Computational study of heat-transfer in extended surfaces with various geometries

Mohankumar D, Shashank, Pazhaniappan Y, Nithesh Kumar RA,
Ragul R, Manoj Kumar P, Nikhil Babu P

Department of Mechanical Engineering, KPR
Institute of Engineering and Technology,
Coimbatore.
dmohankumar94@gmail.com

Abstract

In this work, an analysis has been done on extended surfaces with various geometries to identify the better heat transfer rate. The geometries of extended surfaces namely – bar fins, stepped fins, stepped fins with indentations have been modelled, investigated and studied. Based on the design identification and numerical analysis the extended surfaces with increases surface area has increased heat transfer. From numerical data the fins with indentations has increased surface area and heat transfer. The indentations have been designed with varying diameter used in the fins are 4mm, 3mm, 2mm respectively and analysed using a fixed computational method. It is found that the spherical notches with varying diameter were more effective than the other fins and making the notches increases the heat transfer was much effective than increasing the diameter of the indentation in the stepped fin. This work shows the design, analysis, and result of some extended surface geometries with fixed input boundary condition.

Keywords: Fins, Notches, Heat Transfer, Varying Shape, CFD, Spherical Notches, Indentation.

1. Introduction

An extended surface called as fin is attached with a heated body to increase the convective heat transfer. Fins find applications in electro and mechanical components like internal combustion engines, compressors, heat exchangers, motors, etc. In electronics industry fins are used to avoid overheating or burning like in computers and laptops where hardware’s are placed in a compact and small space as microstructures. The main objective of using the fins is, to increase convective heat transfer between the hot surface where fin is attached and its environment. The optimization of heat transfer rate is based on the following two approaches: i) to minimize the volume or mass for a given body and ii) to increase the surface area of the body. The rectangular geometry is mostly used because it is simple and inexpensive to manufacture.

From the analysis carried out on rectangular fins [1], it was observed that high fins have optimum heat transfer that occurs within a narrow range of spacing between the fins, whereas in shallow fins, optimum
Heat transfer occurs over a wider range of fin spacing. In an experiment conducted [2] on perforated fins, it was observed that along the perforated fin length the temperature drop is higher than that for non-perforated fin. According to [3] observation on heat transfer by natural convection with perforated pin, fin array implementation of notch and holes in extended surfaces dramatically increase the surface area and heat dissipation rate. Review of [4] heat transfer enhancement methods to maximize TEG (Thermo Electric Generator) performance in automotive applications showed that the diamond shaped pin fins provided the best heat transfer characteristics compared to other types [5]. The analysis also resulted in heat transfer enhancement features with different fin height to the channel height ratio while keeping a steady hydraulic diameter [6]. Fin geometry investigation [7] on heat exchanger efficiency by simulation and optimization methods for the application of diesel exhaust shows that fins arranged longitudinally are more efficient than circular or annular ones due to lower back pressure and improved heat transfer [8]. Experimentation on natural convection and surface heat transfer [9] using a cavity with vertically arranged fins shows that by increasing the number of vertical fins results in increased fluid temperature, increased convective and radiative heat transfers for $N < 7$ and stabilize beyond $N \geq 9$ fins. Heat transfer optimization and analysis of the engine fins with varying surface roughness [10] shows that, when the roughness of the body increases, the heat flux and the rate of heat dissipation increases. The scope of the work is to analyse all the three types fin geometries for maximum heat transfer rate.

2. Geometric modelling and material selection

2.1 Geometric modelling

Three types of fins i.e. normal rectangular fins, rectangular stepped fins, stepped fins with circular indentation are to be investigated here [11],[12], the basic dimensions of different types of fins are shown in Table 1.

| Fin Type                  | Normal Fin | Stepped Fin | Stepped Fin with indentations |
|--------------------------|------------|-------------|------------------------------|
|                          |            | Step from bottom | Step from bottom |
|                          |            | 1 | 2 | 3 | 1 | 2 | 3 |
| Length (mm)              | 70         | 23 | 23 | 24 | 23 | 23 | 24 |
| Breadth (mm)             | 50         | 50 | 50 |
| Width (mm)               | 5          | 5 | 4 | 3 | 5 | 4 | 3 |
| Total Area (mm$^2$)      | 7250       | 7500 | 8799.4 |
| Material Used            | Aluminium 6061 |

