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Numerical Investigation of Varying Fin Geometries with Different Material Assignments for Natural Convection

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Abstract

Fins are the extended surfaces which are added in order to enhance the rate of heat transfer. As the addition of fins enhance the dissipation of heat from the body, this causes the rate of heat transfer to get increased. This increasing of heat transfer rate is the objective behind of the addition of fins. In this paper, five types of fins (pinned, tapered pin, rectangular, tapered rectangular, and tapered fin with triangular profile) are simulated to find out their respective fin tip temperatures, along with three types of material assignments (Copper, Aluminium and Structural Steel). The industrial application of fins is very diversified. Fins are used in power plants, electronic components, automotive components, chemical & nuclear processes, etc. One of many reasons why this research is performed is due to its immense importance in the industry. The objective is to find out the best finned surface along with the most suitable material assignment. The software to be used for performing this analysis is Ansys Workbench 2021 R2 (Steady State Thermal).

Keywords
Ansys Workbench, Free convection, Heat Transfer, Fin, and Steady State.

1. Introduction

The main objective of adding extensive heat transfer surface area is to enhance heat dissipation in order to increase the rate of heat transfer from a heated body. There are normally two ways of increasing the rate of heat transfer: either by increasing the convective heat transfer co-efficient, or by extending the heat transfer surface area (Cengel et al. 2016). Addition of fins increase the area of heat transfer. Which is why one of the primary purposes of a fin is to increase the heat transfer surface area as well as heat transfer co-efficient (Chaudhari et al. 2014). The industrial purpose of fin is very versatile. For the manufacturing sector, device miniaturization posesnumerous challenges. Hybrid cooling using mini-channel heat sinks in combination with nanofluid is one of thepromising cooling techniques to maintain the temperature of such high heat-generatingdevices(Babar et al. 2019). In a broad range ofindustrial applications, including heat exchangers and microchannel heatsinks, fins are employed in large scale forthe enhancement of the rate of heat transfer (Sowmya et al. 2022). Industrial sectors including chemical, nuclear,and power plants where enormous amount of heat generation occurs require techniques of dissipating heat (Sowmyaet al. 2022), which is why finned surfaces are required for these fields.

1.1 Objectives

The importance of performing research over finned surfaces is immensely important. In the field of thermal and electronic systems, fins serve the main purpose of providing heat transfer with effectiveness and efficiency in industrial and engineering equipment (Sobamowo et al. 2022). The primary objectives based upon which we've conducted our research are enlisted below.

- To design fins of five varying geometries.
- To graphically analyze and compare their thermal performances.
- To find out the most effective fin geometry (among the fins that we've simulated) along with the most suitable material for the fabrication of fins.

2. Literature Review

There were various experimental and numerical works done regarding the heat transfer enhancement in innovative heatsink fin along with the addition of fan (Kim et al. 2008). Researchers had performed an experimental work to find out the temperature distribution along the length of pinned fin, which was further analyzed and investigated numerically (YP et al. 2015). Researchers had also done various research regarding the heat transfer analysis of pinned fin (Hossain et al. 2013, Karabacak et al. 2011, Dhumne et al. 2014, Elshafei et al. 2010, and Ismail et al. 2013). A research work was experimentally performed the heat transfer characteristics along with pressure loss for the case of pin fin of varying material assignments (Gawai et al. 2013). Researchers had performed experimental and comparative study regarding the effectiveness and heat transfer rate for circular and elliptical fins under varying conditions of operation (Nagarani et al. 2010). A group of researchers had performed comparative heat transfer analysis for the case of pin, circular, square and elliptical shaped fins. These comparative analyses were done in order to find out the compatible heatsink fins under given conditions (Yang et al. 2007). Research work was done regarding the unsteady thermal dispersion along varying fins, which includes rectangular, triangular, concave, and convex fins (Mosayebidorcheh et al. 2014). Researchers had worked on the thermal distribution through the exponential fins (Turkyilmazoglu et al. 2021). Study was done regarding the effects of bifurcated fins over melting and solidification, along with the discussion regarding local and global entropy generation (Chen et al. 2022). Researchers had done research process of parallel plate finned heatsink which is subjected to impinging airflow in a broadcast vehicle system, and their simulation results showed that the maximum temperature of the model design was smaller than the upper limit of the electronic equipment (Cuong 2022). Regarding fins, researchers had illustrated a significant approach for increasing the rate of energy transfer through the porous fin by applying both magnetic and electrical effects (Das et al. 2021). A research work was previously done regarding the consideration of porous concave fin at inclined position in order to examine the unsteady thermal distribution in the extended surfaces (Kumar et al. 2022). Researchers hadexamined the temperature variation and heat transmission along the inclined permeable straight fin of trapezoidal and dovetail profile with radiation and convective heat transfer (Gireesha et al. 2021). Therefore, the importance of experimental and numerical investigations in this field is immense.

