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Thermal Stresses in a Thermoelastic Hollow Cylinder Subjected to Magnetic field

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Abstract: In this paper, propagation of harmonic plane waves is considered in a linear thermoelastic an infinite cylinder for an isotropic material has been investigated. The effects of a magnetic field in a propagation of harmonic plane waves is considered in a linear magneto-thermoelastic an infinite cylinder. A finite difference method is proposed to obtain the solution of the transient coupled thermoelasticity in an infinite cylinder with its base suddenly subject to a heat flux of a decayed exponential function of time. The present method is a second-order accurate in time and space and unconditionally stable. A numerical method is used to calculate the temperature, displacement components and the components of stresses with time t and through the radial of an infinite cylinder. Comparisons have been made with the obtained results in the presence and absence of the considered variables and displayed graphically. The results indicate that the applicable of the phenomena in diverse fields as biology, astronomy, petroleum extracting. The findings show that the impacts of the magnetic field is very pronounced.

Keywords: Thermoelasticity; Thermal stress; Finite difference method; Nonhomogeneous; Magnetic field.

Introduction

Isotropic propagation of elastic waves is an assumption that offers mathematical conve-nience. Else, elastic anisotropy is a reality in any real material, be it a rock, man-made structure or industrial material. Any study on the propagation of waves in a thermoelastic material can be significant in structural engineering, geophysics, and seismology. Such a study becomes more realistic if the presence of a magnetic field could be considered in modeling in situ materials. Hussein and Bayones [1] investigated the effect of rotation on Rayleigh waves in a fiber-reinforced solid anisotropic magneto-thermo-viscoelastic media. Abo-Dahab *et al*. [2] studied the magnetism and rotation effect on surface waves in fibre-reinforced anisotropic general viscoelastic media of higher order. Singh [3] discussed the wave propagation in thermally conducting linear fibre-reinforced composite materials. Sharma [4] investigated the propagation of Rayleigh waves at the boundary of an orthotropic elastic solid: Influence of initial stress and gravity. Mohajer *et al*. [5] studied the small amplitude Rayleigh-lamb wave propagation in a finitely deformed viscoelastic dielectric elastomer layer. Singh *et al*. [6] investigated the Love-type waves in a piezoelectric-viscoelastic bimaterial composite structure due to an impulsive point source. Manna and Kumar [7] discussed the dynamic behavior of multi-layer heterogeneous composite magneto-elastic structures for surface wave scattering. Sengupta and Nath [8] studied the surface waves in fibre-reinforced anisotropic elastic media. Sharma [9] investigated the propagation of elastic energy in a general anisotropic medium. Sharma [10] studied the Rayleigh waves in isotropic viscoelastic solid half-space. Bayones and Hussien [11] sided the propagation of Rayleigh waves in fiber-reinforced anisotropic solid thermo-viscoelastic media under the effect of rotation. Abd-Alla *et al*. [12] studied the rotational effect on thermoelastic Stoneley, Love and Rayleigh waves in fibre-reinforced anisotropic general viscoelastic media of higher order. Hussein *et al*. [13] investigated the influence of rotation and initial stress on Propagation of Rayleigh waves in fiber-reinforced solid anisotropic magneto-thermo-viscoelastic media. Ala *et al*. [14] studied the shear wave propagation in a magneto poroelastic medium sandwiched between self reinforced poroelastic medium and poroelastic half space. Alexandrov *et al*. [15] obtained the stress and strain fields in rotating elastic/plastic annular disks of pressure-

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dependent material. Arefi and Arani [16] investigated the higher order shear deformation bending results of a magneto-electrothermoelastic functionally graded nanobeam in thermal, mechanical, electrical, and magnetic environments. Biswas *et al*. [17] studied the effect of rotation in magneto-thermoelastic transversely isotropic hollow cylinder with three-phase-lag model. Kalkal et al. [18] introduced the two-dimensional magneto-thermoelastic interactions in a micropolar functionally graded solid. Mondal and Kanoria [19] obtained the thermoelastic solutions for thermal distributions moving over thin slim rod under memory-dependent three-phase lag magneto-thermoelasticity. Yuan et al. [20] investigated the analysis of attenuation and dispersion of Rayleigh waves in viscoelastic media by finite-difference modeling. The extensive literature on the topic is now available and we can only mention a few recent interesting investigations in [21-24].

