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FINITE ELEMENT ANALYSIS OF THERMAL CHARACTERISTICS OF ANNULAR FINS WITH DIFFERENT PROFILES

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ABSTRACT

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 a silicon carbide (SiC) ceramic 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. 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, $Q_{convection} = h\,A_s\,(T_s - T_a)$ 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 effective area of the primary surface, which results in an 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. These metals are limited to low temperature application only, i.e., below 400°C. For high temperature heat exchangers, operating with a process fluid above 1000°C, metals cannot be used and hence ceramics are preferable [6]. Ceramic tubes in high temperature heat exchangers are normally provided with extended surfaces called as fins to enhance the rate of heat transfer. Silicon Carbide (SiC) is the widely used ceramic material for high temperature heat exchanger tubes. At high temperature it is a better substitute to metal as it exhibits high strength and resistance to chemical attack, high oxidation and corrosion resistance and also possesses high temperature and thermal stress capability [7].

There are three prime candidate industrial areas of ceramic heat exchange: process heat exchange, power generation heat exchange and industrial waste heat recovery. The two main advantages for using ceramic materials in heat exchanger construction over more traditional metallic materials are their temperature resistance and corrosion resistance. First, ceramic materials can withstand operating temperatures (i.e., 1400°C) that far exceed those of conventional metallic alloys. For example, the bulk material temperature of a heat exchanger made of carbon steel should not exceed 425°C. The second major advantage of ceramic based heat exchangers is their resistance to corrosion and chemical erosion. Corrosion which occurs under normal conditions

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is exacerbated by elevated operating temperatures. For example, an exhaust stream rich in oxygen can actually attack a metallic surface. The other advantages are very good thermal conductivity, high strength in high temperature, anti oxidation, excellent thermal shock resistance, long service life, modest degree of maintenance, dependable and stable properties likewise as simple operation [8]. The high cost of ceramic finned tubes is the major unsolved problem in case of high temperature heat exchangers.

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 SiC ceramic 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 modeling approach with PLANE13 element.

2. 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 SiC ceramic [9] 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 1200 K and convective heat transfer coefficient of 1000 W/m^{2}K.
- The fin surfaces subjected to fluid bulk temperature of 300 K and convective heat transfer coefficient of 100 W/m^{2}K.

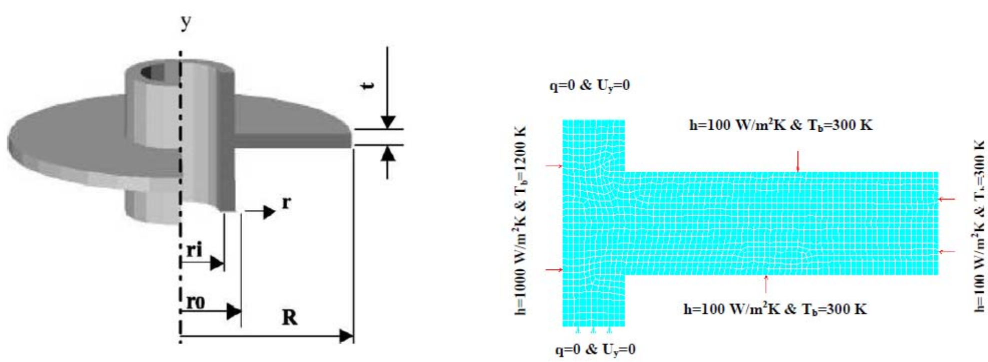

Figure-1. Configuration and representative axisymmetric finite element model of annular fin with rectangular profile.

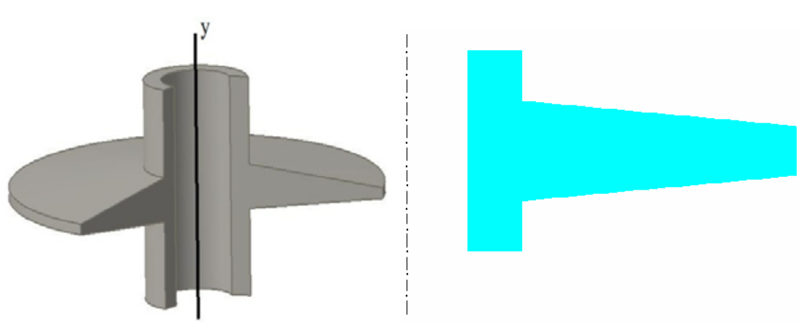

Figure-2. Configuration and representative axisymmetric finite element model of annular fin with trapezoidal profile

