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# Dufour Effects on Unsteady MHD Convective Heat and Mass Transfer Flow of Micropolar Fluid Past a Vertical Moving Porous Plate

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An investigation of Dufour effects on unsteady MHD convective flow of micropolar fluid past a vertical moving semi-infinite plate embedded in a porous medium is carried out. The dimensionless governing equations for this investigation are solved analytically using small perturbation approximation. The effect of various dimensionless parameters entering into the problem on the velocity, temperature and concentration profiles across the boundary layer are investigated through graphs. Also, the result of the skin friction coefficient, the rate of heat and mass transfer at the wall are prepared with various values of the parameters. It is observed that the velocity increases with the increase of Dufour number whereas it decreases with the increasing value of Schmidt number, Prandtl number and Eckert number. Also, magnitude of micro rotation increases with the increase of Eckert number.

## 1. Introduction

The theory of micropolar fluid introduced by Eringen (1966) deals with a class of fluids which exhibit certain microscopic effects arising from local structure and micro motions of the fluid elements. These fluids can support stress moments and body moments are influenced by spin inertia. These molecular fluids contain microconstituents that can undergo rotation. It can consist of a suspension of small, rigid, cylindrical elements such as large dumbbell- shaped molecules. The presence of these micropolar molecules can affects the hydrodynamics of the flow so that it can be distinctly non- Newtonian. The micro molecular fluid flow in porous medium has a number of applications such as oil exploration chemical catalytic reactors, thermal insulation and geothermal energy extractions etc. In view of its applications in large number of engineering problems many researchers have been carried out till date. The equations governing the flow of a micropolar fluid involve a spin vector (Microrotation vector) and microinertia tensor (gyration parameter) in addition to the velocity vector. Peddison et al., (1970) derived boundary layer theory for micropolar fluid which is important in a number of technical processes and applied this equation to the problem of steady stagnation point flow, steady flow past a semi- infinite plate. Eringen (1972) extended the theory of micropolar fluid and developed the theory of thermomicropolar fluid. The flow characteristics of the boundary layer flow of a micropolar fluid over a semi- infinite plate was investigated by Ahmadi (1976). The heat transfer aspect of the flow of micropolar fluid of semi- infinite plate was analysed by Soundagekhar et al., (1983). Due to the effect of magnetic fields on the boundary layer flow control and on the performance of many systems using micropolar fluid there has been a growing interest in the study of MHD flow in heat transfer in porous medium. The application of MHD attracted attention of many researchers in solution of many Engineering problems such as MHD generators, plasma studies, nuclear reactors, geothermal energy extractions. The mixed convection flow of micropolar fluid over a horizontal plate has been studied by Yucel (1989). The mixed convection in a micropolar fluid from a vertical surface with uniform heat flux was studied by Gorla (1992).

## 2. Mathematical analysis

We consider the unsteady two- dimensional MHD convection with heat and mass transfer flow of an incompressible, electrically conducting and micropolar fluid with Dufour effect, past a semi- infinite vertical

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moving plate embedded in a porous medium. It is assumed that there is no applied voltage which implies the absence of an electrical field. The plate is semi-infinite in length; therefore, the flow variables are functions of y' and *t'* only. Under the usual Boussinesq's approximation, the equations of mass, linear momentum, micro-rotation, energy and diffusion can be written as follows:

Continuity equation: $$\frac{\partial v'}{\partial y'} = 0 \quad (1)$$

Linear momentum equation: $$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = (\upsilon + v_r)\frac{\partial^2 u'}{\partial y'^2} + g\beta_f(T' - T'_\infty) + g\beta_c(C' - C'_\infty) - \left(\frac{\sigma B_0^2}{\rho} + \frac{\upsilon}{K'}\right)u' + 2v_r\frac{\partial \omega'}{\partial y'} \quad (2)$$

Angular momentum equation: $$\rho j'\left(\frac{\partial \omega'}{\partial t'} + v'\frac{\partial \omega'}{\partial y'}\right) = \gamma\frac{\partial^2 u}{\partial y'^2} \quad (3)$$

Linear equation: $$\frac{\partial T}{\partial t'} + v'\frac{\partial T}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} + \frac{v}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2 + \frac{D_M K_T}{C_p C_s}\frac{\partial^2 C'}{\partial y'^2} \quad (4)$$