3. Methods

In this simulation, we've assumed the condition to be steady state. Hence, we've used the Steady State Thermal tool. In the simulation, the ambient temperature is assigned to be 22^{o}C, and the convective heat transfer co-efficient is assigned to be 50 W/m^{2}K. The base temperature is assigned to be 70^{o}C, and the fin tip is assigned to be adiabatic (zero heat flux). In the meshing section of the simulation, we've done three modes of mesh (Fine, Coarse, and Medium).

Table 1. Nodes & Elements of Varying Mesh Types

Mesh Types	Nodes	Elements
Coarse	4316984	1098231
Medium	4110236	1002459
Fine	4556378	1121302

As we can see in the table above, the number of nodes for the case of coarse and medium meshes are 4316984 and 4110236 respectively. And the number of elements for the case of coarse and medium meshes are 1098231 and 1002459 respectively. Contrarily,the number of nodes and elements for the case of fine meshing are 4556378 and 1121302 respectively, which are highest among the three types of mesh modes. Hence, we chose fine meshing as the mode of meshing for our simulation. During our mesh optimization process, we have assigned our element size to 0.5mm along with the transition ratio of 0.272 and growth rate of 1.2.

The governing equations upon which our simulation system was based are enlisted below.
Fourier's law of heat conduction equation: $Q_{cond}= kA(\frac{dT}{dx})$
Newton's law of cooling: $Q_{conv}= hA_s(T_s-T_a)$
Temperature distribution equation along the length of fin with insulated tip: $\frac{T-Ta}{Tbase-Ta} = \frac{\cosh(m(L-x))}{\cosh(mL)}$

4. Data Collection

In the simulation section, we've assigned thermal boundary condition for the fin base to be 70°C, ambient temperature to be 22°C, and convective boundary condition to be 50 W/m^{2}K. We've done simulation for five types of fins- pinned fin, tapered pin, rectangular, tapered fin (triangular profile), and tapered rectangular. After simulating, we've positioned thermal probe to find out the trajectory of temperature distribution along the length of varying fins. The results of the probes are illustrated below in Figure 1.

