Steady State Free Convection through some Variable Fin Geometries

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Abstract

Thermal performances on some typical variable geometries were conducted in this work which can be reported into two phases. In the first phase of this work, fins of rectangular, cylindrical, and conical geometries having the same total surface area were studied. It is found that the cylindrical fin is the least efficient and least effective among the three. In the second phase, design modification in the form of grooves is made on cylindrical fins. Cutting grooves on cylindrical fins increase its surface area. The three grooved cylindrical fins are namely- fully grooved cylindrical fins, bottom half grooved cylindrical fins, and top half grooved cylindrical fins. All three grooved fins have the same volume. It was noticed hat, on cutting groove the on fin the quality of convective heat transfer, as well as the effectiveness, improves, but the efficiency degrades.

Keywords: Finite Element Method, thermal steady state, fin effectiveness, fin efficiency, free convection

1. Introduction

To safeguard various mechanical or electrical or electronic appliances from overheating during working, extended parts of them are used for facilitating thermal energy dissipation, which are considered as fins. Fins are widely employed to enhance the rate of heat loss from surface initially by conductions through core cross section and subsequently by convection through surface to the ambient air. Fins are extended surfaces attached to electronic and mechanical components. Application of fins are found in computers, laptops, I.C. engines, motors, transformers, heat exchangers, compressors, etc. Since there is no heat generation within the fins, the magnitude of rate of heat loss and heat gain of the fin is the same [1]. Cuce and Cuce [2] have presented how fins have been used in the field of heat transfer over the last few decades. Dubey et el. [3] have compared 1-D and 2-D heat flows through longitudinal and annular fin assemblies. Grebenişan and Anton [4] have used the analytical solution of 3D heat equation for the analysis of a plate fin heat sink having thermally steady state. Heggs and Stones [5] have used ANSYS software to simulate their work. Joneidi et al. [6] have optimized a heat sink and performed a numerical study of its thermal performance under thermal steady state using ANSYS Software. In their paper they have investigated the effects of the total surface area, maximum surface temperature and material and compared the geometrical features. Khaled [7] have studied heat exchangers under thermally steady-states for different purposes. In this work also fins have been studied under thermally steady state. Mohankumarem et al. [8-9] have used different methods to work on fins having temperature dependent thermal conductivity and analyzed both fin efficiency and fin effectiveness. Mokheimer [10] have used different methods to work on fins having temperature dependent thermal conductivity. He has analyzed the fins on the basis of fin efficiency only whereas we have discussed the performance of the fins on the basis of both fin efficiency and effectiveness. Mueller et al. [11] has conducted an analytical study for the investigation of optimum dimensions of cylindrical pin fins and rectangular fins considering temperature-dependent heat transfer coefficient. Nagarani and Mayilsamy [12] have analyzed multiple fins subjected to variable heat transfer coefficients under natural convection. However, in this research, the fins are subjected to a constant heat transfer coefficient. Purwadi and Pratama [13] have studied heat transfer from different fins under natural convection and performed thermal optimization of fins in heat sinks which have variable thickness and the fin thickness varied in the direction of the flow. Xianghui, and Shuo [14] investigated by using porous fins which have better thermal performance in comparison to that of conventional solid fins of equal weight. Wood et al. [15-16] have modified bar fins to stepped fins and stepped fins with indentation. After analysis it is concluded that extended surface having greater surface area has higher heat transfer rate. Present work involved comparative analysis fins considering both the efficiency and as well as the effectiveness of fin geometries as performance parameters. Many mechanical and electronic components which have to undergone through repeated working cycles with high frequency. Waste heat is generated in the components for each working cycle. Since the frequency of the working cycles is usually very high, time assigned for the waste heat dissipation is very less. As a result, after each cycle some amount of waste heat get accumulated within the device. The heat accumulation rises the temperature of the device and it may overheat or burn the device gradually. Due to this problem, fins are introduced in industries.

Present work encompasses a comprehensive analysis of the variation of efficiency along with the effectiveness of some geometrical variants of fins. Comparative studies were performed on the performances of regular as well as geometrically modified design variants of fins, subjected to a constant heat flux under free convection in a thermally steady state. The geometries of extended surfaces namely- rectangular fins, cylindrical fins, conical fins, fully grooved cylindrical fins, bottom half grooved cylindrical fins, and top half grooved cylindrical fins have been modeled, investigated, and studied.