Diffusion: $$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D'\frac{\partial^2 C'}{\partial y'^2} \quad (5)$$

where x', y' and t' are the dimensional distances along and perpendicular to the plate and dimensional time, respectively, u' and v' are the components of dimensional velocities along x' and y' directions, respectively, C' and T' are the dimensional concentration and temperature, respectively, ρ is the fluid density, υ is the kinematic viscosity, $C_\rho$ is the specific heat at constant pressure, σ is the fluid electrical conductivity, g is the acceleration due to gravity, $\beta_f$ and $\beta_C$ are thermal and concentration expansion coefficients, respectively, K' is the permeability of the porous medium, $B_0$ is the magnetic induction, $D_M$ is the chemical molecular diffusivity $K_T$ is the thermal diffusion ratio and k is the fluid thermal conductivity. The magnetic and viscous dissipations are neglected in this study. The second and third terms on the right-hand side of the momentum equation (2) denote the thermal and concentration buoyancy effects, respectively.

It is assuming that the porous plate moves with constant velocity in the longitudinal direction. We also assume that the plate temperature and concentration are exponentially with time. Under these assumptions, the appropriate boundary conditions for the velocity, microrotation, temperature and concentration fields are:

at $y' = 0, u' = u'_p, T = T_w + \varepsilon(T_w - T_\infty)e^{n't'}, \omega' = -\frac{\partial u'}{\partial y'}, C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{n't'}$

as $y' \to \infty, u' \to 0, T \to T_\infty, \omega' \to 0, C' \to C'_\infty$ (6)

where $u'_p, C'_W$ and $T_W$ are the wall dimensional velocity, concentration and temperature, respectively, $C'_\infty$ and $T_\infty$ are the free stream dimensional concentration and temperature, respectively, n' is constant. From (1), we have $\nabla = -v_0 (v_0 > 0)$ (7), where $v_0$ is the constant suction velocity at the plate and the negative sign indicating that the suction velocity is directed towards the plate. We introduce the following non- dimensional quantities to normalize the flow mod $U = \frac{u'}{U_0}, v = \frac{v'}{V_0}, y = \frac{V_0 y'}{\upsilon}, U_p = \frac{u'_p}{U_0}, n = \frac{n'v}{V_0^2}, \omega = \frac{\upsilon}{U_0 V_0}\omega', t = \frac{t'V_0^2}{\upsilon}, \theta = \frac{T' - T'_\infty}{T'_W - T'_\infty}$

$$C = \frac{C' - C'_\infty}{C'_W - C'_\infty}, j = \frac{V_0^2}{\upsilon^2}j', K = \frac{K'V_0^2}{\upsilon^2}, Sc = \frac{\upsilon}{D'}, M = \frac{\sigma B_0^2 \upsilon}{\rho V_0^2}, Pr = \frac{\upsilon \rho C_p}{k} = \frac{\upsilon}{\alpha} = \frac{\mu C_P}{k}, \quad (8)$$

$$Gr = \frac{v\beta_f g(T'_W - T'_\infty)}{U_0 V_0^2}, Gc = \frac{v\beta_C g(C'_W - C'_\infty)}{U_0 V_0^2}, Du = \frac{D_M K_T (C'_W - C'_\infty)}{C_p C_s \upsilon (T'_W - T'_\infty)}, Ec = \frac{U_0^2 v}{C_p \upsilon (T'_W - T'_\infty)}$$

where Gc, Gr, M, K, Pr, Sc, Ec and Du are denote the solute Grashof number, thermal Grashof number, Hartmann number, permeability parameter, Prandtl number, Schmidt number, Eckert number and Dufour number respectively. Furthermore, the spin- gradient viscosity $\gamma$ which gives some relationship between the coefficients of viscosity and micro-inertia, is defined as

$$\gamma = \left(\mu + \frac{\Lambda}{2}\right)j' = \mu j'\left(1 + \frac{1}{2}\beta\right), \beta = \frac{\Lambda}{\mu} \quad (9)$$

where β denote the dimensionless viscosity ratio, in which Λ is the Coefficient of gyro-viscosity (or vertex viscosity). The governing equations (2), (3), (4) and (5) reduces to the following non-dimensional form:

$$\frac{\partial U}{\partial t} - \frac{\partial U}{\partial y} = (1+\beta)\frac{\partial^2 U}{\partial y^2} + Gr\theta + GcC - NU + 2\beta\frac{\partial \omega}{\partial y} \tag{10}$$

$$\frac{\partial \omega}{\partial t} - \frac{\partial \omega}{\partial y} = \frac{1}{\eta}\frac{\partial^2 \omega}{\partial y^2} \tag{11}$$