In the present study proposes a mathematically correct procedure to study the effects of magnetic field on the propagation of wave in thermoelastic cylinde. The magnetic field effect plays a big role to study the thermal stresses in an isotropic medium. By applying finite difference scheme to the equation of motion, the numerical solution is obtained. Numerical simulated results are depicted graphically to show the effect of magnetic field on the temperature, displacement, and stresses. Comparisons have been made with the obtained results in the presence and absence of the considered variables and displayed graphically. Moreover, the present paper applies to the design and optimal use of nanoplates and microplates.

Formulations of the Problem

Let us consider the cylindrical coordinates (r, θ, z) with the $z-$ axis coinciding with the axis of the cylinder. The strains symmetry about the z-axis of the problem imply that all of the field variables depend on the distance r and time t, we have only the radial displacement $u_r = u$, $u_\theta = 0$, $u_z = 0$ and these are independent of θ and z.
The governing electrodynamics Maxwell equations are given by

$$\vec{j} = curl\,\vec{h},\ -\mu_e \frac{\partial \vec{h}}{\partial t} = curl\,\vec{e},\ \ div\,\vec{h} = 0, \qquad (1)$$
$$\vec{h} = curl\,(\vec{u} \wedge \vec{H}).$$

Here $\vec{h}$ is the perturbed magnetic field over the constant primary magnetic field H_0, μ_e is the magnetic permeability, $\vec{e}$ is the electric intensity, $\vec{j}$ is the electric current density. Applying an initial magnetic field vector $\vec{H}(0,0,H_0)$ in cylindrical polar coordinates (r,θ,z).

The heat conduction equation in the absence of heat sources is

$$\frac{\partial^2 T'}{\partial r^2} + \frac{1}{r}\frac{\partial T'}{\partial r} = \frac{1}{k_1}\left(\frac{\partial}{\partial t} + \tau\frac{\partial^2}{\partial t^2}\right)T + \gamma T_0\left(\frac{\partial}{\partial t} + \tau\frac{\partial^2}{\partial t^2}\right)\left[\frac{u}{r} + \frac{\partial u}{\partial r}\right] \qquad (2)$$

The equation of motion is

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{(\sigma_{rr} - \sigma_{\theta\theta})}{r} + f_r = \rho\frac{\partial^2 u}{\partial t'^2}, \qquad (3)$$

where f_r is defined as Lorentz's force, which may be written as

$$f_r = \mu_e(\vec{j} \wedge \vec{H}) = \mu_e H_0^2\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right) \qquad (4)$$

The nonzero components of the stress tensor are given in terms of the nonzero component of the displacement vector $u(r, t')$,

$$\sigma_{rr} = (\lambda + 2\mu)\frac{\partial u}{\partial r} + \lambda\frac{u}{r} - \gamma(T' + \tau\dot{T}')$$
$$\sigma_{\theta\theta} = \lambda\frac{\partial u}{\partial r} + (\lambda + 2\mu)\frac{u}{r} - \mu\frac{u}{r} - \gamma(T' + \tau\dot{T}') \qquad (5)$$

where σ_{rr} and $\sigma_{\theta\theta}$ are the stress components, u is the displacement vector t' is the time, ρ is the mass density, λ *and* μ are Lame's elastic constants, T' is the absolute temperature, T_0 is the reference temperature solid, $\gamma = \alpha_t(3\lambda + 2\mu)$, k is the thermal conductivity of the material. We characterize the elastic constants λ, μ and density ρ of non-homogeneous material by

$$\lambda = \lambda_0 r^{2m},\ \mu = \mu_0 r^{2m} \quad and \quad \rho = \rho_0 r^{2m} \qquad (6)$$

where λ_0, μ_0 and ρ_0 are constants (they are the values λ, μ and ρ inhomogeneous matter), and m is a rational number. Substituting from equations (6) into equations (2), we have:

$$\frac{\partial^2 u}{\partial r^2} + \frac{\alpha_1}{r}\frac{\partial u}{\partial r} - \alpha_2^2\frac{u}{r^2} - \frac{\gamma_0}{(\lambda_0 + 2\mu_0 + \mu_e H_0^2)}\left[\frac{\partial}{\partial r} + \frac{2m}{r}\right](T' + \tau\dot{T}') +$$
$$+\frac{\rho_0\Omega^2}{(\lambda_0 + 2\mu_0 + \mu_e H_0^2)}u = \frac{\rho_0}{(\lambda_0 + 2\mu_0 + \mu_e H_0^2)}\frac{\partial^2 u}{\partial t^2}. \qquad (7)$$

