A problem of thick circular plate in modified couple stress theory of thermoelastic diffusion

Rajneesh Kumar1 and Shaloo Devi2*

Abstract: The present investigation deals with an axisymmetric problem of thick circular plate in modified couple stress theory with mass diffusion. The Laplace and Hankel transforms technique have been used to investigate the problem. The displacements, stress components, temperature change, and chemical potential are obtained in the transformed domain subjected to thermal and chemical potential sources. Resulting quantities are obtained in the physical domain using a numerical inversion technique and depicted graphically. Comparisons are made with and without couple stress for both the Lord–Shulman (1967) and Green–Lindsay (1972) theories of thermoelasticity. Some particular cases of interest are also deduced.

Subjects: Mathematics & Statistics; Physical Sciences; Science

Keywords: modified couple stress theory; thermoelastic diffusion; thermal and chemical potential sources; Laplace and Hankel transforms

1. Introduction

Couple stress theory is an extended continuum theory that includes the effects of a couple per unit area on a material volume, in addition to the classical direct and shear forces per unit area. The...
existence of couple stress in materials was originally postulated by Voigt (1887). However, Cosserat and Cosserat (1909) were the first to develop a mathematical model to analyze materials with couple stresses.

Lacking an internal material length scale parameter, classical elasticity and plasticity cannot be used to interpret the size effect observed in numerous tests at micron and nanometer scales. However, higher order (non-local) continuum theories contain material length scale parameters and are capable of explaining microstructure related size (and other effects). Couple stress theories represent one class of such higher order theories. The classical couple stress elasticity theory (e.g. Koiter, 1964; Mindlin & Tiersten, 1962; Toupin, 1962) contains four material constants two classical and two additional for isotropic elastic materials. The couple stress theory can be viewed as a special format of strain gradient theory which uses rotation as a variable to describe curvature, while the strain gradient theory uses strain as variable to describe curvature.

The couple stress theory admits the possibility of asymmetric stress tensor since shear stress no longer have to be conjugate in order to ensure rotational equilibrium. The two additional constants are related to the underlying microstructure of the material and are inherently difficult to determine (e.g. Lakes, 1982; Lam, Yang, Chong, Wang, & Tong, 2003). Every physical theory possesses a certain domain of applicability outside which it fails to predict the physical phenomena with reasonable accuracy. Hence, there has been a need to develop higher order theories involving only one additional material length scale parameter.

Recently, Yang, Chong, Lam, and Tong (2002) developed a modified couple stress model, in which the couple stress tensor is symmetrical and only one material length parameter is needed to capture the size effect which is caused by micro-structure. Variational formulation of a modified couple stress theory and its application to a simple shear problem was studied by Ma, Gao, and Reddy (2008). Chen, Li, and Xu (2011) presented a modified couple stress model for bending analysis of composite laminated beams with first-order shear deformation. Asghari (2012) studied the geometrically nonlinear micro-plate formulation based on the modified couple stress theory. Şimşek and Reddy (2013) investigated the bending and vibration of functionally graded microbeams using a new higher order beam theory and the modified couple stress theory. Recently, the size-dependent buckling analysis of microbeams based on modified couple stress theory with high-order theories and general boundary conditions have been studied by Mohammad-Abadi and Daneshmehr (2014).


Thermodiffusion in an elastic solid is due to the coupling of the fields of temperature, mass diffusion and strain. Heat and mass exchange with the environment during the process of the thermodiffusion in an elastic solid. The concept of thermodiffusion is used to describe the processes of thermomechanical treatment of metals (carboning, nitriding steel, etc.) and these processes are thermally activated, and their diffusing substances being, e.g. nitrogen, carbon, etc. They are accompanied by deformations of the solid.


In the present paper, a problem of thick circular plate in modified couple stress theory by applying Laplace and Hankel transforms technique. The generalized theories of thermoelasticity developed by Sherief et al. (2004) and Kumar and Kansal (2008) are used to investigate the problem. The displacements, stress components, temperature change, and chemical potential are obtained numerically and represented graphically.

2. Governing equations
Following Yang et al. (2002), Kumar and Kansal (2008), the constitutive relations and the equations of motion in a modified couple stress generalized thermoelastic with mass diffusion in the absence of body forces, body couples, heat and mass diffusion sources are given by

(i) Constitutive relations

\[ t_{ij} = \lambda e_{ik} \delta_{kj} + 2\mu e_{ij} - \frac{1}{2} \epsilon_{ijk} m_{akj} - \beta_1 \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) T \delta_{ij} - \beta_2 \left( 1 + \tau^2 \frac{\partial}{\partial t} \right) C \delta_{ij}, \]  

\[ m_{ij} = 2\alpha \chi_{ij}, \]  

\[ \chi_{ij} = \frac{1}{2} \left( \omega_{ij} + \omega_{ji} \right), \]  

\[ \omega_i = \frac{1}{2} \epsilon_{ipa} u_{ap}. \]  

