Simultaneous effects of soret and ohmic heating on MHD free convective heat and mass transfer flow of micropolar fluid with porous medium

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ABSTRACT
We investigate the simultaneous effects of soret and ohmic heating on MHD free convective heat and mass transfer flow for a micro polar fluid bounded by a vertical infinite surface. Approximate solutions have been derived for the velocity, angular velocity, temperature field, concentration profiles, skin friction and rate of heat transfer using multi-parameter perturbation method. The effects of various pertinent parameters on flow, heat and mass transfer properties are discussed numerically and explained graphically. Also the velocity profiles of micropolar fluid is compared with the corresponding flow problem for a Newtonian fluid and found that the polar fluid velocity is decreasing.

Introduction
The theory of micropolar fluids was developed by Eringen [1-3] describes some physical systems which do not satisfy the Navier-Stokes equations. This theory may be applied to the explanation for the phenomenon of the flow of colloidal fluids, liquid crystals, polymeric suspensions, animal blood, etc. Radhakrishnamacharya [4] analyzed the flow of micropolar fluid through a constricted channel. Rees and Pop [5] discussed the free convection boundary-layer flow of a micropolar fluid from a vertical flat plate. Sharma and Gupta [6] studied the effects of medium permeability on thermal convection in micropolar fluids. Prathap Kumar et al. [7] have investigated the problem of fully developed free convective flow of micropolar and viscous fluids in a vertical channel. Muthu et.al. [8] studied peristaltic motion of micropolar fluid in circular cylindrical tubes. Srinivasacharya et.al. [9] analyzed the unsteady stokes flow of micropolar fluid between two parallel porous plates. Recently Muthuraj and Srinivas [10] investigated, fully developed MHD flow of a micropolar and viscous fluids in a vertical porous space using HAM. Kim [11] investigated the effects of heat and mass transfer in the MHD micropolar fluid flow past a vertical moving plate. The simultaneous effects of heat and mass transfer with chemical reaction are of great importance to engineers and scientists because of its occurrence in many branches of science and engineering. The effects of the chemical reaction and mass transfer on MHD unsteady free convection flow past an infinite/semi infinite vertical was analyzed by [12-17].

The study of fluid flows and heat transfer through porous medium has attracted much attention recently. This is primarily because of numerous applications of flow through porous medium, such as separation processes in chemical industries, filtration, transpiration cooling, ground water pollution etc. Effect of heat generation or absorption on free convective flow with heat and mass transfer in geometries with and without porous media has been studied by many scientists and technologists [18-24].The free convection effects on the oscillatory flow of couple stress fluids through a porous medium have been investigated by Hiremath and Patil [25]. Sharma and Sharma [26] have discussed effects of the thermo solutal convection of micropolar fluids with MHD through a porous medium. Ibrahim et al.[27] have examined the effects of unsteady MHD micropolar fluids over a vertical porous plate through a porous medium in the presence of thermal and mass diffusion with a constant heat source. Kim [28] has studied the effects of heat and mass transfer on MHD micropolar flow over a vertical moving porous plate in a porous medium. Recently Rajagopal et.al. [29] investigated the linear stability of Hagen-Poiseuille flow in a chemically reacting fluid. Ogulu [30] has studied the effects of oscillating temperature flow of a polar fluid past a vertical porous plate in the presence of couple stresses and radiation. Rehman and sattar [31] have analyzed the effect of magnetohydrodynamic convective flow of a micropolar fluid past a continuously moving porous plate in the presence of heat generation/ absorption.

The role of thermal radiation on the flow and heat transfer process is major importance in the design of many advanced energy conversion systems operating at higher temperatures. Thermal radiation with in the system is the result of emission by hot walls and the working fluid. Sunil et al. [32] have analyzed the effects of radiation on a layer of micropolar ferromagnetic fluids heated from below saturating a porous medium are investigated. Effects of chemical reaction and thermal radiation on heat and mass transfer flow of MHD micropolar fluid in rotation frame of reference is investigated by Das [33]. A
complete analytic solution to heat transfer of a micropolar fluid through a porous medium was analyzed by Rashidi et al. [34]. MHD flow of a micropolar fluid towards a vertical permeable plate with prescribed surface heat flux is investigated by Nor Azizah et al. [35]. Ezzat et al. [36] steadied the combined heat and mass transfer for unsteady MHD flow of perfect conducting micropolar fluid with thermal relaxation. Peristaltic motion of a magnetohydrodynamic micropolar fluid in tube is analyzed by Yongqi Wang et al. [37]. When heat and mass transfer occur simultaneously in a moving fluid, the effects of the viscous dissipations are more realistic to include Soret and Ohmic effect in order to bring the chemical reactions into the picture. The integration of the continuity equation (1) yields
\[ \frac{\partial v^*}{\partial y^*} = 0 \tag{1} \]

\[ v^* \frac{\partial \theta^*}{\partial y^*} = \frac{\gamma}{I} \frac{\partial^2 \omega^*}{\partial y^*^2} \tag{2} \]