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} + Ec\left(\frac{\partial U}{\partial y}\right)^2 + Du\frac{\partial^2 C}{\partial y^2} \tag{12}$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{13}$$

where, $\eta = \frac{\mu j'}{\gamma} = \frac{2}{2+\beta}, N = M + \frac{1}{K}$ Subject to the boundary conditions: at $y \to 0, U = U_p, \theta = 1 + \varepsilon e^{nt}, \omega = -\frac{\partial U}{\partial y}, C = 1 + \varepsilon e^{nt}$,

as $y \to \infty, U \to 0, \theta \to 0, \omega \to 0, C \to 0$ (14)

## 3. Solution of the problem

The system of equations (10) – (13) are non- linear and in order to obtained solution we expand velocity, microrotation, temperature and concentration in powers of the Eckert number Ec assuming that is very small. This is justified in low speed incompressible flows. Hence

$$U = U_0(y) + \varepsilon e^{nt} U_1(y) + o(\varepsilon^2) + \ldots\ldots \quad \omega = \omega_0(y) + \varepsilon e^{nt}\omega_1(y) + 0(\varepsilon^2) + \ldots..$$

$$\theta = \theta_0(y) + \varepsilon e^{nt}\theta_1(y) + 0(\varepsilon^2) + \ldots.. \quad C = C_0(y) + \varepsilon e^{nt} C_1(y) + 0(\varepsilon^2) + \ldots\ldots \tag{15}$$

where ε is a very small positive quantity and <<1. Substituting (15) in (10) – (13) and neglecting the higher order terms of $0(\varepsilon^2)$, we have the following pairs of equations for $(u_0, \omega_0, \theta_0, C_0)$ aid $(u_1, \omega_1, \theta_1, C_1)$.

$$(1+\beta)U_0'' + U_0' - NU_0 = -Gr\theta_0 - GcC_0 - 2\beta\omega_0' \tag{16}$$

$$(1+\beta)U_1'' + U_1' - (N+n)U_1 = -Gr\theta_1 - GcC_1 - 2\beta\omega_1' \tag{17}$$

$$\omega_0'' + \eta\omega_0' = 0 \tag{18}$$

$$\omega_1'' + \eta\omega_1' - \eta n\omega_1 = 0 \tag{19}$$

$$\theta_0'' + Pr\,\theta_0' = -Pr\,Ec(U_0')^2 - Du\,Pr\,C_0'' \tag{20}$$

$$\theta_1'' + Pr\,\theta_1' - n\,Pr\,\theta_1 = -2\,Pr\,Ec\,U_0'U_1' - Du\,Pr\,C_1'' \tag{21}$$

$$C_0'' + ScC_0' = 0 \tag{22}$$

$$C_1'' + ScC_1' - nScC_1 = 0 \tag{23}$$

The boundary conditions (14) reduces to the following form:

at $y = 0, U_0 = U_p, U_1 = 0, \omega_0 = -U_0, \omega_1 = -U_1', C_0 = 1, C_1 = 1, \theta_0 = 1, \theta_1 = 1$

as $y \to \infty, U_0 = 0, U_1 = 0, \omega_0 \to 0, \omega_1 \to 0, C_0 \to 0, C_1 \to 0, \theta_0 \to 0, \theta_1 \to 0$ (24)

Now using multi parameter perturbation technique, we make the following substitution using Ec as the perturbation parameter:

$$U_0(y)=U_{01}(y)+EcU_{02}(y)+-- \quad U_1(y)=U_{11}(y)+EcU_{12}(y)+--$$

$$\omega_0(y)=\omega_{01}(y)+Ec\omega_{02}(y)+-- \quad \omega_1(y)=\omega_{11}(y)+Ec\omega_{12}(y)+-- \tag{25}$$

$$\theta_0(y)=\theta_{01}(y)+Ec\theta_{02}(y)+-- \quad \theta_1(y)=\theta_{11}(y)+Ec\theta_{12}(y)+--$$

