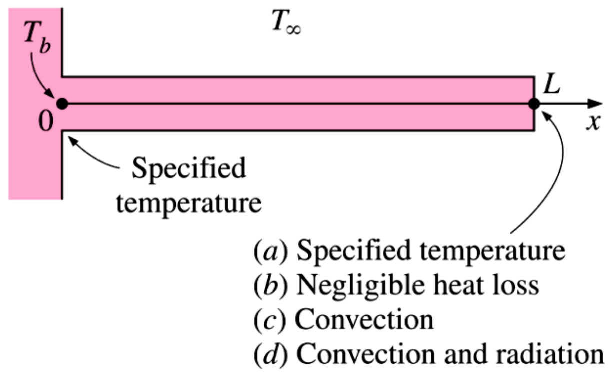
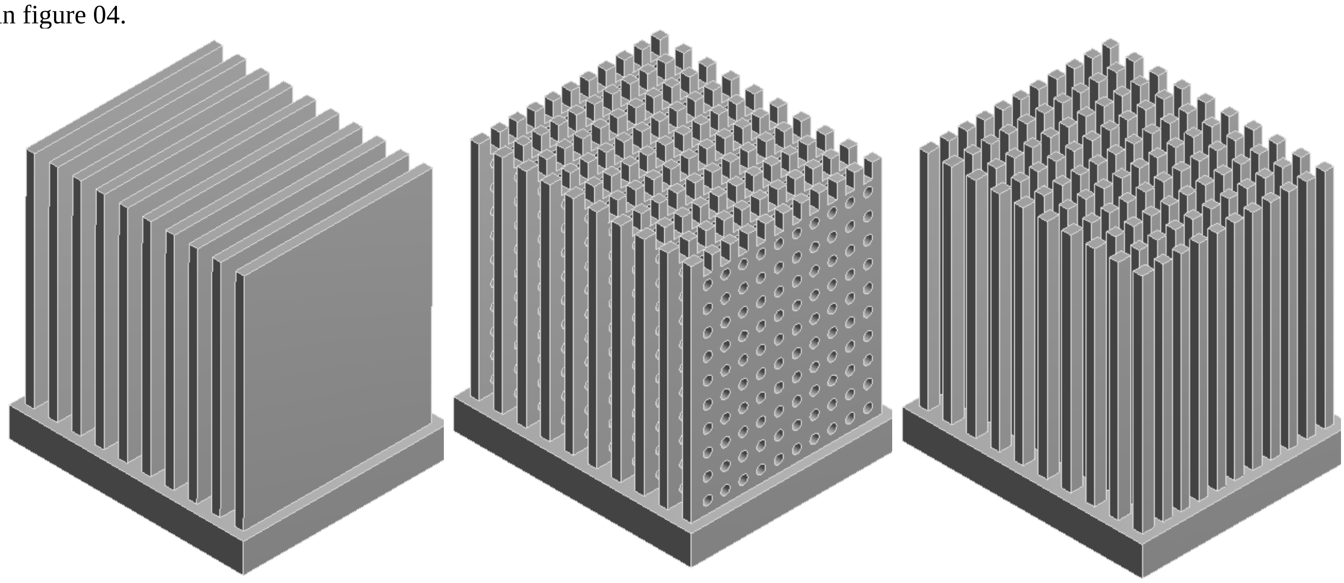


Figure 03: Boundary conditions at the fin base and the fin tip.

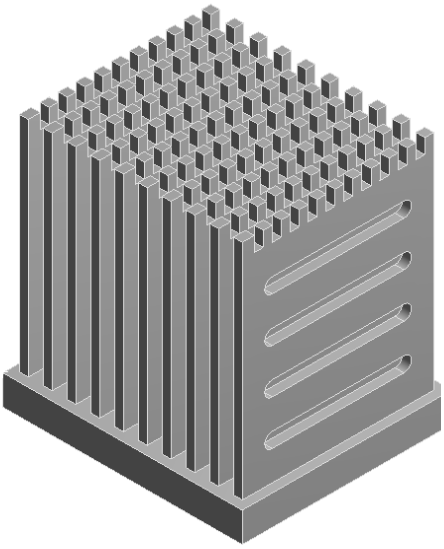
Fin Effectiveness: The performance of the fins is judged on the basis of the enhancement in heat transfer relative to the no-fin case.

$$\varepsilon_{fin} = \frac{Heat\ transfer\ rate\ from\ the\ fin\ of\ base\ area}{Heat\ trasnfer\ rate\ from\ the\ surface\ of\ area}$$