The effects of the viscous dissipations and Darcy dissipation are accounted in the energy balance equation. The chemical reactions are taking place in the flow field and all thermo physical properties are assumed to be constant. The flow is due to buoyancy forces generated by the temperature gradient. The concentration of the porous medium is \( C_w \) concentration of species far from the surface \( C_w^* \). The effects of the viscous dissipation and Darcy dissipation are accounted in the energy balance equation. The chemical reactions are taking place in the flow and all thermo physical properties are assumed to be constant. The flow is due to buoyancy effects arising from density variations caused by differences in the temperature as well as species concentration. Taking into consideration these assumptions, the equations that describe the physical situation can be written in Cartesian frame of references, as follows:

\[ \frac{\partial v^*}{\partial y^*} = 0 \tag{3} \]

\[ v^* \frac{\partial \theta^*}{\partial y^*} = \frac{\gamma}{I} \frac{\partial^2 \omega^*}{\partial y^*^2} \tag{4} \]

\[ v^* \frac{\partial \theta^*}{\partial y^*} = \frac{\lambda}{\rho C_p} \frac{\partial^2 T^*}{\partial y^*^2} + \frac{v}{K C_p} u^2 - \frac{Q}{\rho C_p} \frac{1}{\partial y^*} \frac{\partial \theta^*}{\partial y^*} \tag{5} \]

The appropriate boundary conditions are

\[ y^* = 0: u^* = 0, \frac{\partial \omega^*}{\partial y^*} = 0, \frac{\partial^2 \theta^*}{\partial y^*^2}, T^* = T_w^*, C^* = C_w^* \tag{6} \]

The boundary conditions (6) are derived from the assumption that the couple stresses are dominant during the rotation of the particles.

\[ \int_{0}^{1} K_{\text{geo}} \frac{\partial u^*}{\partial y^*} \, dy^* = 4(T_w^* - T_{\infty}^*) \tag{7} \]

Where \( u^* \) the constant suction velocity at the wall and the negative sign is indicates that the suction velocity is directed towards the plate.

The radiative heat flux is given by

\[ E = \frac{K^*}{C^*} (T_{\infty}^* - T_{\infty}^*) \tag{8} \]

In the view of the above non-dimensional variables, the basic equations (2)-(5) can be expressed in non dimensional form as

\[ (1 + \alpha) u^* + u^- (\frac{1}{K} + M) u = -\left( \theta Gr + \phi Gm + 2 \alpha \omega^* \right) \tag{9} \]

\[ \alpha \omega^* + \beta \omega^* = 0 \tag{10} \]

\[ \theta^* + \Pr \theta^* = -\Pr E \left( \frac{u^* u^*}{K} \right) \tag{11} \]

\[ \phi^* + \alpha \omega^* = -\alpha \omega^* \theta^* \tag{12} \]

Where \( Gr \) is the Grashof number, \( Gm \) is the solutal Grashof number, \( Pr \) is the Prandtl number, \( M \) is the magnetic field.
parameter, $F$ is the radiation parameter, $Sc$ is the Schmidt number, $\phi$ is the heat source parameter, and $\Delta$ is the chemical reaction parameter. $Q$ is heat generation parameter, $\alpha, \beta$ are the polar (material) parameters, $K$ is the permeability of the porous medium, $E$ is the viscous and Darcy’s dissipation parameter and $S_p$ is the Soret number.

The corresponding boundary conditions in dimensionless form are

\[
y = 0: \quad u = 0, \omega = -u', \theta = 1, \phi = 1
\]
\[
y \to \infty: \quad u \to 0, \omega \to 0, \theta \to 0, \phi \to 0
\]  

(14)

Where the prime denotes the differentiation with respect to $y$. The mathematical statement of the problem is now complete and now move on to obtain the solution of Eqns. (10) - (13) subject to boundary conditions (14).