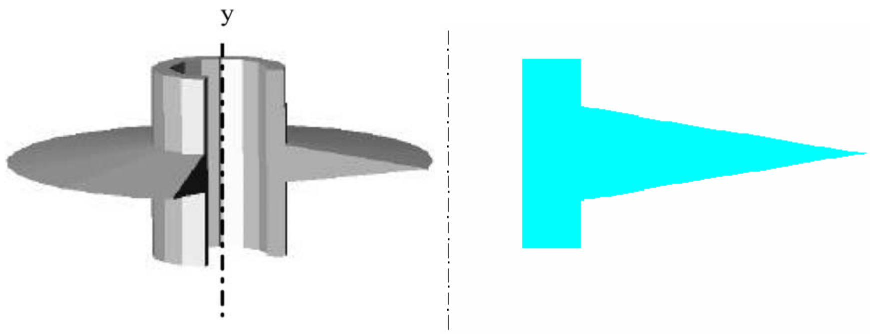

Figure-3. Configuration and representative axisymmetric finite element model of annular fin with triangular profile.

Table-1. Properties of SiC ceramic at room temperature.

Young's modulus, E (GPa)	427
Poisson ratio, ν	0.17
Thermal expansion coefficient, α ($^{o}C^{-1}$)	4.8×10^{-6}
Thermal conductivity, k (W/mK)	42
Density, ρ (kg/m³)	3210
Specific heat capacity, c_p (J/kgK)	2540

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 [10].

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 [11]. In the present analysis, the effect of varying the number of nodes on the accuracy of the result was studied in order to get the element resolution that gives an accurate result. The finite element solution for the base temperature developed in an annular fin with rectangular, trapezoidal and triangular profiles with radius ratio 1.5 has been obtained by varying the number of nodes from 25 to 10,000 as shown in Figure-4. The base temperature of the fin was noted for different resolutions and a graph of number of nodes v/s temperature was plotted for the different fin profiles.

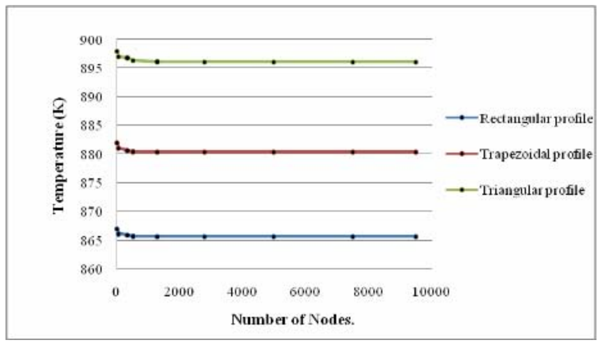

Figure-4. Effect of varying the grid size on the base temperature.

From the above graph the following observations can be made, the value of the base temperature changed significantly when the number of nodes was varied from 25 to 1000 which is indicated by the deviation in the curve.

Increasing the number of nodes beyond 1000 yields no considerable amount of change in the result and hence the graph shows a linear line parallel to the X-axis.

The maximum difference between the fin base temperatures with 1000 nodes with respect to that obtained with 10000 nodes was only about 0.05%.

As a result of the convergence study the number of nodes adopted throughout the work is between 1000 and 2000.

3. 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 SiC ceramic 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 11.

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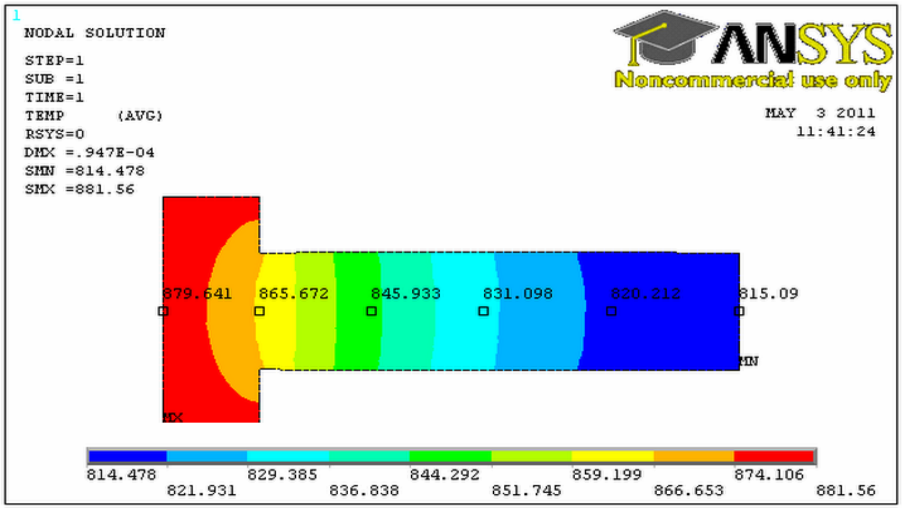

Figure-5. Temperature distribution along the centerline of fin with rectangular profile.

