Performance and Optimization of Annular Fins by Using Finite Element Analysis

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Abstract- The main purpose of extended surfaces called fins to increase the heat transfer rate. Fins offer an economical and trouble free solution in many situations demanding natural convection heat transfer. The selection of a particular fin configuration in any heat transfer application depends on the space, weight, manufacturing technique and cost considerations as well as the thermal characteristics it exhibits. Radial or annular fins are one of the most popular choices for enhancing the heat transfer rate from the primary surface of cylindrical shape. Different profiles have profound influence on the thermal characteristics of annular fins. In the present study, a detailed work has been carried out to develop a finite element methodology to estimate the temperature distribution for steady-state heat transfer and thermal stresses induced by temperature difference in Aluminium finned-tube of the heat transfer equipment. Finite element method (FEM) was used to compute the temperature and the stress fields. An extensive study was carried out using ANSYS, a powerful platform for finite element analysis. Results obtained were presented in a series of temperature and thermal stress distribution curves for annular fins with rectangular, trapezoidal and triangular profiles for a wide range of radius ratios. The stress distribution curve is optimum with trapezoidal fin with wide range of radius ratio. It was found that the radius ratio and fin profiles are the significant parameters affecting the temperature and thermal stress distribution in annular fins.

Keywords: FEM, Thermal Characteristics, Annular Fin, Radius Ratio, ANSYS.

1. INTRODUCTION

Heat transfer is a phenomenon which occurs due to the existence of the temperature difference within a system or between two different systems, in physical contact with each other. The heat generated may be dissipated to another body or to the surrounding through conduction, convection and radiation which are collectively termed as ‘modes of heat transfer’. Heat transfer by convection is given by Newton’s law of cooling which states that, “the rate of heat transfer by convection between a surface and a surrounding is directly proportional to the surface area of heat transfer and also to the temperature difference between them”. It can be mathematically be expressed as, \[ Q_{\text{convection}} = h A_s (T_s - T_a) \] Where \(A_s\) is the heat transfer surface area, \(h\) is the convection heat transfer coefficient and \((T_s - T_a)\) is the temperature difference between the surface and the surrounding [1-3]. When temperatures \(T_s\) and \(T_a\) are fixed by design considerations, it is obvious that there are only two ways by which the rate of heat transfer can be increased, i.e., one by increasing the heat transfer coefficient \(h\) and the other by increasing the surface area \(A_s\). Increasing \(h\) may require the installation of a blower, a pump or a fan to the normal setup which may not be possible due to the design considerations. Hence the only alternative by which the rate of heat transfer can be increased is by increasing the surface area \(A_s\), which can be achieved by attaching extended surfaces called as fins, made of highly conductive materials, to the primary surfaces [4]. In many engineering applications large quantity of heat has to be dissipated from small areas. The fins are most suitable for this job as they increase the increase in the heat transfer rate by convection. Heat exchanger is the equipment used to exchange the heat between two fluids which are at different operating temperatures. It consists of tubes, through which the process fluid flows and are made up of different materials based on the different operating temperatures of the fluid and the design considerations [5]. Metals are the most commonly used tube material in heat exchangers as they are good thermal conductors. The thermal conductivity of aluminium is 225 W/mK and the melting and boiling point of aluminium are 658˚ and 2057˚. Pure aluminium has silvery colour and it has greater resistance to corrosion. It is used in deoxidizing molten irons and steel. It is used to prepare the metals from their oxides by heating a mixture of powdered aluminium and the oxides of the metal to be reduced. Its electrical resistivity is 2.669 micro-ohms/cm [6]

In the light of the above, the present work deals with:

i. Developing a FEM methodology using ANSYS for the coupled-field analysis of annular fins having coupled thermal and structural capabilities.

ii. Studying the variation in base temperature of the fin by varying number of nodes and carrying out a convergence study.
iii. Studying the influence of different fin profiles and radius ratios on the characteristics such as temperature distribution, hoop stress and radial stress developed along the length of the fin.

The methodology involves that a series of finite elements analysis have been conducted on Aluminium finned-tube system to study the influence on temperature distribution and thermal stresses. The front end commercial software ANSYS 12.0.1 was adopted in the present study. The FEM formulation was carried out using axisymmetric modelling approach with PLANE 13 element.

