iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 3 Issue: VIII Month of publication: August 2015

DOI:

Volume 3 Issue VIII, August 2015
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Finite Element Analysis of Transient Thermo Mechanical Stresses of Multilayered Composite Hollow Thick Cylindrical Pressure Vessel

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Abstract: The study of thermo mechanical stresses on pressure vessels has a great significance from the theoretical and practical point of view due to their importance in many applications. This paper presents a complete analysis of thermo mechanical stresses within a thick-walled hollow multi layered composite cylinder subjected to internal fluid pressure and thermal load under transient condition. A complete evaluation of temperature and stress distributions, in a transient state, is obtained using finite element tool.
Keywords- Thermo mechanical stress, composite, transient condition.

I. INTRODUCTION

The thick walled cylindrical pressure vessel is a very important structure in most of the industries such as chemical, petroleum, nuclear industries etc. Practical examples of such structures are industrial boiler, long pipes used for carrying gasses/ oil, offshore pipelines, gun barrels, pressure vessels for transportation and storage of oil/ gases, nuclear reactors etc. Pressure vessels are closed shell structures that contain gasses and liquid under pressure. Design of pressure vessel is governed by two main but contradictory constraints. First constraint is minimum weight and cost to save material and resources and second one requires the proper reliability and safety of the structure [1]. For commercial pressure vessel, the second constraint is much more important than the first while the safety constraint is ensured by design guides, codes and standards developed by ASME Boiler and pressure vessel code, section VIII, dividion-1. Pressure vessels often subjected to high temperature, high fluid pressure and strong corrosive condition. Vessels made up of single material can not satisfy the requirement of such conditions. Therefore a multilayered laminated composite pressure vessel consisting of thin layers of different material, bonded together perfectly are generally used. The inner layer is generally made up of strong corrosive resistant material. The design and development of pressure vessel are guided by design codes and standards. Pressure vessels are designed based on simple equations of shell theory whose solutions can be found by using numerical method. Some times in many complex problems, it is very difficult to formulate the exact mathematical model of the problem. In that case, finite element packages like ANSYS 14.0 are very effective in solving that problem. The rapid development of finite element software and integration of CAD and CAM with it, has remarkably improved the detailed design and analysis of pressure vessel components. If the wall of the cylinder is subjected to thermal flux, thermal stresses are developed that re-establish the congruence of deformations; the congruence is, however, perturbed by thermal dilations that vary throughout the wall. If the cylinder is subjected to both pressure and thermal field, then thermo mechanical stresses are created [2]. The development of thermal stress and thermo mechanical stress in thick cylinder pressure vessel subjected to pressure load and thermal load are studied by many researchers.

Multilayered composite cylinders subjected to thermal field (uniform or non-uniform) or thermo mechanical field represent both theoretical as well as practical interest due to their wide applications in different industries. Examples of such structures are long pipeline coated with protective coating used for transportation of oil, gases etc., multilayered or fiber reinforced composite pressure vessel used in different industries, hydrogen fuel tank etc. Solid multilayered cylinders such as coated fibers or wires are used in fiber optics where the temperature of the core increases due to flow of electrons. Two type of composite pressure vessels are widely used in different engineering applications. One is fiber reinforced composite i.e. a polymer matrix is reinforced with a fiber or other reinforcing material with a sufficient aspect ratio (length to thickness) to provide a discernible reinforcing function in one or more directions. Another is laminated composite consisting of thin layers of different materials bonded together such as bimetals, clad metals, plywood etc. Axis symmetric thermo elastic problem was solved by Timoshenko and Goodier [3] in their book on "Theory of elasticity". A large number of papers related to thermo elastic analysis of multilayered cylinder have been published. Ambartsumian, S.A. [4] formulated several problems on thermo elastic analysis of multilayered and composite shells. P. G. Pimshtein and V. N. Zhukova [5] calculate the stresses in a laminated cylinder with an allowance for the specificities of contact between layers.

