Radiation and Chemical Reaction Effects on Unsteady MHD Mixed Convection Flow over a Vertical Porous Plate with Radiation Absorption

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Abstract

In this paper, a numerical investigation is carried out to discuss the unsteady mixed convection and mass transfer flow past an infinite vertical porous plate embedded in a porous medium in the presence of radiation absorption, heat source, thermal radiation with Soret and chemical reaction effects. The Darcy-Frochhiemer model is used for the momentum equation (porous media). The governing partial differential equations are converted into ordinary differential equations by using non-dimensional variables, which are solved numerically by employing the finite difference method. The influence of various emerging flow parameters on velocity, temperature and concentration distributions are discussed numerically and presented through the graphs. Numerical values of the skin-friction, Nusselt number, and Sherwood number at the plate are discussed numerically for various values of physical parameters and are presented through tables. It is observed from the results that radiation absorption decreases the concentration and increases the velocity and temperature profiles. Also, the Soret number and Schmidt number have tendency to decrease the Nusselt number but it has a tendency to increase the value of chemical reaction parameter.

Keywords: Darcy-Frochhiemer model, finite difference method, mixed convection, Radiation absorption, Heat source, Chemical reaction.

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1. INTRODUCTION

In recent years, transport processes through porous media play important roles in diverse applications such as petroleum industries, seepage of water in river-beds, filtration and purification, and many others. Moreover, the combined forced and free convection flow (mixed convection flow) is encountered in several industrial and technical applications such as nuclear reactors cooled during emergency shutdown, electronics devices cooled by fans, heat exchangers placed in a low velocity environment, solar central receivers exposed to wind currents, etc. Nield and Bejan [1] made a comprehensive survey of convective heat transfer mechanism through porous media. The influence natural convection currents on the oscillatory flow through a porous medium, bounded by vertical plane surface of constant temperature were studied by Hiremath and Patil [2]. Sharma et al. [3] investigated fluctuating heat and mass transfer flow on three-dimensional through a porous medium with variable permeability. At present magnetohydrodynamic is undergoing a period of great amplification and parting of subject matter. The interest in these new problems generates from their importance in liquid metals, electrolytes and ionized gases. Several authors have studied the hydromagnetic free convection flow of heat and mass transfer through porous media under different boundary conditions [4-7].

In many transport processes existing in nature and in industrial applications in which heat and mass transfer is a consequence of buoyancy effects caused by diffusion of heat and chemical species. The study of such processes is useful for improving a number of chemical technologies such as polymer production and food processing. In addition, chemical reactions can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous if it takes place at an interface and homogeneous if it takes place in solution. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of first-order, if the rate of reaction is directly proportional to the concentration itself (Cussler [8]). A few representative fields of interest in which combined heat and mass transfer along with chemical reaction plays an important role is the chemical process industries such as food processing and polymer production. For example, formation of smog is a first order homogeneous chemical reaction. Because of its importance and possible applications, combined heat and mass transfer problems with chemical reaction effect received a considerable amount of attention from researchers. The effects of first order chemical reaction on the flow past an impulsively started infinite vertical plate with constant heat flux and mass transfer was studied by Das et al. [9]. Muthucumarswamy and Ganesan [10] and Muthucumarswamy [11] studied first order homogeneous chemical reaction on flow past infinite vertical plate. Some other related works can also be found in the papers [12–14].
In all the previous investigations, the effects of heat sources/sinks and radiation have been neglected. Recently, many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes imperative for the design of the pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites, and space vehicles are examples of such engineering areas. The effects of suction on boundary layer flow also have greater influence over the engineering application and have been widely investigated by numerous researchers. Various authors have studied the effects of viscous dissipation and constant suction in different surface geometries. The effects of heat and mass transfer along a wedge with heat source and concentration in the presence of suction/injection taking into account the first order chemical reaction was investigated by Kandasamy et al. [15]. Simultaneous effects of thermal and mass diffusion in MHD mixed convection flow from a vertical surface in the presence of radiation were reported by Sharma et al. [16, 17]. Uwanta [18] studied the effects of chemical reaction and radiation on heat and mass transfer past a semi-infinite vertical porous plate with constant mass flux and dissipation. Mansour et al. [19] described the influence of chemical reaction and viscous dissipation on MHD natural convection flow. Govardhan et al. [20] presented a theoretical study on the influence of radiation on a steady free convection heat and mass transfer over an isothermal stretching sheet in the presence of a uniform magnetic field with viscous dissipation effect. Sattar [21] analyzed the effect of free and forced convection boundary layer flow through a porous medium with large suction. Similarly, Mohammed et al. [22] investigated the effect of similarity solution for MHD flow through vertical porous plate with suction. Jai [23] presented the study of a viscous dissipation and chemical reaction effects on flow past a stretching porous surface in a porous medium. In another article, a detailed numerical study on the combined effects of radiation and mass transfer on a steady MHD two-dimensional marangoni convection flow over a flat surface in presence of joule-heating and viscous dissipation under influence of suction and injection is studied by Ibrahim [24]. Khaleque and Samad [25] described the effects of radiation, heat generation, and viscous dissipation on MHD free convection flow along a stretching sheet.

