The Effects of Variable Viscosity and Thermal Conductivity of a MHD Micropolar Fluid Past a Continuously Moving Plate with Soret and Dufour Effects

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ABSTRACT
In the present work, the effects of variable viscosity and thermal conductivity on the boundary layer flow and heat and mass transfer of a MHD micropolar fluid past a continuously moving plate embedded in porous media with Soret and Dufour effects have been studied. Both viscosity and thermal conductivity are assumed to be the inverse linear functions of temperature. The governing partial differential equations are transformed into dimensionless forms using similarity transformations. The effects of variable viscosity, variable thermal conductivity and the other parameters involved in the study on the velocity, micro-rotation, temperature and concentration distribution profiles as well as skin friction coefficients, couple stress, Nusselt number and Sherwood number are investigated by solving the governing transformed ordinary differential equations with the help of Runge–Kutta fourth order method with shooting technique and shown graphically and in tabulated form and discussed in detail.

Keywords
Variable viscosity, variable thermal conductivity, micropolar fluid, magnetic field, heat transfer, mass transfer, Soret and Dufour effects, shooting technique.

1. INTRODUCTION
The problems of micropolar flow and heat and mass transfer in the boundary layers of a continuously moving plate have been attracted considerable attention of researchers due to their numerous technological applications. Micropolar fluids are referred to those fluids that contain micro-constituents that can undergo rotation which affect the hydrodynamics of the flow. These fluids are distinctly non-Newtonian in nature. The concept of micropolar fluid was introduced by Eringen [1] where he derived the constitutive laws of fluid with micro structure and taking into account the effect of micro-elements of fluids on both the kinematics and conduction of heat, the theory of thermo-micropolar fluids has been developed by Eringen [2]. Micropolar fluid theory has been employed to study a number of flow situations such as the flow of low concentration suspensions, liquid crystals, real fluid with suspensions and animal blood etc. Over the years, the dynamics of micropolar fluids has been a popular area of research. A thorough review of the subject and the applications of micropolar fluid mechanics has been given by Ariman et al. [3,4]. Flow in the boundary layer on moving solid surface was historically first investigated by Sakiadis [5,6] who observed that the boundary layer growth is in the direction of motion of the continuous solid surface and deviates from that of the classical Blasius flow past a flat plate. Also, heat and mass transfers simultaneously affecting each other will also cause a cross-diffusion effect. The mass transfer caused by the temperature gradient is called the Soret effect, while the heat transfer caused by concentration gradient is called Dufour effect. Ishak et.al [7] discussed the problem of steady boundary layer flow and heat transfer of a micropolar fluid on an isothermal continuously moving surface. Gorla [8] studied mixed convection in a micropolar fluid from a vertical surface with uniform heat flux. Adrian [9] studied numerically the heat and mass transfer by natural convection from vertical surface in porous media in presence of magnetic field considering Soret and Dufour effects. The effects of Dufour and Soret on unsteady MHD free convection and mass transfer flow past a vertical porous plate was discussed by Alam et.al [10]. Hazarika [11] discussed the heat transfer between two parallel disks. Kafoussias et.al [12] studied the boundary layer flows in presence of Soret and Dufour effects associated with thermal diffusion and diffusion thermo for the mixed forced-natural convection. EL–Kabir et.al [13] studied the Soret and Dufour effects on heat and mass transfer from a continuously moving plate embedded in porous media with temperature dependent viscosity and thermal conductivity.

In the present study, an attempt has been made to incorporate the combined effects of variable viscosity and thermal conductivity on the boundary layer flow and heat and mass transfer of a MHD micropolar fluid over a continuously moving plate embedded in a porous medium with Soret and Dufour effects. Following Lai and Kulacki [14], the fluid viscosity and thermal conductivity are assumed to vary as an inverse linear function of temperature. Using similarity transformations the governing partial differential equations of motion are reduced to ordinary differential equations, which are solved numerically for prescribed boundary conditions by shooting technique.
2. MATHEMATICAL FORMULATION

\[ y, v \quad T, C \]

\[ B_0 \]

\[ \text{Boundary layer} \]

\[ x, u \]

\[ \text{U}_0 \]

\[ \text{Fig 1: Physical model and coordinate system} \]