(ii) Equations of motion

\[ \left( \lambda + \mu + \frac{\alpha}{4} \Delta \right) \nabla (\nabla \cdot \mathbf{u}) + \left( \mu - \frac{\alpha}{4} \Delta \right) \nabla^2 \mathbf{u} - \beta_1 \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) \nabla T - \beta_2 \left( 1 + \tau^2 \frac{\partial}{\partial t} \right) \nabla C = \rho \ddot{\mathbf{u}}, \]  

(iii) Equation of heat conduction

\[ K^* \Delta T - \rho C_e \left( \frac{\partial}{\partial t} + \tau_0 \frac{\partial^2}{\partial t^2} \right) T - \sigma T_0 \left( \frac{\partial}{\partial t} + \gamma \frac{\partial^2}{\partial t^2} \right) C = T_0 \beta_1 \left( \frac{\partial}{\partial t} + \tau_0 \frac{\partial^2}{\partial t^2} \right) (\nabla \cdot \mathbf{u}). \]
(iv) Equation of mass diffusion

\[ D\beta_2 \Delta (\nabla \cdot \mathbf{u}) + Da \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) \Delta T + \left( \frac{\partial}{\partial t} + \tau_0 \frac{\partial^2}{\partial t^2} \right) C - Db \Delta \left( 1 + \tau_1 \frac{\partial}{\partial t} \right) C = 0, \tag{8} \]

where \( t_1 \) are the components of stress tensor, \( \lambda \) and \( \mu \) are material constants, \( \delta \) is Kronecker's delta, \( e_1 \) are the components of strain tensor, \( e_{\alpha\beta} \) is alternate tensor, \( m_{ij} \) are the components of couple stress, \( \beta_1 = (3\lambda + 2\mu)\alpha_1 \), \( \beta_2 = (3\lambda + 2\mu)\alpha_2 \). Here, \( \alpha_1, \alpha_2 \) are the coefficients of linear thermal expansion and diffusion expansion, respectively, \( T \) is the temperature change, \( C \) is the mass concentration, \( \alpha \) is the couple stress parameter, \( \chi_i \) is symmetric curvature, \( w \) is the rotational vector, \( P \) is the chemical potential of the material per unit mass, \( b \) is the coefficient describing the measure of mass diffusion effects, and \( a \) is the coefficient describing the measure of thermoelastic diffusion. \( \mathbf{u} = (u_1, u_2, u_3) \) is the components of displacement vector, \( \rho \) is the density, \( \Delta \) is the Laplacian operator. \( K^* \) is the coefficient of the thermal conductivity, \( c_\delta \) is the specific heat at constant strain, and \( T_0 \) is the reference temperature assumed to be such that \( |T/T_0| \ll 1 \). \( D \) is the thermoelastic diffusion constant. Here, \( \tau, \tau' \) are the diffusion relaxation times with \( \tau_1 \geq \tau_0 \geq 0 \). Here, \( \tau_1 = \tau_0 = 0, \eta_0 = 1, \gamma = \tau_0 \) for Lord–Shulman (L–S) model and \( \eta_0 = 0, \gamma = \tau_0 \) for Green Lindsay (G–L) model.

3. Formulation of the problem

Let us consider a homogeneous isotropic, modified couple stress generalized thermodiffusion elastic thick plate of thickness \( 2d \) occupying the region defined by \( 0 \leq r \leq \infty, -d \leq z \leq d \). Cylindrical polar coordinates \((r, \theta, z)\) having origin on the surface \( z = 0 \), between the lower and upper surfaces of the plate and the \( z \)-axis is assumed to be the axis of symmetry. Due to symmetry about \( z \)-axis, all the field quantities depend only on \( r, z, t \).

The initial temperature in the thick plate is given by a constant temperature \( T_0 \) and the heat flux \( g_3 F(r, z) \) is prescribed on the upper and lower boundary surfaces. Under these conditions, thermodiffusion elastic quantities for a thick circular plate are required to be determined.

For the two-dimensional problem, we take the displacement vector \( \mathbf{u} = (u_r, 0, u_z) \).

We define the dimensionless quantities:

\[
\begin{align*}
    r' &= \omega^* r, \quad z' = c_1 \omega^* z, \quad u'_r = \frac{\omega^*}{c_1} u_r, \quad u'_z = \frac{\omega^*}{c_1} u_z, \quad t' = \omega^* t, \quad t'_y = \frac{t_y}{\beta_1 T_0}, \quad m'_y = \frac{\omega^* m_y}{c_1 \beta_1 T_0}, \quad r' = \omega^* r, \\
    \tau'_1 &= \omega^* \tau_1, \quad \tau'_0 = \omega^* \tau_0, \quad \tau'' = \omega^* \tau_0, \quad \tau''' = \omega^* \tau''_1, \quad T' = \frac{\beta_1 T}{\rho c_1^2}, \quad C' = \frac{\beta_1 C}{\rho c_1^2}, \quad P' = \frac{P}{\beta_2}, \\
    c_1^2 &= \frac{\lambda + 2\mu}{\rho}, \quad \omega^2 = \frac{\lambda}{(\mu t^2 + \rho \alpha)}. \tag{9}
\end{align*}
\]