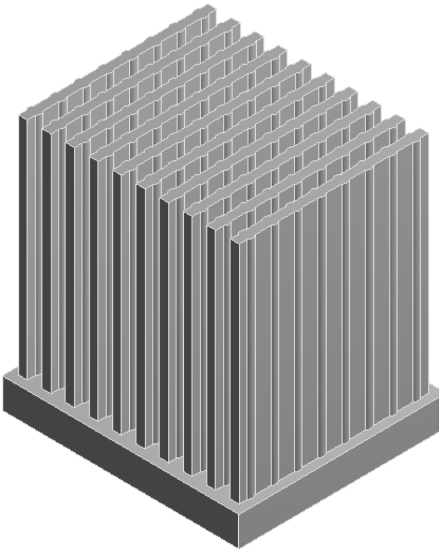
2.1CAD modeling for rectangular plate fin *[7]***:** For the creation of three dimensional CAD model of different design of fin using ANSYS workbench modeling tool has been used in the present work. For geometry creation base dimension of 80 mm × 70 mm x 10 mm, for the rectangular fin 75 mm height 64 mm width and 3 mm thickness, total number of fins are 10 as shown in figure 04.



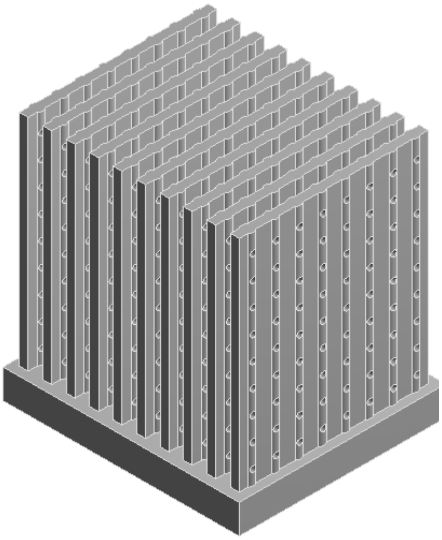
Rectangular plate fin Rectangular plate fin with hole Rectangular perforated fin



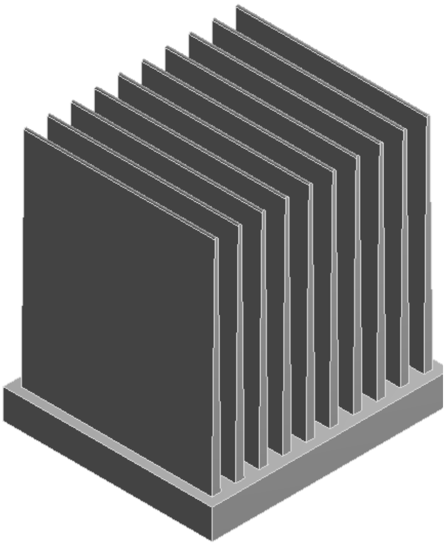
Rectangular plate fin with slot



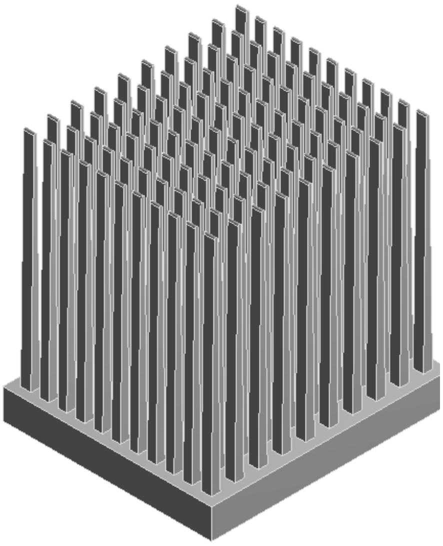
Rectangular plate with pin inserted fin



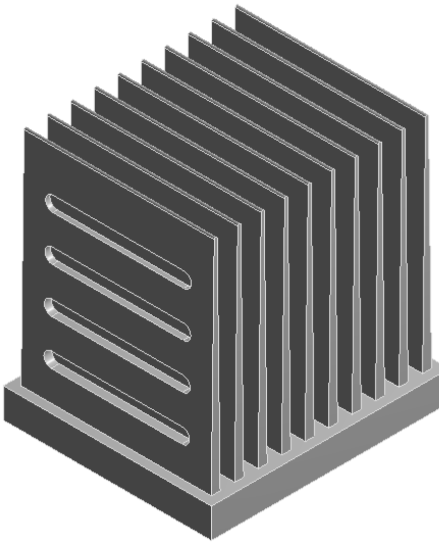
Rectangular plate inserted pin with hole fin