**Solution of the problem:**

A set of partial differential Eqns. (10) – (13) cannot be solved in closed – form. However, it can be solved analytically after these equations are reduced to a set of ordinary differential equations in dimensionless form which can be done by representing the velocity, angular velocity, temperature and concentration as follows:

\[
u(y) = u_0(y) + Eu_0(y) + o(E^2)
\]
\[
\omega(y) = \omega_0(y) + E\omega_0(y) + o(E^2)
\]
\[
\theta(y) = \theta_0(y) + E\theta_0(y) + o(E^2)
\]
\[
\phi(y) = \phi_0(y) + E\phi_0(y) + o(E^2)
\]  

(15)

Where the zeroth order term correspond to the case in which the viscous and Darcy’s dissipation is neglected (E=0), the substitution of Eqns. (15) into Eqns. (10) - (13) and the Appendix.

Subjected to the reduced boundary conditions

\[
y = 0: \quad u_0 = 0, \omega_0 = -u_0', \theta_0 = 1, \phi_0 = 1
\]
\[
y \to \infty: \quad u_0 \to 0, \omega_0 \to 0, \theta_0 \to 0, \phi_0 \to 0
\]  

(20)

First-order:

\[
(1 + \alpha)u_0' + u_0' - \left[1 + \alpha \frac{K}{M} \right] u_0 = \{-\theta_0 \phi_0 \theta_0 + \phi_0 \phi_0 \phi_0 \alpha + 2\alpha \phi_0 \}
\]  

(16)

\[
\omega_0' + \beta \omega_0' = 0
\]  

(17)

\[
\theta_0' + Pr \theta_0' = Pr(1 + \alpha \frac{K}{M}) = 0
\]  

(18)

\[
\phi_0' + Sc \phi_0' - Sc \Delta \phi_0' = -Sc \phi_0 \phi_0
\]  

(19)

Subjected to the reduced boundary conditions

\[
y = 0: \quad u_0 = 0, \omega_0 = -u_0', \theta_0 = 1, \phi_0 = 1
\]
\[
y \to \infty: \quad u_0 \to 0, \omega_0 \to 0, \theta_0 \to 0, \phi_0 \to 0
\]  

(20)

First-order:

\[
(1 + \alpha)u_0' + u_0' - \left[1 + \alpha \frac{K}{M} \right] u_0 = \{-\theta_0 \phi_0 \theta_0 + \phi_0 \phi_0 \phi_0 \alpha + 2\alpha \phi_0 \}
\]  

(21)

\[
\omega_0' + \beta \omega_0' = 0
\]  

(22)

\[
\theta_0' + Pr \theta_0' = Pr(1 + \alpha \frac{K}{M}) = 0
\]  

(23)

\[
\phi_0' + Sc \phi_0' - Sc \Delta \phi_0' = -Sc \phi_0 \phi_0
\]  

(24)

Subjected to the reduced boundary conditions

\[
y = 0: \quad u_0 = 0, \omega_0 = -u_0', \theta_0 = 1, \phi_0 = 1
\]
\[
y \to \infty: \quad u_0 \to 0, \omega_0 \to 0, \theta_0 \to 0, \phi_0 \to 0
\]  

(25)

By solving Eqns. (16) - (19) under the conditions (20) and Eqns. (21)- (24) under the conditions (25) and the substituting the obtained solutions in Equation (15), we obtain

\[
u(y) = c_1 e^{-\beta y} + A_1 e^{\beta y} + A_2 e^{\alpha y} + A_3 e^{\beta y} + E[c_1 e^{-\beta y} + A_1 e^{\beta y} + A_2 e^{\alpha y} + A_3 e^{\beta y} + A_4 e^{\beta y} + A_5 e^{\beta y} + A_6 e^{\beta y} + A_7 e^{\beta y} + A_8 e^{\beta y} + A_9 e^{\beta y} + A_{10} e^{\beta y} + A_{11} e^{\beta y}]
\]
\[
\theta(y) = e^{\beta y} + E[\theta_1 y + A_1 e^{\beta y} + A_2 e^{\beta y} + A_3 e^{\beta y} + A_4 e^{\beta y} + A_5 e^{\beta y} + A_6 e^{\beta y} + A_7 e^{\beta y} + A_8 e^{\beta y} + A_9 e^{\beta y} + A_{10} e^{\beta y} + A_{11} e^{\beta y} + A_{12} e^{\beta y} + A_{13} e^{\beta y} + A_{14} e^{\beta y} + A_{15} e^{\beta y} + A_{16} e^{\beta y} + A_{17} e^{\beta y}]
\]
\[
\phi(y) = e^{\beta y} + E[\phi_1 y + A_1 e^{\beta y} + A_2 e^{\beta y} + A_3 e^{\beta y} + A_4 e^{\beta y} + A_5 e^{\beta y} + A_6 e^{\beta y} + A_7 e^{\beta y} + A_8 e^{\beta y} + A_9 e^{\beta y} + A_{10} e^{\beta y} + A_{11} e^{\beta y} + A_{12} e^{\beta y} + A_{13} e^{\beta y} + A_{14} e^{\beta y} + A_{15} e^{\beta y} + A_{16} e^{\beta y} + A_{17} e^{\beta y}]
\]  