Upon introducing (9) in Equations (6)–(8), after suppressing the primes, we obtain:

\[
\begin{align*}
    a_1 \frac{\partial u_r}{\partial r} + a_2 \left( \nabla^2 - \frac{1}{r^2} \right) u_r + a_3 \Delta \left( \frac{\partial u_r}{\partial r} - \left( \nabla^2 - \frac{1}{r^2} \right) u_r \right) - r_1 \frac{\partial T}{\partial r} - r_1 \frac{\partial C}{\partial r} = \frac{\partial^2 u_r}{\partial t^2}, \tag{10}
\end{align*}
\]

\[
\begin{align*}
    a_3 \frac{\partial u_z}{\partial z} + a_2 \nabla^2 u_z + a_3 \Delta \left( \frac{\partial u_z}{\partial z} - \nabla^2 u_z \right) - r_1 \frac{\partial T}{\partial z} - r_1 \frac{\partial C}{\partial z} = \frac{\partial^2 u_z}{\partial t^2}, \tag{11}
\end{align*}
\]
\[ \nabla^2 T - a_4 \tau_0 \nabla T - a_5 \tau_0 C = \alpha_6 \tau_0 e, \] (12)

\[ a_7 \nabla^2 e + a_8 \tau_1 \nabla^2 T + \tau_1 \nabla^2 C = 0, \] (13)

where

\[ a_1 = \frac{\rho + \mu}{\rho c_1^2}, \quad a_2 = \frac{\mu}{\rho c_1^2}, \quad a_3 = \frac{\alpha \omega^2}{4 \rho c_1^2}, \quad a_4 = \rho c_2 \omega^2, \quad a_5 = \frac{\alpha T_0 \beta_1 c_1^2}{\beta_2 K' \alpha}, \quad a_6 = \frac{T_0 \beta_1^2}{\rho K' \alpha^2}, \]

\[ a_7 = \frac{\rho \beta_2 D \omega^*}{\rho c_1^2}, \quad a_8 = \frac{\alpha \beta_2 D \omega^*}{\beta_1 c_1^2}, \]

\[ a_9 = \frac{bD \omega^*}{c_1^2}, \quad \tau_1 = (1 + \tau_1 \frac{\partial}{\partial t}), \quad \tau_1^2 = (1 + \tau_1 \frac{\partial}{\partial t}), \quad \tau_0^0 = (\frac{\partial}{\partial t} + \eta_0 \tau_0 \frac{\partial^2}{\partial t^2}), \]

\[ \tau_R^0 = \left( \frac{\partial}{\partial t} + r \frac{\partial^2}{\partial t^2} \right), \quad \tau^2_{10} = \left( \frac{\partial}{\partial t} + \eta_0 \tau_0 \frac{\partial^2}{\partial t^2} \right), \quad \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}, \quad e = \frac{u_t}{r} + \frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z}. \]

The displacement components \( u_r \) and \( u_z \) in terms of potential functions \( \phi \) and \( \psi \) in dimensionless form are given by,

\[ u_r = \frac{\partial \phi}{\partial r} + \frac{3}{r} \frac{\partial \psi}{\partial z}, \quad u_z = \frac{\partial \phi}{\partial z} - \left( \frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right). \] (14)

We define Laplace and Hankel transforms as:

\[ \mathcal{L}(f(r, z, s)) = \int_0^\infty f(r, z, t)e^{-st} \, dt \]

\[ \mathcal{H}[f(r, z, s)] = \int_0^\infty f(r, z, s)J_n(\eta r) \, dr \] (15)

where \( s \) is the Laplace transform parameter, \( \eta \) is the Hankel transform parameter and \( J_n(\cdot) \) is the Bessel function of the first kind of order \( n \).

Making use of (14) in (10)–(13) and applying the Laplace and Hankel transforms defined by (15) on the resulting equation (after simplification), we obtain:

\[ \left[ D^6 + G_1 D^4 + G_2 D^2 + G_3 \right] \left( \phi, \hat{T}, \hat{C} \right) = 0, \] (16)

\[ \left[ D^4 - B_1 D^2 + B_2 \right] \hat{\phi} = 0, \] (17)

where \( G_1, G_2, G_3, B_1, \) and \( B_2 \) are given in Appendix (1).

