Effect of various fin geometries on heat dissipation of traction motors used in Electric vehicles

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Abstract. The traction motor is one of the major components in an electric vehicle subjected to high temperature variations and thermal stresses. In order to cool the motor, fins are proposed on the housing. Present study investigates the effect of various fin geometries such as rectangular fin, rectangular fin with a rectangular protrusion, tapered pin fin integrated with rectangular fin, step fin and wavy fin on heat dissipation of an electric motor by developing a numerical model and the comparative study is presented. 3D geometrical model of the motor housing is developed using CATIA V5 and analyzed using ANSYS Workbench 2019 R3. Steady-state temperature distribution in the housing cross section is obtained. The obtained results were found in satisfactory quantitative agreement with the published literature results and deviated not more than 7 percent. Research confirmed that rectangular fin with rectangular protrusions gives the greatest heat transfer comparatively and it is concluded that the life of an electric motor increases as there is a decrease in temperature of the motor.

Keywords:

1. INTRODUCTION

India is becoming one of the leading producers of automobiles industry in the last few years. It’s due to the increase in the customers which are generally middle-class people but in recent days there is a huge amount of increase in the cost of fuels such as petrol, diesel etc. that are essentially required to run these vehicles resulting in need for an alternative way for this fuels, and the best alternative as of now is the Electric vehicles. Another important reason behind this replacement is the harm caused to the environment due to the emissions from these conventional vehicles. Along with the advantages, it also has some major disadvantages. The problem to be addressed is the heat generated at the stator of an electric motor. The temperature rise inside the motor may occur mainly due to, Friction between rotating parts such as bearing (Mechanical losses), Iron or Eddy current losses in steel laminates due to variation in magnetic fields and Copper Loss in copper coils due to electrical resistance.

Mechanical and Iron losses are considered to be very small in comparison with the Copper losses in the motor. The effort should be made to reduce the heat generated due to the copper losses. To reduce the temperature due to the copper losses the area of the winding should be increased but as copper is a limited resource and expensive too it will lead to the motor to be very costly. This leads to the need of an efficient method to cool the motor which will lead to decrease the amount of copper used in the motor and therefore make the machine more cost-effective. Increasing heat transfer from the surface of the motor body is one way to address the temperature rise that occurs over the stator winding.
To maximize the heat transfer from motor body heat should be dissipated in maximum amount by all the three modes of heat transfer. Considering general motor any difference into the radiation cannot be made and for increasing conductive heat transfer the housing material which is having maximum possible thermal conductivity as well as it should satisfy all other requirements such as strength, cost-effectiveness etc. which leads to constraints. One way is to focus on increase the heat transfer by increasing convective heat transfer. Convective heat transfer can be increased by three methods, increasing surface area, temperature difference or heat transfer coefficient. Temperature difference depends on ambient temperature and the temperature due to the heat generated inside motor both of which cannot be changed or controlled. Other options left is increasing heat transfer coefficient by increasing velocity of air flowing over an electric motor body and surface area can be increased by changing fin geometry to maximize heat transfer. Hence, if heat dissipation increases only by changing fin geometry it will be an effective method to address these problems.

Problems were studied and demonstrated either by experimental, analytical or numerical means by many researchers and various solutions were discussed. Sabriet al. [1] studied a 20hp in-wheel electric motor which was used in a light electric vehicle application. Analysis was performed using ANSYS for three types of fin arrangements viz. straight fin, slanting fin and transverse fin. It was found that the straight fin arrangement has the highest efficiency of temperature distribution. Pradeep et al. [2] analysed the heat transfer performance of fin by implementing the design of fin with various extensions such as rectangular extension, trapezium extension, triangular extensions and circular segmental extensions. Rectangular extensions provided on the fin proved to be the most effective fin among all the other extensions having same length and width which is used as one of the fin to be analysed in present research. Grabowski et al. [3] studied a typical squirrel-cage AC induction motor with finned housing made of cast iron. Steady-state temperature distribution in the housing was calculated numerically and validated with experimental data. Present research was validated with these research which justifies the methodology to be correct.