(26)

From the engineering point of view, the most important characteristics of the flow are the skin-friction co-efficient $c_f$, Nusselt number $Nu$ and Sherwood number $Sh$ are given below:

\[
c_f = \left[ \frac{du}{dy} \right]_{y=0} = \left[ \frac{d\omega}{dy} + E \frac{du}{dy} \right]_{y=0}
\]  

(30)

\[
Nu = \left[ \frac{d\theta}{dy} \right]_{y=0} = \left[ \frac{d\phi}{dy} \right]_{y=0} - E \left[ \frac{d\phi}{dy} \right]_{y=0}
\]  

(32)

\[
Sh = \left[ \frac{d\phi}{dy} \right]_{y=0} - \left[ \frac{d\phi}{dy} \right]_{y=0} - E \left[ \frac{d\phi}{dy} \right]_{y=0}
\]  

(34)

Where the expressions for the constants are given in the Appendix.

**Results and Discussions**

Numerical evaluation of analytical results reported in the previous section was performed and a representative set of results is reported graphically in figures 1-15. These results are obtained to illustrate the influence of various parameters on the velocity $u$, angular velocity $\omega$, temperature $\theta$ and concentration $\phi$ profiles etc. In these calculations, the values of chemical reaction parameter $\Delta$, Soret number $S_p$, the polar parameters $\alpha$ and $\beta$ are 0.5,1.0,0.1 and 2.0 respectively. The values of the remaining parameters are mentioned in the corresponding graphs itself.

Figure (1) presents typical profiles of the velocity and angular velocity for varying values of Schmidt number $Sc$. It is noted from figure that an increase in the value of $Sc$ leads to a decrease in the velocity of fluid. Further it is observed that the velocity of the polar fluid is found to decrease in comparison with Newtonian fluid ($\alpha=0$ and $\beta=0$). This is due to the fact that as the Schmidt number increases the concentration decreases which leads to decrease in concentration buoyancy effect, hence

...
a decrease in fluid velocity. The opposite behavior is found in the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effect of the material parameters $\alpha$ and $\beta$, Grashof number $Gr$, solutal Grashof number $Gm$, permeability of the porous medium $K$ and Prandtl number $Pr$ on velocity and angular velocity are observed from fig. (4). The velocity and angular velocity fields are influenced by the combined effect of chemical reaction, internal heat generation, constant suction and viscous and Darcy’s dissipation. We observe that velocity increases as $Gr$, $Gm$, $K$ and $Pr$ increase while it decreases as $\alpha$ and $\beta$ increase. The opposite behavior is found in the case of angular velocity.

The effects of internal heat generation parameter $Q$ on the velocity and angular velocity is displayed in the fig. (3). It is clear from the figure that as the parameter $Q$ increases there is a fall in the velocity in both polar and Newtonian cases. This is due to homogeneous chemical reaction and constant suction. Further, the velocity in the case of Newtonian fluid decreased more remarkably as compared to polar fluids. Hence, it is noticed that the influence of internal heat generation is more on the Newtonian fluid when compared to the polar fluid. The opposite behavior we can see in the case of angular velocity also.

The effect of the Schimidt number $Sc$ on velocity profiles is shown in fig. (1). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effects of chemical reaction parameter $\Delta$ on velocity profiles is shown in fig. (2). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effects of internal heat generation parameter $Q$ on velocity profiles is shown in fig. (3). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effects of material parameters $\alpha$ and $\beta$, Grashof number $Gr$, solutal Grashof number $Gm$, permeability of the porous medium $K$ and Prandtl number $Pr$ on velocity and angular velocity are observed from fig. (4). The velocity and angular velocity fields are influenced by the combined effect of chemical reaction, internal heat generation, constant suction and viscous and Darcy’s dissipation. We observe that velocity increases as $Gr$, $Gm$, $K$ and $Pr$ increase while it decreases as $\alpha$ and $\beta$ increase. The opposite behavior is found in the case of angular velocity.