Using (25) in the equations (16) – (23) and equating the co-efficient of $Ec^0, Ec^1$ and neglecting the higher powers of Ec, we have the following equations: The zeroth order equations are:

$$(1+\beta)U''_{01}+U'_{01}-NU_{01}=-Gr\theta_{01}-GcC_{01}-2\beta\omega'_{01} \tag{26}$$

$$(1+\beta)U''_{02}+U'_{02}-NU_{02}=-Gr\theta_{02}-GcC_{02}-2\beta\omega'_{02} \tag{27}$$

$$\omega''_{01}+\eta\omega'_{01}=0 \tag{28}$$

$$\omega''_{02}+\eta\omega'_{02}=0 \tag{29}$$

$$\theta''_{01}+\Pr\theta'_{01}=-Du\Pr C''_{01} \tag{30}$$

$$\theta''_{02}+\Pr\theta'_{02}=-\Pr\left(U'_{01}\right)^2-Du\Pr C''_{02} \tag{31}$$

$$C''_{01}+ScC'_{01}=0 \tag{32}$$

$$C''_{02}+ScC'_{02}=0 \tag{33}$$

Subject to the boundary conditions:

at $y=0, U_{01}=U_p, U_{02}=0, \theta_{01}=1, \theta_{02}=0, \omega_{01}=-U'_{01}, \omega_{02}=-U'_{02}, C_{01}=1, C_{02}=1$

as $y\to\infty, U_{01}\to 0, U_{02}\to 0, \theta_{01}\to 0, \theta_{02}\to 0, \omega_{01}\to 0, \omega_{02}\to 0, C_{01}\to 0, C_{02}\to 0$ (34)

The first order equations are:

$$(1+\beta)U''_{11}+U'_{11}-(N+n)U_{11}=-Gr\theta_{11}-GcC_{11}-2\beta\omega'_{11} \tag{35}$$

$$(1+\beta)U''_{12}+U'_{12}-(N+n)U_{12}=-Gr\theta_{12}-GcC_{12}-2\beta\omega'_{12} \tag{36}$$

$$\omega''_{11}+\eta\omega'_{11}-\eta n\omega_{11}=0 \tag{37}$$

$$\omega''_{12}+\eta\omega'_{12}-\eta n\omega_{12}=0 \tag{38}$$

$$\theta''_{11}+\Pr\theta'_{11}-n\Pr\theta_{11}=-\Pr DuC''_{11} \tag{39}$$

$$\theta''_{12}+\Pr\theta'_{12}-n\Pr\theta_{12}=-2\Pr U'_{01}U'_{11}-\Pr DuC''_{12} \tag{40}$$

$$C''_{11}+ScC'_{11}-nScC_{11}=0 \tag{41}$$

$$C''_{12}+ScC'_{12}-nScC_{12}=0 \tag{42}$$

Subject to the boundary conditions:

at $y=0, U_{11}=0, U_{12}=0, \theta_{11}=1, \theta_{12}=0, \omega_{11}=-U'_{11}, \omega_{12}=-U'_{12}, C_{11}=1, C_{12}=1$

as $y\to\infty, U_{11}\to 1, U_{12}\to 0, \theta_{11}\to 0, \theta_{12}\to 0, \omega_{11}\to 0, \omega_{12}\to 0, C_{11}\to 0, C_{12}\to 0$ (43)

Solutions of equations (26) – (42) are obtained but not presented for the sake of brevity

## 4. Skin- friction, the rate of heat transfer and the rate of mass transfer

The co-efficient of skin- friction is defined in non- dimensional form as: $\tau = \left[\frac{\partial u}{\partial y}\right]_{y=0}$

The non- dimensional rate of heat transfer in terms of Nusselt number Nu is given by: $\mathrm{Nu} = \left[\frac{\partial \theta}{\partial y}\right]_{y=0}$

The non- dimensional rate of mass transfer in terms of Sherwood number Sh is given by: $\mathrm{Sh} = \left[\frac{\partial C}{\partial y}\right]_{y=0}$

