Effect of Thermal Conductivity on Magneto-hydrodynamic Heat and Mass Transfer in Porous Medium Saturated with Kuvshinshiki Fluid

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Abstract - The effects of Kuvshinshiki fluid on Magnetohydrodynamic (MHD) heat and mass transfer flow over a vertical porous plate with chemical reaction of nth order and thermal conductivity was carried out. The governing partial differential equations were solved numerically using implicit Crank-Nicolson method. A parametric study was performed to illustrate the impact of visco-elastic parameter, radiation parameter, thermal conductivity parameter, magnetic parameter, Prandtl number on the velocity, temperature and concentration profiles. The results were presented graphically with tabular presentations of the skin friction, rate of heat and mass transfer which were all computed and discussed for different values of parameters of the problem. The numerical results revealed that the visco-elastic of Kuvshinshiki fluid type is growing as concentration profile increases, while the velocity and temperature profile falls, then the radiation and thermal conductivity were growing as velocity and temperature increases. Also Sherwood number decreases as radiation increases but Sherwood number remains unchanged as thermal conductivity growing.

Keywords: Thermal Conductivity, Magnetohydrodynamic (MHD), Heat and Mass Transfer, Porous Medium and Kuvshinshiki Fluid

1 INTRODUCTION

Research work on non-Newtonian fluids has been intensified due to their wide applications in industry and engineering fields of chemical and geophysical sciences. This phenomenon plays an important role in chemical industry such as drying, filtration and purification processes. The study of stellar structure on solar surface is connected with mass transfer phenomena. Its origin is attributed to difference in temperature caused by the non-homogeneous production of heat, which in many cases can rest not in the formulation of convective current but in violent explosion. On strength of this phenomenon, Rachna (2013) investigated the unsteady Magnetohydrodynamic (MHD) flow, heat and mass transfer along an accelerated vertical porous plate in the influence of viscous dissipation, heat source and variable suction.

The flow of an electrically conducting fluid in the presence of a magnetic field is of importance in various area of technology such as MHD flow meters, MHD generators, geothermal energy extraction, MHD generators and MHD pumps. Also, hydromagnetic techniques are used for the purification of molten metals from non-metallic inclusions. Hartmann [6], started work on the investigation of hydromagnetic flow between two infinite vertical parallel plates experimentally and theoretically which provided the platform for the development of many MHD devices such as MHD pumps, MHD generators, brakes, flow meters, plasma studies and geothermal energy extraction. Visco-elastic fluid flow through porous media plays an important role in many areas of scientific and engineering applications. This type of flow is of great importance in the petroleum engineering, it is concerned with the movement of oil, gas and water through reservoir of oil or gas field. To the hydrologist in the study of the migration of underground water and to the chemical engineer is the purification and filtration processes; it is likened to drug permeation through human skin.

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Based on these investigations, the study on Kuvshinshiki fluid flow on MHD thermal conductivity and Dufour effects has not been considered. Thus, this research work considered the effect on MHD free convective flow of Kuvshinshiki fluid with mass transfer past a vertical porous plate through porous medium with thermal conductivity, chemical reaction of nth order and Dufour parameters.

2 PROBLEM FORMULATION AND METHOD OF SOLUTION

An unsteady thermal conductivity MHD heat and mass transfer of Kuvshinshiki fluid flow pass a vertical porous plate with variable suction using the visco-elastic Kuvshinshiki fluid type was considered. The fluid is assumed to be grey absorbing-emitting, but, not scattering. The $y^*$ is taking normal to the plate and $x^*$axis is taking along the plate in the vertically upward direction. At $t^*$=0, it is assumed that the plate and the fluid are at the same ambient temperature $T_\infty$ and when $t^*$>0, the plate temperature and mass concentration were raised to $T_{w*}$ and $C_{w*}$, respectively. The physical variable are functions of $y^*$ and $t^*$ where $y^*$ is taking normal to the plate and $x^*$-axis is taking along the plate in the vertically upward direction. It is assume that both the variable thermal conductivity and the nth order chemical reaction are not constant.