There have been many papers dealing with the transient thermo elasticity problem. Yang and Chen [6] investigated the transient response of one-dimensional axisymmetric quasistatic coupled thermo elastic problems of an infinitely long annular cylinder composed of two different materials. The governing equations are formulated in terms of temperature increment and displacement taking into account of the thermo mechanical terms. Laplace transform with respect time is used to obtain the general solution of the governing equation in transform domain. The inversion to the real domain is obtained by using Fourier series technique and matrix operation simultaneously and no thermo elastic potentials are introduced in the solution process. It is found that the coupling effect behaves as a clear lag in both the stress and the temperature distribution. K.C Jane and Z.Y. Lee [7] consider the problem of thermoelastic transient response of multilayered annular cylinders of infinite lengths subjected to known temperatures at traction-free inner and outer surfaces. Laplace transformation and finite difference method are used to analyze the Thermo elasticity problem. Using the Laplace transform with respect to time, the general solutions of the governing equations are obtained in transform domain. The solution is obtained by using the matrix similarity transformation and inverse Laplace transform. Solutions for the temperature and thermal stress distributions in a transient state were obtained. There is no thermo elasticity potentials are introduced in the solution process. Numerical results of three and five layered cylinders at different time steps were discussed. The discontinuity in circumferential stress at each interface was noted. It was noted that the temperature distribution, the displacement and the thermal stresses vary slightly as time increases. There is no limit of number of annular layers of the cylinder in the presented computational procedures. The numerical procedures discussed in this paper can solve the generalized thermoelasticity problem for a multilayered composite laminated annular cylinder with non-homogeneous materials. Marie [8] considered a simple solution for any variation of the temperature in the fluid where covered the influence of cladding on the inner surface. The approach consists of breaking down the fluid temperature variation into a succession of linear shocks. Using the linear shock resolution approach, it is possible to propose a simple analytical solution, using the same constant. F. Jacquemin and A.Vautrin [9] assess the internal stresses in thick laminated pipes, composed of orthotropic plies, subjected to transient thermal fields. A analytical solutions is obtained to compute the internal stresses due to transient thermal fields throughout the pipe thickness based on well-founded assumptions and theory of thermoelasticity. A thick, laminated and anisotropic pipes of infinite length subjected to heat flux conditions on their inner and outer surfaces due to the environmental conditions, are considered. The transient thermal field is determined and the thermoelastic stresses are derived by using the classical equations of solid mechanics and assuming thermoelastic orthotropic ply behaviour. Zong-Yi Lee [10] investigated the one-dimensional quasi-static axisymmetric coupled thermoelasticity problem of infinitely long multilayered hollow cylinder whose boundaries are subjected to time-dependent temperatures, adiabatic and clamped. In the case of a infinitely long cylinder, numerical results of multilayered hollow cylinder were calculated. The finite difference and Laplace transform methods were employed to obtain the numerical results. The temperature, displacement and thermal stress distributions were obtained.

In order to reach the equilibrium thermal state i.e. steady state from initial uniform temperature, a transient thermal gradient i.e. dependent on time first occur. The transient thermal gradient of cylindrical pressure vessel due to sudden change of thermal environment is important for the design of many advanced engineering application. Examples of such applications are found in nuclear engineering, nozzle sections of rockets, gun and barrel tubes, internal combustion engines, and dies of hot forming tools. Therefore, the design of such cylinders needs to be combined with a more accurate thermal stress analysis taking into account the time-dependent variation. Few works has been reported to investigate the transient thermal stress in thick cylinder. Zhang et al. [11] derived an analytical solution for determining the stress distribution of a multilayered composite pressure vessel subjected to an internal fluid pressure and a thermal load. The stress distribution of the pressure vessel was computed using FE method. Wang and Ding [12] obtained the thermoelastic dynamic solution of a multilayered orthotropic hollow cylinder in the state of axisymmetric plane strain. Atefi and Mahmoudi [11] offered an analytical solution for obtaining thermal stresses in a pipe caused by periodic time varying of temperature of medium fluid. Jabbari, Sohrabpour, and Eslami [12] developed a general analysis of one-dimensional steady-state thermal stresses in a hollow thick cylinder made of functionally graded material. Shao, Wang, and Ang [13] carried out thermo-mechanical analysis of functionally graded hollow cylinder subjected to axisymmetric mechanical and transient thermal loads.

Despite the fact that the theory of thermo elasticity has been widely used to solve the problem related to the pressure vessel [14-17], there is not enough literature available to determine the thermo mechanical stresses in pressure vessel using finite element approach. However, most investigators have only dealt with the analysis of thermal stresses of thick-walled cylinders under steady-state and unsteady state conditions. In this paper, transient thermo mechanical stresses were computed in a two layered composite hollow thick cylindrical pressure vessel. The proposed finite element solution may be used to design multilayered composite pressure vessel under transient state condition.

II. PROBLEM FORMULATION

Consider an infinitely long thick hollow cylinder composed of multilayered laminate bonded together perfectly as in fig. 1. The cylinder is made of a homogeneous isotropic material and is long enough in the axial direction such that the assumption of the plane strain condition satisfies. This work deals with the one-dimensional, coupled, thermo elastic problem i.e. cylindrical vessel is subjected to both transient thermal load and internal fluid pressure.

A. Generalized Assumptions

In this work, the following assumptions are taken into consideration during the analysis:

The ends of the cylinders are assumed to be unrestrained.
The material of each layer is assumed to be homogenous.
Deformation and strain satisfy Hooke's law and small strain theory.
The composite cylinder is constructed of multilayer laminates bonded perfectly together
The longitudinal strain developed as a result of the stress is uniform and constant, i.e. plane strain with $\varepsilon_z = 0$.
The temperature of the cylinder is considered to vary only in the radial direction and is time-dependent, i.e. T = $T(r, t)$.
There is no source of heat generation within the cylinder thickness.
The outside surface of the cylinder is exposed to ambient conditions which are large enough so that its temperature can be assumed to remain constant. Therefore, the mean value of the convective heat transfer coefficient is used in the analysis.
The thermal conductivity of the cylinder material, the coefficient of linear expansion, modulus of elasticity and Poisson's ratio are assumed to be independent of temperature.