The general solution of Equation (16) can be written as:

\[ \hat{\phi} = \hat{\phi}_1 + \hat{\phi}_2 + \hat{\phi}_3, \] (18)

where \( \hat{\phi}_i \) is a general solution of the homogeneous differential equation given by:

\[ \left( D^2 - m_i^2 \right) \hat{\phi}_i = 0, \quad i = 1, 2, 3. \] (19)
where \( m_1, m_2, \) and \( m_3 \) are the roots of the characteristic equation
\[
D^6 + G_1D^4 + G_2D^2 + G_3 = 0.
\]

The complete solution of Equation (19) can be written as:
\[
\hat{\phi} = \sum_{i=1}^{4} A_i \cosh(m_i z),
\]
Solving Equation (17), we get:
\[
\hat{\psi} = \hat{\psi}_0 + \hat{\psi}_5,
\]
where \( \hat{\psi}_i \) \((i = 4, 5)\) is a solution of the homogeneous differential equation given by:
\[
\left(D^2 - m_i^2\right)\hat{\psi}_i = 0, \quad i = 4, 5.
\]
The solution of the Equation (17), yield:
\[
\hat{\psi} = \sum_{i=4}^{5} A_i \sinh(m_i z),
\]
where \( m_4 \) and \( m_5 \) are the roots of the characteristic equation
\[
D^4 - B_4D^2 + B_2 = 0.
\]
The solution of the Equation (16) is
\[
\left(\hat{\phi}, \hat{T}, \hat{C}\right)(\eta, z, s) = \sum_{i=1}^{3} \left(1, R_i, S_i\right)A_i \cosh(m_i z),
\]
where \( R_i \) and \( S_i \) are given in Appendix (2).

4. Boundary conditions
The appropriate boundary conditions for this problem are:

1. \( \frac{\partial l}{\partial z} = \pm g_0 F(r, z) \) at \( z = \pm d \),
2. \( t_{zz} = t_{zr} = m_{z\phi} = 0 \) at \( z = \pm d \),
3. \( P = \delta(t)f(r) \) at \( z = \pm d \)

where
\[
F(r, z) = \frac{z^2}{\omega} e^{-\omega r}, \quad \omega > 0.
\]
\[
f(r) = H(a - r),
\]
and \( \delta (\cdot) \) is the Dirac delta function, \( H(\cdot) \) is the Heavy side unit step function.

Applying Laplace and Hankel transforms defined by (15) on (30) and (31), we obtain:
\[
\hat{F}(\eta, z) = \frac{z^2 \omega}{(\omega^2 + \alpha^2)^{\frac{3}{2}}},
\]  
(32)

\[
\hat{f}(\eta) = \frac{a J_1(\eta a)}{\eta},
\]  
(33)

The non-dimensional values of \(t_z\), \(t_\phi\), \(m_z\), and \(P\) are given by (1)-(5) and (9), (14) as:

\[
t_{zz} = a_{10} V^2 \phi + 2a_{11} \left\{ \frac{\partial^2 \phi}{\partial z^2} - \frac{\partial^2 \psi}{\partial r \partial z} + \frac{1}{r} \frac{\partial^2 \psi}{\partial r \partial z} \right\} - a_{12} \{ \tau_1 T + \tau_1 C \},
\]  
(34)

\[
t_{\phi\phi} = a_{11} \left( 2 \frac{\partial^2 \phi}{\partial r \partial z} + \frac{1}{r} \left( \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} \right) \right) - a_{13} \left[ \frac{\partial}{\partial r} \left( \frac{\partial^2 \phi}{\partial r^2} + \frac{\partial^2 \psi}{\partial r^2} \right) \right],
\]  
(35)

\[
m_{z\phi} = 2a_{13} \frac{\partial^2 \psi}{\partial z^2} \left( \frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} \right),
\]  
(36)

\[
P = -V^2 \phi + a_{14} \tau_1 C - a_{15} \tau_1 T,
\]  
(37)

where

\[
a_{10} = \frac{\lambda}{\beta_1 T_0}, \quad a_{11} = \frac{\mu}{\beta_1 T_0}, \quad a_{12} = \frac{\rho c_1^2}{\beta_1 T_0}, \quad a_{13} = \frac{\alpha^2 \omega}{16c_1^2 \beta_1 T_0}, \quad a_{14} = \frac{b \rho c_1^2}{\beta_2^2}, \quad a_{15} = \frac{q \rho c_1^2}{\beta_2^2}.
\]

Substituting the values of \(\phi^*, \bar{F}, \bar{C}\) and \(\hat{\phi}\) from (24) and (26) in the boundary conditions (27)-(29) and with the aid of (15) and (32)-(37), we obtain the expressions for displacement components, stresses, temperature change, chemical potential, and concentration as

\[
\hat{u}_z = -\eta \left[ \sum_{i=1}^{3} A_i \cosh(m_i d) + \sum_{i=4}^{5} A_i m_i \cosh(m_i d) \right],
\]  
(38)

\[
\hat{u}_\phi = \sum_{i=1}^{3} m_i A_i \sinh(m_i d) + \eta^2 \left( \sum_{i=4}^{5} A_i \sinh(m_i d) \right),
\]  
(39)

\[
\hat{T} = \sum_{i=1}^{3} R_i A_i \cosh(m_i d),
\]  
(40)