The fluid properties were assumed to be constant except for the body forces terms in the momentum equation which have being approximated by Boussinesq relations. Radiation is assumed to be present and will acts transverse to the vertical surface, where $\sigma$ is the Stefan-Boltzmann constant, i and $k^*$ are the mean absorption coefficient. It should be noted that by using the Rosseland approximation, the present analysis is limited to the optical thickness. Using the Boussinesq and boundary layer approximations, the boundary layer equations to be considered were derived from the Continuity, Momentum, Energy and Concentration equations and were formulated in an $(x, y)$ coordinate system as follow.

The governing equations of the model in dimensional form are

\[
\frac{\partial \nu}{\partial t^*} = 0 \tag{1}
\]

\[
(1+\lambda)^* \frac{\partial \nu^*}{\partial t^*} + v^* \frac{\partial \nu^*}{\partial y^*} = \frac{\nu^2}{\partial x^*} + g \beta^*(T^* - T_\infty) + g \beta^*(C - C_\infty) - (1 + \lambda^*) \left( \frac{\partial u^*}{\partial x^*} \right)^2 - \frac{\partial u^*}{\partial y^*} \frac{\partial u^*}{\partial y^*} \tag{2}
\]

\[
(1+\lambda)^* \frac{\partial \nu^*}{\partial t^*} + v^* \frac{\partial \nu^*}{\partial y^*} = \frac{k}{\rho \mu} \frac{\partial^2 \nu^*}{\partial y^*} \left( 1 + m(T^* - T_\infty) \right) \frac{\partial y^*}{\partial y^*} + \frac{d_{nu} \kappa^*}{\rho \mu} \frac{\partial C^*}{\partial y^*} \frac{\partial y^*}{\partial y^*} \frac{\partial y^*}{\partial y^*} + \frac{d_{nu} \kappa^*}{\rho \mu} \frac{\partial C^*}{\partial y^*} \frac{\partial y^*}{\partial y^*} \frac{\partial y^*}{\partial y^*} \tag{3}
\]

\[
(1+\lambda)^* \frac{\partial \nu^*}{\partial t^*} + v^* \frac{\partial \nu^*}{\partial y^*} = D \frac{\partial C^*}{\partial y^*} - \frac{\partial \nu^*}{\partial y^*} - R^* (C^* - C_{\infty}) \tag{4}
\]

Equations (1)–(4) are the continuity, Momentum, Energy and Concentration Equations respectively, where $x$ and $y$ are dimensions coordinates, $u^*$ and $v^*$ are dimensionless velocities, $\nu$ is the kinematic viscosity, $t^*$ is dimensionless time, $T^*$ is the dimensional temperature, $g$ the acceleration due to gravity, $\beta$ the volumetric coefficient of thermal expansion, $\beta^*$ is the volumetric coefficient of thermal expansion with concentration, $\rho$ the density of the fluid, $C_p$ is the specific heat at constant pressure, $Dm$ is the species diffusion coefficient, $K^*$ is the permeability of the porous medium, $\alpha_f$ is the heat generation/absorption constant, $B_0$ is the magnetic induction, $g$ is the acceleration due gravity, $\beta$ and $\beta^*$ are the thermal and concentration expansion coefficient respectively. $T$ is the dimensional temperature, $C$ is the dimensional concentration, $\alpha$ is the fluid thermal diffusivity, $\mu$ is the coefficient of viscosity, $qr$ is the relative heat flux. $U_0$ is the scale of free stream velocity, $K^*$ is the wall dimensional temperature, $T_w^*$ is the free stream temperature far away from the plate, $D$ is the chemical molecular diffusivity, $T_f$ is reference temperature, $k_f$ is the dimensional chemical reaction.