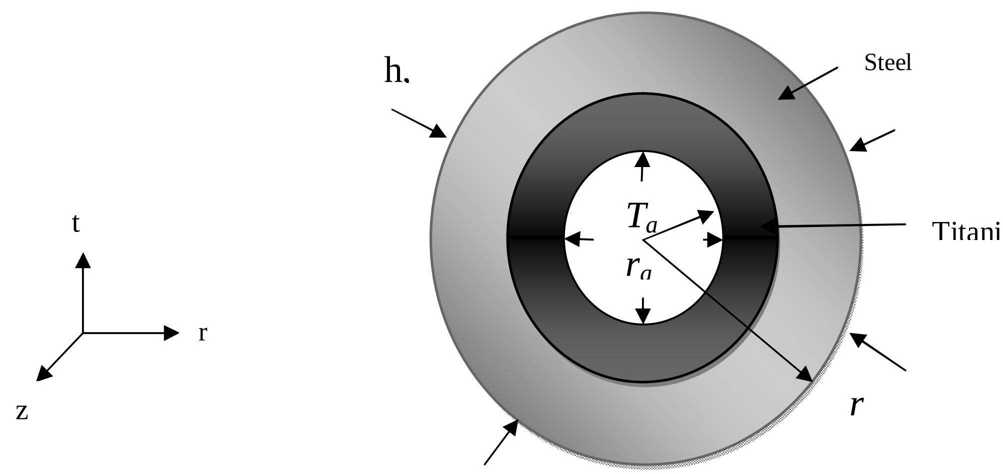

Fig1: Sketch of two layered open ended cylindrical pressure vessel

B. Temperature Distribution

The general form of the heat equation in cylindrical coordinates system $(r, \emptyset, z)$ is [18]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2} + \frac{\partial^2 T}{\partial z^2} + \frac{g}{k} = \frac{1}{\alpha *}\frac{\partial T}{\partial t} \quad (2.1)$$

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The differential equation of time-dependent heat flow in the radial direction is given in polar coordinates by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha *}\frac{\partial T}{\partial t} \qquad (2.2)$$

Boundary condition:

$$-k\frac{\partial T}{\partial r} = h(T - T_\alpha) \quad when\ r = r_b$$
$$T = T_0 \qquad when\ t = 0$$
$$T_a - T_0 = f \qquad when\ r = r_a \qquad (2.3)$$

The temperature distribution in transient state can be obtained by using either separation of variable method or finite difference method. Kandil [19] find out the temperature distribution for single cylinder in transient state by using finite difference method. The temperature at an interior node (m) in the fig. 2a, after a time interval Δt is given by the equation [19]:

$$T_m^{\Delta t} = F_0\left(\frac{r_{m-1,m}}{r_m}T_{m-1} + \frac{r_{m,m+1}}{r_m}T_{m+1}\right) + (1 - 2F_0)T_m \qquad (2.4)$$

For the non-interior node (n) (at the outside surface) in the fig. 2b, the equation of temperature is given by

$$T_n^{\Delta t} = 2F_0\left(\frac{r_{n-1,n}}{r_n}T_{n-1} + B_iT_0\right) + [1 - 2F_0(\frac{r_{n-1,n}}{r_n} + B_i)]T_n \qquad (2.5)$$

Then, the temperature distribution is obtained by solving these equations at specified time intervals Δt. F_0 is Fourier number, $B_i$is Biot number, t is time.
Wang [20, 21] obtained the transient temperature distribution in hollow cylinder by using separation of variable method. Not too many paper published regarding the solution of temperature distribution by using separation of variable method.

(a) (b)

Fig 2: Thick cylinder with (a) interior node (b) non interior node [16]

C. Thermo-Mechanical Stresses

In order to calculate the stresses due to heat flow and internal pressure the following equilibrium equations are used:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_t - \sigma_r}{r} = 0 \qquad (2.6)$$

And the strain displacement equation is as

$$\varepsilon_r = \frac{du}{dr}\ , \varepsilon_t = \frac{u}{r}\ , \varepsilon_z = 0 \qquad (2.7)$$

The stresses in the cylindrical pressure vessel can be written as [8]

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$$\left.\begin{aligned}
\sigma_r &= \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_r + \mu\varepsilon_t\right] - \frac{E\alpha T}{1-2\mu} \\
\sigma_t &= \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_t + \mu\varepsilon_r\right] - \frac{E\alpha T}{1-2\mu} \\
\sigma_z &= \frac{E}{(1+\mu)(1-2\mu)}\left[\mu(\varepsilon_t + \varepsilon_r)\right] - \frac{E\alpha T}{1-2\mu}
\end{aligned}\right\} \tag{2.8}$$

Where ε_r, ε_t, and ε_z are the radial strain, hoop strain and axial strain, respectively and $\sigma_r, \sigma_t, \sigma_z$ denotes the radial, hoop and axial stress. u denotes the radial displacement, μ denotes Poisson's ratio, and E denotes Young's modulus. T denotes the temperature change from the reference temperature, and the reference temperature is given as zero in this work.