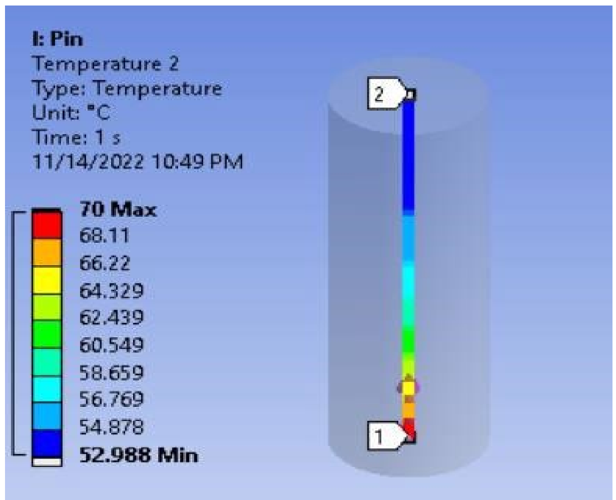

Figure 1. Temperature Distribution Along the Length of Pinned Fin

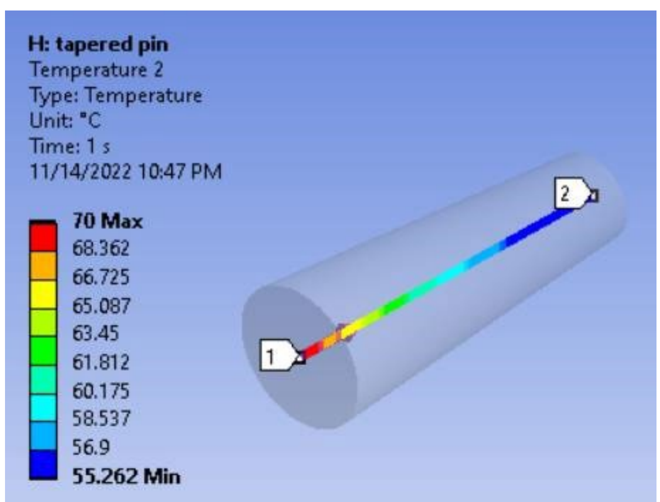

Figure 2. Temperature Distribution Along the Length of Tapered Pin Fin

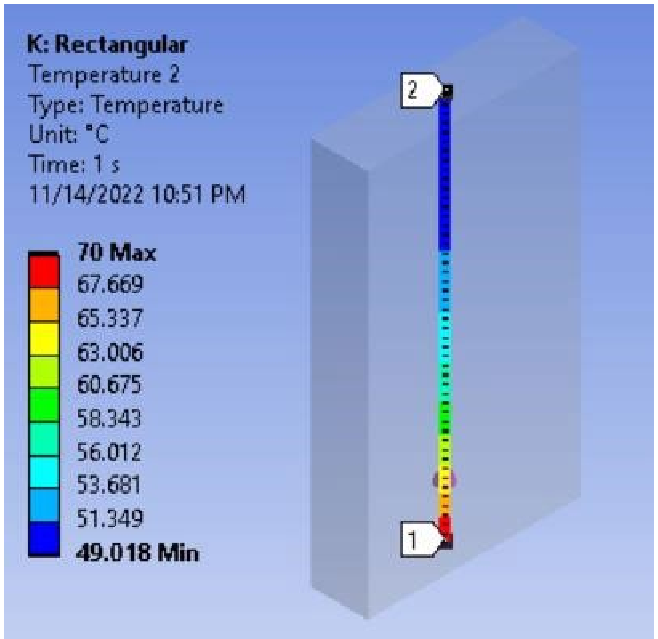

Figure 3. Temperature Distribution Along the Length of Rectangular Fin

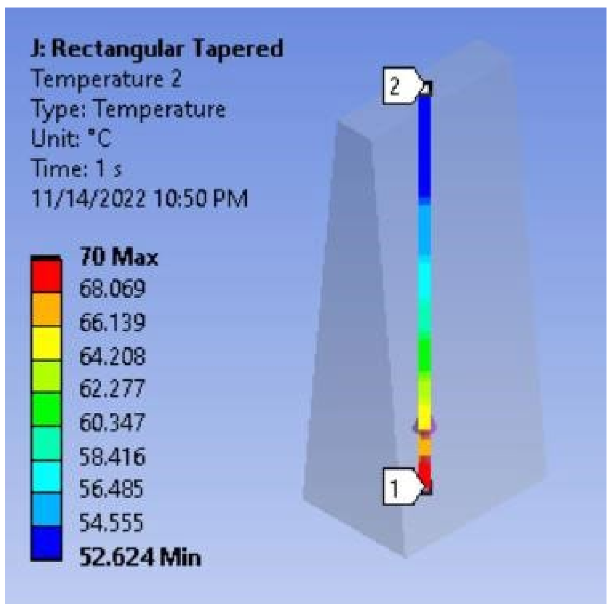

Figure 4. Temperature Distribution Along the Length of Tapered Rectangular Fin

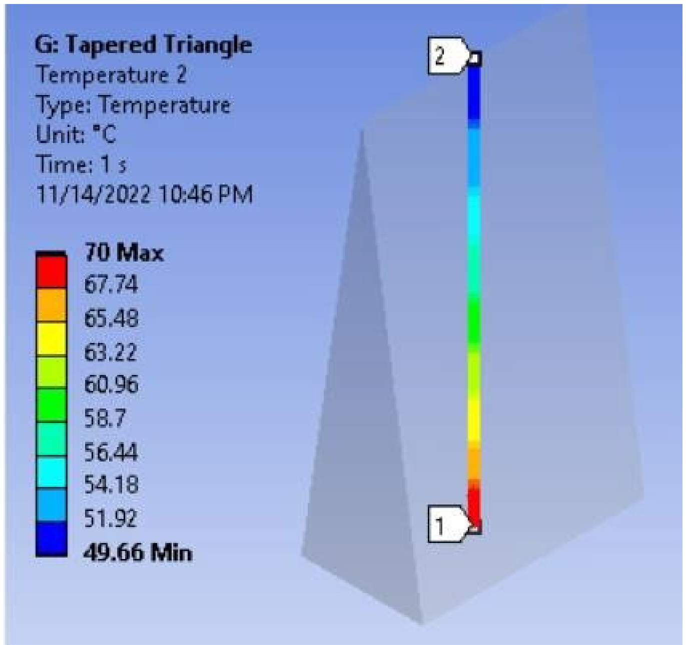

Figure 5. Temperature Distribution Along the Length of Tapered Fin (Triangular Profile)

After simulations, we've found out that the fin tip temperature for the case of tapered pin fin is highest among the five types of fins that we've simulated. Therefore, the rate of heat dissipation provided by the tapered pin fin is highest among the five types of simulated fins.

5. Results and Discussion

By simulating our system, we've found out our anticipated results and datum which are illustrated in the below sub sections.

5.1 Numerical Results

From the above Table 2, it is clearly visible that, Tapered Pin fin has the highest tip temperature. We have already mentioned in the Methods section that we have parameterized the fin tip temperature in order to find the better fin. Since, one of the major ways of the heat removal process is Natural Convection, the higher fin tip temperature would make a greater temperature difference, hence it will allow to dissipate heat faster.

Table 2. Tip Temperature of Different Fin Geometries

Fin Type	Tip Temperature (^oC)
Pin	52.988
Tapered Pin	55.262
Rectangular	49.018
Rectangular Tapered	52.624
Triangular Tapered	49.66

5.2 Graphical Results

From the Figure 6, it is clearly seen that Tapered fin has the highest tip temperature and contrarily, rectangular fin has the lowest tip temperature. There are no significant sudden drops in the graphs due to the symmetrical geometries, rather all the graphs are very close in nature with each other. The constant volume and length might be the reason of this similarity. Also, the different shapes have different surface area, that is the crucial factor for certain dissimilarities among the graphs.