The problem under consideration is a steady two dimensional laminar flow of an incompressible, electrically conducting fluid over a continuously moving plate embedded in a porous media. The x-axis is taken along the plate in the direction of the fluid motion and y-axis taken normal to it. A uniform magnetic field \( B_0 \) is imposed along y-axis. Then under the usual boundary layer approximations, the flow and heat and mass transfer of a MHD micropolar fluid in porous medium with Soret and Dufour effects included are governed by the following equations:

**Basic Equations:**

Continuity Equation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  

(1)

Momentum Equation:

\[ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{1}{\rho} \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) + k \left( \frac{\partial N}{\partial y} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{\mu}{K} u - K u^2 - \frac{\sigma B_0^2}{\rho} u \]  

(2)

Angular momentum Equation:

\[ \rho j(u \frac{\partial N}{\partial x} + v \frac{\partial N}{\partial y}) = -k(2N + \frac{\partial u}{\partial y}) + \gamma \frac{\partial^2 N}{\partial y^2} \]  

(3)

Energy Equation:

\[ u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{\rho c_p} \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{1}{\rho c_p} \left( \mu + k \right) \left( \frac{\partial u}{\partial y} \right)^2 + \frac{D_m \lambda_T}{c_p \epsilon_s} \frac{\partial^2 C}{\partial y^2} \]  

(4)

Concentration Equation:

\[ u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{\partial}{\partial y} \left( D_m \frac{\partial C}{\partial y} \right) + \frac{D_m \lambda_T}{T_m} \frac{\partial^2 T}{\partial y^2} \]  

(5)

where \( u \) and \( v \) are the components of velocity along \( x \) and \( y \)-directions respectively, \( \rho \) is the fluid density, \( \mu \) is the coefficient of dynamic viscosity, \( k \) is the vortex viscosity, \( N \) is the microrotation component, \( K \) is the permeability of the porous medium, \( \mu^* \) is the inertia coefficient, \( \gamma \) is the spin gradient viscosity, \( j \) is the micro-inertia density, \( T \) is the temperature of the fluid, \( \lambda \) is the thermal conductivity, \( c_p \) is the specific heat at the constant pressure, \( T \) is the temperature and \( \lambda_T \) is the thermal conductivity. \( B_0 \) is the external magnetic field, \( C \) is the concentration of the fluid within the boundary layer. \( D_m \) is the molecular diffusivity of the species concentration. \( \lambda_T, \ c_p, \ c_s, \ \epsilon_s \) and \( T_m \) are the thermal diffusion ratio, specific heat at constant pressure, concentration susceptibility and mean fluid temperature respectively.

The boundary conditions are given as:

\[ y = 0: u = U_0, \]

\[ y = 0, N = -\frac{1}{2} \frac{\partial u}{\partial y}, T = T_w, C = C_w \]

\[ y \to \infty: u \to 0, \quad N \to 0, T \to T_\infty, C \to C_\infty \]  

(6)

Where \( U_0 \) is the uniform velocity of the plate, \( T_w \) and \( C_w \) are the temperature and concentration on the surface, \( T_\infty \) and \( C_\infty \) are the temperature and concentration of the fluid at infinity.

Following Lai and Kulacki [14] let us assume that,

\[ \frac{1}{\mu} = \frac{1}{\mu_\infty} [1 + \delta (T - T_\infty)] \quad \text{or} \quad \frac{1}{\mu} = \zeta (T - T_\infty) \]  

where \( \zeta = \frac{\delta}{\mu_\infty} \) and \( T_r = T_\infty - \frac{1}{\delta} \)

\[ \frac{1}{\lambda} = \frac{1}{\lambda_\infty} [1 + \xi (T - T_\infty)] \quad \text{or} \quad \frac{1}{\lambda} = \xi (T - T_\infty) \]  

where \( \mu_\infty \) is the viscosity at infinity, \( \zeta \) and \( T_r \) are constants, \( T_r \) is transformed reference temperature, \( \delta \) and \( \xi \) are constants based on thermal property of the fluid. Similarly, \( \lambda_\infty \) is the thermal conductivity at the infinity, \( \epsilon \) and \( T_c \) are constants and their values depend on the reference state and thermal properties of the fluid.