Sebastian et al. [4] introduced novel fin designs which enhances conductive as well as convective heat transfer along the fin surface simultaneously. Three types of fins viz. Oval tubes with circular plain fins (CPF), circular integrated pin fins (CIPF) and a serrated integrated pin fins (SIPF) were analyzed. From all the results it was concluded that if compactness is of importance then CIPF design with lowest fin spacing was well suited while if required surface area, material cost and weight are relevant then SIPF design was recommended.Deep et al. [7] studied various parameters such as heat transfer rate, convective heat transfer coefficient and temperature distribution over three types of fins i.e. straight fin, offset strip fin and sine fin. For simulation FLUENT component of ANSYS Workbench 15.0 was used with varying geometry and wind velocity. Sine profile was found to be most beneficial among all the fins.Mohsin et al. [9] simulated heat transfer through different geometry of fins i.e. Straight fin, Step fin and ‘S’ shape fin on engine of Bajaj discover using FLUENT component of ANSYS. Simulation was performed by varying geometry and velocity of air flowing over the fins. 3D steady state heat transfer analysis was done by assuming a constant temperature at inner surface of the wall as 250ºC. HTC and turbulence both the factors increased with change in geometry and it was found that the increase was greatest for Step shape fin.

It can be recalled from literature that the temperature rise in an electric motor leads to severe issues in future. Various research works on improving the efficiency of the motor are presented but there is a limited literature on the thermal management of motors. Other works such as liquid cooling, using of heat pipes, usage of PCM, etc. have been studied but this methods increase complexity as well as increase the cost and weight of the vehicle. From literature review, it was important to investigate the performance of the cooling fins commonly found on the fan-cooled electrical machine, and if the cooling could be improved just by changing the design of the fins.In present work, the best fins from each research are analyzed and comparison between the results is presented. Improving heat dissipation from the surface of an electric motor body and obtaining efficient as well as effective methods of development is the main concern. Determination of best possible fin geometry for better heat dissipation and analysis of the effect of changing the thickness of fin and spacing between fins on heat dissipation is addressed. In further sections detailed methodology and results obtained are discussed and best fin is concluded from the obtained results. The paper is structured as follows. Introduction section comprises of the background, need, aims and objectives for the research, followed by detailed
explanation on the methodology adopted for the numerical analysis which consists of solver details, boundary conditions and post-processing. Further results obtained are discussed in details followed by conclusion.

2. Methodology

A 3D simplified geometrical model of traction motor is developed that has close geometry with the conventional motor. This small geometry changes do not make a big difference for our solution and this is a standard procedure for simulation also referred to geometry cleanup. All the cases are simulated using the Steady-State Thermal module in Ansys workbench 2019 R3. The steps followed during the simulations are described in details.

2.1. Assigning materials

Once entering the steady-state thermal analysis module, Engineering Data is selected for submission of appropriate material and its properties. Grabowski et al. [3] suggested Gray Cast Iron which is generally used for manufacturing of motors due to its strength and ease of manufacturing. The properties used for analysis are stated in Table 1.

| Property                     | Value |
|------------------------------|-------|
| Density (kg/m³)              | 7200  |
| Specific Heat Capacity (J/kg K) | 447   |
| Thermal Conductivity (W/m K) | 45    |

2.2. CAD model generation

For all the simulations the CAD models are generated using CATIA V5 software and the models thus created are imported in the Geometry module. All the CAD model dimensions are stated in Table 2 and 3.

| Parameter | Length of housing (mm) | Height of fin (mm) | Fin thickness (mm) | No. of fins | Inner diameter of housing (mm) | Outer diameter of housing (mm) | Angular spacing (degree) |
|-----------|------------------------|--------------------|--------------------|-------------|-------------------------------|-------------------------------|--------------------------|
| Dimension | 250                    | 20                 | 2                  | 72          | 210                           | 230                           | 5º                       |