D. Boundary Conditions

The analysis was conducted assuming different two cases.

Boundary conditions are as:

Case-1: The pressure vessel subjected to a temperature of T_a at the inside layer and the outer layer is exposed to ambient temperature of T_α, and a convection with mean convective heat transfer coefficient of 200 W/m K.

$$\left.\begin{aligned}
\sigma_r(r) &= 0 \quad & when\ r = r_a \\
\sigma_r(r) &= 0 \quad & when\ r = r_b \\
T(r,t) &= T_a \quad & when\ r = r_a \\
-k\frac{\partial T}{\partial r} &= h(T - T_\alpha) \quad & when\ r = r_b \\
T &= T_\alpha \quad & \text{when } t = 0
\end{aligned}\right\} \tag{2.9}$$

Case-2: The pressure vessel subjected to internal fluid pressure and inner layer of the cylinder is subjected to a temperature of T_a and the outer layer is exposed to ambient temperature of T_α, and convection with mean convective heat transfer coefficient of 200 W/m^2 K.

$$\left.\begin{aligned}
\sigma_r(r) &= -P_i \quad & when\ r = r_a \\
\sigma_r(r) &= 0 \quad & when\ r = r_b \\
T(r,t) &= T_a \quad & when\ r = r_a \\
-k\frac{\partial T}{\partial r} &= h(T - T_\alpha) \quad & when\ r = r_b \\
T &= T_\alpha \quad & \text{when } t = 0
\end{aligned}\right\} \tag{2.10}$$

For an infinitely long cylinder, hoop stress is considered as the critical parameter to determine the wall thickness of the pressure vessel and axial stress is neglected. The hoop stress and the radial stress are calculated by introducing radial interface pressure, *p* between two consecutive layers [25].

The interfacial displacement between two consecutive layers should be

$$u_k \Big|_{r = r_k^{(+)}} = u_{k+1} \Big|_{r = r_k^{(-)}} \tag{2.11}$$

Combining the equations (4) to (9) and applying the boundary conditions for case-1 and case-2, the thermo mechanical stresses in the multilayered composite pressure vessel can be computed. For a multilayered hollow cylindrical pressure vessel considering closed end, the radial and hoop stresses have been proposed [8]. In this work, these stress formulas for cylindrical vessels were modified as:

Case-1: (Only thermal load)

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$$\sigma_{rk} = \frac{\alpha_k E_k}{1-\mu_k}\left[\frac{\int_{r_{k-1}}^{r_k} T_k r dr}{r_{k-1}^2 - r_k^2}\left(\frac{r_{k-1}^2}{r^2} - 1\right) - \frac{1}{r^2}\int_{r_{k-1}}^{r} T_k r\, dr\right] \quad (2.12)$$

$$\sigma_{tk} = \frac{\alpha_k E_k}{1-\mu_k}\left[-\frac{\int_{r_{k-1}}^{r_k} T_k r dr}{r_{k-1}^2 - r_k^2}\left(\frac{r_{k-1}^2}{r^2} + 1\right) + \frac{1}{r^2}\int_{r_{k-1}}^{r} T_k r\, dr - T_k\right] \quad (2.13)$$

Case-2: (Thermal and mechanical load)

$$\sigma_{rk} = \frac{\alpha_k E_k}{1-\mu_k}\left[\frac{\int_{r_{k-1}}^{r_k} T_k r dr}{r_{k-1}^2 - r_k^2}\left(\frac{r_{k-1}^2}{r^2} - 1\right) - \frac{1}{r^2}\int_{r_{k-1}}^{r} T_k r\, dr\right] + \frac{p_k r_k^2 - p_{k=1} r_{k-1}^2}{r_{k-1}^2 - r_k^2} + \frac{r_{k-1}^2 r_k^2 (p_{k-1} - p_k)}{(r_{k-1}^2 - r_k^2) r^2} \quad (2.14)$$

$$\sigma_{tk} = \frac{\alpha_k E_k}{1-\mu_k}\left[-\frac{\int_{r_{k-1}}^{r_k} T_k r dr}{r_{k-1}^2 - r_k^2}\left(\frac{r_{k-1}^2}{r^2} + 1\right) + \frac{1}{r^2}\int_{r_{k-1}}^{r} T_k r\, dr - T_k\right] + \frac{p_k r_k^2 - p_{k-1} r_{k-1}^2}{r_{k-1}^2 - r_k^2} - \frac{r_{k-1}^2 r_k^2 (p_{k-1} - p_k)}{(r_{k-1}^2 - r_k^2) r^2} \quad (2.15)$$