Triangular plate fin



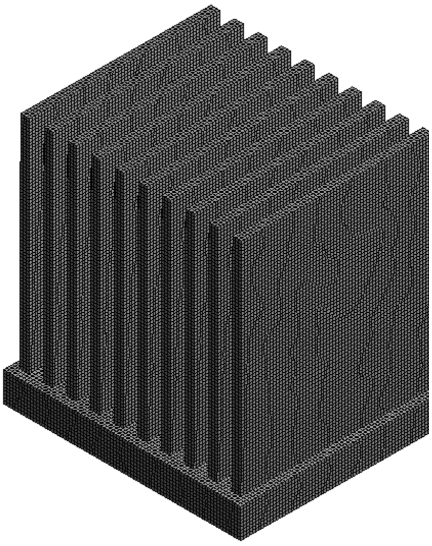
Triangular plate with perforated fin



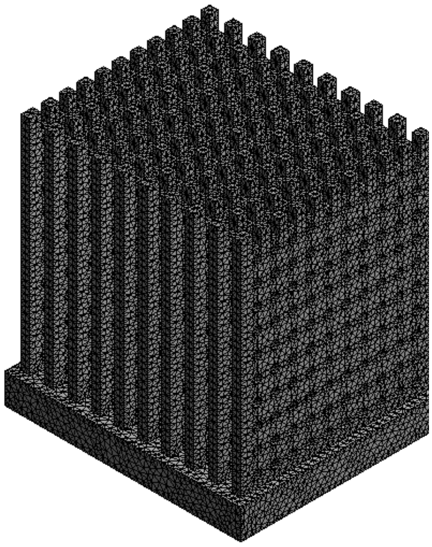
Triangular plate fin with slot

Figure 04: Three dimensional CAD model of different designs of fin

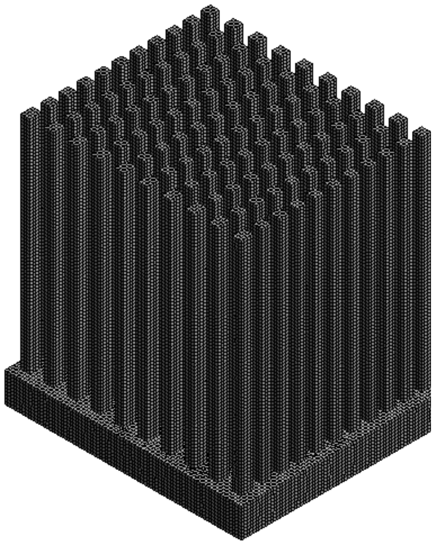
Meshing: Meshing is a critical process in finite element analysis where CAD geometry is separated into large numbers of small pieces. The small pieces are called mesh. The analysis accuracy and time rest on the mesh size and orientations. After completing the CAD geometry of rectangular plate fin is imported in ANSYS workbench for further thermal analysis and the next step is meshing. The mesh created in this work is shown in figure 05.