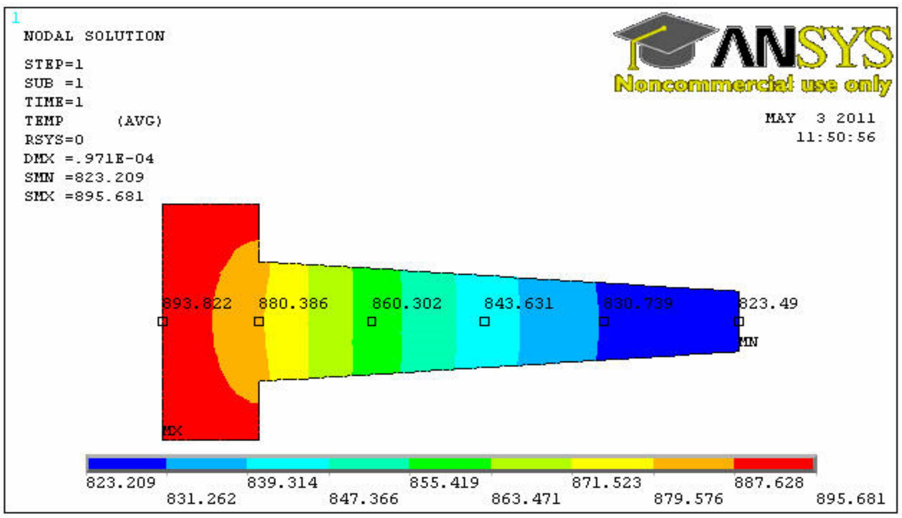

Figure-6. Temperature distribution along the centerline of fin with trapezoidal profile.

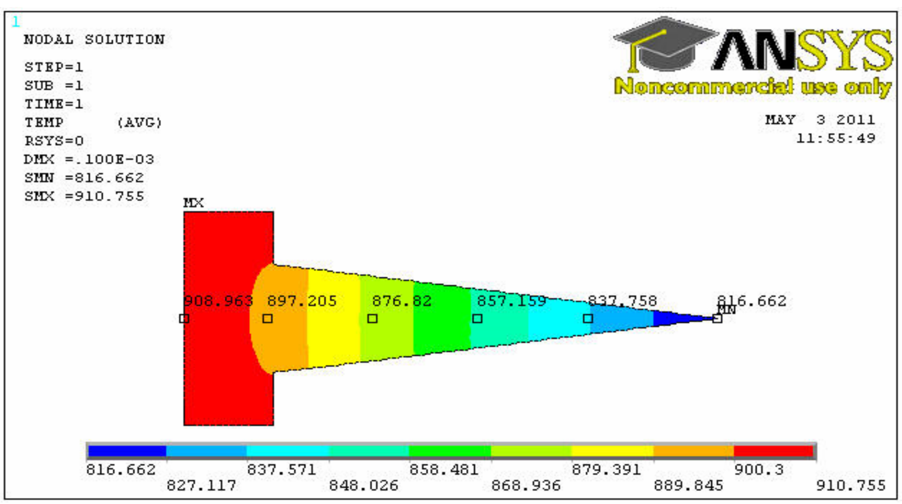

Figure-7. Temperature distribution along the centerline of fin with triangular profile.

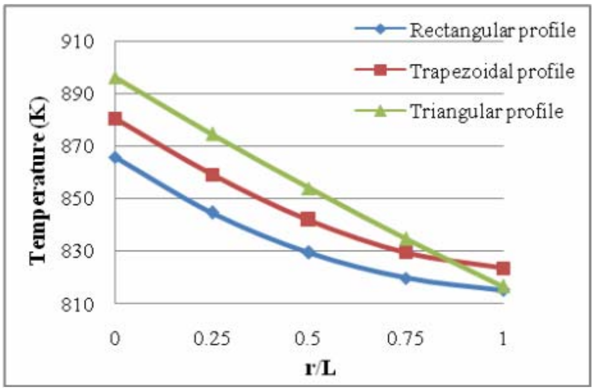

Figure-8. Temperature distribution along the fin for different profiles with radius ratio 1.5.