Various fin geometries are as follows,
1. Housing for validation with rectangular fins.
2. Housing with rectangular fins.
3. Housing with rectangular fin increasing no. of fins and reducing thickness.
4. Housing with rectangular fin having a rectangular protrusion.
5. Housing with tapered pin fin integrated with rectangular fin.
6. Housing with step shape fin.
7. Housing with wavy.

| Fin geometry | Parameter     | Dimension |
|--------------|---------------|-----------|
| 1            | Pitch (mm)    | 20        |
| 1            | Height of fin (mm) | 25   |
| 2            | No. of fins   | 32 (8*4)  |
| 2            | Pitch (mm)    | 20        |
| 4            | No. of fins   | 32 (8*4)  |
| 4            | Protrusion thickness (mm) | 4     |
| 5            | Taper angle (degree) | 5.69º |
2.3. Meshing

Good quality of mesh is required for accurate numerical simulation. A mesh is created for the imported CAD model and is evaluated for various grid (mesh) metrics here before proceeding for imposing boundary conditions. It has been well established that the simulation results significantly depend on the quality of the mesh/grid generated. Hence, for checking the quality of mesh, orthogonality and skewness test is done so that results will be accurate. Table 4 shows the no. of elements, no. of nodes, orthogonality and skewness values for maximum no. of elements of each geometry. These values are taken from the software after meshing is performed and the quality of the mesh is justified from these values. The grid generated for all the fin geometries are shown in Fig.1 to Fig.7. For all the cases it is taken care that the grid generated must have the recommended value of skewness and orthogonality so that the accuracy of results seems to be extremely good and anyone can easily rely to proceed for experimentation based on simulation results.

![Figure 1. Grid generated for fin geometry 1.](image1)

![Figure 2. Grid generated for fin geometry 2.](image2)

![Figure 3. Grid generated for fin geometry 3.](image3)

![Figure 4. Grid generated for fin geometry 4.](image4)
Table 4. Orthogonality, Skewness, No. of nodes and no. of elements for all fin geometries.

| Fin Geometry | No. of elements | No. of nodes | Skewness | Orthogonality |
|--------------|-----------------|--------------|----------|---------------|
| 1            | 169884          | 229200       | 0.15     | 0.97          |
| 2            | 231856          | 57357        | 0.2      | 0.88          |
| 3            | 889108          | 1148112      | 0.06     | 0.98          |
| 4            | 2834382         | 637209       | 0.22     | 0.78          |
| 5            | 627041          | 160275       | 0.25     | 0.7           |
| 6            | 2296363         | 553928       | 0.23     | 0.76          |
| 7            | 2099821         | 506326       | 0.23     | 0.76          |

2.4. Meshing
The setup phase essentially includes applying boundary conditions on the model. The boundary condition applied for simulation were as follows,
- Inner wall of housing, Constant Heat flux of 612.8 W/m²
- Front and end surface of housing, Perfectly Insulated
- Outer surface of housing (finned surface),
  Convective Heat Transfer with heat transfer coefficient of 42.46 W/m² K
2.5. Solver

Computational Fluid Dynamics (CFD) is the science of solving the governing equation numerically. The equation can represent steady or unsteady, Compressible or Incompressible, and inviscid or viscous flows, including non-ideal and reacting fluid behaviour. The particular form can be chosen depending on the application of the work. The steady-state analysis is done in these research hence, the RHS term of Energy equation below will be equal to zero.