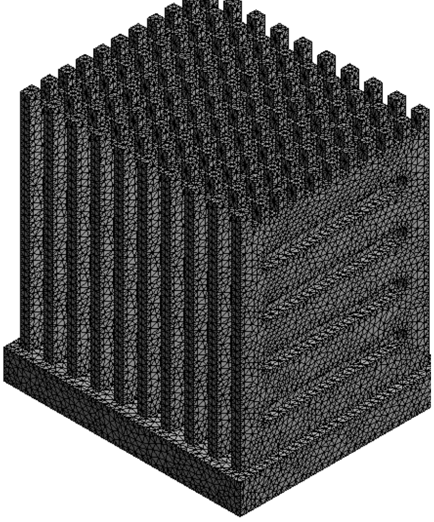
Rectangular plate fin



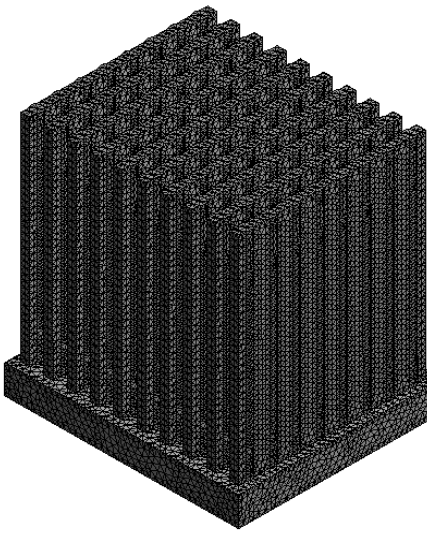
Rectangular plate fin with hole



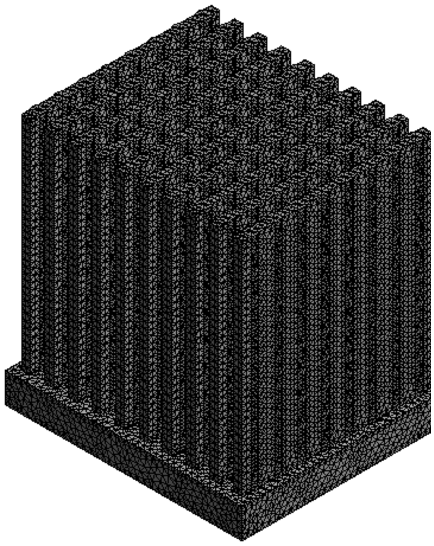
Rectangular perforated fin



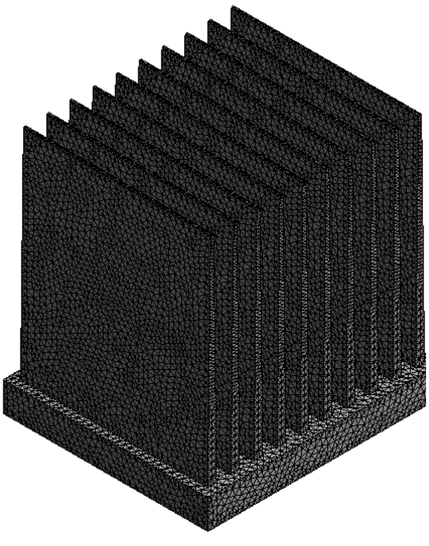
Rectangular plate fin with slot



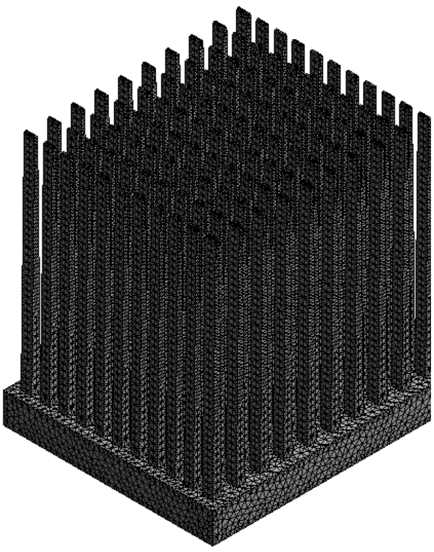
Rectangular plate with pin inserted fin



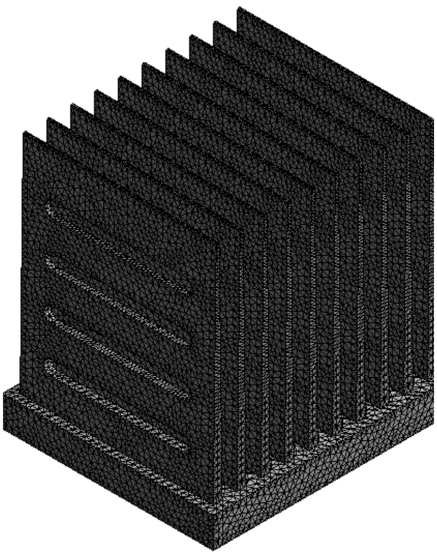
Rectangular plate inserted pin with hole