II. FINITE ELEMENT ANALYSIS

The finite element analysis was based on the following common assumptions:

a. Steady-state heat flow.
b. The materials are homogeneous and isotropic.
c. There is no heat source.
d. The convection heat transfer co-efficient is same all over the surface.
e. The temperature of the surrounding fluid is uniform.
f. The thermal conductivity of the material is constant. The material property plays a very important role in determining the temperature distribution and the thermal stresses induced.

The properties of the Aluminium used in the present analysis are given in Table-1. The representative models of the finned-tube considered in the present study are shown in Figures 1-3. The boundary conditions (Figure-1) applied to the finite element model is as follows.

- The displacement along Y-axis on both the tube edges were kept zero (i.e., \( U_y = 0 \)).
- The heat flux on both the tube edges was kept zero (i.e., \( q = 0 \)).
- The inner surface of the tube along Y-axis was subjected to fluid bulk temperature of 60°C and convective heat transfer coefficient of 30 W/m²K.
- The fin surfaces subjected to fluid bulk temperature of 25°C and convective heat transfer coefficient of 10 W/m K.

The operating parameter investigated for Rectangular, Trapezoidal And triangular profiles was the radius ratio \( R/r_o \) of the annular fin. This dimensionless geometrical parameter which governs the problem was varied from \( R/r_o = 1.5, 2, 3 \) and 4 [8]. Increasing the number of nodes for an analysis requires prohibitive amount of computer memory and time, but it gives accurate results. Although, increased number of nodes gives better results for any problem, there will be certain number of nodes beyond which the accuracy of the result cannot be improved by significant amount [7].
Table 1. Properties of Aluminium at room temperature.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus E (GPa)</td>
<td>70000 Mpa</td>
</tr>
<tr>
<td>Thermal expansion coefficient, (a(°C^{-1}))</td>
<td>2.21 e-5</td>
</tr>
<tr>
<td>Thermal conductivity, (k(W/mK))</td>
<td>220 w/mk</td>
</tr>
<tr>
<td>Density, (\rho(kg/m^3))</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Poisson ratio, (\nu)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSIONS

3.1 Temperature distribution along the length of the fin with different profiles and radius ratios-
A thermal-structural analysis was carried out on Aluminium finned-tube with different profiles to determine the temperature distribution along the length of the fin. Temperature distribution contours in case of radius ratio 1.5 for the three different profiles are shown in Figures 5 to 7, and the effect of different fin profiles on the temperature distribution for various radius ratios are represented in the Figures 8 to 10.

It is evident that there is a decrease in the temperature along the length of the fin for all the three profiles with various radius ratios. It is found that the base temperature is maximum in the case of triangular profile and minimum for rectangular profile, while that of the trapezoidal profile lies in between the triangular and rectangular profile. It is also seen that the temperature distribution along the length of the fin for all the three profiles decreases with an increase in the radius ratio. This is because large radius ratio value will lead to more heat being transferred to the surrounding and less heat stored in the fin material, hence resulting in low base temperature. This reduced temperature will induce smaller thermal stresses and the consequent distortion of the finned-tube [9, 10].

3.2 Thermal stress distribution along the length of the fin with different profiles and radius ratios-
A thermal-structural analysis was carried out on Aluminium finned-tube with different profiles to determine the radial and hoop stress distribution along the length of the fin.

3.2.1 Radial stress distribution along length of the fin-
Radial stress distribution contours in case of radius ratio 1.5 for different profiles are shown in Figures 11-13. In Figures 14-16, the effect of different fin profiles on the radial stress distribution for various radius ratios are shown.

From the Figures 14-16, it can be seen that the nature of the radial stress is compressive near its base and reaches zero close to the tip of the fin for all the three profiles. It is also observed that the magnitude of the radial stress is maximum in the case of annular fin with rectangular profile and the least for triangular profile. It is found that the radial stress distribution decreases as the radius ratio of the annular fin \(R/r_o\) increases. From stress contours presented for various radius ratios, it is found that radius ratio \(R/r_o = 1.5\), leads to higher stress contours than the other radius ratios.
3.2.2 Hoop stress distribution along length of the fin-

Figures 17-19 shows the hoop stress distribution contour in case of radius ratio 3 for different profiles and the effect of different fin profiles on the hoop stress distribution for various radius ratios is represented in the Figures 20-22.

It is clear that the nature of the hoop stress is compressive near its base and changes to tensile towards the tip of the fin for all the three profiles. It is also observed that the magnitude of the hoop stress is maximum in the case of annular fin with rectangular profile and the least for triangular profile. It is found that the hoop stress distribution decreases as the radius ratio of the annular fin R/r₀ increases. This is due to the fact that a large R/r₀ value will cause less temperature rise and thus less thermal stresses are induced.