Whereas radial interface pressure p_k can be computed as:

$$p_k = \frac{\left(J_k + \left(\frac{z_k + n_k}{1 - q_k^2}\right) p_{k-1} + \left(\frac{z_{k+1} q_{k+1}^2 + n_{k+1} q_{k+1}^2}{1 - q_{k+1}^2}\right) p_{k+1}\right)}{\frac{z_{k+1} + n_{k+1} q_{k+1}^2}{1 - q_{k+1}^2} + \frac{z_k q_k^2 + n_k}{1 - q_k^2}} \quad (2.16)$$

Where $n_k = \frac{(-1+\mu_k)}{E_k}$; $l_k = \frac{\mu_k}{E_k}$; $z_k = \frac{\mu_k - 1}{E_k}$ and $J_k = \frac{2\alpha_{k+1}\int_{r_k}^{r_{k+1}} T_{k+1} r dr}{r_k^2 - r_{k+1}^2}$ - $\frac{2\alpha_k \int_{r_{k-1}}^{r_k} T_{k+1} r dr}{r_{k-1}^2 - r_k^2}$

Where R denotes the interfacial radius, T denotes the temperature which varies with time and in radial direction, and the subscript k (1, 2, , ,n) represents the kth layer . Where q is the radius ratio, and $q_k = \frac{r_k}{r_{k-1}}$

III. FINITE ELEMENT MODELING OF TWO LAYERED COMPOSITE PRESSURE VESSEL

Finite element model of a two layered composite cylindrical pressure vessel of infinite length was modeled. Due to the axis-symmetry of the pressure vessel and boundary conditions, a quarter of the geometrical model (Fig. 3) was constructed with the axisymmetric 4-node thermal elements Plane55 and the axisymmetric 4-node plane elements Plane182 using the finite element tool: ANSYS. The symmetrical boundary condition was applied at the bottom and top of the cylinder, and the numbers of nodes and elements were 26466 and 25632, respectively. Two layers are bonded together perfectly. The inside layer is made up of titanium and outside laminate is made up of Steel. The inner radius of the cylinder is 1m and outer radius is 4.5 m. inside layer has a thickness of 2m and that of outside is 2.5m. The internal fluid pressure was 22 MPa, and the outer pressure 0 MPa. The inner temperature was 200 °C, and the outer temperature 25 °C and convection is applied at the outside with mean convective heat transfer coefficient of 200 w/m^2 k. The thermo mechanical properties and the wall thicknesses of each layer are listed in Table 1.

An indirect approach [11] was used to calculate the thermo mechanical coupling stresses of the two-layered composite pressure vessel. The solution procedure was as follows: Firstly, the thermal model was created and the temperature boundary condition was given, and the temperature distribution was calculated. Secondly, the element type was converted from the thermal element PLANE55 to the mechanical element PLANE182. Finally, the internal fluid pressure was imposed on the inner layer of the FE model of the pressure vessel, and the two stresses (σ_t, σ_r) were determined.

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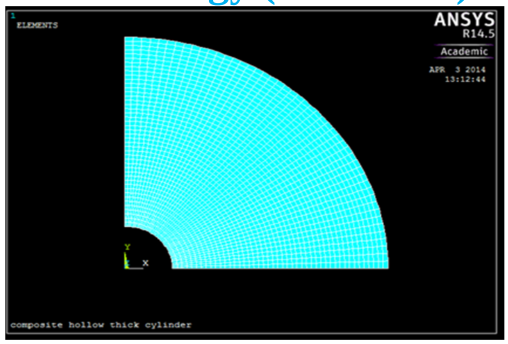

Fig 3: FEA model of two layered pressure vessel

TABLE 1: MATERIAL AND GEOMETRIC PROPERTIES OF EACH LAYER.

	Layer-1(Titanium)	Layer-2 (Steel-1025)
Thickness	2 m	2.5 m
Young's Modulus	108e9 kJ	207e9
Poisson's Ratio	0.3	0.3
Thermal conductivity	20 kW/m k	17
Thermal expansion coefficient	11e-6	11e-6
density	4 kg/m^3	7.8
Specific heat	0.4 kJ/kg k	0.48

IV. RESULT AND DISCUSSION

The pressure vessel has multilayered properties, so there is step changes in the distribution of radial and hoop stress. In this work two cases are considered. Case-1 considered the effect of thermal load only and case-2 considered the effect of both thermal load and internal fluid pressure. The radial and hoop stressed are computed for both the cases. Fig. 4 shows the temperature distributions along the radial direction at different time intervals. The obtained temperature distribution along the thickness of the cylinder is plotted with respect to time in fig. 5. Fig. 6 and fig.7 show the radial stress distribution for case-1 and case-2 respectively along the radial direction for different time interval. Fig. 8 and Fig. 9 show the hoop stress distribution for case-1 and case-2 respectively along the radial direction for different time interval. However, it is found that the hoop stress has a significant jump at the interference due the change in material properties at different layers. The stresses vary characteristically in each layer, especially due to the occurrence of discontinuities at the interference. Fig. 10 and 11 show the variation of displacement along the radial direction. From the figures it can be interpreted where the maximum displacement occurs. From the above mentioned figures, it can be concluded that the stresses and displacement in case-2 is greater than that of case-1 due to the simultaneous presence of thermal load and internal fluid pressure.