Triangular plate fin



Triangular plate with perforated fin



Triangular plate fin with slot

Figure 04: Meshing of different designs of fin

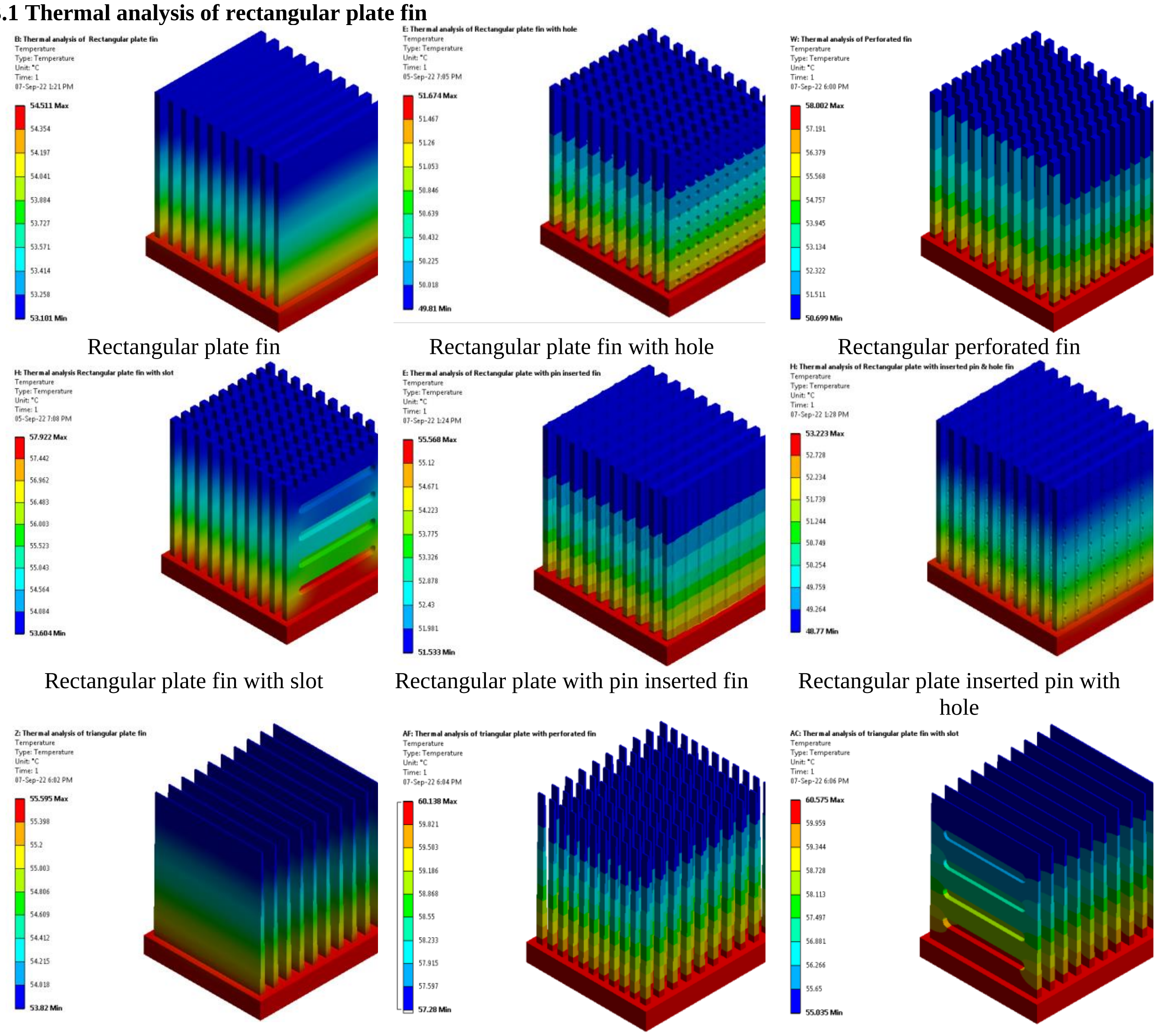
2.2 Material Properties: There are thousands of materials available in the ANSYS environment and if required library is not available in ANSYS directory the new material directory can be created as per requirement. For the current work aluminum 1060 is used as a material for the different design of fin. The material properties of the current work is: Density: 2700 kg m^-3, Coefficient of Thermal Expansion: 2.3e-005 C^-1, young modulus 69000 MPa, Ultimate tensile strength 310 MPa & Thermal conductivity 200 W/m_ºC*[R. Kumar et al.2020]*.

2.3 Boundary condition:

Aluminum 1060 is used as a material for all designs of fin, Heat supply at the bottom of the heat sink 13 W which is equal to the power supply. Air Temperature (Ambient temperature) 22 ºC and convection coefficient at the fin base is taken as 6e-6 W/mm^2 and at the fin surface stagnation air coefficient has been used.

3. Result and Discussion: Various results of temperature distribution, total heat flux and thermal stresses for all designs have been discussed in this section with the help of contours and graphs.

3.1 Thermal analysis of rectangular plate fin



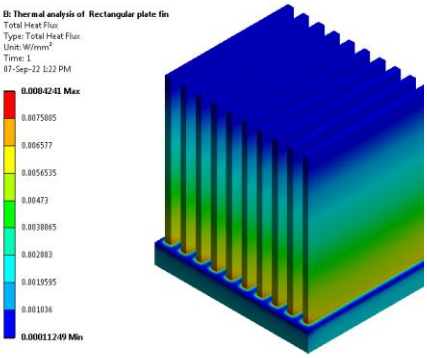
Rectangular plate fin — Rectangular plate fin with hole — Rectangular perforated fin

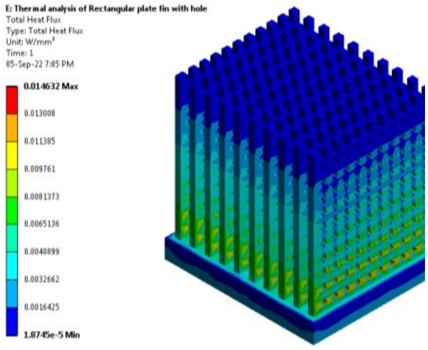
Rectangular plate fin with slot — Rectangular plate with pin inserted fin — Rectangular plate inserted pin with hole