It is convenient to introduce the following non-dimensionalization scheme,

$$b(U,R) = (u,r), \qquad t' = \frac{b}{v}t, \qquad T' = T_0 T \qquad (8)$$

where T_0 is a reference temperature and v is the dimension of velocity. Substituting from equations (8) into the equation (2) and (7) we have:

$$\frac{\partial^2 T'}{\partial R^2}+\frac{1}{R}\frac{\partial T'}{\partial R}=\alpha(\frac{\partial}{\partial t}+\tau_1\frac{\partial^2}{\partial t^2})T+\gamma_0 T_0(\frac{\partial}{\partial t}+\delta\tau_1\frac{\partial^2}{\partial t^2})[\frac{1}{R}U+\frac{\partial U}{\partial R}] \quad (9)$$

$$\frac{\partial^2 U}{\partial R^2}+\frac{\alpha_1}{R}\frac{\partial U}{\partial R}-\alpha_2\frac{U}{R^2}-\alpha_3\left[\frac{\partial}{\partial R}+\frac{2m}{R}\right](T+\tau\dot{T})+\alpha_5 u=\alpha_4\frac{\partial^2 U}{\partial t^2}. \quad (10)$$

In terms of these non-dimensional variables, the stress components induced by the temperature T relate to displacement component U by

$$\sigma_{RR}=(bR)^{2m}[\lambda_0+2\mu_0)\frac{\partial U}{\partial R}+\lambda_0\frac{U}{R}-\gamma_0 T_0(T+\tau\dot{T})] \quad (11)$$

$$\sigma_{\theta\theta}=(bR)^{2m}[\lambda_0\frac{\partial U}{\partial R}+(\lambda_0+2\mu_0)\frac{U}{R}-\mu_0\frac{U}{R}\ -\gamma_0 T_0(T+\tau\dot{T})], \quad (12)$$

where

$$\alpha=\frac{vb}{k_1},\quad \alpha_1=2m+\rho,\quad \alpha_2=\frac{\left((1-2m)\lambda_0+P(3-P)\mu_0\right)}{(\lambda_0+2\mu_0+\mu_e H_0^2)}$$

$$\alpha_3=\frac{\gamma_0 T_0}{(\lambda_0+2\mu_0++\mu_e H_0^2)},\quad \alpha_4=\frac{\rho_0 v^2}{(\lambda_0+2\mu_0++\mu_e H_0^2)},\quad \gamma_0=(3\lambda_0+2\mu_0)\alpha_1$$

$$\alpha_5=\frac{\rho_0}{(\lambda_0+2\mu_0+\mu_e H_0^2)},\qquad \varepsilon=\gamma_0 T_0$$

where α_t is the coefficient of linear thermal expansion.

Boundary conditions

From preceding description, the initial conditions may be expressed as:

$$T=0 \text{ at } t=0, \quad (13)$$

$$U=\frac{\partial U}{\partial t}=0 \text{ at } t=0. \quad (14)$$

For the cylindrical problem, the boundary conditions can be written as follows

$$\frac{\partial U}{\partial R}=0,\quad T=1, \text{ at } R=\frac{a}{b} \quad (15)$$

$$U=0,\ \frac{\partial U}{\partial R}=0. \text{ at } R=1 \quad (16)$$

Numerical scheme

The set of hyperbolic partial differential (9) and (10) along with the initial conditions (13) and (14) and boundary conditions (15) and (16) represent a linear two-point boundary value problems for partial differential equations which will be solved by an implicit finite difference scheme is described by Abd-Elslam et al. [9]. We take the finite difference grids with spatial intervals, h in the direction R and K as the time step and use the subscripts i and n to denote the ith discrete points in the R direction and nth discrete time. The solution domain {(R, t): $R \in [1, M/a]$, $t \in [0, \infty]$} is divided into intervals described by the nodes set (R_i, t_n) in the direction of the variable R, and in the direction time t. So, $R_i = 1 + ih$; $i = 0, 1, \ldots, N$; $t_n = n\Delta t$, $n = 0, 1, \ldots, K$; $h = \frac{M-1}{N}$ is a uniform mesh width, $t = t\max / K$ is the time step and t max is the final time, where N and K are positive integers. Applying an implicit finite difference technique, the implicit finite difference equations corresponding to (7) and (8) are as follows:

The functions T (R, t) and U (R, t) may be at any nodal location

$$T(R_i,t^n)=T_i^n \quad (17)$$

$$U(R,t^n)=U_i^n \quad (18)$$

The heat conduction equation (9) in difference form as follows:

$$T_i^{n+1}=T_i^n+\frac{\rho}{a}(T_{i+1}^n-2T_i^n+T_{i-1}^n+\rho\left(\frac{h}{\frac{a}{b}+ih}\right)(T_{i+1}^n-T_i^n)).-$$

$$-\frac{\varepsilon}{2h}(U_{i+1}^{n+1}-2U_{i+1}^n+U_{i+1}^{n-1}-U_{i-1}^{n+1}+2U_{i-1}^n-U_{i-1}^{n-1})-\frac{\varepsilon}{R_i}(U_i^{n+1}-2U_i^n+U_i^{n-1}) \quad (19)$$

Also, the equation of motion (10) may be expressed in the difference as follows:

$$U_i^{n+1}=(2+\alpha_5)U_i^n+U_i^{n-1}+\frac{\rho}{\alpha_4}[U_{i+1}^n-2U_i^n+U_{i-1}^n+\alpha_1(\frac{h}{\frac{a}{b}+ih})(U_{i+1}^n-U_i^n)$$

$$-\alpha_2(\frac{h}{\frac{a}{b}+ih})^2 U_i^n-\alpha_3 h(T_{i+1}^n-T_i^n+(\frac{2mh}{\frac{a}{b}+ih})T_i^n]$$

where $\rho = \frac{k}{h^2}, \qquad \rho_1 = \left(\frac{k}{h}\right)^2$

Numerical Results and Discussion

Let us consider the distribution of the transient temperature, displacement, and thermal stresses in a non-homogeneous cylinder. As an illustrative purpose of the forging solution, the cylinder has the following geometric and material constants. The material chosen for the purpose is Cobalt, the physical data for which are given as [5] and [9], the numerical constants of the problem were taken as T_0 = 2000 °C, M = 2,

$$\tau = 0.02,$$
$$\lambda_0 = 1.387\times10^{12} dyne/cm^2, \quad \mu_0 = 0.448\times10^{12} dyne/cm^2$$
$$\rho_0 = 8.93 g/cm^3, \quad k_1 = 1.14\, cm^2/s, \quad \alpha_t = 1.67\times10^{-8}/{}^0C.$$

Results are presented for cylinder with a = 0.1, b = 1 and $T_0 = 1$. We present our results for isotropic cylinder in the forms of graphs (Figures. 1–7). We study the non-homogeneous case by taking $m = 0.5$. We represented the numerical results graphically.

Figures 1 show the temperature variation for various non-dimensional times *t* in the non-homogeneous case $(m = 0.5)$. It is noticed that the temperature decreases with increasing *R*, while it increases with increasing of time *t* and it satisfied the boundary conditions for the cylinder problem. Figure 2 shows the radial displacement *U* with respect to *R* for different values of magnetic field and time *t* in the non-homogeneous case $(m = 0.5)$. It is obvious that the displacement decreases with increasing *R*, and it increases with increasing *t*, while it decreases with increasing of magnetic field. Figures 3, 4 show the variations of the radial stress σ_{RR} and hoop stress $\sigma_{\theta\theta}$ with respect to *R* for different values of magnetic field and time *t* in the non-homogeneous case $(m = 0.5)$. It is observed that the radial stress and and hoop stress decrease with increasing of magnetic field and time. Figure 5 shows the variations of the radial displacement with respect to *R* for different values of magnetic field and time *t* in the homogeneous case $(m = 0)$. It is observed that the radial stress increases with increasing of magnetic field, while it decreases with increasing of time, as well it decreases and increases with increasing of *R* - the axis. Figures 6, 7 show the variations of the radial displacement with respect to *R* for different values of magnetic field and time *t* in the homogeneous case $(m = 0)$. It is observed that the radial stress increases with increasing of magnetic field, while it decreases with increasing of time. The heat wave propagates with a finite speed in the medium with the passage of time. This is not the case for the classical theories of thermoelasticity where an infinite speed of propagation is inherent and hence all the considered functions have a nonzero value for any point in the medium. This indicates that the generalized heat mechanism is, in essence, completely different from the classic Fourier's theory. In thermoelasticity theory, heat propagates as a wave with finite velocity instead of infinite velocity in the medium. The results are specific to the example considered, but other examples may have different trends because of the dependence of the results on the mechanical and thermal constants of the material.