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q_v = \rho C_p \frac{\partial T}{\partial t}
\]

where, 
- \( k \) - materials conductivity (W/m K)
- \( q_v \) - rate at which energy is generated per unit volume of the medium (W/m³)
- \( \rho \) - density (kg/m³)
- \( C_p \) - specific heat capacity (J/kg K)

2.6. Post-processing

To obtain the results in the form of contours of temperature distribution on housing select the contour option available in post-processing window. Additionally maximum, minimum and average values of temperatures are obtained from the contour details. Graphs are obtained by plotting a vertical line which starts from the internal surface and extends till the fin tip. This line is drawn symmetric to the two side faces of any one of the fin and the sampling value for this should be given as per convenience. After line creation, the graph is plotted as distance on X-axis vs Temperature on Y-axis and directly the corresponding temperature at a different height from the internal surface is obtained from software. Fig.16 shows the comparison of all the graphs obtained for various cases. All the results obtained are discussed further in details.

3. Results and Discussion

Present section consists of cases which investigates the effect of fin geometry on the heat dissipation from the motor housing body as a primary concern. Housing used for validation purpose is discussed and in subsequent sections, all the fin geometry cases are explained in details. The last section comprises of the comparison of all fin geometries and in that section, the best possible fin geometry among all other geometries studied in the current research work is concluded.

3.1. Housing for validation with rectangular fins

The regions of highest temperature values are seen in the upper part of the housing where power connection box, holding screws etc. are located and due to this, there are fewer fins attached. The temperature is considerably lower at locations where fins are attached. This demonstrates the influence of extended surfaces on the heat dissipation. The temperature which can be determined on the outer surface of the motor housing by using temperature contour can be used as a basis for the thermal-structural analysis. Fig.8 shows the temperature distribution on the extended surfaces of the casing. The temperature range obtained on various sections is in good agreement with the results of Grabowski et. al. [3].
Temperature contours clearly manifest that at corners the temperature is higher than the other finned regions from which it is obvious that the beams cannot dissipate the same amount of heat as fins. For further simulations, the beams are replaced by fins as research intends to maximize heat dissipation. From the graphical representation of the temperature field comparison of numerical simulation results with the literature study results which are based on mathematical and experimental models can be presented. Fig.9 represents temperature distribution along the fin height comparison with results of Grabowski et al. [3].

The accuracy of the simulation was evaluated by comparing the obtained values \( T_{\text{simul}} \) with the results of the literature study [3] temperature \( T_{\text{lit}} \). Temperature values simulated/measured at fin base and fin head are noted in Table 5. The value of relative difference ‘\( \varepsilon \% \)’ is calculated with the formula as follows,

\[
\varepsilon = \frac{T_{\text{simul}} - T_{\text{lit}}}{T_{\text{lit}}} \times 100
\]

where,

\begin{center}
\begin{tabular}{|c|c|c|}
  \hline
  Temperature (K) & Base of fin & Head of fin \\
  \hline
  \( T_{\text{simul}} \) & 299.074 & 298.485 \\
  \( T_{\text{lit}} \) & 298.97 & 298.418 \\
  \hline
\end{tabular}
\end{center}

The relative difference is approximately 6%, as are relative temperature differences determined in the same manner for other fins. Consequently, the simulation results can be deemed satisfactory. The uncertainty in results may be due to various reasons such as modelling errors due to simplified geometry representation, inaccurate material properties and numerical errors due to discrete representation of the continuous relationship.
3.2. Housing with rectangular fins

In this section, rectangular fin geometry is analyzed reducing the height of fins by 5mm. The weight as well as space, are the most important criteria for selection of any motor into any of the application hence, reduction in weight as well as space is done just by changing the height of fin by a small value. There are some ill effects too as decreasing height results in decreasing the surface area of heat transfer but there will be a small decrease in the area if other two parameters i.e. weight and space constraints are considered. The temperature distribution can be seen from the Fig.10.

The maximum temperature was found as 299.8 K and minimum temperature was 299 K which increases maximum and minimum temperature by approximately 0.6ºC. If the weight values of both the cases are considered then it can be observed that the weight for validation case and housing with reduced fin heights was found as 20.5 kg and 19.2 kg respectively. Hence, it can be interpreted that the increase in temperature is marginal but the reduction in weight and space is comparatively notable. For all the further geometries of fins, this case will be considered as a baseline for comparison with the conventional design.