The appropriate initial and boundary conditions relevant to the fluid flow are:

\[
u^* = 0, T^* = T_w^*, C^* = C_{w*}, as \ y^* = 0 \tag{5}
\]

\[
u^* \to 0, T^* \to T_w^*, C^* \to C_{w*}, as \ y^* \to \infty \tag{6}
\]

where $U_0$ is the scale of free stream velocity, $T_w^*$ is the free stream temperature, $C_{w*}$ is the free stream concentration, $T_w^*$ and $C_{w*}$ are wall dimensional temperature and concentration respectively, $n^*$ is a constant.

The thermal conductivity depends on temperature. It is used by Molla et al (2005), as follows:

\[K(T) = k_0([1 + m(T^* - T_\infty)]) \tag{7}\]

Where $k_0$ is the thermal conductivity of the ambient fluid, $m$ is a constant depending on the nature of the fluid and $m$ is defined by

\[m = \frac{1}{k(\rho)(\frac{\partial \rho(T)}{\partial T})} \tag{8}\]

In order to solve the governing equations in dimensionless form, we introduce the following non-dimensional quantities into (2),(3),(4) as follows:

\[u = \frac{u^*}{U_0}, U = \frac{U^*}{U_0}, y = \frac{v^*}{\nu}, t = \frac{v^*}{\nu}, n = \frac{v^*}{\nu}, \theta = \frac{T^* - T_{\infty}}{T_w^* - T_{\infty}}, C = \frac{C^* - C_{\infty}}{C_{w*} - C_{\infty}}, P_e = \frac{v^* C_p}{k} = \]

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where \( u \) and \( v \) are dimensionless velocities, \( T \) is the dimensionless temperature function, \( F \) is the conduction-radiation heat transfer parameter, \( Pr \) is the Prandtl number, \( Da \) is Darcy number, \( Gr \) is the thermal Grashof number, \( Gc \) is the mass Grashof number, \( M \) is the Magnetic field, \( K \) is the permeability parameter, \( Sc \) is the Schmidt number, \( Kr \) is the chemical reaction, \( n \) is the order reaction and \( \eta \) is the thermal conductivity.

The above governing equations (2),(3),(4) and (9) in dimensionless form are

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\partial u}{\partial y} - (1 + \epsilon \Delta e^{-n t}) \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + G_t \theta + G_c \eta - N (1 + \lambda \frac{\partial}{\partial t}(U + u)) \tag{10}
\]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\partial \theta}{\partial y} - (1 + \epsilon \Delta e^{-n t}) \frac{\partial \theta}{\partial y} = \frac{1}{Pr} (2 + \eta \theta + \frac{4\eta}{3} \Delta \frac{\partial^2 \theta}{\partial y^2} + \eta \frac{\partial}{Pr} \Delta \eta \frac{\partial \theta}{\partial y}^2 + Du \frac{\partial^2 \eta}{\partial y^2} + Ec \frac{\partial^2 \epsilon}{\partial y^2} \text{ and } N \tag{11}
\]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\partial \eta}{\partial y} - (1 + \epsilon \Delta e^{-n t}) \frac{\partial \eta}{\partial y} = \frac{1}{Sc} \frac{\partial^2 \eta}{\partial y^2} - K_t \eta^n \tag{12}
\]

Subject to boundary conditions

\[
u = 1 + \epsilon e^{-n t}, T = 1, C = 1 \text{ at } y = 0
\]

\[
u \rightarrow 0, T \rightarrow 0, C \rightarrow 0 \text{ as } y \rightarrow \infty \tag{13}
\]

In order to access the influence of parameters on the flow variables namely; visco-elastic of kuvshinshiki fluid parameter, thermal Grashof number, mass Grashof number, Schmidt number, Prandtl number, magnetic parameter, Soret number, Dufour number, permeability parameter, Eckert number, chemical reaction and order of chemical reaction on the velocity, temperature and concentration, and have grips of the physical problem, the unsteady coupled non-linear partial differential equations (10) – (12) with boundary conditions (13) have been solved by implicit finite difference schemes of Crank – Nicolson type.