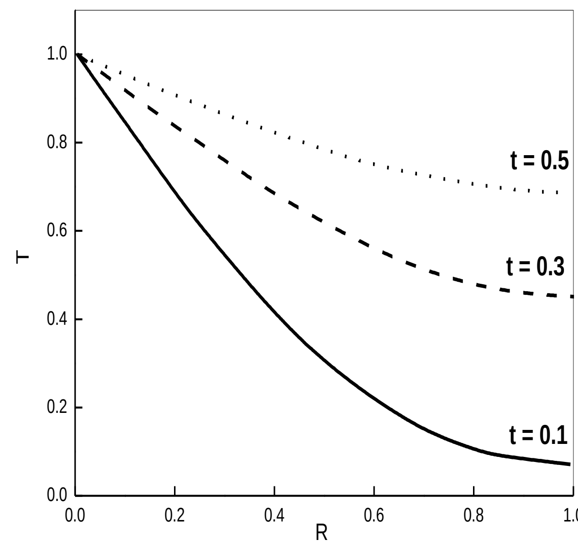

Fig. 1: Variations of temperature with respect to *R* - axis for different values of time t at $m = 0.5$,

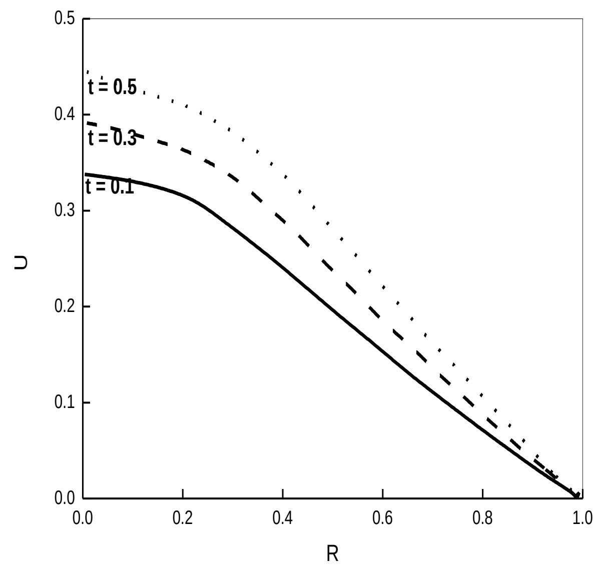

Fig. 2: Variations of radial displacement with respect to *R* - axis for differences values of magnetic field and time at

$$m = 0.5, \quad ....H_0 = .2x\,10^2,$$
$$---H_0 = 0.5x10^2, \quad \_\_\_\_H_0 = 0.8x10^2.$$

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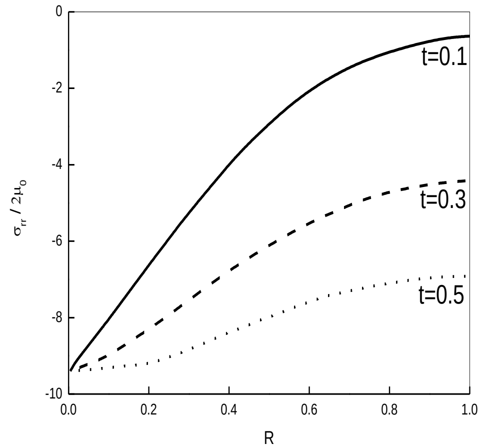

Fig. 3: Variations of radial stress with respect to R - axis for differences values of magnetic field and time at $m = 0.5$ $....H_0 = .2x\,10^2, \_\_\_H_0 = .5x\,10^2, \_\_\_\_H_0 = .8x\,10^2.$

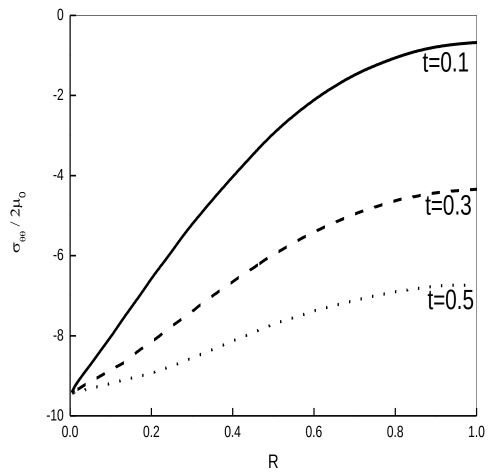

Fig. 4: Variations of hoop stress with respect to R - axis for differences values of magnetic field and time at $m = 0.5$, $....H_0 = .2x\,10^2, \_\_\_H_0 = .5x\,10^2, \_\_\_\_H_0 = .8x\,10^2.$