## 5. Results and discussion

In this paper, Dufour effects on unsteady MHD convective heat and mass transfer flow of micropolar fluid past a vertical porous plate have been investigated. In order to get physical insight into the problem, the numerical calculations are carried out for velocity, microrotation, temperature, concentration, Sherwood number, Nusselt number and Skin-friction at the plate by assigning some arbitrary chosen specific values to the physical parameters like *Du, Ec* and *Sc.*

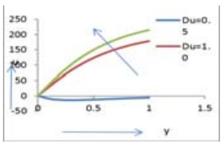


*Figure 1: (a): Velocity profile for different Du when Gr=2.0, Gc=4.0, M=0.5, Ec=0.05, Sc=2.0, Pr=0.71, n=0.1, t=1.0, n=0.2,* $\varepsilon = 0.001$, $\beta = 1.0, \eta = 1.0$, $U_p = 0.5$,

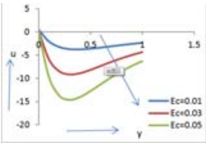


*Figure 1: (b): Velocity profile for different Ec when Gr=2.0, Gc=4.0, M=0.5, Pr=0.71, Du=0.25, Sc=2.0, n=0.1, t=1.0, N=0.2,* $\varepsilon = 0.001$, $\beta = 1.0, \eta = 1.0$, $U_p = 0.5$

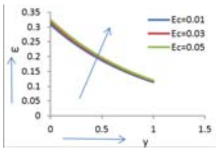


*Figure 2: Microrotation profile for different Ec when Gc=4.0, M=0.5, Pr=0.71, Du=0.25, Sc=2.0, n=0.1, t=1.0, N=0.2,* $\varepsilon = 0.001$, $\beta = 1.0, \eta = 1.0$, $U_p = 0.5$ *, Gr=2.0*

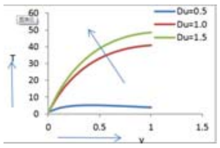


*Figure 3: (a): Temperature profile for different Du when Gc=4.0, Gr=2.0, M=0.5, Ec=0.05, Pr=0.71, Sc=2.0, n=0.1, t=1.0, N=0.2,* $\varepsilon = 0.001$, $\beta = 1.0, \eta = 1.0$, $U_p = 0.5$

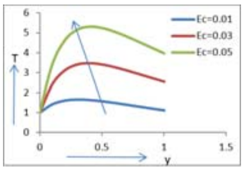


*Figure 3: (b): Temperature profile for different Ec when Gc=4.0, Gr=2.0, M=0.5, Sc=2.0, Pr=0.71, Du=0.25, n=0.1, t=1.0, N=0.2,ε=0.001, β=1.0, η=1.0,* $U_p = 0.5$

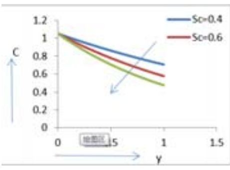


*Figure 4: (a): Concentration profile for different Sc when Gc=4.0, Gr=2.0, M=0.5, Ec=0.05, Pr=0.71, Du=0.25, n=0.1, t=1.0, N=0.2ε=0.001, β=1.0, η=1.0* $U_p = 0.5$

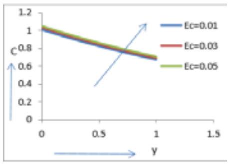


*Figure 4: (b): Concentration profile for different Ec when Gr=2.0, Gc=4.0, M=0.5, Pr=0.71, Du=0.25, Sc=2.0, n=0.1, t=1.0, N=0.2, ε=0.001, β=1.0, η=1.0,* $U_p = 0.5$,

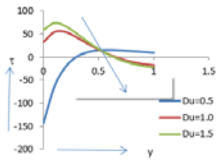


*Figure 5: (a): Skin-friction coefficient for different Du when Gc=4.0, Gr=2.0, M=0.5, Ec=0.05, Pr=0.71, Sc=2.0, n=0.1, t=1.0, N=0.2,ε=0.001, β=1.0,η=1.0,* $U_p = 0.5$