2.2 Material selection

According to the analysis of materials [13] Aluminum 6061 is an Al-alloy hardened through precipitation. Aluminum 6061 consist of 97.9% Al, 0.6% Si, 1.0%Mg, 0.2%Cr and 0.28%Cu. It is best suitable material for stepped fin with circular indentations. The Alloy plate is one of the most versatile alloys which is used in welding assemblies, marine frames, chemical equipment’s, electronics parts, fasteners, heat exchangers [14] and heat sinks. It is extremely popular for its medium to high strength requirements, good toughness, corrosion resistance and excellent thermal properties [15]. The physical properties of Al 6061 are mentioned in Table 2 below.
Table 2: Physical Properties of Aluminum 6061

| PROPERTY               | MAGNITUDE        |
|------------------------|------------------|
| Density                | 2710 kg/m³       |
| 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         |

2.3. CFD modelling - 3D Physical model

The 3D model of the fins, created using SolidWorks 2016 modelling software and their isometric view are shown in Figure 1. The size of indentations of the fins with indentations are fixed in way that the surface won’t become porous and accordingly the stepped structures will have decreasing size of indentations when going from from the base of the fins.

![Figure 1: 3D models of (a) Rectangular normal fin](image-url)
(b) Rectangular stepped fin (c) Rectangular stepped fin with indentations.

2.4. Meshing
The fine meshed images of all the three models taken into study are shown in the below figure 2.

Table 3: Mesh Independency test results

| S.No | Element Size  | No. of Elements | $T_{tip}$ ($^\circ$C) | $\Delta T$ ($^\circ$C) |
|------|---------------|-----------------|-----------------------|------------------------|
| 1    | Very Coarse   | 142084          | 456                   | 194                    |
| 2    | Less Coarse   | 250863          | 424                   | 226                    |
| 3    | Coarse        | 436076          | 412                   | 238                    |
| 4    | Fine          | 1341528         | 370                   | 280                    |
| 5    | Very Fine     | 1892045         | 366                   | 284                    |

Figure 2: Mesh models of (a) Rectangular normal fin (b) Rectangular stepped fin (c) Rectangular stepped fin with indentations.

2.4.1 Mesh Independency Test. The Mesh Independency test for Stepped Fin with Indentation has been carried out at very coarse, less coarse, coarse, Fine and very fine element size. As seen in result Table 2 and Figure 3 the difference between $\Delta T$ for fine and very fine mesh is only 1.40%. So, fine mesh is selected.
3. Mathematical methodology

The heat transfer rate [16] from the application at the base temperature (T_b) to the surrounding atmospheric temperature (T_∞) is given by Newton’s law of cooling [17], [18].

\[ Q = \eta_f h A_f (T_b - T_\infty) \]

Where,
- \( \eta_f \) – total fin efficiency, \( \eta_f = (\tanh (mL)) / mL \)
- \( A_f \) – Surface area of the fin in m², \( A_f = 2wl \)
- \( h \) – Convective heat transfer coefficient in W/m²K
- \( m \) – dimensional function
- \( L \) – Length of the extended surface
- \( w \) – Width of the extended surface

4. Boundary conditions

The boundary conditions applied to the solid and fluid domain during the analysis in ANSYS FLUENT are as follows,

| Material      | –  | Air   |
|---------------|----|-------|
| Material      | –  | Solid |
| Density       | –  | 1.1768 Kg/m³ |
| Inlet velocity of air | –  | 10 m/s |
| Specific heat | –  | \( C_p=1005 \) J/kg.K |
| Inlet air temperature | –  | 300 K |
| Thermal conductivity | –  | K= 0.0262 W/m² |
| Operating condition | –  | 1 bar |

5. Results and Discussions

5.1 Temperature Contour

After the analysis, the result from CFD are shown by means of vectors and contour plots, the following images in Figure 4 shows the temperature contour of normal fins, stepped fins and fins with indentations. From these results it is clear that the temperatures at the tip of the stepped fins with indentations have less temperature than the normal and stepped fins and highest temperature difference.
5.2 Velocity contour

The below Figure 5 shows the velocity streamline of different types of fins, from this it is clear that the average velocity of air around the rectangular stepped fin is highest among all three fins and rectangular fins with indentation least. But the velocity of air near the surface of the fin is highest in rectangular fins with
circular indentation due to increased drag. Since drag is more in rectangular fin with notch, the time of contact between air and fin surface is more which improves heat transfer rate.