This method has been extensively developed in recent years and remains one of the best reliable methods for solving partial differential equation because it converges faster. The finite difference equations corresponding to equations (10) to (13) are as follows:

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{u^{k+1} - u^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{u^{k+1} - u^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\theta^{k+1} - \theta^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\theta^{k+1} - \theta^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\eta^{k+1} - \eta^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\eta^{k+1} - \eta^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\epsilon^{k+1} - \epsilon^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\epsilon^{k+1} - \epsilon^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\gamma^{k+1} - \gamma^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\gamma^{k+1} - \gamma^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\delta^{k+1} - \delta^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\delta^{k+1} - \delta^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\lambda^{k+1} - \lambda^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\lambda^{k+1} - \lambda^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\alpha^{k+1} - \alpha^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\alpha^{k+1} - \alpha^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

\[
(1 + \lambda \frac{\partial}{\partial t} \frac{\beta^{k+1} - \beta^k}{\Delta t} - (1 + \epsilon \Delta e^{-n t}) \frac{\beta^{k+1} - \beta^k}{\Delta t} = \frac{G_c}{2}(u^{k+1} - u^k) - \frac{4\Delta y}{2}\n \]

3 RESULTS AND DISCUSSION

In order to get a physical view of the present work, numerical computations was carried out for different values of thermal Grashof number(Gr), mass Grashof number(Gc),Prandtl number(M),Porous parameter(K),Variable suction(V0),Radiation parameter(R),Chemical reaction(Kr),order of chemical reaction(n),Thermal conductivity(Pr),Schmidt number(Sc) and Visco-elastic parameter of Kuvshinshiki type(\( \lambda \)). The purpose of this computations is to assess the influence of these physical parameters upon the nature of the flow.

The skin-friction, rate of heat and mass transfer in terms of Nusselt number and Sherwood number respectively are given by

\[
C_f = \left( \frac{\partial v}{\partial y} \right)_{y=0}, Nu = \left( \frac{\partial \theta}{\partial y} \right)_{y=0}, Sc = \left( \frac{\partial \eta}{\partial y} \right)_{y=0}
\]

Computations are obtained for fluids with Prandtl number (Pr=0.71, 1.0 and 7.0) corresponding to air, salt water and water respectively. The value of Schmidt number is taking as (Sc=0.22, 0.66, 0.94, 2.62) representing diffusing chemical species of most common
interest in air for hydrogen, oxygen, carbon dioxide and propyl benzene. Attention is focused on positive values of the buoyancy parameters i.e Grashof number Gr>0 (which corresponds to the cooling problem) and mass Grashof number Gc>0 (which indicates that the chemical species concentration in the free stream region is less than the concentration at the boundary surface). The default values of the physical parameters are as follows:

Gr=2.0, Gc=2.0, M=1, K=100, Pr=0.71, Sc=0.22, R=1, Kr=0.5, n=0.1, η=0.01, λ=0.1.

Figures 1 and 2 illustrate the momentum boundary layer thickness generally decreases with increasing values of Gr and Gc since the cooling problem is often encountered in engineering applications; for example in the cooling of electronic components and nuclear reactors. Since convective-boundary-layer flow are often controlled by injecting or withdrawing fluid through a porous bounding heated surface. This can lead to enhanced heating or cooling of the system. Meanwhile, it is interesting to note that a reverse flow occurs within the boundary layer as the intensity of buoyancy forces increases due to the values of parameters. Figures 3-4 shows the variation across the boundary layer for various values of magnetic parameter(M)and porous parameter(K). The porosity medium has considerable effect on the velocity. An increase in porosity leads to increasing the resistance of the velocity profiles, which will tend to accelerate the flow and therefore increase the velocity. The impact of magnetic parameter (M) on the velocity profile in the boundary layer is plotted in figure (4). It can be seen that as M increases, the velocity decreases. This results agrees with the expectations since the magnetic field exerts a restraining force on the fluid which tends to impede it motion. Retards