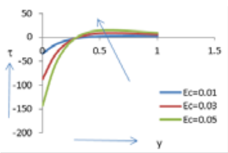


*Figure 5: (b): Skin-friction coefficient for different Ec when Gc=4.0, Gr=2.0, M=0.5, Pr=0.71, Du=0.25, Sc=2.0, n=0.1, t=1.0, N=0.2,ε=0.001,β=1.0, η=1.0,* $U_p = 0.5$

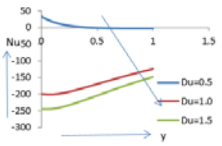


*Figure 6: (a): Nusselt number for different Du when Gc=4.0, Gr=2.0, M=0.5, Ec=0.05, Pr=0.71, Sc=2.0, n=0.1, t=1.0, N=0.2, ε=0.001, β=1.0,η=1.0,* $U_p = 0.5$

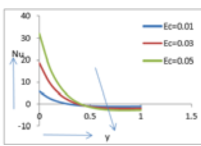


*Figure 6: (b): Nusselt number for different Ec when Gc=4.0, Gr=2.0, M=0.5, Pr=0.71, Du=0.25, Sc=2.0, n=0.1, t=1.0, N=0.2,ε=0.001,β=1.0,η=1.0* , $U_p = 0.5$

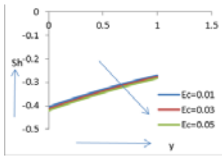


*Figure 7: Sherwood number for different Ec when Gc=4.0, Gr=2.0, M=0.5, Sc=2.0, Du=0.25, Pr=0.71, n=0.1, t=1.0, N=0.2,ε=0.001,β=1.0, η=1.0,* $U_p = 0.5$

Figures 1(a) and 1(b) represent the variations of non- dimensional velocity profile u against y for different values of different governing parameters like *Du* and *Ec*. Figure 1(a) shows that the velocity profile increases on increasing the Dufour number *Du* in the region away from the plate. This implies that, Dufour number tends to rises the fluid velocity in the region away from the plate. Figure 1(b) displays the influence of the Eckert number *Ec* on the velocity profile. Increasing the *Ec* decreases the velocity. Figure 2 depicts the effect of Eckert number *Ec* on the microrotation. It is observed that the microrotation increases with an increasing of the Eckert number. Figures 3(a)and 3(b) demonstrate the variations of temperature distribution against y under the influence of the parameters *Du* and *Ec*. Increasing the Dufour number *Du*, increases the temperature of the flow fluid as seen in figure 3(a). This implies that the Dufour number tends to enhance fluid temperature throughout the boundary layer region. Figure 3(b) shows the temperature profile across the boundary layer for different values of Eckert number *Ec*. The figure shows that an increase in *Ec* results in a increasing the temperature distribution. The influence of Schmidt number *Sc*, Eckert number *Ec* on the concentration profiles are plotted in figures 4(a) and 4(b). Figure 4(a) depicts the effect of Schmidt number *Sc* on concentration profile. This implies that an increase in the value of *Sc* cause a fall in the concentration throughout the boundary layer. Figure 4(b) shows that the concentration distribution increases with the increasing of the *Ec*. Figure 5(a) depicts that skin-friction $\tau$ at the plate decreases with the increasing value of Dufour number *Du*. From figure 5(b) it is clear that $\tau$ at the plate increases due to the effect of *Ec*. Figures 6(a) and 6(b) display the rate of heat transfer decelerates under the influence of *Du, Ec* and *Pr*. The nature of Sherwood number (rate of ass transfer) is presented in figures 7. From these figure shows that the rate of mass transfer decreases with the increasing value *Ec*.

## 6. Conclusion

Our theoretical investigation can be summarized to the following conclusions:
1. A rise in Dufour number increases the velocity profile and temperature profile whereas velocity decreases and temperature profile rise with the increasing value of Eckert number. 2. An increase in Eckert number contributes to increase the Magnitude of microrotation. 4. The concentration profile decreases with the increasing value of Schmidt number whereas it rises with the increasing value of Eckert number. 5. Skin-friction decreases with the increase of Du whereas it increases with the increase of Ec and Sc. 6. The rate of heat transfer decreases with the increasing values of Dufour number and Eckert number. 7. The rate of mass transfer tends to decrease with the increasing value of Eckert number.

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