\[
\hat{t}_{zz} = \sum_{i=1}^{3} M_i A_i \cosh(m_i d) + \sum_{i=4}^{5} M_i A_i \cosh(m_i d),
\]  
(41)

\[
\hat{t}_{\phi\phi} = -\eta \left[ \sum_{i=1}^{3} N_i A_i \sinh(m_i d) + \sum_{i=4}^{5} N_i A_i \sinh(m_i d) \right],
\]  
(42)

\[
\hat{P} = \sum_{i=1}^{3} K_i A_i \cosh(m_i d) + \sum_{i=4}^{5} K_i A_i \cosh(m_i d),
\]  
(43)
\[ \hat{m}_{x0} = -2\eta a_{14} \left[ \sum_{i=1}^{5} Q_i A_i \cosh(m_i d) \right], \quad (44) \]

\[ \hat{C} = \sum_{i=1}^{3} S_i A_i \cosh(m_i d), \quad (45) \]

where

\[ A_1, A_2, A_3, A_4, \text{and } A_5, \sum_{i=1}^{3} M_i, \sum_{i=1}^{3} N_i, \sum_{i=1}^{3} K_i, \sum_{i=1}^{5} M_i, \sum_{i=1}^{5} N_i, \sum_{i=1}^{5} K_i, \sum_{i=1}^{5} Q_i \]

are given in Appendix (3).

5. Particular cases

(1) If \( \alpha = 0 \), in Equations (38)–(45), we obtain the components of displacement and stresses for a generalized thermoelastic with mass diffusion model. The results obtained are similar as given by Tripathi et al. (2015) with the changed value of

\[ \hat{F}(\eta, z) = \frac{Z^2 \omega}{(\omega^2 + a^2)^2}. \]

(2) In the absence of diffusion (\( \alpha = D = r_1^2 = 0 \)), in Equations (38)–(45), we obtain the components of displacement and stresses in a modified couple stress thermoelastic medium.

(3) If \( r_1 = r_0 = 0, \eta_0 = 1, \gamma = r_0 \) in Equations (38)–(45), we obtain the corresponding results for modified couple stress thermoelastic with mass diffusion for Lord Shulman (L–S) model.

(4) If \( \eta_0 = 0, \gamma = r_0 \) in Equations (38)–(45), we obtain the corresponding results for modified couple stress thermoelastic with mass diffusion for Green Lindsay (G–L) model.

6. Numerical inversion of the transforms

The solution is obtained in physical domain, we must invert the transforms in (38)–(45), for all the theories. Here, the displacement components, stresses, temperature change, mass concentration, and chemical potential are functions of \( z \), the parameters of Laplace and Hankel transforms \( s \) and \( \eta \), respectively, and hence are of the form \( \hat{f}(\eta, z, s) \) and \( f(r, z, t) \) is a known function of \( r, z, \) and \( t \). To obtain the solution of the problem in the physical domain, we invert the Laplace and Hankel transforms using the method described by Kumar and Deswal (2007).

7. Numerical results and discussion

For numerical computations, following Daliwal and Singh (1980), we take the magnesium material (thermoelastic diffusion solid) as:

\[ \lambda = 2.696 \times 10^{10} \text{ kg m}^{-1} \text{ s}^{-2}, \mu = 1.639 \times 10^{10} \text{ kg m}^{-1} \text{ s}^{-2}, T_0 = 0.293 \times 10^3 \text{ K}, \]

\[ c_e = 1.04 \times 10^3 \text{ J K}^{-1} \text{ m}^{-1}, \alpha_t = 1.78 \times 10^{-5} \text{ K}^{-1}, \alpha_c = 1.98 \times 10^{-4} \text{ m}^3 \text{ kg}^{-1}, \]

\[ a = 1.02 \times 10^4 \text{ m}^2 \text{ s}^{-2} \text{ K}^{-1}, b = 9 \times 10^5 \text{ kg}^{-1} \text{ m}^5 \text{ s}^{-2}, D = 0.85 \times 10^{-8} \text{ Kg s m}^{-3}, \]

\[ \rho = 1.74 \times 10^3 \text{ Kg m}^{-3}, K^* = 1.7 \times 10^2 \text{ W m}^{-1} \text{ K}^{-1}, \alpha = 1 \text{ kg m}^{-2}, \]

\[ t = 1 \text{ s}, \omega = 10 \text{ s}^{-1}, \tau_0 = 0.01 \text{ s}, \tau^0 = 0.03 \text{ s}, \tau_1 = 0.02 \text{ s}, \tau^1 = 0.04 \text{ s}. \]
The software Matlab 7.10.4 has been used to determine the normal stress, tangential stress, temperature change, mass concentration, and couple stress for different values of $\alpha$ for both L–S and G–L theories are computed numerically and shown graphically in Figures 1–5, respectively.