2. Materials and Methods

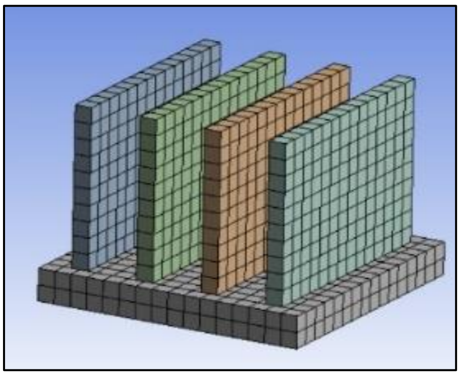
As shown in figure 1, Six different fins (rectangular fins, cylindrical fins, conical fins, fully grooved cylindrical fins, bottom half grooved cylindrical fins, and top half grooved cylindrical fins) have been modeled in this work Dimensions of them are shown in Table 1.

Table 1. Dimensions of various fin geometries

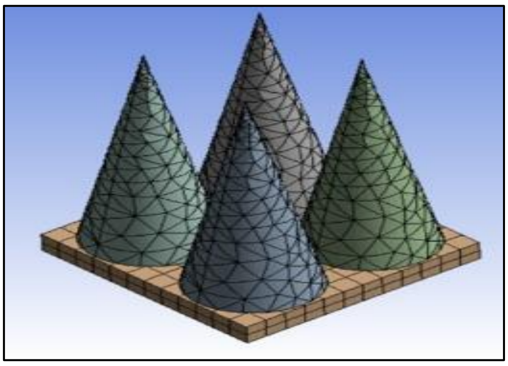
Fin geometry	Rectangular	Cylindrical	Conical	Fully grooved cylindrical	Bottom Half grooved cylindrical	Top half grooved cylindrical
Dimensions (mm)	50×70×5	10.892(radius),108.92(height)	19.197 (base radius), 115.18 (height)	10.892 (radius), 108.92 (height)	10.892 (radius), 108.92 (height)	10.892 (radius), 108.92 (height)
Number of grooves	-	-	-	4	8	8
Groove dimensions (mm)				2 (radius), 108.92 (height)	2 (radius), 54.46 (height)	2 (radius), 54.46 (height)
Total Surface Area (mm^2)	8200	8200	8200	19875.3088	19925.574	19925.574

Volume (mm^3)	17500	40598	44450.067	37860.542	37860.542	37860.542
Material	Aluminum 6061					

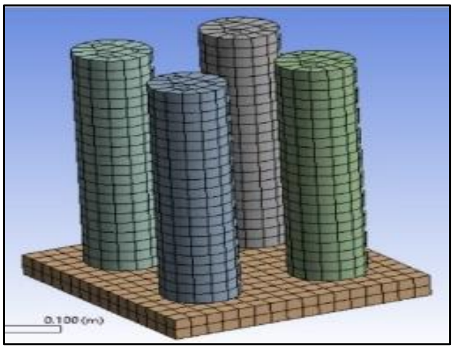
Total surface area of rectangular fins, cylindrical fins and conical fins are kept the same (8200 mm^2) in order to compare their performances. Height equals 10 times radius for cylindrical fins and height equals 6 times for conical fins to keep the same surface area of the dimension of conical fin and cylindrical fin. Half cylindrical grooved of 2 mm radius area cut on the cylindrical fins in the form of design modification. This increases the total surface area on the basis of length and the location of the grooves, the design modification gives three types of fins namely - fully grooved cylindrical fins, bottom half grooved cylindrical fins, top half grooved cylindrical fins. Volume of all three grooved fins is same because same amount of material is removed from cylindrical fins in all the three cases. All the fins are mounted on a square base having sides of 80 mm and width of 10mm. The 3D Models of the fins are created using the NX-12.0 modelling Software.