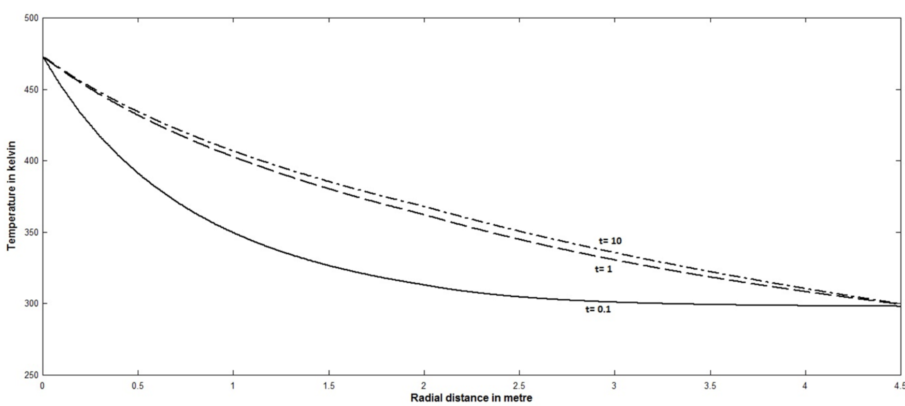

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Fig 4: Temperature distribution for different time interval

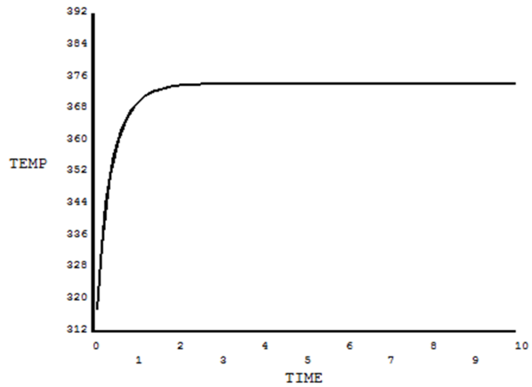

Fig 5: Temperature variation with respect to time

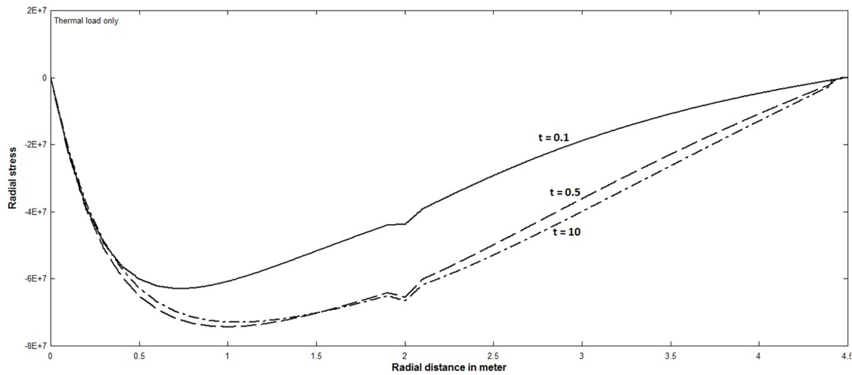

Fig 6: Radial stress distributions at different time interval considering only thermal load.

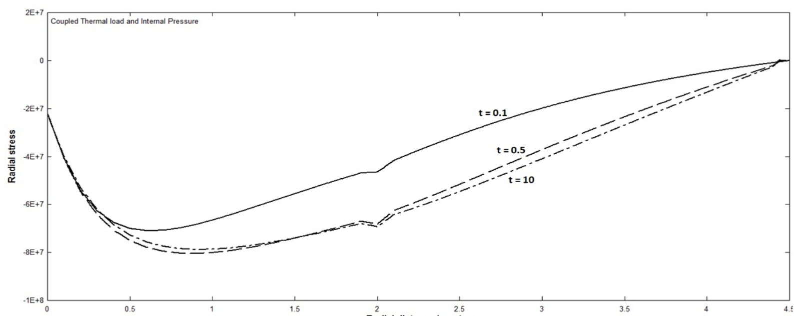

Fig 7: Radial stress distributions at different time interval considering both thermal load and internal pressure.