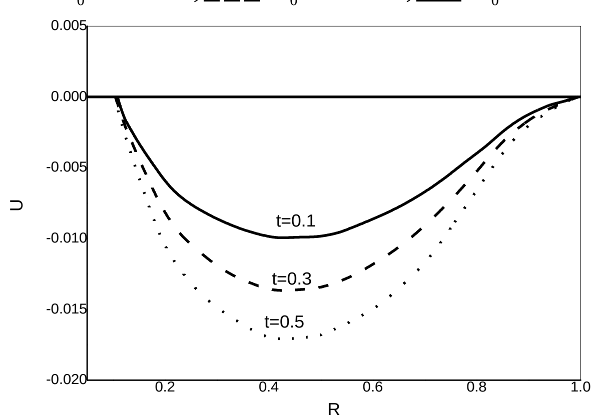

Fig. 5: Variations of radial displacement with respect to R - axis for differences values of magnetic field and time at $m = 0$, $....H_0 = .2x\,10^2,$ $\_\_\_H_0 = .5x\,10^2, \; H_0 = .8x\,10^2.$

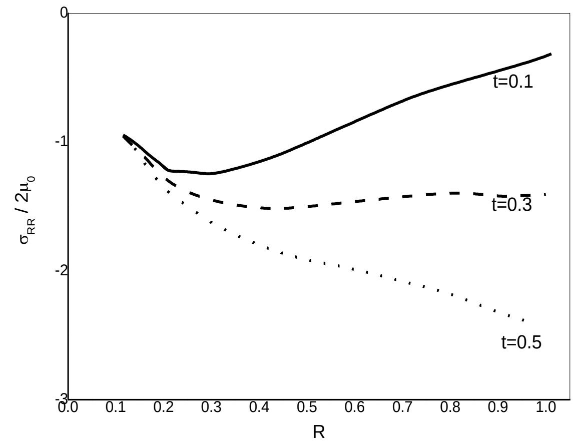

Fig. 6: Variations of radial stress with respect to R - axis for differences values of magnetic field and time at $m = 0$, $....H_0 = .2x\,10^2, \; \_\_\_H_0 = .5x\,10^2, \; H_0 = .8x\,10^2.$

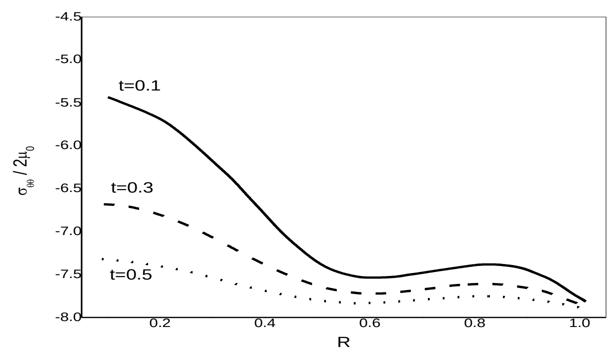

Fig. 7: Variations of tangential stress with respect to R - axis for differences values of magnetic field and time at $m = 0$, $....H_0 = .2x\,10^2,$ $\_\_\_H_0 = .5x\,10^2, \; H_0 = .8x\,10^2.$

Conclusions

The analysis of graphs permits us some concluding remarks:

1- The boundary conditions were satisfied by all the physical quantities.

2- The performance of temperature, stress, and displacement was comparable to and affected by magnetic field.

3- While time significantly affected the displacement components, temperature and stress, impacts were noted in the temperature field. Higher magnetic field increased the degrees of the measured fields except for displacement components that had rising and falling impacts.

4- Temperature distribution T, normal stress σ_{RR}, $\sigma_{\theta\theta}$, and displacement component U almost showed a comparable pattern for various values of magnetic field and an increment in the value of magnetic field causes a decrement in the values of all the fields. Besides improving the diagnostic applications, the suggested model presented benefits for the researchers of thermoelasticity and the scientists who try to understand the viscoelastic features of human soft tissues. The findings could help enhance the observational and theoretical propagation of waves.

5- The result provides a motivation to investigate conducting thermo-electric materials as a new class of applications thermo-electric solids. The results presented in this paper should prove useful for researchers in material science, designers of new materials, physicists as well as for those working on the development of magneto-thermoelasticity and in practical situations as in geophysics, optics, acoustics, geomagnetic and oil prospecting etc. The used methods in the present article are applicable to a wide range of problems in thermodynamics and thermoelasticity.

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