In Figures 1–4, solid line (–) corresponds to L–S $\alpha = 0$, solid line with center symbol (–*–) corresponds to L–S $\alpha = 1$, small dash line (----) corresponds to G–L $\alpha = 0$ and small dash line with center symbol (---*---) corresponds to G–L $\alpha = 1$.

**Figure 1.** Variation of normal stress with distance.

**Figure 2.** Variation of tangential stress with distance.

**Figure 3.** Variation of temperature change with distance.
Similarly, in Figure 5, solid line (–) corresponds to L–S \( \alpha = 1 \), solid line with center symbol (–*–) corresponds to L–S \( \alpha = 2 \), small dash line (----) corresponds to G–L \( \alpha = 1 \) and small dash line with center symbol (---*---) corresponds to G–L \( \alpha = 2 \), respectively.

Figure 1 shows that the variations of normal stress \( t_{zz} \) with \( r \). The value of normal stress decreases rapidly in the range \( 0 \leq r < 0.6 \) and oscillatory behavior is noticed for the remaining range for both values of \( \alpha \) and both theories of thermodiffusion elastic media. On the other hand, the values of normal stress for G–L theory is more in comparison to L–S theory for with and without \( \alpha \).

Figure 2 depicts that the variation of tangential stress \( t_{zr} \) with \( r \). Oscillatory behavior is shown for both cases and both L–S and G–L theories. Similarly, the values of tangential stress for L–S (\( \alpha = 0 \)) is greater in comparison to L–S (\( \alpha = 1 \)) and similar behavior is noticed for both values of \( \alpha \) for G–L theory.

Figure 3 depicts the variation of temperature change with \( r \) for \( \alpha = 0, 1 \). It is noticed that the behavior of \( \alpha = 0, 1 \) is similar for both the theories of thermodiffusion elastic. It is noticed that the values of temperature change decreases in the range \( 0 \leq r < 0.8 \) and increases in the remaining values of \( r \) for both values of \( \alpha = 0, 1 \) and both L–S and G–L theories. In the presence of couple stress, the values of \( T \) for L–S theory is higher in comparison to G–L theory, whereas in the absence of couple stress, reverse behavior is observed.

Figure 4 shows that the variations of chemical potential with \( r \). Similar behavior is noticed for both values of \( \alpha \). Also, the values of chemical potential \( P \) increases due to the presence of couple stress and decreases in the absence of couple stress for G–L theory in comparison to L–S theory.
Figure 5 represents that the variation of couple stress \( m_{\alpha} \) with \( r \). Similar trend is noticed for both the values of \( \alpha \) and both theories of thermodiffusion elastic. On the other hand, the values of \( m_{\alpha} \) for L–S theory is less in comparison to G–L theory for \( \alpha = 1 \) and opposite behavior is noticed for \( \alpha = 2 \).

8. Conclusions

A problem of thick circular plate in modified couple stress theory is a significant problem of continuum mechanics. The result obtained from above study is summarized as:

The resulting quantities depicted graphically are observed to be very sensitive towards the couple stress parameters. It is evident that the physical quantities are also affected by the different non-classical theories of thermodiffusion elasticity. It is observed that couple stress increase the values of normal stress \( t_{zz} \) and chemical potential \( P \) for G–L theory in comparison to L–S theory and reverse behavior is observed for temperature change \( T \). Couple stress parameter \( \alpha \) dominate the values of \( t_{zz} \) and \( m_{\alpha} \) for both theories of thermodiffusion elastic. Due to relaxation time the value of couple stress increases. The effect of couple stress and thermo elastic diffusion plays a significant role on the physical quantities. The stresses, temperature change and chemical potential gives a better information which lead to the understanding of material structure. The result presented may be beneficial to the researchers working in material science, engineers and physicists as well as those working in the hyperbolic thermoelastic diffusion solid.

Funding

The authors received no direct funding for this research.

Author details

Rajneesh Kumar
E-mail: rajneesh_kuk@rediffmail.com
Shaloo Devi
E-mail: shaloocharma2673@gmail.com

1 Department of Mathematics, Kurukshetra University
Kurukshetra, Kurukshetra, India.
2 Department of Mathematics & Statistics, Himachal Pradesh University Shimla, Shimla, India.

Citation information

Cite this article as: A problem of thick circular plate in modified couple stress theory of thermoelastic diffusion, Rajneesh Kumar & Shaloo Devi, Cogent Mathematics (2016), 3: 1217969.