Figure 5: Streamline Velocity (a) Normal Fin (b) Stepped Fins (c) Stepped Fin with Indentations

5.3 Pressure contour

Figure 6 shows the pressure contour of different types of fin developed due to impact of flowing fluid medium particles. From the observation, the pressure generated on rectangular normal fin is the highest due to the higher impact surface area and the pressure generated on rectangular stepped fin with indentation has the lowest due to small impact surface.
5.4 Comparison of parameters of different geometry of fins

Table 4: Comparison of surface area, volume, heat transfer and heat transfer per unit volume when fin base temperature and surrounding temperature is constant

| S. No | Type of Fin          | A (cm²) | ηf % | V (cm³) | Q (W)  | Q/V (KW/m³) |
|-------|----------------------|---------|------|---------|--------|-------------|
| 1     | Normal Fin           | 0.725   | 84   | 0.183   | 189.7  | 10466       |
| 2     | Stepped Fin          | 0.75    | 81   | 0.151   | 186.9  | 12418       |
| 3     | Fin with indentation | 0.88    | 80   | 0.142   | 219.3  | 14598       |
Where,
- Surface area \( A \)
- Volume \( V \)
- Heat transfer \( Q \)
- Heat transfer per unit volume \( Q/V \)
- Efficiency \( \eta \)

According to the Table 3 data the efficiency of the rectangular fin is 3.51% better than the stepped fin and 5% better than the stepped fin with indentation but the volume of the normal fin is 16.96% more than stepped fin and 99.84% more than stepped fin with indentation. The ratio of heat transfers and volume shows that stepped fin with indentation have better geometry for improved heat transfer capability.

Table 5: Comparison of fin base temperature, fin tip temperature, actual heat dissipation rate and efficiency according to actual data

| S. No | Variable | Normal Fin | Steppe d Fin | Fins with Indentation |
|-------|----------|------------|-------------|-----------------------|
| 1     | \( T_b \) (°C) | 650        | 650         | 650                   |
| 2     | \( T_{tip} \) (°C) | 447        | 428         | 370                   |
| 3     | \( \Delta T \) (°C) | 203        | 222         | 280                   |
| 4     | \( Q_{fin} \) (W) | 172.55     | 185.63      | 243.31                |
| 5     | \( \eta \) | 51%        | 53%         | 60%                   |

Where
- Temperature at base \( T_b \)
- Temperature at tip \( T_t \)
- Temperature Difference \( \Delta T \)
- Heat Transfer \( Q_{fin} \)
- Efficiency \( \eta \)

All the fins are subjected to similar base temperature of 650°C but the highest temperature difference is seen in rectangular stepped fin with indentation of 280°C and lowest in rectangular normal fins of 203°C. Due to high temperature difference rectangular stepped fin with indentation has highest heat transfer rate of 243.303W.

6. Conclusion

The thermal analysis of fins by modifying its geometry has been completed. By observing the analysis, the results of aluminum alloy 6061 fins with circular notches is more efficient, as the temperature difference and rate of heat transfer are more than the normal bar fins and the stepped fins of same material.

- Weight and volume of the material used can be reduced with the increase in surface area of the fins, so that number of fins for fixed heat transfer rate can also be reduced wherever needed.
- The usage of less material and resources results in the improved efficiency. Also, in the fins with indentations wake zone is reduced and drag is increased, which improves the time of contact between the heated surface of the fin and the surrounding atmospheric air, which increases the overall efficiency of the extended surface.
Acknowledgements

The authors would like to thank the Simulation and Analysis section, Department of Mechanical Engineering, KPR Institute of Engineering and Technology, Coimbatore – India, for providing the system facilities and their continuous support.