3.2.3 Von mises stress distribution along length of the fin-

Von-mises stress distribution contours in case of radius ratio 3 for different profiles are shown in Figures 23-25. In Figures 26-28, the effect of different fin profiles on the radial stress distribution for various radius ratios are shown. It is clear that the nature of the Von mises stress is compressive near its base and changes to tensile towards the tip of the fin for all the three profiles. It is also observed that the magnitude of the Von mises stress is maximum in the case of annular fin with rectangular profile and the least for triangular profile.

Figure 5. Temperature distribution along the centerline of fin with rectangular profile.

Figure 6. Temperature distribution along the centerline of fin with trapezoidal profile.

Figure 7. Temperature distribution along the centerline of fin with triangular profile.
Figure 8. Temperature distribution along the fin for different profiles with radius ratio 1.5.

Figure 9. Temperature distribution along the fin for different profiles with radius ratio 2.

Figure 10. Temperature distribution along the fin for different profiles with radius ratio 3.

Figure 11- Radial stress distribution along the centerline of fin with rectangular profile.
Figure 12- Radial stress distribution along the centerline of fin with trapezoidal profile.

Figure 13- Radial stress distribution along the centerline of fin with triangular profile.

Figure 14. Radial stress distribution along the fin for different profiles with radius ratio 1.5.

Figure 15. Radial stress distribution along the fin for different profiles with radius ratio 2.
Figure 16. Radial stress distribution along the fin for different profiles with radius ratio 3.

Figure 17. Hoop stress distribution along the centerline of fin with rectangular profile.

Figure 18. Hoop stress distribution along the centerline of fin with trapezoidal profile.

Figure 19. Hoop stress distribution along the centerline of fin with triangular profile.
Figure 20. Hoop stress distribution along the fin for different profiles with radius ratio 1.5.

Figure 21. Hoop stress distribution along the fin for different profiles with radius ratio 2.

Figure 22. Hoop stress distribution along the fin for different profiles with radius ratio 3.

Figure 23. Von mises stress distribution along the centerline of fin with rectangular profile.
Figure 24. Von mises stress distribution along the centerline of fin with trapezoidal profile.

Figure 25. Von mises stress distribution along the centerline of fin with triangular profile.

Figure 26. Von mises stress distribution along the fin for different profiles with radius ratio 1.

Figure 27. Von mises stress distribution along the fin for different profiles with radius ratio 3.
IV. CONCLUSIONS

The current analysis has presented a study of thermal characteristics of annular fins of different profiles. Coupled-field analysis was carried out on Alumunium finned-tube system. The effect of rectangular, trapezoidal and triangular profiles of the annular fin with radius ratios 1.5, 2, 3 and 4 on the temperature and thermal stress distribution along the length of the fin was studied. From the analysis of the results, following conclusions can be drawn.

4.1 Influence of different fin profiles-
- The temperature along the centerline is found to be maximum at the base of the fin and decreases along the length up to the tip of the fin for all the three profiles. The temperature distribution along the centerline is maximum in the case of triangular profile and minimum for rectangular profile, while that of the trapezoidal profile lies in between the triangular and rectangular profile.
- The magnitude of the radial stress is maximum in the case of annular fin with rectangular profile and the least for triangular profile. The nature of the radial stress is compressive near its base and reaches zero close to the tip of the fin for all the three profiles.
- The nature of the hoop stress is compressive near its base and changes to tensile towards the tip of the fin for all the three profiles.
- In a comparison with the stress contours, the radial stress distribution resulted in higher tensile characteristics close to the base of the fin for a rectangular profile. The hoop stress contours are smaller than the radial stress values for all the three profiles.

4.2 Influence of varying the radius ratio-
- The temperature distribution along the length of the fin for all three profiles decreases with an increase in the radius ratio.
- The radial, hoop and von mises stress distribution along the center line decreases with an increase in the radius ratio of annular fin.
- From stress contours presented, it is found that radius ratio \( R/r = 1.5 \), leads to higher stress value than other radius ratios.

The comparative results for selected parameters showed that the convective heat transfer characteristics of the annular fin is best for a triangular profile with \( R/r = 1.5 \), the operating parameter. Fin with triangular profile is nearly as economic as the profile of minimum material requirement and the construction cost is also less compared with rectangular and trapezoidal profiles. Hence triangular profile is attractive because for equivalent heat transfer it requires much less volume than other profile.

REFERENCES