In sight of the above studies, the purpose of present investigation is to examine the influence of radiation absorption, Soret and chemical reaction effects on unsteady mixed convection and mass transfer flow past an infinite radiative vertical porous plate embedded in a porous medium in the presence of heat source and constant suction. The governing equations are converted into non dimensional partial differential equations, which are simplified and solved by finite difference method. The effects of various emerging parameters in the fluid flow are analyzed by plotting graphs.

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2. MATHEMATICAL FORMULATION

Consider the flow of an unsteady two-dimensional flow of an incompressible and electrically conducting viscous fluid, along an infinite vertical porous flat plate embedded in a porous medium in the presence of radiation absorption, heat source and chemical reaction. The $x$-axis is taken on the infinite plate, and parallel to the free-stream velocity which is vertical, and the $y$-axis is taken normal to the plate. A magnetic field $B_0$ of uniform strength is applied transversely to the direction of the flow. Initially the plate and the fluid are at same temperature $T_{\infty}$ in a stationary condition with concentration level $C_{\infty}$ at all points. For $t > 0$, the plate starts moving impulsively in its own plane with a constant velocity $U_0$, its temperature is raised to $T_w$ and the concentration level at the plate is raised to $C_w$. The flow configuration and coordinate system are shown in the Figure 1. The fluid is assumed to have constant properties except that the influence of the density variations with temperature and concentration, which are considered only in the body force term. Under the above assumptions, the physical variables are functions of $y$ and $t$ only.

Assuming that the Boussinesq and boundary layer approximation hold and using the Darcy-Forchheimer model, the basic equations, which govern the problem, are given by:

$$\frac{\partial \overline{v}}{\partial \overline{y}} = 0$$

(1)
\[
\frac{\partial \vec{u}}{\partial t} + \vec{v} \cdot \nabla \vec{u} = \nu \nabla^2 \vec{u} + g \beta (\vec{T} - \vec{T}_\infty) + g B(x, y) (\vec{C} - \vec{C}_\infty) + \frac{\sigma B^2}{\rho} \vec{u} - \frac{\nu}{K} \vec{u} - \frac{b}{Kr} \nabla^2 \vec{u}^2 \tag{2}
\]

\[
\frac{\partial \vec{T}}{\partial t} + \vec{v} \cdot \nabla \vec{T} = \frac{k}{\rho c_p} \frac{\partial^2 \vec{T}}{\partial y^2} - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial y} + \frac{\partial}{\partial y} (\vec{T} - \vec{T}_\infty) + \frac{\partial}{\partial y} (\vec{C} - \vec{C}_\infty) + \frac{\nu}{c_p} \left( \frac{\partial \vec{u}}{\partial y} \right)^2 \tag{3}
\]

\[
\frac{\partial \vec{C}}{\partial t} + \vec{v} \cdot \nabla \vec{C} = D_m \frac{\partial^2 \vec{C}}{\partial y^2} + \frac{D_m k L}{T_m} \frac{\partial^2 \vec{T}}{\partial y^2} - \vec{C}_r (\vec{C} - \vec{C}_\infty) \tag{4}
\]