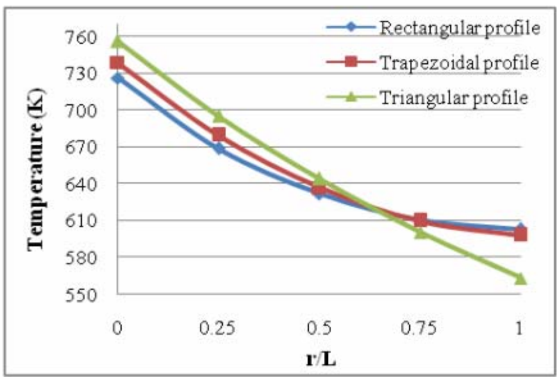

Figure-9. Temperature distribution along the fin for different profiles with radius ratio 2.

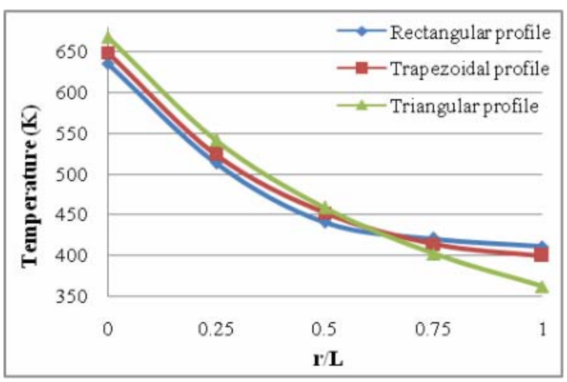

Figure-10. Temperature distribution along the fin for different profiles with radius ratio 3.

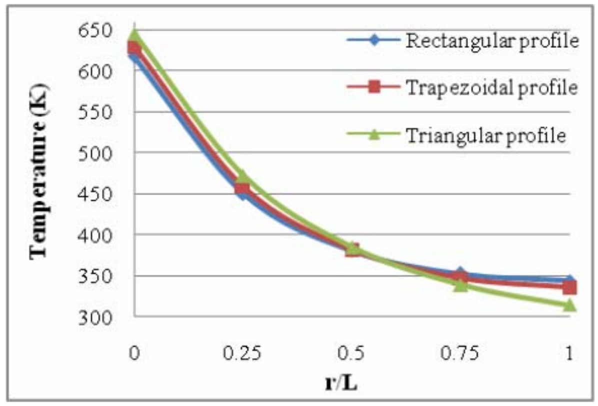

Figure-11. Temperature distribution along the fin for different profiles with radius ratio 4.

From the Figures 8-11, 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 [12, 13].

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 SiC ceramic 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 12-14. In Figures 15-18, the effect of different fin profiles on the radial stress distribution for various radius ratios are shown.

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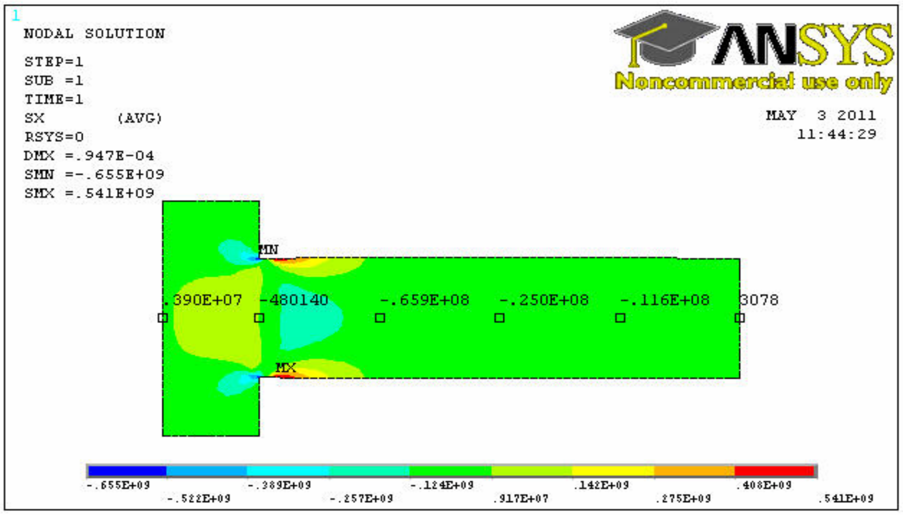

Figure-12. Radial stress distribution along the centerline of fin with rectangular profile.