The effect of the material parameters $\alpha$ and $\beta$, Grashof number $Gr$, solutal Grashof number $Gm$, permeability of the porous medium $K$ and Prandtl number $Pr$ on velocity and angular velocity are observed from fig. (4). The velocity and angular velocity fields are influenced by the combined effect of chemical reaction, internal heat generation, constant suction and viscous and Darcy’s dissipation. We observe that velocity increases as $Gr$, $Gm$, $K$ and $Pr$ increase while it decreases as $\alpha$ and $\beta$ increase. The opposite behavior is found in the case of angular velocity.

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The effects of internal heat generation parameter $Q$ on velocity profiles is shown in fig. (3). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effects of chemical reaction parameter $\Delta$ on velocity profiles is shown in fig. (2). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effect of the material parameters $\alpha$ and $\beta$, Grashof number $Gr$, solutal Grashof number $Gm$, permeability of the porous medium $K$ and Prandtl number $Pr$ on velocity and angular velocity are observed from fig. (4). The velocity and angular velocity fields are influenced by the combined effect of chemical reaction, internal heat generation, constant suction and viscous and Darcy’s dissipation. We observe that velocity increases as $Gr$, $Gm$, $K$ and $Pr$ increase while it decreases as $\alpha$ and $\beta$ increase. The opposite behavior is found in the case of angular velocity.

The effect of the Schimidt number $Sc$ on temperature profiles is shown in fig. (5). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effects of internal heat generation parameter $Q$ on temperature profiles is shown in fig. (3). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.

The effect of the Schimidt number $Sc$ on concentration profile is shown in fig. (6). The behavior observed is similar to the case of angular velocity. The negative values of the angular velocity indicate that the micro rotation of sub structures in the polar fluid is clock-wise. We can observe the same behavior from fig. (2) when $Sc$ is replaced by the chemical reaction parameter $\Delta$.
for small values of $Sc$, as the increase of $Sc$ means decrease of molecular diffusion. Hence there is a decrease in concentration with the increase of $Sc$.

Figure 7: Effects of chemical reaction parameter $\Delta$ on concentration profile

Figure 8: Effects of Magnetic field parameter $M$ on velocity and angular velocity profiles
The effects of magnetic field parameter $M$ on the velocity and angular velocity is displayed in Fig. (8). It is obvious that as the parameter $M$ increases velocity decreases, this is due to the fact that the presence of magnetic field in an electrically conducting fluid introduces a force called Lorentz force, which resists the flow if the applied magnetic field is in normal direction. The opposite behavior is found in angular velocity.

Figure 9: Effects of radiation parameter $F$ on velocity and temperature profiles
The effects of Radiation parameter $F$ on velocity and temperature profiles is shown in the Fig. (9). It can be seen that both velocity and temperature leads to fall as the Radiation parameter increases. It is due to the fact that increase in radiation parameter $F$ results in a increase in the velocity and temperature within the boundary layer, as well as decreased thickness of the velocity and temperature boundary layers.

Figure 10: Effects of Soret number $S_o$ on velocity and concentration profiles
Figure (10) shows the effects of Soret number $S_o$ on the velocity and concentration profiles. It is clear that as the parameter increases both velocity and concentration increases.

Figure 11(a): Effects of polar parameter $a$ on skin friction against chemical reaction parameter $\Delta$

Figure 11(b): Effects of Gr and $G_m$ on skin friction against chemical reaction parameter $\Delta$

Figure 11(c): Effects of polar parameter $a$ and permeability $K$ on skin friction against heat generation parameter $Q$
In Fig. (11), skin friction coefficient is plotted against chemical reaction parameter $\Delta$ and heat generation parameter $Q$. It is observed that the (wall slope of the velocity) skin friction increases against the chemical reaction parameter $\Delta$, as the polar
parameter \( \alpha \), Grashof number \( Gr \) and solutal Grashof number \( Gm \) increase (Fig. 11(a), (b)) while it decrease with \( K \) and increase with \( \alpha \) as the heat generation parameter \( Q \) increases (Fig. 11(c)).