3.3. Housing with rectangular fins increasing no. of fins and reducing the thickness

This section comprises of analysis of the effect of change in thickness of fin and increasing no. of fins on heat dissipation. Increasing no. of fins there is an increase in area for heat transfer this will lead to a better heat dissipation which is our main concern. When no. of fins are increased the thickness of fins is reduced to half of the previous one so that the air passing over the fins should not be obstructed due to less space. The temperature distribution can be seen from the Fig.11.
Figure 11. Temperature distribution on the casing for fin geometry 3.

The maximum temperature was found as 298.208 K and minimum temperature was 297.619 K which results in the decrease of maximum and minimum temperature by approximately 1 K even when there is no change in fin shape. This means that this method is proven to be marginally better.

3.4. Housing with rectangular fins having rectangular protrusions

In these section analysis of rectangular fin with rectangular protrusion is performed. This fin geometry was proven to be the best among different fin geometries considered by Pradeep et. al. [2] and Malagouda et. al. [6]. This section aims to increase the turbulence of air flowing through the channel between two consecutive fins as well as the area of heat dissipation. The temperature distribution can be seen from the Fig.12.

Figure 12. Temperature distribution on the casing for fin geometry 4.

The maximum temperature was found as 298.01 K and the minimum temperature was 297.499 K which is less comparatively. It can be observed that there is a slight increase in heat dissipation for these particular fin geometry.

3.5. Housing with tapered pin fin integrated with rectangular fin

In this section tapered pin-fin integrated with the rectangular fin is analyzed. This fin geometry was derived from the two shapes i.e. tapered pin-fin and pin-fin integrated with the rectangular fin which were proven to be best among all the fin shapes considered by Lakshminarasimha et. al. [8] and
Sebastinet. al. [4]. From literature integration of results is done and a novel fin geometry is created which blends advantages of the tapered fin as well as pin-fin integration with rectangular fins just by replacing pin-fin by tapered pin-fin. The temperature distribution can be seen from the Fig.13.

![Figure 13. Temperature distribution on the casing for fin geometry 5.](image1)

The maximum temperature was found as 298.10 K and minimum temperature was 297.5 K. The heat seems to be dissipated much faster than the rectangular fin case as having tapered pin-fin integrated with rectangular fin has substantially increased our area of heat transfer and also induced turbulence in the air flowing above the finned surface over housing. Despite being superior to the rectangular fin case it can be observed that the rectangular fin with rectangular protrusions had better results. This means that the rectangular fin with rectangular protrusion is more effective than tapered pin-fin integrated with a rectangular fin.

3.6. Housing with step fin

In this section step fin is selected for analysis. This fin geometry was proven to be the best among all the fin shapes considered by Mohsinet. al. [9]. There is a notable change in fin geometry and the geometry has “C-shaped” inclusions. The temperature distribution can be seen from the Fig.14.

![Figure 14. Temperature distribution on the casing for fin geometry 6.](image2)

The maximum temperature was 298.2 K and the minimum temperature was 296.6 K these indicates better heat transfer. There are alternate bands of red and yellow colour on the internal surface which justifies variable heat transfer at different locations on the internal surface. The location at which the internal surface is yellow coloured denotes better heat transfer contrary to red coloured region. It is a favourable effect considering the heat dissipation but it also has the ill effects on the material as the thermal stresses will increase on the material. It can be stated that fin has two disadvantages i.e. fin is adding thermal stress to the material of housing as well it is complex in nature. It can be concluded that
this fin is better considering the conventional rectangular fin case as the temperature is reduced by a considerable amount.

3.7. Housing with wavy fin

In this section analysis on wavy fin shape is performed. This fin type was proven to be best among different geometry fins considered by Mehulet et al. [5] and Deep et al. [7]. The temperature distribution can be seen from the Fig. 15.