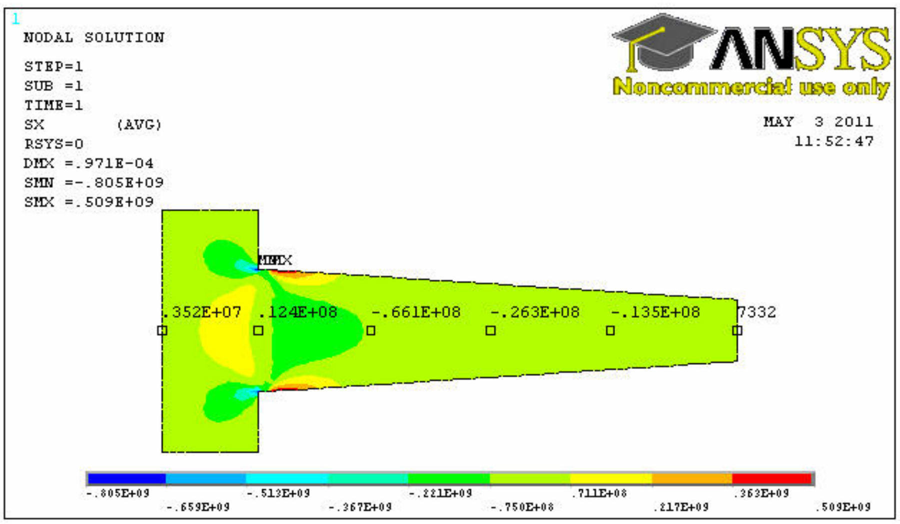

Figure-13. Radial stress distribution along the centerline of fin with trapezoidal profile.

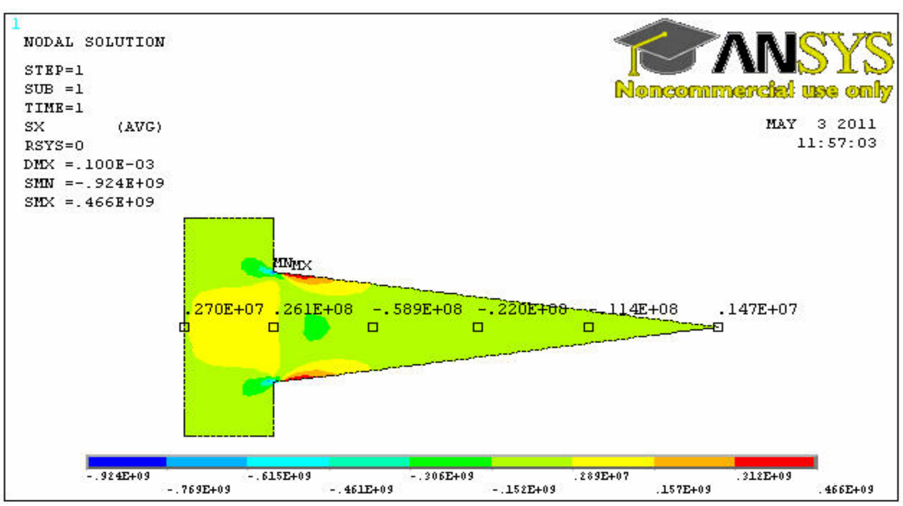

Figure-14. Radial stress distribution along the centerline of fin with triangular profile.

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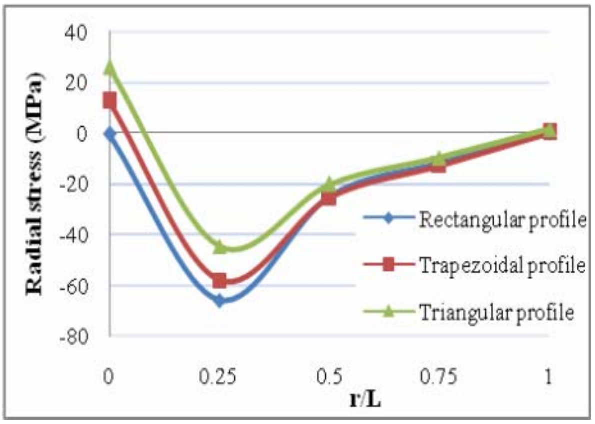

Figure-15. Radial stress distribution along the fin for different profiles with radius ratio 1.5.