To solve equations (1)-(5) subject to the boundary conditions given in equation (6) the following similarity transformations have been used,

\[ \eta = \left( \frac{U_0}{2 \nu} \right)^{\frac{1}{2}} y, \quad \psi = \left( 2 \nu \frac{U_0}{x} \right)^{\frac{1}{2}} f(\eta), \]

\[ N = U_0 \left( \frac{U_0}{2 \nu x} \right)^{\frac{1}{2}} g(\eta), \]

\[ \theta(\eta) = \frac{T - T_w}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_w}{C_w - C_\infty}, \]

\[ u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x} \]  

(8)
Where $\eta$ is the similarity parameter and $\nu_\infty$ is the kinematic viscosity at $T = T_\infty$.

Also from equations (7) and (8),
\[ \nu = -\nu_\infty \frac{\theta_e}{\theta - \theta_e}, \lambda = -\frac{\theta_e}{\theta - \theta_e} \]

Where $\theta_e$ and $\theta_e$ are the dimensionless parameters characterising the influence of viscosity and thermal conductivity respectively and are given by,
\[ \theta_e = \frac{T_e - T_\infty}{T_e - T_\infty} = \frac{1}{\delta(T_e - T_\infty)}, \]
\[ \theta_e = \frac{T_e - T_\infty}{T_e - T_\infty} = \frac{1}{\xi(T_e - T_\infty)} \]

Equation of continuity in equation (1) is identically satisfied using equation (8) and therefore the velocity field is compatible with continuity equation and represents the possible fluid motion.

Using equations (8) - (10) in equations (2)-(5) the following differential equations are obtained:
\[ \left( \frac{\theta_e}{\theta - \theta_e} - K \right) f'' = \left[ \frac{\theta_e}{(\theta - \theta_e)^2} \theta' + f' \right] f'' - \alpha (f')^2 
+ \left( \frac{\theta_e}{\theta - \theta_e} M \right) f' + K_1 g' \]
\[ g'' = \frac{1}{\Delta} \left( f'g + fg' \right) - \frac{1}{G} \left( 2g + f^* \right) \]
\[ \left( \frac{\theta_e}{\theta - \theta_e} \right)^2 = \text{Pr} f \theta' + \left\{ \frac{\theta_e}{(\theta - \theta_e)^2} \right\} (\theta')^2 
+ \text{Pr Ec} (K_1 - \frac{\theta_e}{\theta - \theta_e}) (f^*)^2 + D_P g' \]
\[ \frac{\theta_e}{\theta - \theta_e} \phi'' = \frac{\theta_e}{(\theta - \theta_e)^2} \phi' + S_f f \phi' + S_s \phi' \]

Where the primes denote differentiation with respect to $\eta$,
\[ K_1 = \frac{k}{\mu_e} \] is the coupling constant parameter,
\[ Da = \frac{KU_0^2}{2 \rho \text{Re} \nu_\infty} \] is the Darcy number,
\[ M = \frac{2 \sigma B_e^2 x}{\rho U_0} \] is the magnetic parameter, $\alpha = 2K^* x$ is the inertia coefficient parameter,
\[ \Delta = \frac{\gamma}{\mu_e J} \] is the material constant, $G = -\frac{\gamma U_0}{2k \nu_\infty x}$ is the local microrotation parameter,
\[ \text{Pr} = \frac{\nu_\infty \rho e}{\lambda_e} \] is the Prandtl number,
\[ Ec = \frac{U_0^2}{\rho \nu_\infty} \] is the Eckert number,
\[ S_c = \frac{\nu}{D_m} \] is the Schmidt number,
\[ S_t = \frac{D_m \nu_\infty (C_w - C_\infty)}{T_m (C_w - C_\infty) \nu_\infty} \] is the Soret number,
\[ D_f = \frac{D_m \nu_\infty (C_w - C_\infty)}{c_P c_s (T_w - T_\infty) \nu_\infty} \] is the Dufour number,
\[ \text{Re} = \frac{U_0 x}{\nu_\infty} \] is the Reynolds number.