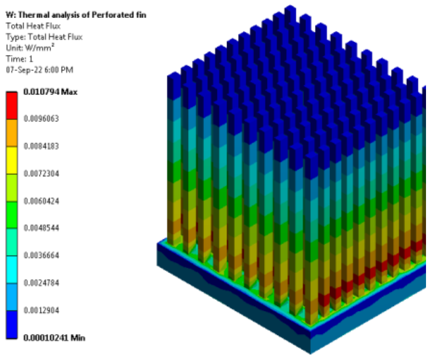
Triangular plate fin — Triangular plate with perforated fin — Triangular plate fin with slot

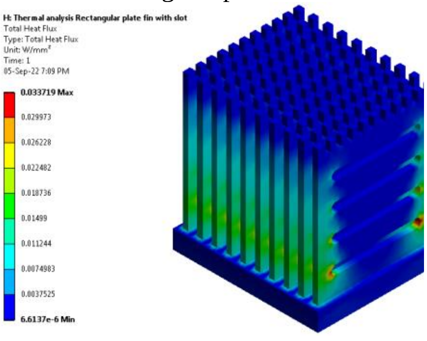
Figure 05: Temperature distribution over the different designs of fin

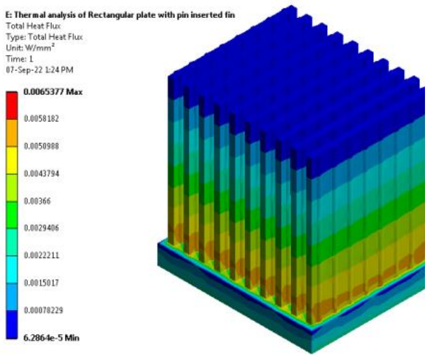
After performing thermal analysis on different design of fin, the temperature distribution has been analyzed where the maximum temperature of 54.5 ºC and minimum temperature of 53.1 ºC with a temperature difference of 1.4 degree for rectangular plate fin, the maximum temperature of 51.67 ºC and minimum temperature of 49.81 ºC with a temperature difference of 1.86 degree for rectangular plate with hole, the temperature distribution has been analyzed where the maximum temperature of 58.00 ºC and minimum temperature of 50.699 ºC with a temperature difference of 7.3 degree for rectangular perforated fin, the maximum temperature of 57.922 ºC and minimum temperature of 53.604 ºC with a temperature difference of 4.318 degree for rectangular plate fin with slot, the maximum temperature of 55.568 ºC and minimum temperature of 51.533 ºC with a temperature difference of 4.035 degree for rectangular plate with pin inserted fin, the maximum temperature of 53.223 ºC and minimum temperature of 48.77 ºC with a temperature difference of 4.453 degree for the rectangular plate inserted pin with hole fin, the maximum temperature of 55.595 ºC and minimum temperature of 53.82 ºC with a temperature difference of 1.775 degree for triangular plate fin, the maximum temperature of 60.138 ºC and minimum temperature of 57.28 ºC with a temperature difference of 2.858 degree for triangular plate with perforated fin and the maximum temperature of 60.575 ºC and minimum temperature of 55.035 ºC with a temperature difference of 5.54 degree for triangular plate fin with slot have been observed as shown in the figure 05.