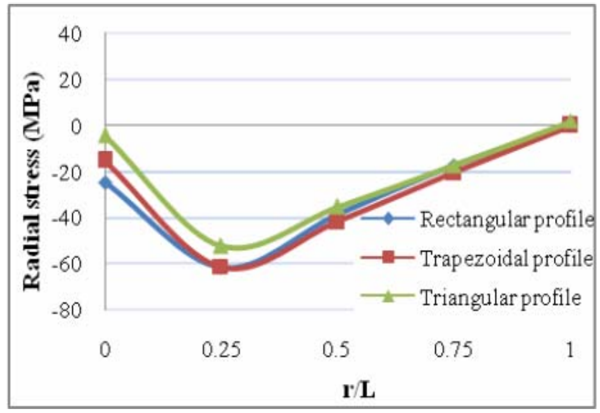

Figure-16. Radial stress distribution along the fin for different profiles with radius ratio 2.

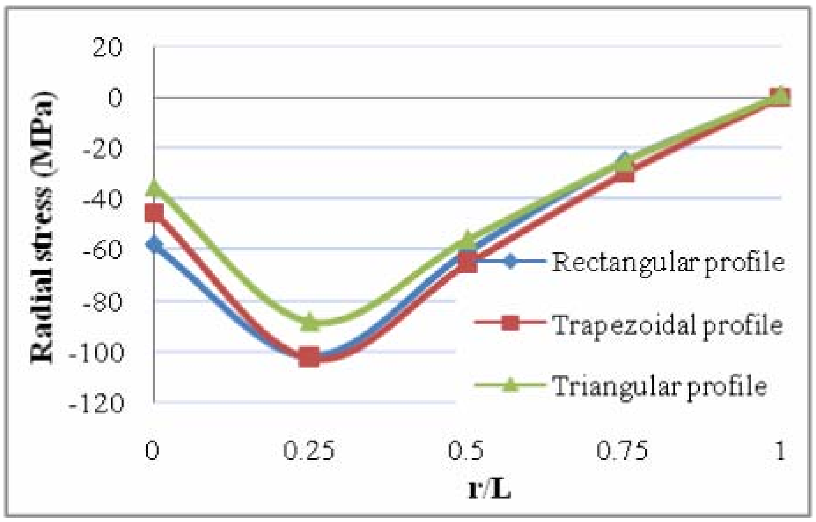

Figure-17. Radial stress distribution along the fin for different profiles with radius ratio 3.

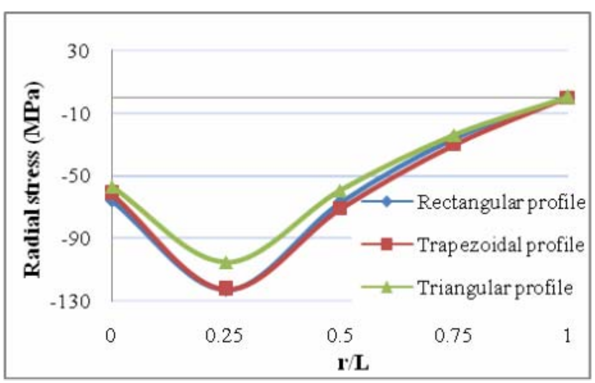

Figure-18. Radial stress distribution along the fin for different profiles with radius ratio 4.

From the Figures 15-18, 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. This is due to the fact that a large R/r_o value will cause less temperature rise and thus less thermal stresses are induced [14]. 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 19-21 shows the hoop stress distribution contour in case of radius ratio 1.5 for different profiles and the effect of different fin profiles on the hoop stress distribution for various radius ratios is represented in the Figures 22-25.