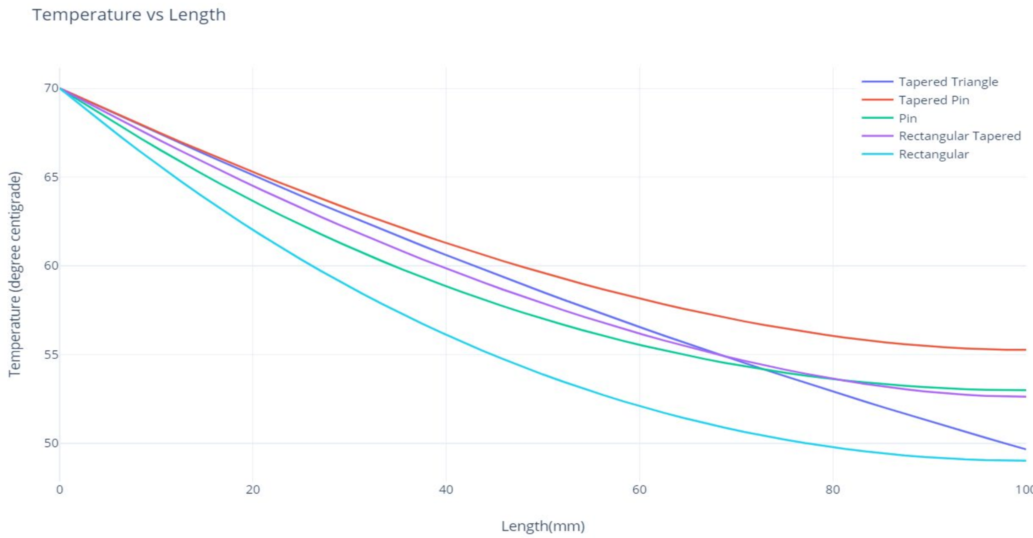

Figure 6. Temperature distribution along fin length of different shaped fins

5.3 Proposed Improvements

Thermal conductivity and other characteristics of the material used to make the fins determine how quickly heat is dissipated through them (Karthik et al. 2018). We have further simulated the tapered pin fin for two more materials, which is copper and aluminium. While selecting fins, some of the factors should be kept in mind. Heat transfer is definitely one of the major criteria, but also weight of the material and cost effectiveness has a huge significance when it comes to industrial use.

Table 3. Properties of Different Fin Material along with their Costing

Material	Thermal Conductivity(W/mK)	Specific Density (gm/cm^3)	Cost per kg in USD
Structural Steel	60.4	7.85	0.8
Aluminium	237	2.7	2.29
Copper	400	8.96	7.85

From the above Table 3, it is clearly seen that copper is the better heat conductor among the all three materials that will allow the natural convection process to happen at a greater rate. But on the other hand, it has the highest pricing and specific density in the whole table, making it unreasonable to choose. Contrarily, Aluminium is a moderate heat conductor that will fulfil the criteria of heat removal at a decent rate, alsohaving the lowest specific gravity and a decent pricing makes it the perfect material for a heat sink among the three materials.

5.4 Validation

For the case of Pin fin,
Base temperature, T_o=70^{o}C
Ambient temperature, T_a=22^{o}C
Convective co-efficient, h=50 W/m^{2}K
Thermal Conductivity, k=60.4W/mK (For Structural Steel)
Fin length, L=100mm

Now, mL = L* $\sqrt{\frac{4h}{kD}}$ = 0.1* $\sqrt{\frac{4*50}{60.4*32.34*0.01}}$ = 1.001187

Now, $\frac{T-22}{70-22} = \frac{1}{\cosh(1.01187)}$

=> T=52.8256ºC

From our simulated result, the fin tip temperature of the pin fin was 52.988ºC, which deviates with the theoretical value by almost 0.3% error, which is almost negligible.

After performing analytical verification processes, further we've performed a validation process by replicating an experimental work (Kumar et al. 2018) using our simulation system. In accordance with the experimental model, we've designed the pinned fin configuration, along with proper boundary conditions were assigned. After doing the simulation with our simulation system, we've found out the tip temperature to be around 83ºC.