The transformed boundary conditions are,
\[ f(0) = 0, f'(0) = 1, g(0) = -\frac{1}{2} f^*(0), \theta(0) = 1, \phi(0) = 1 \]
\[ f'(\infty) = 0, g(\infty) = 0, \theta(\infty) = 0, \phi(\infty) = 0 \]

The four important physical quantities of our interest in the problem are the skin friction coefficient ($C_f$), the wall couple stress ($m_w$), Nusselt number ($Nu$) and Sherwood number ($Sh$) are defined as,
\[ c_f = \frac{2 \tau_w}{\rho U_0^2} \] where the shear stress at the surface is given by$
\tau_w = [((\mu + k) \frac{\partial u}{\partial y} + kN), \nu_\infty]_{y=0} \]
\[ m_w = \gamma \frac{U_0^2}{2 \nu_\infty x} \] is the Soret number, $Nu = \frac{xq_w}{\lambda_e (T_w - T_\infty)}$, where
\[ Sh = \frac{js}{U_0 (C_w - C_\infty)} \]

Therefore,
\[ c_f (2 \text{Re})^\frac{1}{2} = \left( \frac{2 \theta_e}{\theta - \theta_e} + K_1 \right) f^*(0) \]
\[ m_w = \gamma \frac{U_0^2}{2 \nu_\infty x} g'(0) \]
\[ \text{Nu Re}^{\frac{1}{2}} 2^{\frac{1}{2}} = \frac{\theta_r}{1 - \theta_r} \theta'(0) \] and \[ \text{Sh}(2 \text{Re})^{\frac{1}{2}} = -\frac{\theta_r}{1 - \theta_r} S^{-1} \phi'(0). \]

3. RESULTS AND DISCUSSION

The system of coupled non-linear ordinary differential equations (11)-(14) together with the boundary conditions (15) is solved numerically by using the fourth order Runge-Kutta method along with the shooting technique. The numerical values of different parameters are taken as \( \theta_r = -5, \theta_r = -5, M = 1, S_r = 4, G = 2, P_r = 7, Ec = 1, K = 1, \Delta = 1, S = 1, Dafour = 15, a = 3 \), unless otherwise stated. The purpose of this study is to bring out the effects of variable viscosity and thermal conductivity on the governing flow with the combination of the other flow parameters. The numerical computations have been carried out by developing codes for MATLAB and results are presented graphically in order to get a physical insight of the problem for the dimensionless velocity profile \( f'(\eta) \), dimensionless microrotation profile \( g(\eta) \), temperature profile \( \theta(\eta) \) and concentration profile \( \phi(\eta) \) with the variation of different parameters in figures 2-23. In several practical problems, the surface characteristics such as skin-friction, wall couple stress, Nusselt number and Sherwood number play important roles and hence, the missing values of \( f'(0), g(0), \theta'(0) \) and \( \phi'(0) \) for various values of viscosity parameter \( \theta_r \), thermal conductivity parameter \( \theta_r \), microrotation parameter \( G \), Magnetic parameter \( M \), Dufour number \( Dafour \), and Soret number \( S_r \) have been derived in tables 1-4.