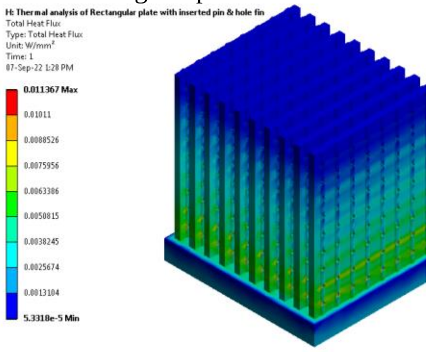

Rectangular plate fin

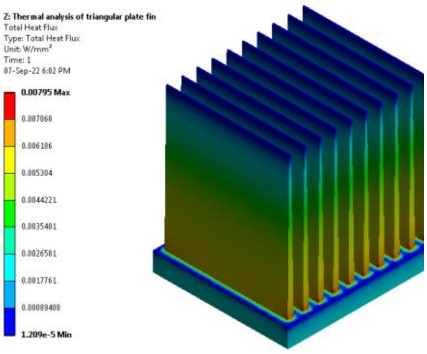

Rectangular plate fin with hole

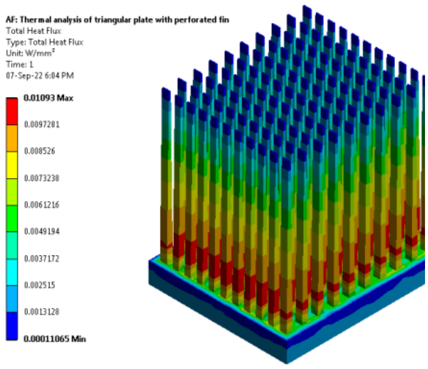

Rectangular perforated fin


Rectangular plate fin with slot


Rectangular plate with pin inserted fin


Rectangular plate inserted pin with hole


Triangular plate fin


Triangular plate with perforated fin

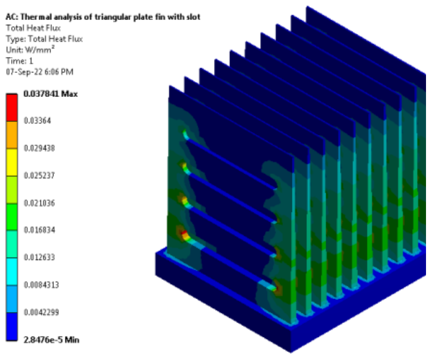

Triangular plate fin with slot

Figure 06: Total heat flux over the different designs of fin

After performing thermal analysis on the different designs of fin, the total heat flux has been analyzed where the maximum total heat flux of 0.0084 W/mm^2 for has been observed near the bottom end of the rectangular plate fin, the maximum total heat flux of 0.0146 W/mm^2 has been observed near the bottom end of the rectangular plate fin with hole, the maximum total heat flux of 0.0108 W/mm^2 has been observed near the bottom end of the rectangular perforated fin, the maximum total heat flux of 0.0337 W/mm^2 has been observed near the bottom end of the rectangular plate fin and in the slot, maximum total heat flux of 0.0065 W/mm^2 has been observed near the bottom end of the rectangular plate with pin inserted fin, the maximum total heat flux of 0.0114 W/mm^2 has been observed near the bottom end of the rectangular plate inserted pin with hole fin, the maximum total heat flux of 0.00795 W/mm^2 has been observed near the bottom end of the triangular plate fin, the maximum total heat flux of 0.0109 W/mm^2 has been observed near the bottom end of the triangular plate with perforated fin and the maximum total heat flux of 0.0378 W/mm^2 has been observed near the bottom end of the triangular plate fin and slot as shown in the figure 06.

III. COMPARATIVE RESULT

It has been observed from the figure 07 that the 48.76 ºC is the lowest temperature for the rectangular plate inserted pin with hole fin which is 8.9% lower than the plane rectangular plate fin and the figure 08 show that the 51.67 ºC is the lowest temperature for the rectangular plate fin with hole which is 5.5% lower than the plane rectangular plate fin.

It has been observed from the figure 09 that the 7.3 degree is the highest temperature difference for the rectangular perforated fin which is 4.2 times higher than the plane rectangular plate fin. The figure 10 show that the 0.0378 W/mm^2 is the lowest temperature for the triangular plate fin with slot which is 3.5 times greater than the plane rectangular plate fin.

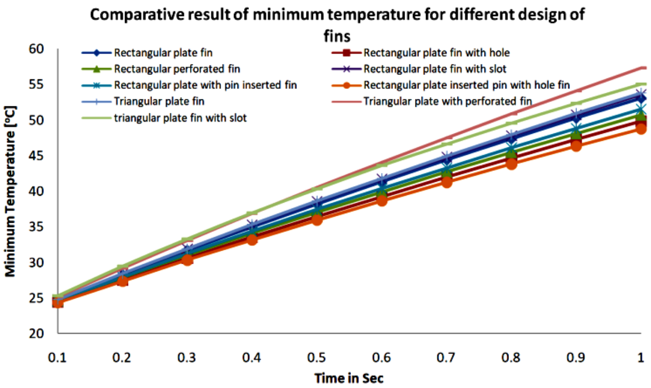


Figure 07: Comparative result of minimum temperature for different design of fins

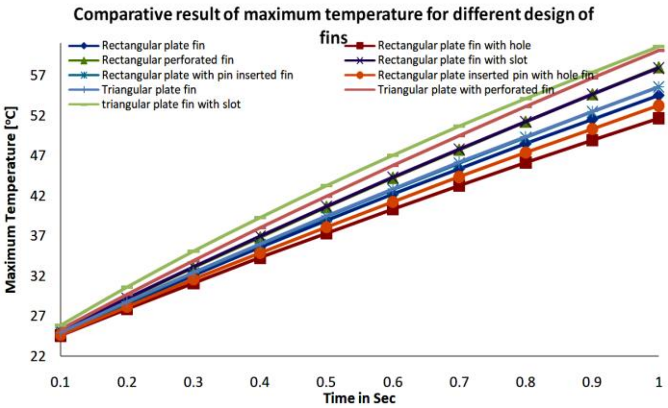


Figure 08: Comparative result of maximum temperature for different design of fins