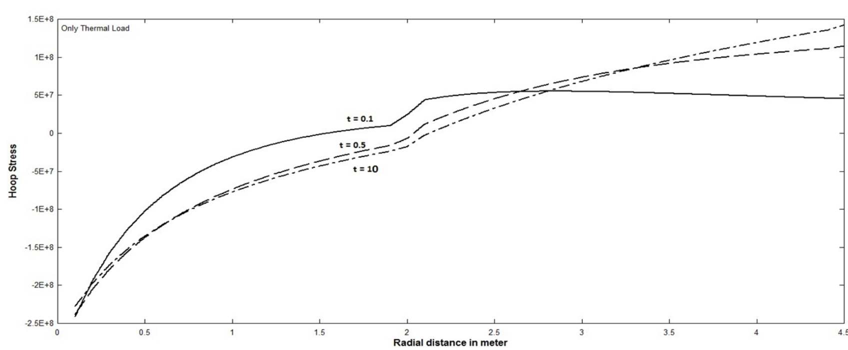

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Fig 8: Hoop stress distributions at different time interval considering only thermal load.

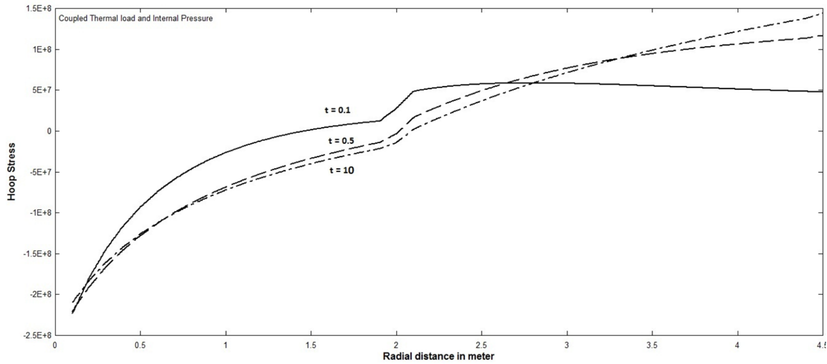

Fig 9: Hoop stress distributions at different time interval considering both thermal load and internal pressure.

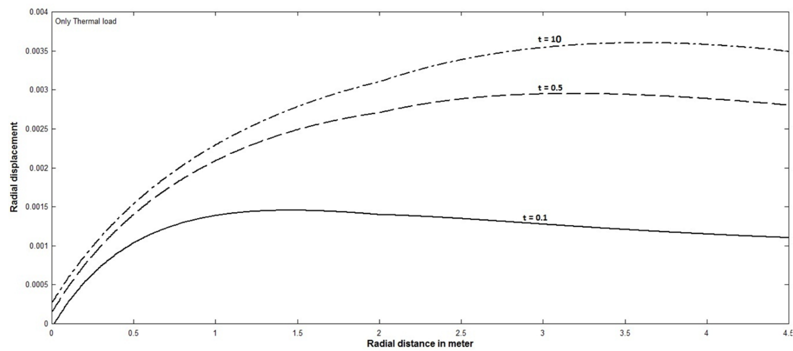

Fig 10: Radial displacement at different time interval considering only thermal load.

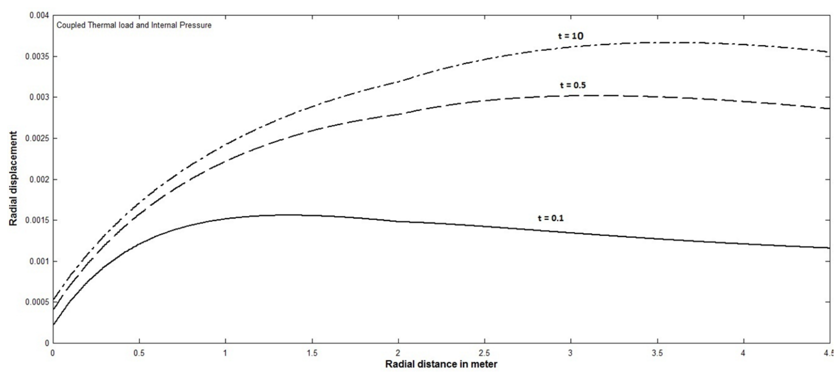

Fig 11: Radial displacement at different time interval considering both thermal load and internal pressure.

V. CONCLUSION

In this study, an attempt has been made to investigate the problem for the combined mechanical and thermal stresses as well as only thermal stress in a multilayered composite hollow cylinder in a transient condition. It is found that there is a step change in the distribution of radial (fig. 6 & 7) and hoop (fig. 8 & 9) stress at the interface of each layer due to the change in material properties of each layer. From the above discussion it can be further concluded that the stresses and displacement in the case of pressure vessel subjected to thermal load only is less than that of vessel subjected to combined thermal load and internal fluid pressure due to the effect of the simultaneous presence of thermal load and internal pressure. Further, the temperature, displacement and stress distribution obtained in this paper can be applied to the engineering design of structures and machines. Therefore, the Finite element method is an easier technique to deal with such type of complex problems.