In this study, a numerical analysis is presented to investigate the influence of soret and thermal radiation on steady, laminar, viscous incompressible free convective flow of a polar fluid through a porous medium occupied by a semi infinite region of the space over a porous flat surface. A set of non-linear coupled governing differential equations are solved by two-term perturbation method. The parameters that arise in the governing differential equations are solved by two-term perturbation analysis are Eckert number \( E \) (viscous dissipation), prandtl number \( Pr \), chemical reaction parameter \( \beta \) (characterizes the polarity of the fluid), magnetic field parameter \( M \), radiation parameter \( F \), Soret number \( S_o \), \( C_f \) skin friction coefficient, nusselt number \( Nu \) (wall heat transfer coefficient) and Sherwood number \( Sh \) (wall mass transfer coefficient). A set of graphical results for the velocity, angular velocity, temperature and concentration is presented and discussed. It can be easily observed that skin friction, nusselt number and Sherwood number are effected by the presence of radiation, magnetic field and soret effect. It is also investigated that the velocity of the polar fluid is considerably reduced as compared to the Newtonian fluid in the presence of combined effects of chemical reaction, soret and ohmic heating, internal heat generation and viscous and Darcy’s dissipation. The analytical results obtained in this work are more generalized form of Dulal pal [38] and Chaudhary [39] and can be taken as a limiting case by taking \( \alpha=0, \beta=0, S_o =0 \) and \( \Delta=0, \alpha=0 \) \( \beta=0, S_o =0 \) respectively.

**References:**
16. J.Gireesh Kumar , P.V. Satya Narayana and S.Ramakrishna, Effects of the chemical reaction and mass transfer on MHD unsteady free convection flow past an infinite vertical plate with
34. M.M. Rashid, S.A. Mohimanian Pour, S.Abbasbandy, Approximate analytic solutions for heat transfer of a micropolar fluid through a porous medium with radiation, *Communications in Non-linear science and numerical simulation*, 16 (2011) 1874-1889.

### Table 1: Comparison of Skin Friction $C_f$, Nusselt number $Nu$ and Sherwood number $Sh$ of present case with those of Dulal pal et al. [38] and Chaudhary [39]. for different values of $Sc$

<table>
<thead>
<tr>
<th>$Sc$</th>
<th>Chaudhary [39]</th>
<th>Dulal Pal et al. [38]</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_f$</td>
<td>$NuR_s^{1/3}$</td>
<td>$ShR_s^{1/3}$</td>
<td>$NuR_s^{1/3}$</td>
</tr>
<tr>
<td>$\alpha=0, \beta=0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.22$</td>
<td>$2.4202$</td>
<td>$1.0296$</td>
<td>$0.4640$</td>
</tr>
<tr>
<td>$0.62$</td>
<td>$2.1274$</td>
<td>$1.0376$</td>
<td>$0.9567$</td>
</tr>
<tr>
<td>$0.78$</td>
<td>$2.0518$</td>
<td>$1.0389$</td>
<td>$1.1375$</td>
</tr>
</tbody>
</table>

Note: $C_f$ is the skin friction coefficient, $Nu$ is the Nusselt number, $Sh$ is the Sherwood number, $R_s$ is the radius of the sphere, and $Sc$ is the Schmidt number.
Table (2): Comparison of Skin friction $C_f$, Nusselt number Nu and Sherwood number Sh of present case with those of Dulal pal et al. [38] and Chaudhary [39], for different values of Pr.

<table>
<thead>
<tr>
<th>Pr</th>
<th>Chaudhary [39] ($\Delta=0, S_o=0.0, \alpha=0.0, \beta=0.0$)</th>
<th>Dulal Pal et al. [38] ($S_o=0.0, \alpha=0.0, \beta=0.0$)</th>
<th>Present ($F=0.1, M=0.1, S_o=0.1, \alpha=0.1, \beta=2.0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_f$</td>
<td>$Nu R_x^{-1}$</td>
<td>$Sh R_x^{-1}$</td>
</tr>
<tr>
<td>0.71</td>
<td>2.4202</td>
<td>1.0296</td>
<td>0.4640</td>
</tr>
<tr>
<td>1.00</td>
<td>2.3064</td>
<td>1.3435</td>
<td>0.4640</td>
</tr>
<tr>
<td>1.25</td>
<td>2.2309</td>
<td>1.6074</td>
<td>0.4640</td>
</tr>
</tbody>
</table>