References

[1] Adhikari C, Wood D H and Pahlevani M 2020 Optimizing Rectangular fins for natural Convection cooling using CFD Therm. Sci. Engg. Prog. 17 100484.

[2] Ibrahim Tamir K., Mohammed Marwah N, Mohammed Kamil Mohammed and Najafi G 2018 Experimental Study on the effects of perforations shapes on vertical (heated fins performance under forced convection heat transfer IJHMT 118 832-846.

[3] Shitole Pankaj, Bhosle Santosh, Kulkarni Kishor, Joshi Sarang 2018 Experimental Investigation of Heat Transfer by Natural Convection with Perforated Pin Fin array Procedia Manufacturing 20 311-317.

[4] Jaideep Pandit, Megan Thompson, Srinath Ekkad V and Huxtable Scott T 2014 Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels Int. J. Heat Mass Tran. 77 359-368.

[5] Kumar P M, Saravanakumar P T, Mylsamy K, Kishore P and Prakash K B 2019 Study on thermal conductivity of the candle making wax (CMW) using nano-TiO$_2$ particles for thermal energy storage applications AIP Conf. Proc. 2128 1 020027.

[6] Manoj Kumar P, Anandkumar R, Sudarvizhi D, Prakash K B and Mylsamy K 2019 Experimental investigations on thermal management and performance improvement of solar PV panel using a phase change material AIP Conf. Proc. 2128 1 020023.

[7] Hatami M, Ganji D D and Gorji Bandpy M 2015 Investigation of fin geometry on heat exchanger performance by simulation and optimization methods for diesel exhaust applications Neural Comput & App. https://doi.org/10.1007/s00521-015-1973-1

[8] Manoj Kumar P, K Mylsamy, Karthick Alagar and K Sudhakar 2020 Investigations on an evacuated tube solar water heater using hybrid-nano based organic phase change material Int. J. Green Energy 17 13 872-883. doi.org/10.1080/15435075.2020.1809426

[9] El Moutaouakil, Bounkendil M, Zrikem Z and Abdelbaki A 2020 Natural Convection and surface radiation heat transfer in a cavity with vertically oriented fins Int. J. Thermophys. 41.

[10] Pulkit Sagar, Puneet Teotia, Akash Deep Sahlot and Thakur H C 2017 Heat Transfer analysis and optimization of engine fins of varying surface roughness Mat. Today-Proc. 4 8565-8570.

[11] Saurabh Pathak, Om Parkash, Ravikant, “Thermal analysis of fins with Varying Geometry of different materials, IJSRD, 2321-0613.

[12] Kumar P M, Anandkumar R, Mylsamy K and Prakash K B 2020 Experimental investigation on thermal conductivity of nanoparticle dispersed paraffin (NDP) Mater. Today-Proc. doi.org/10.1016/j.matpr.2020.02.798

[13] Obula Reddy Kummitha and Reddy B V R 2017 Thermal Analysis of cylinder block with fins for different materials using ANSYS Mat. Today-Proc. 4 8142-8148.

[14] Karthick A, Manokar Athikesavan M, Pasupathi M K, Manoj Kumar N, Chopra S S and Ghosh A 2020 Investigation of inorganic phase change material for a semi-transparent photovoltaic (STPV) module Energies 13 14 3582. doi.org/10.3390/en13143582

[15] Kumar P M, Saravanakumar P T, Mylsamy K, Kishore P and Prakash K B 2019 Study on thermal conductivity of the candle making wax (CMW) using nano-TiO$_2$ particles for thermal energy storage applications AIP Conf. Proc. 2128 1 020027.

[16] Yunus A. Cengel, "Heat Transfer A Practical Approach", Tata McGraw Hill, 2010
[17] Frank P. Incropera and David P. Dewitt, "Fundamentals of Heat and Mass Transfer", Wiley & Sons, 1998.
[18] Kothandaraman, C.P., "Fundamentals of Heat and Mass Transfer", New Age International, New Delhi, 1998.