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NOTATION

T Temperature (K)

ε_z longitudinal strain

ε_t Tangential strain

ε_r Radial strain

Δt time interval (s)

Δr radial interval (m)

α* Thermal diffusivity (m^2/ s)

α coefficient of thermal expansion (mm^{-1} °C^{-1})

F_0 Fourier number

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ISSN: 2321-9653

B_i Biot number

t time (s)

T_m Temperature of interior node (m) (°C)

T_n Temperature of non interior node (n) (°C)

$T_m^{\Delta t}$ Temperature of interior node (m) after time interval Δt (°C)

$T_n^{\Delta t}$ Temperature of non interior node (n) after time interval Δt (°C)

r Radius (m)

u radial displacement (m)

σ_t Tangential stress (Pa)

σ_r Radial stress (Pa)

σ_z Axial stress (Pa)

μ Poisson's ratio

E Young's modulus (Pa)

K Thermal conductivity (W/m K)

h convective heat transfer coefficient (W/m^2 K)

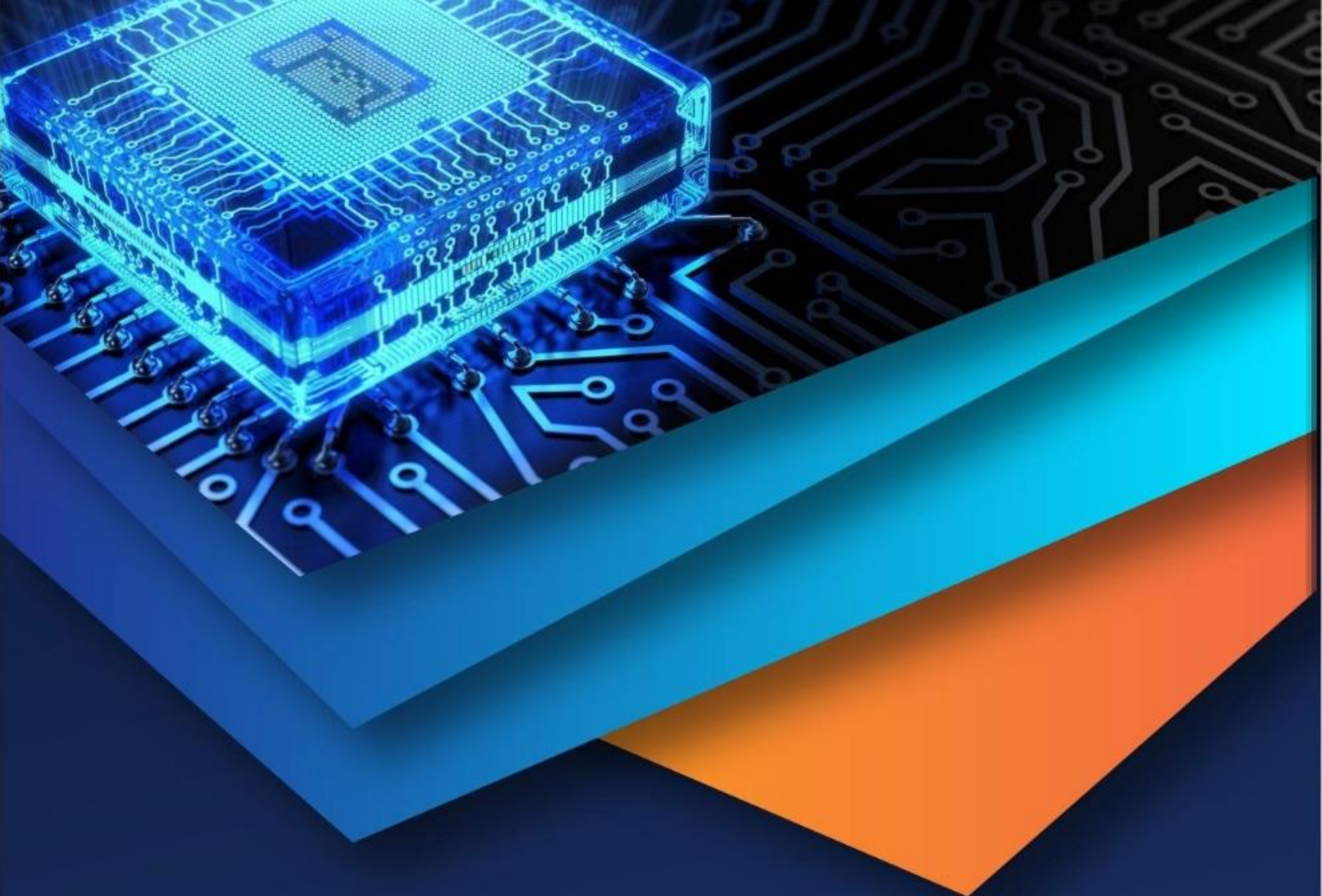
T_α Ambient temperature (K)

T_a Fluid temperature (K)

P_i Fluid pressure (N/m^2)

r_a Inside radius of cylinder (m)

r_b outside radius of cylinder (m)



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