References


Appendix (1)

\[ G = ( \delta a_3 - \alpha_3 ) r_1^{22} \]

\[ G_1 = \left\{ -3 \eta^2 \delta a_3 t_1^{22} - \left( s^2 a_5 t_1^{22} + \delta \left( t_1^{66} + a_2 a_8 t_1^{11} t_1^{44} + a_4 a_9 t_1^{22} t_1^{33} \right) \right) \right\} \]

\[ + t_1^{11} \left( a_2 a_5 t_1^{22} t_1^{55} + a_2 a_7 t_1^{44} \right) - t_1^{22} \left( a_4 a_9 t_1^{11} t_1^{55} - a_4 a_7 t_1^{33} - 3 \eta^2 t_1^{22} \right) \] / G,

\[ G_2 = \left\{ 3 \eta^4 \delta a_3 t_1^{22} + 2 \eta^2 \left( s^2 a_5 t_1^{22} + \delta \left( t_1^{66} + a_2 a_8 t_1^{11} t_1^{44} + a_4 a_9 t_1^{22} t_1^{33} \right) \right) \right\} \]

\[ + s^2 \left( t_1^{66} + a_2 a_8 t_1^{11} t_1^{44} + a_3 a_9 t_1^{22} t_1^{33} \right) + a_4 \delta t_1^{33} t_1^{66} + t_1^{11} \left( a_6 t_1^{55} t_1^{66} \right) \]

\[ + 2 \eta^2 \left( a_2 a_5 t_1^{22} t_1^{55} + a_2 a_7 t_1^{44} \right) - t_1^{22} \left\{ 3 a_7 t_1^{22} + 2 a_9 t_1^{11} t_1^{55} - a_4 a_7 t_1^{33} \right\} \] / G,

\[ G_3 = \left\{ \delta a_3 t_1^{22} t_1^{66} - \eta^4 \left( s^2 a_5 t_1^{22} + \delta \left( t_1^{66} + a_2 a_8 t_1^{11} t_1^{44} + a_4 a_9 t_1^{22} t_1^{33} \right) \right) \right\} \]

\[ - \eta^2 \left( s^2 \left( t_1^{66} + a_2 a_8 t_1^{11} t_1^{44} + a_3 a_9 t_1^{22} t_1^{33} \right) + a_4 \delta t_1^{33} t_1^{66} \right) - t_1^{11} \left( a_6 t_1^{55} t_1^{66} \right) \]

\[ - \eta^4 \left( a_2 a_5 t_1^{22} t_1^{55} + a_2 a_7 t_1^{44} \right) - t_1^{22} \left( -a_7 t_1^{66} + \eta^4 \left( a_6 a_9 t_1^{11} t_1^{55} - a_4 a_7 t_1^{33} \right) \right) \] / G,

\[ B_1 = \frac{a_2 + 2 a_3 \eta^2}{a_3}, \quad B_2 = \frac{a_2 \eta^2 + a_3 \eta^2 + s^2}{a_3}, \quad r_1^{22} = (1 + r_1 s), \quad r_1^{33} = (s + r_1 s^2), \quad r_1^{11} = (1 + r_1 s), \quad r_1^{22} = (1 + r_1 s), \quad r_1^{22} = (s + r_1 s^2), \]
\[ \tau_{s4} = (s + \gamma s^2), \quad \tau_{s5} = (s + \eta_0 s^2), \quad \tau_{s6} = (s + \eta_0 s^2), \quad \delta = (a_1 + a_2), \quad \epsilon = \sqrt{2}\phi. \]

**Appendix (2)**

\[ R_i = \sum_{i=1}^{3} \frac{a_r \tau_{s5} \left( m_i^2 - \eta^2 \right) \left( \tau_{s6} - \eta^2 \right) \tau_{s2}^2 - a_r a_r \tau_{s6} \left( m_i^2 - \eta^2 \right)^2}{\left( \left( -m_i^2 - \eta^2 \right) + a_r \tau_{s3}^3 \right) \left( \tau_{s6} - \left( m_i^2 - \eta^2 \right) \left( a_r \tau_{s2}^2 + a_r a_r \tau_{s6} \tau_{s4}^2 \right) \right)^2}, \]

\[ S_i = \sum_{i=1}^{3} \frac{a_r a_r \tau_{s5} \left( m_i^2 - \eta^2 \right) \left( \tau_{s6} - \eta^2 \right) \tau_{s3}^2 + a_r \left( m_i^2 - \eta^2 \right)^2 \left( \left( m_j^2 - \eta^2 \right) - a_r \tau_{s3}^3 \right)}{\left( \left( -m_i^2 - \eta^2 \right) + a_r \tau_{s3}^3 \right) \left( \tau_{s6} - \left( m_i^2 - \eta^2 \right) \left( a_r \tau_{s2}^2 + a_r a_r \tau_{s6} \tau_{s4}^2 \right) \right)^2}, \quad i = 1, 2, 3. \]