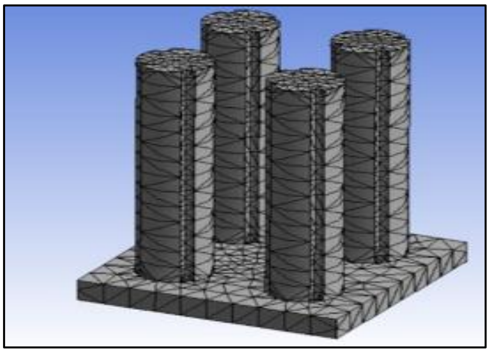
Rectangular Fins



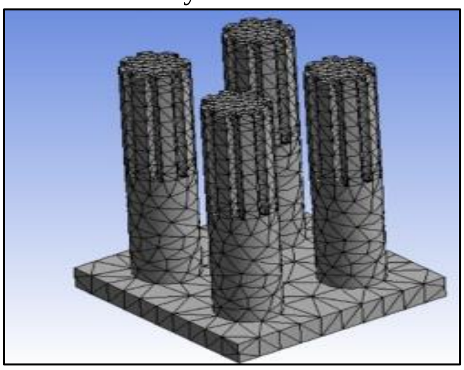
Conical Fins



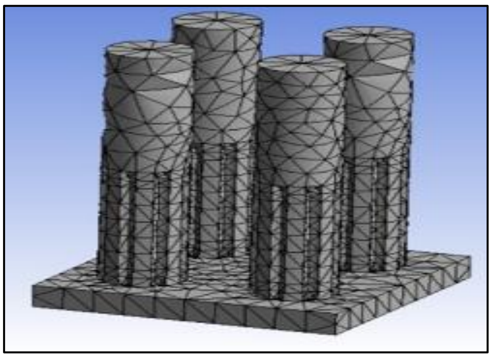
Cylindrical Fins



Fully Grooved cylindrical Fins



Top Half Grooved



Bottom Half Grooved

Figure 1. Various fin geometries along with meshing

Table 2. Physical Properties of Aluminum 6061

Density	2710 kg/m^3
Thermal conductivity	152 – 202 W/m K
Specific heat capacity	897 J/kg K
Specific gravity	2.7
Tensile yield strength	276 MPa
Shear strength	207 MPa
Fatigue strength	96.5 MPa

The physical properties The properties of Aluminum 6061 are enlisted in Table 2. Aluminum 6061 (an Al-alloy consisting of 97.9% Al, 0.6% Si, 1.0%Mg, 0.2%Cr and 0.28%Cu) is widely used in welding assemblies, electronics parts, marine frames, heat exchangers and heat sink owing to its exceptional resistance to corrosion, weldability, machinability, and strength.

3. Modelling and analysis

The domains are too complex to apply the grooving equation analytically and get a temperature profile easily. Thus, Finite Element Method (FEM) is applied with the help of ANSYS. In FEM firstly the entire domain discretized into numerous small elements. The integration of weak integral form of the grooving equation is done element by element for a domain. From the resulting equation, the algebraic equation for each node present in the domain are found out and separated. Then the algebraic equation of all the nodes is arranged in a matrix format. In the matrix format itself, the value of boundary conditions is plugged into the expression of corresponding nodes present on the boundary surface of geometry. After solving the matrix system of equation, the value of temperature of all the nodes present in the domain are obtained. On interpolating the nodal temperature values, temperature at any point present in the domain can be obtained. Thus, temperature profile is achieved. All the steps of Finite Element Method are performed by ANSYS automatically. After importing the geometries into ANSYS, discretization of the domains into small elements are done. This is known as meshing. Then selecting the face of geometries, corresponding boundary conditions are applied. On solving, temperature profile is obtained. These all steps are performed in ANSYS Mechanical. The process of discretizing the entire domain into several elements is known as meshing the finer the mesh, the lesser is the element size, and the more is the number of nodes and the elements, this helps to get accurate results.

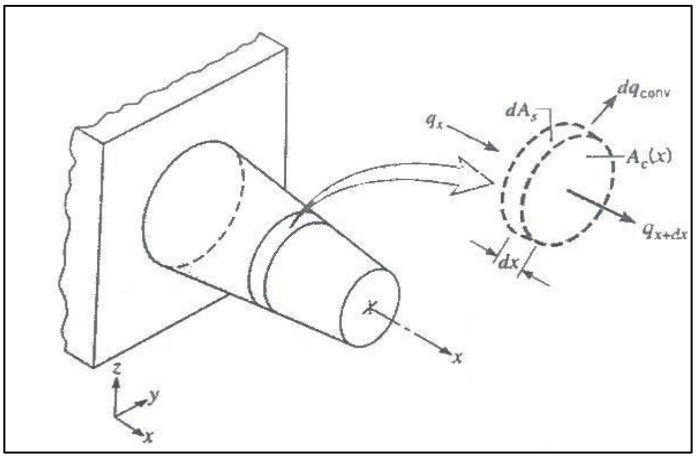


Figure 2. Diagram representing the fin and the differential element

From the fin a differential element or chunk of dx thickness is analyzed. q_x is the amount of heat conducted into the chunk. q_{x+dx} is the amount of heat conducted out from the chunk. dq_{conv} is the amount of heat converted to the surrounding. dA_s is the surface area of the differential element with perimeter P, and the cross-sectional area of the chunk A_C (varies along the x-axis).
Following assumptions are considered while studying the differential element:

- 1 D Conduction is considered where, temperature is varying along the longitudinal axis (x-axis) only. So, the temperature distribution is uniform over across-section.
- Steady state conduction is considered. So, temperature doesn't vary with time.
- No heat is radiated from the surface. So, there is no heat loss by radiation to the surroundings. Also, no heat is generated within the differential element.
- The convective heat transfer coefficient (h) is constant all over the surface and the thermal conductivity (k) of the material is constant.

3.1 Governing Equation

The 1D energy balance equation is given by: -

$$\frac{d^2T}{dx^2} + \left(\frac{1}{Ac}\frac{dAc}{dx}\right)\frac{dT}{dx} - \frac{hP}{kAc}(T - T_a) = 0 \quad \text{(i)}$$

Where, T = temperature, Ac = cross section area, h = Heat transfer coefficient, P = Perimeter, k = thermal conductivity, and T_a = Ambient temperature

3.2 Boundary condition

The following boundary conditions have been applied to the domain for analysis in ANSYS: -

- Heat flux at the bottom of the base, q = 10 kW/m^2
- Free convection to all the surfaces except the bottom of base of the geometry
- Velocity of air = 0, and Air temperature T_a = 25^{o}C
- Thermal conductivity of the body, k = 170 W/mK
- Convective heat transfer coefficient, h = 30 W/Km^2

4. Result and Discussion

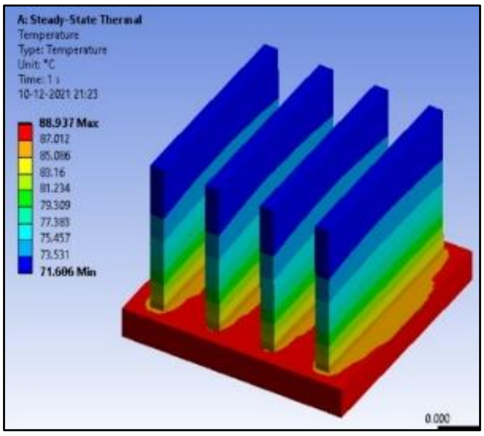
The temperature profile for the domains is obtained by interpolating the nodal temperature values, which are obtained by solving the matrix equation. This is done by ANSYS (Figure 3). The nodal temperature values are directly obtained from the weak integral form of the governing equation. So, these values are almost accurate. Except the nodes, at any other point in the domain, value of temperature is obtained by interpolating the nodal temperature values. So, the value of temperature at any point except the node may not be very accurate. The finer the mesh, the more is the number of nodes and the more accurate temperature profile can be obtained.

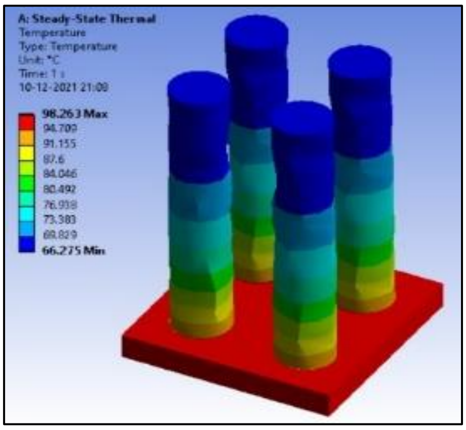
Table 3. Calculations of efficiency and effectiveness of fins

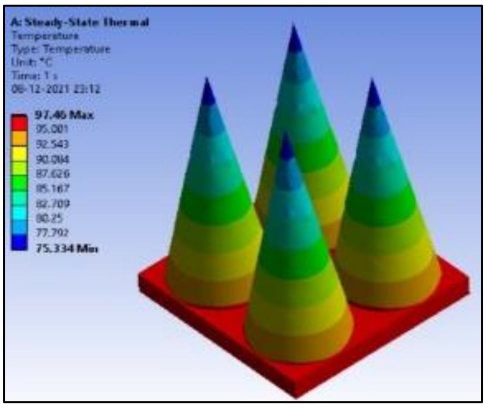
Fin geometry	A_s (Total area through which convection takes place) (in mm^2)	Base Temperature	Tip Temperature	ΔT (Base temperature – Tip temperature)	η (Efficiency)	ε (Effectiveness)
Rectangular	39600	88.937	71.606	17.331	0.843	5.213