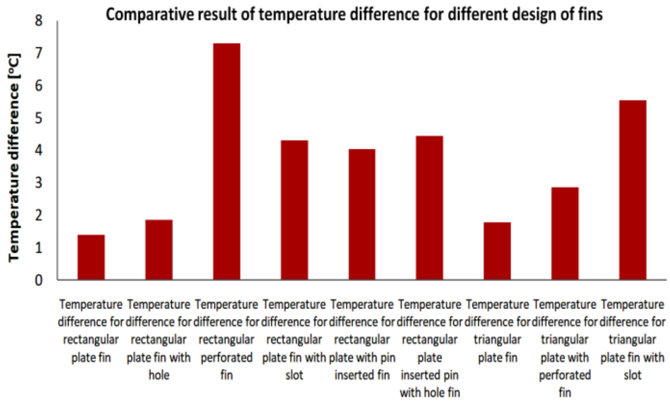


Figure 09: Comparative result of temperature difference for different design of fins

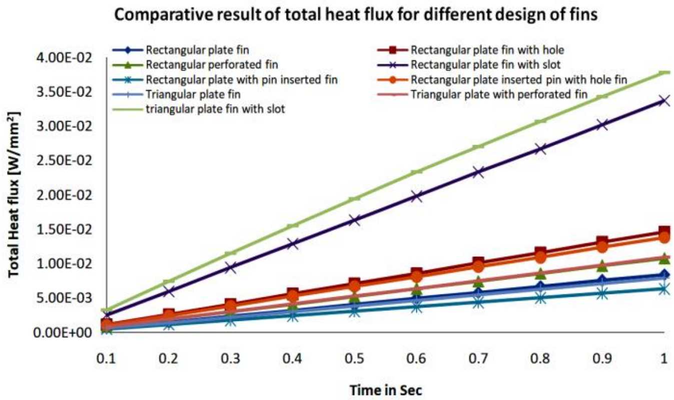


Figure 10: Comparative result of total heat flux for different design of fins

It has been observed from the above figure 11 that the 0.0276 MPa is the lowest thermal stress for the rectangular plate fin with hole & triangular plate with perforated fin which is 5.74 times lower than the plane rectangular plate fin.

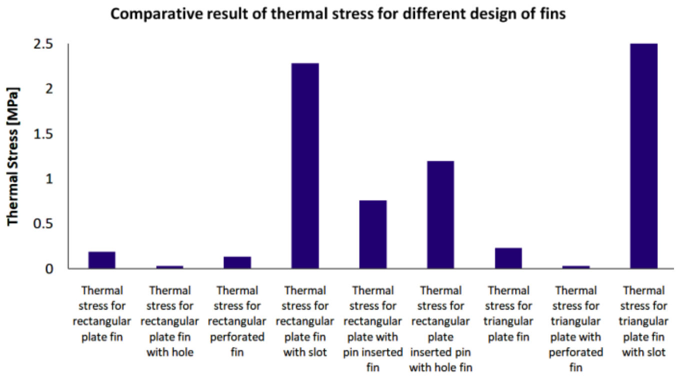


Figure 11: Comparative result of thermal stress for different design of fins

IV. CONCLUSION:

Thermal analysis have been performed in this work on a different designs of fin in order to investigate the temperature distribution, heat flux, and thermal stresses using ANSYS workbench. For this work total nine designs of fin have been created such as rectangular plate fin, rectangular plate fin with hole, rectangular perforated fin, rectangular plate fin with slot, rectangular plate with pin inserted fin, rectangular plate inserted pin with hole fin, triangular plate fin, triangular plate with perforated fin & triangular plate fin with slot. Aluminum 1060 is used as a material for all designs of fin, The 13 W of heat supply at the bottom of the fin have been applied which is equal to the power supply at ambient temperature of 22 ºC. results show that the 48.76 ºC is the lowest temperature for the rectangular plate inserted pin with hole fin which is 8.9% lower than the plane rectangular plate fin and the 51.67 ºC is the lowest temperature for the rectangular plate fin with hole which is 5.5% lower than the plane rectangular plate fin while the 0.0378 W/mm^2 is the lowest temperature for the triangular plate fin with slot which is 3.5 times greater than the plane rectangular plate fin. The 7.3 degree is the highest temperature difference for the rectangular perforated fin which is 4.2 times higher than the plane rectangular plate fin and the 0.0276 MPa is the lowest thermal stress for the rectangular plate fin with hole & triangular plate with perforated fin which is 5.74 times lower than the plane rectangular plate fin. Hence the rectangular plate inserted pin with hole fin is suggested for better heat transfer.

Reference:-

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