Figures 2-5 display the influence of viscosity parameter \( \theta_r \), Darcy number \( Dafour \), magnetic parameter \( M \) and microrotation parameter \( G \) on velocity distribution. From fig.2 it is observed that velocity decreases with the increasing values of viscosity parameter. Since, by definition viscosity is inversely proportional to the velocity and hence the result is obvious. Fig.3 depicts the effect of Darcy number on velocity profiles. Physically, Darcy number is directly proportional to the permeability which causes higher restriction to the fluid flow which in turn slows its motion. From fig.4, it is observed that velocity reduces due to the increasing values of magnetic parameter \( M \) and it is due to the fact that the presence of magnetic field produces a Lorentz force which usually resists the momentum field; whereas from fig.5, it is observed that velocity enhances with the increasing values of microrotation parameter \( G \) because for small values of \( G \), the viscous force is predominant as a result viscosity increases and consequently velocity decreases. Figures 6-10 depict the influence of viscosity parameter \( \theta_r \), Darcy number \( Dafour \), magnetic parameter \( M \), microrotation parameter \( G \) and Dufour number \( Dafour \) on microrotation distribution profiles. From figures 6-8, it is observed that microrotation distribution increases with the increasing values of \( \theta_r \), Da and M while reverse trend is observed from the figures 9 and 10 for the increasing values of \( G \) and \( Df \) respectively. Due to the increase of viscous force and Lorentz force temperature of the fluid increases, so molecules get released from their bonds holding them as a result rotation of the fluid elements increased as shown in figures 6, 7 and 8. Figures 11-18 represents temperature profiles for various parameters. Effect of thermal conductivity parameter \( \theta_r \) is observed in fig.11 and it has been found that temperature decreases with the increasing values of thermal conductivity parameter \( \theta_r \) because due to the increase of thermal conduction the transposition of heat from a region of higher temperature to the region of lower temperature increases, so the temperature of the fluid within the boundary layer decreases. From the figures 12-14 it has been observed that temperature decreases with the increasing values of microrotation parameter \( G \), Soret number \( S_r \) and Prandtl number \( Pr \) respectively. Since Soret number defines the effect of the temperature gradients including significant mass diffusion effects and hence temperature reduces significantly as shown in the fig.13. The effect of Prandtl number is exhibited in fig.14 and the graph depicts that the thermal boundary layer thickness decreases as \( Pr \) increases due to the fact that higher Prandtl number fluid has relatively low thermal conductivity which reduces conduction and there by temperature decreases. Again from the figures 15-18, it is observed that for the increasing values of Darcy number \( Da \), Dufour number \( Dafour \), viscosity parameter \( \theta_r \), and magnetic parameter \( M \) respectively the temperature profile increases significantly. Since Dufour number signifies the contribution of the concentration gradients to the thermal energy flux in the flow and hence from fig.16 it is clearly seen that as \( Da \) increases there is a monotonic increase in the temperature profile. Also, increase of viscosity parameter \( \theta_r \) and magnetic parameter \( M \) lead to the increase of viscous force and Lorentz force respectively. These forces give resistance to the flow of the fluid and the fluid has to work done to overcome these resistances. These energies transformed into thermal energy resulting the temperature of the fluid increases as exhibited in figures 17 and 18. Figures 19-23 represents concentration profile for the various parameters. From the figures 19, 20 and 21 it is noticed that concentration boundary layer thickness decreases as viscosity parameter \( \theta_r \), Dufour number \( Dafour \) and Schmidt number \( Sc \) enhance. Since Schmidt number characterizes the ratio of viscosity and mass diffusion, that is, it is inversely proportional to mass diffusion and hence as a result species concentration reduces which is clearly observed in fig.21. Concentration boundary layer thickness is found to be enhanced significantly due to the increasing values of Darcy number \( Da \) and Soret number \( S_r \) respectively as shown in the figures 22 and 23.

From tables 1 and 2, it is observed that, with the increasing values of viscosity parameter \( \theta_r \), the values of \( f'(0), g(0) \) and \( \phi'(0) \) are decreasing while \( \theta'(0) \) increases and for increasing values of thermal conductivity parameter \( \theta_r \), the values of \( f'(0) \) and \( \theta'(0) \) decreases; but \( g(0) \) and \( \phi'(0) \) increases. Also for increasing values of microrotation parameter \( G \), all the values of \( f'(0), g(0), \theta'(0) \) and \( \phi'(0) \) decreases and for that of magnetic parameter \( M \), the values of \( f'(0) \) and \( g(0) \) decreases whereas the values of \( \theta'(0) \) and \( \phi'(0) \) increases significantly. Tables 3 and 4 depicts a comparison of the present work with the earlier published work of EL-Kabir et al.[13] for various values of Dufour number \( Dafour \) and Soret number \( S_r \) and a significant result has been obtained in the present work and it is found that the behavior of Dufour number and Soret number on temperature and concentration distribution is opposite which remains same with the previous work.
Figures 2–23 for dimensionless velocity distribution $f'(\eta)$, dimensionless microrotation distribution $g(\eta)$, temperature distribution $\theta(\eta)$ and concentration distribution $\Phi(\eta)$ with the variation of different parameters and missing value tables and comparison tables 1–4 are displayed below:
Fig 8: Microrotation for various \( M \)