**Appendix (3)**

\[ A_1 = \frac{\Delta_1}{\Delta}, \quad A_2 = \frac{\Delta_2}{\Delta}, \quad A_3 = \frac{\Delta_3}{\Delta}, \quad A_4 = \frac{\Delta_4}{\Delta}, \quad A_5 = \frac{\Delta_5}{\Delta}, \]

\[ \Delta = R_1 m_1 g_1 h_3 (N_1 K_2 g_1 h_3) + N_1 K_3 g_3 h_3 \]

\[ + N_1 K_2 g_2 h_3 - N_1 K_1 g_2 h_3 - M_1 h_3 (N_1 K_3 g_1 h_3) + N_1 K_2 g_2 h_3 + N_2 K_1 g_2 h_3 - N_4 K_1 g_2 h_3 \]

\[ + M_1 h_3 (N_1 K_1 g_2 h_3) + M_1 h_3 (N_1 K_2 g_2 h_3) + R_1 m_1 g_1 h_3 (N_1 K_1 g_2 h_3) \]

\[ - N_1 K_3 g_3 h_3 - N_1 K_4 g_3 h_3 - N_4 K_4 g_3 h_3 - M_1 h_3 (N_1 K_3 g_1 h_3) - N_1 K_4 g_2 h_3 + N_2 K_4 g_1 h_3 \]

\[ + M_1 h_3 (N_1 K_2 g_1 h_3) - N_1 K_3 g_2 h_3 + N_4 K_3 g_2 h_3 - M_2 h_3 (N_1 K_3 g_2 h_3) - M_2 h_3 (N_1 K_2 g_2 h_3) - N_1 K_1 g_2 h_3 + N_2 K_1 g_2 h_3 \]

\[ + M_2 h_3 (N_1 K_1 g_2 h_3) - N_1 K_1 g_2 h_3 + N_2 K_1 g_2 h_3 - M_2 h_3 (N_1 K_2 g_2 h_3) + M_2 h_3 (N_1 K_1 g_2 h_3) + N_4 K_3 g_1 h_3 - N_1 K_1 g_1 h_3 \]

\[ + M_2 h_3 (N_1 K_2 g_1 h_3) - N_1 K_3 g_1 h_3 + N_4 K_3 g_1 h_3 + M_2 h_3 (N_1 K_2 g_1 h_3) - M_2 h_3 (N_1 K_2 g_2 h_3) - N_1 K_1 g_2 h_3 + N_2 K_1 g_2 h_3 \]

\[ + M_2 h_3 (N_1 K_1 g_2 h_3) - N_1 K_1 g_2 h_3 + N_2 K_1 g_2 h_3 - M_2 h_3 (N_1 K_2 g_2 h_3) + M_2 h_3 (N_1 K_1 g_2 h_3) + N_4 K_3 g_1 h_3 - N_1 K_1 g_1 h_3 \]

\[ \left( \frac{\Delta_1}{\Delta}, \quad A_1 = \frac{\Delta_1}{\Delta}, \quad A_2 = \frac{\Delta_2}{\Delta}, \quad A_3 = \frac{\Delta_3}{\Delta}, \quad A_4 = \frac{\Delta_4}{\Delta}, \quad A_5 = \frac{\Delta_5}{\Delta}, \right. \]

\[ g_1 = \sinh (m_1 d), \quad g_2 = \sinh (m_2 d), \quad g_3 = \sinh (m_3 d), \quad g_4 = \sinh (m_4 d), \quad g_5 = \sinh (m_5 d), \]

\[ g_6 = \sinh (m_1 d), \quad h_1 = \cosh (m_1 d), \quad h_2 = \cosh (m_2 d), \quad h_3 = \cosh (m_3 d), \]

\[ h_4 = \cosh (m_4 d), \quad h_5 = \cosh (m_5 d), \]

\[ \Delta (i = 1, \ldots, 5) \) are obtain by replacing 1st, 2nd, 3rd, 4th and 5th column by \([g_2 \bar{F}(\eta z), 0, 0, (\bar{F}(\eta))']^T \) in \( \Delta. \]

and

\[ \sum_{i=1}^{3} M_i = \sum_{i=1}^{3} \left[ a_{10} \left( m_i^2 - \eta^2 \right) + 2a_{11} m_i^2 - a_{12} \left( \tau_{s1}^1 R_i + \tau_{s2}^2 \right) \right], \]

\[ \sum_{i=1}^{5} M_i = \sum_{i=1}^{5} \left[ 2(a_{10} + a_{11}) \eta^2 m_i \right], \]

\[ \sum_{i=1}^{3} N_i = \sum_{i=1}^{3} \left( 2a_{12} m_i \right), \]

\[ \sum_{i=1}^{5} N_i = \sum_{i=1}^{5} \left[ a_{11} \left( m_i^2 + \eta^2 \right) - a_{12} \left( m_i^2 - \eta^2 \right)^2 \right], \quad \sum_{i=1}^{5} Q_i = \sum_{i=1}^{5} m_i \left( m_i^2 - \eta^2 \right). \]

\[ \sum_{i=1}^{3} K_i = \sum_{i=1}^{3} \left[ -\left( m_i^2 + \eta^2 \right) + a_{14} \tau_{s1}^2 S_i - a_{15} \tau_{s6}^2 R_i \right], \quad \sum_{i=1}^{5} K_i = \sum_{i=1}^{5} \left( -2\eta^2 m_i \right). \]