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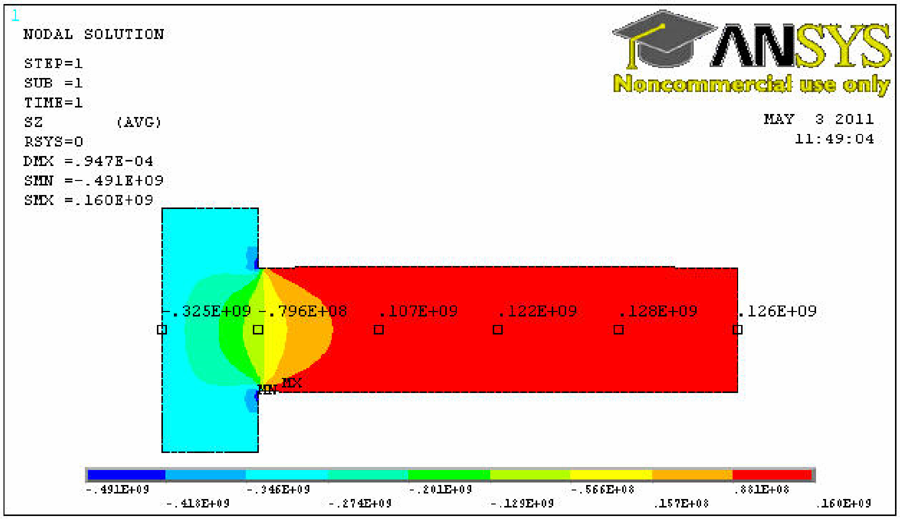

Figure-19. Hoop stress distribution along the centerline of fin with rectangular profile.

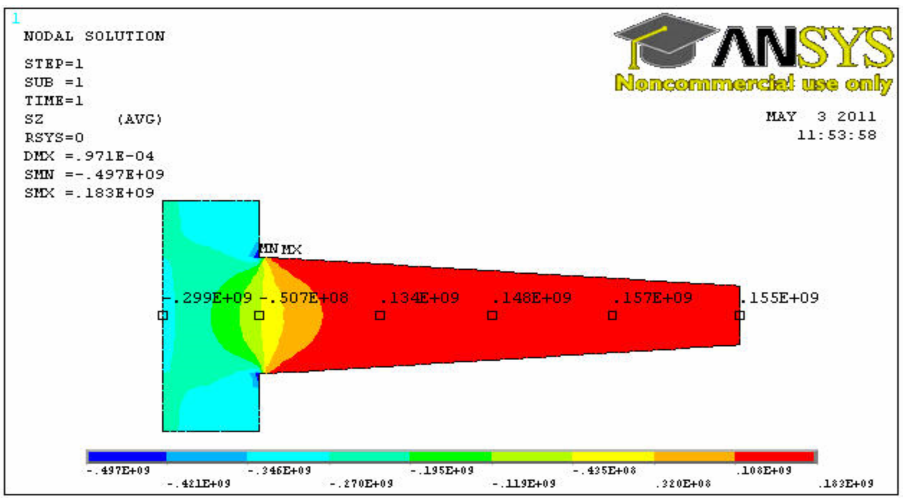

Figure-20. Hoop stress distribution along the centerline of fin with trapezoidal profile.

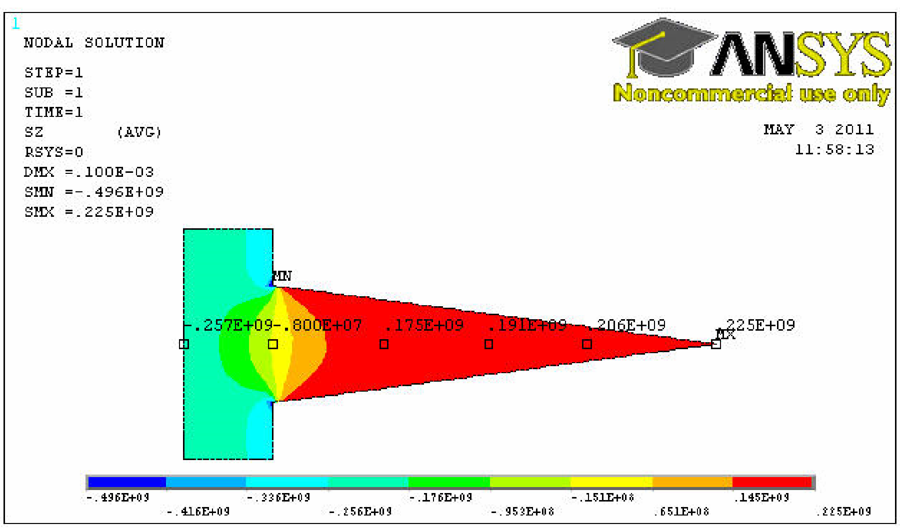

Figure-21. Hoop stress distribution along the centerline of fin with triangular profile.