Fig 9: Microrotation for various \( G \)

Fig 10: Microrotation for various \( D_f \)

Fig 11: Temperature for various \( \theta_c \)

Fig 12: Temperature for various \( G \)

Fig 13: Temperature for various \( S_r \)

Fig 14: Temperature for various \( Pr \)

Fig 15: Temperature for various \( Da \)
Table 1: Estimated missing values of $f''(0)$, $g' (0)$, $\theta'(0)$ and $\phi'(0)$ for various $\theta_r$ and $G$ and $\theta_i = -5$, $D_f = .15$, $M = .1$, $Pr = .7$, $Ec = .10$, $K_r = 1$, $\Lambda = .1$, $S_r = 1$, $S_f = 4$, $\alpha = .3$, $Da = .1$.
Table 2: Estimated missing values of $f''(0)$, $g'(0)$, $\theta'(0)$ and $\phi'(0)$ for various $\theta_c$ and M and $\theta_c = -5$, $D_I = 15$, $G = 2$, $Pr = 7$, $Ec = 10, K_I = 1$, $\Lambda = 1$, $S_s = 1$, $S_r = 4$, $a = 3$, $D_a = 1$.

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Table 3: Comparison of missing values of $f''(0)$, $\theta'(0)$ and $\phi'(0)$ at $\theta_c = -5$, $G = 2$, $Pr = 7$, $Ec = 10$, $K_I = 1$, $\Lambda = 1$, $S_s = 1$, $S_r = 4$, $a = 3$, $D_a = 1$, $S_1 = 4$ for different values of $D_I$ with previously published result of EL-Kabir et al [13].

<table>
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Table 4: Comparison of missing values of $f''(0)$, $\theta'(0)$ and $\phi'(0)$ at $\theta_c = -5$, $G = 2$, $Pr = 7$, $Ec = 10$, $K_I = 1$, $\Lambda = 1$, $S_s = 1$, $S_r = 4$, $a = 3$, $D_a = 1$, $D_I = 15$ for different values of $S_s$ with previously published result of EL-Kabir et al [13].

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4. CONCLUSION:
In this study the effects of variable viscosity and thermal conductivity on the boundary layer flow and heat and mass transfer of a MHD micropolar fluid over a continuously moving plate embedded in a porous medium with Soret and Dufour effects is studied and the following significant observations are made:

1. Velocity distribution reduces due to the increasing values of viscosity parameter $\theta_1$, magnetic parameter M and Darcy number $D_a$ and it increases with the increasing values of microrotation parameter $G$.
2. Microrotation distribution enhances due to the increase of viscosity parameter $\theta_1$, magnetic parameter M and Darcy number $D_a$ while it reduces with the increasing values of microrotation parameter $G$ and Dufour number $D_D$.
3. Temperature distribution decreases due to the increase of thermal conductivity parameter $\theta_r$, microrotation parameter $G$, Soret number $S_r$, and Prandtle number $Pr$; while opposite trend is observed with the values of Darcy number $D_a$, Dufour number $D_D$, viscosity parameter $\theta_1$ and magnetic parameter M.
4. Concentration distribution reduces due to the increase of viscosity parameter $\theta_1$, Dufour number $D_D$ and Schmidt number $S_f$, while it increases with Darcy number $D_a$ and Soret number $S_r$.
5. With the increasing values of viscosity parameter $\theta_1$, the values of $f''(0)$, $g'(0)$ and $\phi'(0)$ are decreasing while $\theta'(0)$ increases and for increasing values of thermal conductivity parameter $\theta_r$, the values of $f''(0)$ and $\theta'(0)$ decreases; but $g'(0)$ and $\phi'(0)$ increases.
6. It is hoped that the findings of this paper will be helpful for further research work in heat and mass transfer problems.

5. ACKNOWLEDGMENTS
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6. REFERENCES