The flow, which is known as Lorentz force. Figure 5 describes the behaviour of various values of visco-elastic parameter λ on the velocity profiles. It is observed that the greater the viscous-elastic parameter of kuvshinshiki fluid type causes a decrease in the velocity profiles across the boundary layer. In figure (6) and (7), it is evident from these figures that as Prandtl (Pr) increases the velocity also increases. Figure 7, depicts the radiation parameter effect on velocity, as radiation increases, velocity also increases. This is because of the type of fluid considered here which is gray, emitting and absorbing radiation but non-scattering medium. It is also observed from the Table 1 that an increase in any of the parameters Gr, Gc, K and λ causes reduction, while, M, Pr and R rises in the skin-friction coefficient.

The temperature profiles have been studied and presented in Figures (8) to (13). Figure (8) presents different values of Prandtl number (Pr=0.71, 1.0, 3.0, 5.0), it is seen that the temperature decrease with increase in the Prandtl number. Also, Figure 9 reveals that the temperature decrease with increase in the radiation parameter. Figure (10) indicates that, the temperature increase whenever the Eckert number increased. In figure (11), it is noticed that, the temperature increases with an increase in the visco-elastic parameter. It is observed in figure (12) and (13) that temperature distribution increases as η and λ increase, we observed that for higher values of thermal conductivity η and Du parameters, maximum temperature occurs. It is noted that an increase in R, Ec, η and Du leads to a rise in the Nusselt number, while an increase in λ, and Pr leads to a fall in the Nusselt number respectively.

### Table 1. Effect of Flow Parameters on the Values of, Nu and Sh for \( t = 0.1 \), A = 1, \( ep = 0.02 \)

| Fluid Parameter | Skin Friction | Nusselt numbers | Sherwood Numbers |
|-----------------|---------------|-----------------|-----------------|
| Gr=1            | 2.6024        | 4.8608          | 0.4907          |
| Gr=3            | 2.5008        | 4.9953          | 0.4907          |
| Gr=5            | 2.5001        | 5.2643          | 0.4907          |
| Gc=1            | 2.9262        | 8.8204          | 0.1924          |
| Gc=3            | 2.924         | 9.0468          | 0.1923          |
| Gc=5            | 2.9125        | 9.2732          | 0.1921          |
| K=1             | 2.5586        | 8.4577          | 0.7576          |
| K=2             | 2.5569        | 6.6512          | 0.7576          |
| K=3             | 2.5562        | 7.097           | 0.7576          |
| M=1             | 2.927         | 8.4253          | 0.1924          |
| M=2             | 2.9314        | 7.0782          | 0.1922          |
| M=3             | 2.9183        | 2.4502          | 0.187           |
| M=4             | λ= 0.01       | 2.9607          | 8.9269          | 0.4556    |
| λ= 0.03         | 2.6073        | 8.4334          | 0.5569          |
| λ= 0.05         | 2.4927        | 8.1728          | 0.6319          |
| Pr=0.71         | 2.5011        | 8.4608          | 0.7576          |
| Pr=1            | 2.5159        | 4.8186          | 0.7576          |
| Pr=3            | 2.6982        | 4.7316          | 0.7576          |
| R=0.1           | 2.4534        | 8.273           | 0.2411          |
| R=0.4           | 2.6424        | 8.334           | 0.2203          |
| R=0.7           | 2.7969        | 8.3867          | 0.2044          |
| Sc=0.1          | 2.4765        | 4.8627          | 0.7576          |
| Sc=0.3          | 2.4213        | 4.867           | 0.7576          |
| Sc=0.5          | 2.3657        | 4.8713          | 0.7576          |
| n=5             | -13.7785      | 5.3129          | 0.7576          |
| n=10            | -15.2877      | 5.4241          | 0.7576          |
| n=15            | -17.4304      | 5.5981          | 0.7576          |
| Du=0.1          | 3.2423        | 8.9081          | 0.2014          |
| Du=0.3          | 3.0858        | 8.9309          | 0.1969          |
| Du=0.5          | 2.9251        | 8.9336          | 0.1924          |
| Sc=0.22         | 2.726         | 8.7006          | 0.1856          |
| Sc=0.64         | 2.4359        | 8.3644          | 0.1715          |
| Sc=0.97         | 2.283         | 8.2634          | 0.1629          |
| Kr=0.5          | 2.9251        | 8.9336          | 0.1924          |
| Kr=1.0          | 2.8752        | 8.8785          | 0.19            |
| Kr=1.5          | 2.8251        | 8.8209          | 0.1877          |