![Figure 15. Temperature distribution on the casing for fin geometry 7.](image)

The maximum temperature was found as 298.2 K and minimum temperature was 297.2 K. It turns out that the temperature difference has increased considerably but the temperature for internal surface is maximum compared to all other cases which is undesirable also fin geometry is complex in nature which further turns out to be major drawback. From all the above results it can be concluded that the rectangular fin with rectangular protrusion and step shape fin are having better heat dissipation. Some more parameters are analysed to justify our conclusion in the subsequent section of comparison of all fin geometries.

3.8. Comparison of all fin geometries selected for analysis

![Figure 16. Temperature distribution in the housing for various fin geometries.](image)

In Fig. 16 a comparison between the temperature distribution along the height of the fin for all types of fins is plotted which indicates rectangular fin with rectangular protrusion is best among all other fin geometries. The temperature difference for the rectangular fin with rectangular protrusion is the smallest among all the cases which means that the cooling effect is comparatively more. When the temperature difference is lower the temperature difference between the ambient and the surface exposed to the ambient will increase due to which the convective heat transfer will increase. For rectangular fins with rectangular protrusion it is clear that due to addition of protrusions the surface area has increased considerably and due to irregularity in the flow passage too the turbulence increases which results in better heat dissipation. Further based on the heat transfer values through the finned and un-finned area, total heat transfer due to fins, percentage increase in heat transfer compared to the
rectangular fin case along with the fin effectiveness values conclusion can be presented clearly. All these parameters are specified in Table 6.

| Fin Geometry | \( Q_{\text{finned}} \) (W) | \( Q_{\text{un-finced}} \) (W) | \( Q_{\text{total}} \) (W) | Increase in heat transfer (%) | Effectiveness |
|--------------|----------------|----------------|----------------|-----------------------------|---------------|
| 2            | 64.74          | 24.31          | 97.57          | -                           | 0.96          |
| 3            | 87.67          | 18.91          | 106.58         | 9.23                        | 1.05          |
| 4            | 93.21          | 14.96          | 108.17         | 10.86                       | 1.07          |
| 5            | 87.61          | 14.26          | 101.87         | 4.41                        | 1.01          |
| 6            | 91.28          | 16.52          | 107.8          | 10.48                       | 1.06          |
| 7            | 85.89          | 20.62          | 106.51         | 9.16                        | 1.05          |

Calculation of the values in Table 6 is obtained by using standard co-relations available for heat transfer through the fins [10] and the values for the base temperature of the fin is taken directly from the software. It can be noted that the fin having highest effectiveness is a rectangular fin with rectangular protrusion and the heat transfer values also seem to be highest as compared to all other fin geometries. If a comparison is done based on values of total heat transfer from the housing with various fin geometries it can be clearly noted that the highest value is observed for a rectangular fin with rectangular protrusion which proves that the fin is effective to dissipate heat from the housing of motor body. The effectiveness for step fin is also noteworthy but as seen earlier it comes with the consequence of thermal stresses and complex shape for manufacturing as compared to the rectangular fin with rectangular protrusion hence, it can be concluded that the rectangular fin with rectangular protrusion is best considering all the parameters.

4. Conclusions

It can be concluded that the present methodology adopted for assessing the temperature distribution and heat transfer characteristics provides foundation stone for development of better traction motor. For cooling, various fin geometries were designed and performance on the fan cooled electrical machine are studied. Various fin geometries such as rectangular fin, tapered pin-fin integrated with rectangular fin, rectangular fin with rectangular protrusion, step fin and wavy fin are tested for evaluation of heat transfer using the steady-state thermal module in ANSYS Workbench 2019 R3. It can be concluded that there is a positive effect of decreasing the thickness and increasing number of fins as the heat dissipation is increasing with this change. The rectangular fin with rectangular protrusion offers the best shape for the heat flux of 612.8 W/m² as there is 10.86 % of increase in heat transfer through housing of the motor compared to the conventional fin design.

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