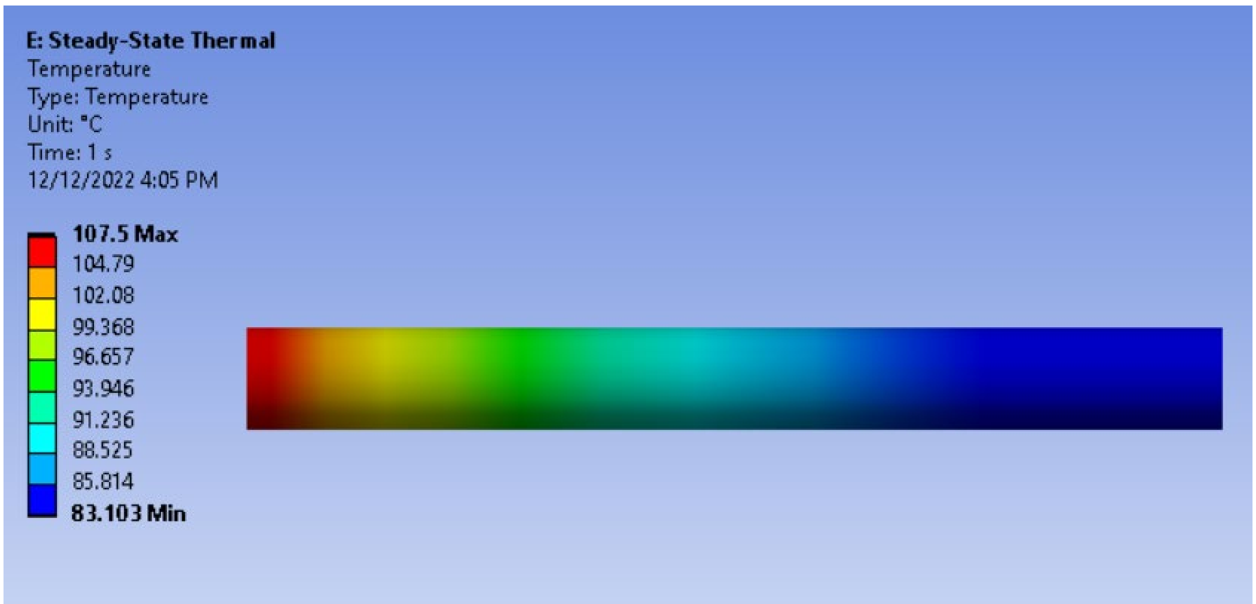

Figure 7. Temperature Distribution Along the Length of Pinned Fin

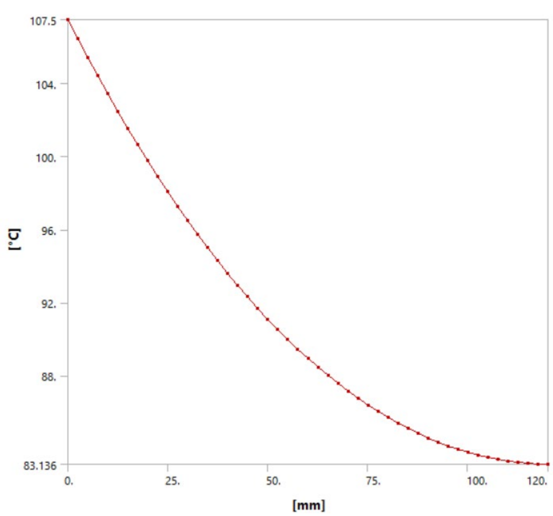

Figure 8. Temperature versus Distance Graph (Pinned Fin)

As we've seen in the experimental analysis, the pin tip temperature was just below 95ºC, which is closer to the tip temperature that we've got after replicating the configuration in our simulation system. Hence, our simulation system is experimentally validated.

6. Conclusion

Five different shaped fins were investigated numerically keeping their volume and characteristic length constant. The simulated data was validated by mathematical analysis. Further, two different materials were assigned to see the heat transfer characteristic alongside their cost and specific gravity. From our simulated analysis, we found that Tapered Pin Fin is the best heat sink among these five fins, as it had the highest tip temperature, allowing it to make a grater temperature difference with the ambient temperature, which will eventually allow to dissipate heat from the tip at a faster rate. From our further analysis, we found that Aluminium is the better material for a heat sink, when heat transfer rate, specific gravity and pricing are considered.

Because fins are used for vital functions in many different industries, such as heaters, hot water, heat exchangers, chemical processes, and steam pipelines systems, as well as electrical refrigerator conductors, many researchers are interested in investigating heat transfer utilizing fins choosing the right material for fins for industrial applications (Hameed et al. 2020). Costs and density have a much higher influence on the both the decision-making process and the rate of heat transmission. Our simulated study, which gives a useful overview of the appropriate fin and material for a free situation convection, which will aid in the choice of industrial applications.

Further researches that can be done in the future regarding this field of research are described below.

- Unconventional or irregular shaped fins with composite material assignments can be simulated for the case of forced and natural convection.
- Regression models can be implemented to predict temperature distributions for further extended lengths of fins.
- Artificial Neural Network (ANN) can be implemented in the thermal analysis of fins, heatsinks, heat pipes, and other heat transfer enhancing equipment.

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