The concentration profiles are illustrated in figures (14) to (17) for different values of Schmidt number (Sc=0.22, 0.64, 0.97 and 1.65), Chemical reaction (Kr=0.5, 1.0, 1.5 and 2.0), Order of reaction (n=0.1, 0.3, 0.5 and 0.7) and visco-elastic of kuvshinshiki type \( (λ=0.01, λ=0.03, λ=0.05 \) and \( λ=0.07) \) parameter as in figures 13, 14 and 15 respectively. Figures (14),(16) and (17) depicts the influence of Schmidt number Sc and chemical reaction on concentration are displayed respectively. As the Schmidt number increases, the concentration profile decreases. This causes the concentration buoyancy effect to decrease yielding a reduction in the fluid concentration. Physically, increase of Sc means decrease in molecular diffusivity. While the concentration
decreases with increasing in chemical reaction Kr and visco-elastic of kuvshinshiki type (λ), this is due to the fact that destructive chemical reduces the solutal boundary layer thickness. The effect of order chemical reaction (n) on the concentration profiles are displayed in figure (15) respectively. It is observed from this figure that an increase in the order of chemical reaction, concentration profile also increases. It is also seen that λ has an appreciable impact on the Sherwood number profile because as λ and n rise sherwood number also increase and a growing Sc and Kr are found to decrease the Sherwood number of the flow fluid.

Fig 1: Effect of Gr on Velocity

Fig 2: Effect of Gc on Velocity

Fig 3: Effect of K on Velocity

Fig 4: Effect of M on Velocity

Fig 5: Effect of λ on Velocity

Fig 6: Effect of Pr on Velocity

Fig 7: Effect of R on Velocity

Fig 8: Effect of Pr on Temperature

Fig 9: Effect of R on Temperature

Fig 10: Effect of Ec on Temperature

Fig 11: Effect of λ on Temperature
4 Conclusion

Numerical solutions of this present work are obtained for the unsteady, visco-elastic of kuvshinshiki fluid type $\eta$ along a vertical porous medium with the variable suction in the presence of MHD, heat and mass transfer, Dufour, chemical reaction, order of chemical reaction and radiation. The Crank-Nicolson method was used to solve the problem and the results are evaluated numerically and displayed graphically and in tabular form. In the light of the present investigation, the following conclusions were drawn:

That the velocity becomes higher when $M$, $Pr$ and $R$ are increased. Also, a decrease in value of $Gr$, $Gc$, $K$, and $\lambda$ leads to sharp fall in the velocity of the boundary layer. The temperature profile increases in the presence of radiation $R$, Eckert $Ec$, thermal conductivity $\eta$ and Dufour $Du$, but reduces for increased values of Prandtl number and visco-elastic $\lambda$. Similarly, concentration rises with order of chemical reaction $n$ and decreases with increasing values of Schmidt number, chemical reaction $Kr$, and visco-elastic $\lambda$.

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