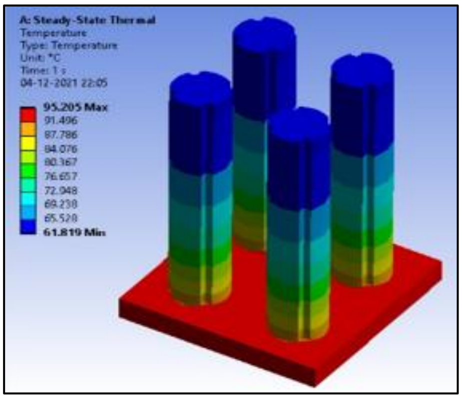
Cylindrical	39418.0369	98.263	66.275	31.988	0.739	4.550
Conical	33137.8956	97.46	75.334	22.126	0.888	4.600
Fully grooved cylindrical	42746.3666	95.205	61.819	33.386	0.711	4.748
Bottom half grooved cylindrical	43132.8086	94.228	61.367	32.861	0.714	4.815
Top half grooved cylindrical	42746.3666	95.001	61.809	33.192	0.713	4.762

From Figure 3, it is observed that the minimum base temperature is for the rectangular fins, whereas the maximum base temperature is for the cylindrical fins, and, the minimum tip temperature is for the bottom half grooved cylindrical fins whereas the maximum tip temperature is for the conical fins. The difference between the base temperature and tip temperature is minimum for the rectangular fins and maximum for the fully grooved cylindrical fins. The calculations of efficiencies in various fin geometries are highlighted in Table 3.









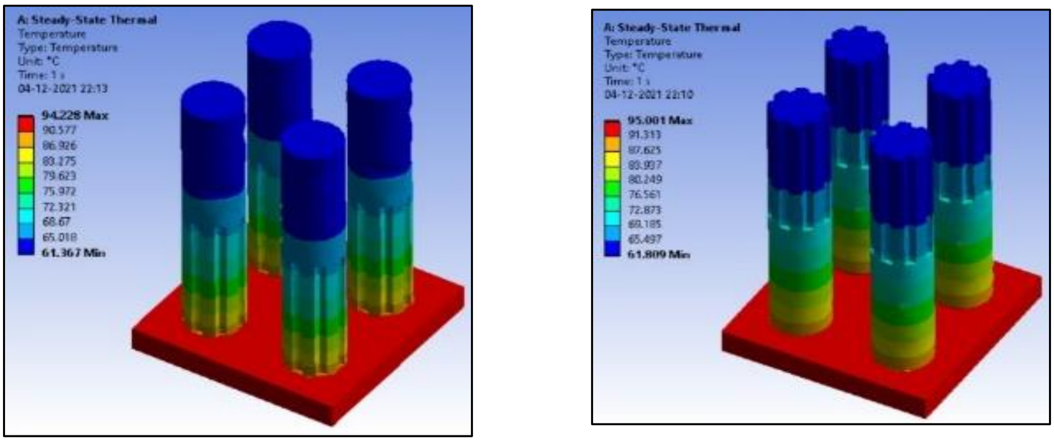


Figure 3. Temperature contours at different fins

5. Conclusion

The most efficient fin was found to be the conical one (84.3% efficiency) among all as because of maximum heat dissipation; whereas the most effective fin was found to be the rectangular one (effectiveness 5.213) the as least amount of heat will be dissipated from the surface if no fin in attached to it, and its temperature is equal to the base temperature when the rectangular fin is attached to it. Cutting of groove increases the surface area of the fin but it is not reducing base temperature adequately in order to increase the efficiency. Therefore, groove cutting reduces efficiency. Three grooved cylindrical fins are less efficient than the cylindrical fins Since cutting Grooves reduces the efficiency of the fin fully grooved cylindrical fins, the bottom half of grooved cylindrical fins, and the top half of grooved cylindrical fins are lesser efficient than cylindrical fins Three grooved cylindrical fins are more efficient than cylindrical fins. Top half grooved cylindrical fins are more effective than cylinder fins.

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