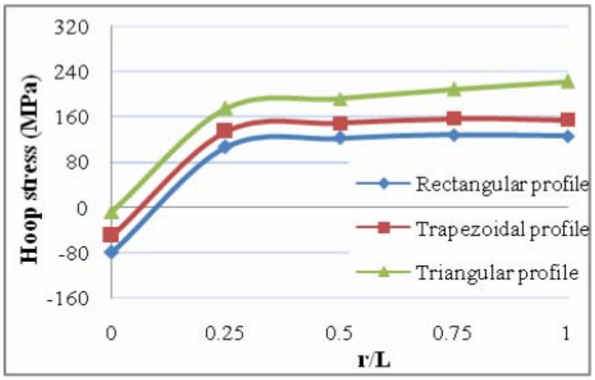

Figure-22. Hoop stress distribution along the fin for different profiles with radius ratio 1.5.

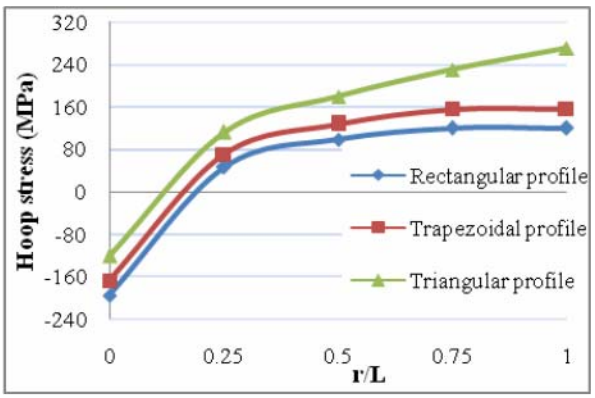

Figure-23. Hoop stress distribution along the fin for different profiles with radius ratio 2.

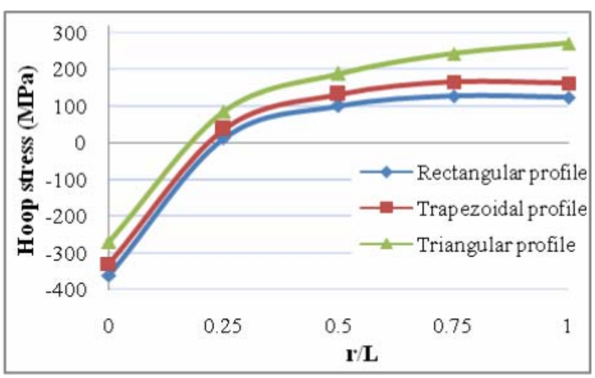

Figure-24. Hoop stress distribution along the fin for different profiles with radius ratio 3.

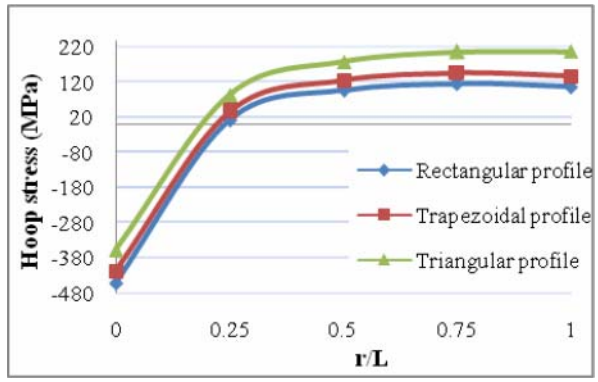

Figure-25. Hoop stress distribution along the fin for different profiles with radius ratio 4.

From the Figures 22-25, 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/r_o increases. This is due to the fact that a large R/r_o value will cause less temperature rise and thus less thermal stresses are induced [14]. 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.

4. CONCLUSIONS

The current analysis has presented a study of thermal characteristics of a ceramic tube with annular fins of different profiles. Coupled-field analysis was carried out on SiC ceramic 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 and hoop 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 $R/r_o = 1.5$, 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 $R/r_o = 1.5$, 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 profiles.

Nomenclature

c_p	Specific heat of the material
σ	Stress
E	Young's modulus of the material
t	Fin thickness
L	Fin length
k	Thermal conductivity of the material
h	Heat transfer coefficient
r	Cylindrical coordinate
r_i	Inner radius of the tube
r_o	Outer radius of the tube
R	Outer radius of the fin
ρ	Density of the material
ν	Poisson's ratio of the material
α	Thermal expansion coefficient
R/r_o	Radius ratio.

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