The initial and boundary conditions at the surface of the plate is given by

\[
\begin{align*}
\bar{r} = 0: & \quad \vec{u} = 0, \quad \vec{v} = 0, \quad \vec{T} = 0, \quad \vec{C} = 0 \quad \text{at} \quad y = 0 \\
\bar{r} > 0: & \quad \vec{u} = U_0, \quad \vec{v} = \nu(t), \quad \vec{T} = \vec{T}_\infty, \quad \vec{C} = \vec{C}_\infty \quad \text{at} \quad y = 0 \\
& \quad \vec{u} \to 0, \quad \vec{T} \to \vec{T}_\infty, \quad \vec{C} \to \vec{C}_\infty \quad \text{as} \quad y \to \infty
\end{align*}
\tag{5}
\]

The continuity eq. (1) on integration, we obtain \( \vec{v} = -\nu_0, \quad \nu_0 > 0. \)

The radiative heat flux term by using Rosseland approximation is given by

\[
q_r = -\frac{4\sigma_1}{k_i} \left( \frac{\partial \vec{T}^4}{\partial y} \right) \tag{7}
\]

The temperature difference within the flow is assumed to be sufficiently small, and then equation (7) can be linearized by expanding \( \vec{T}^4 \) into the Taylor series about \( \vec{T}_\infty \), which after neglecting the higher order terms, thus

\[
\vec{T}^4 = -3\vec{T}_\infty^4 + 4\vec{T}_\infty^3 \tag{8}
\]

Differentiating equation (7) with respect to \( y \) and using eq. (8) to obtain

\[
\frac{\partial q_r}{\partial y} = -\frac{16\vec{T}_\infty^3 \sigma_1}{3k_i} \left( \frac{\partial^2 \vec{T}}{\partial y^2} \right) \tag{9}
\]

In order to write the governing equations and boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

\[
\begin{align*}
\vec{u} &= \frac{\vec{u}}{U_0}, \quad \vec{v} = \frac{U_0 \vec{v}}{\nu}, \quad t = \frac{\vec{T}}{U_0}, \quad \vec{v} = \frac{\vec{v}}{U_0}, \quad \theta = \frac{\vec{T} - \vec{T}_\infty}{\vec{T}_w - \vec{T}_\infty}, \quad \phi = \frac{\vec{C} - \vec{C}_\infty}{\vec{C}_w - \vec{C}_\infty}, \\
S &= \frac{V_0}{U_0}, \quad M = \frac{\sigma B^2}{\rho U_0^3}, \quad Gr = \frac{g \beta \nu (\vec{T}_w - \vec{T}_\infty)}{U_0^3}, \quad Gm = \frac{g \beta \nu (\vec{T}_w - \vec{T}_\infty)}{U_0^3}
\end{align*}
\]
By introducing above dimensionless variables, the Equations (2)-(4) converted as follows:

\[
\frac{\partial u}{\partial t} - S \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr \theta + Gm \phi - \left( M + \frac{1}{Da} \right) u - \frac{Fs}{Da} u^2
\]  

(10)

\[
\frac{\partial \theta}{\partial t} - S \frac{\partial \theta}{\partial y} = \frac{1}{Pr} \left( \frac{3R + 4}{3R} \right) \frac{\partial^2 \theta}{\partial y^2} + Q \theta + Ra \phi + Ec \left( \frac{\partial u}{\partial y} \right)^2
\]  

(11)

\[
\frac{\partial \phi}{\partial t} - S \frac{\partial \phi}{\partial y} = \frac{1}{Sc} \frac{\partial^2 \phi}{\partial y^2} + Sr \frac{\partial^2 \theta}{\partial y^2} - Cr \phi
\]  

(12)

The corresponding initial and boundary conditions (5) are given by

\[
t = 0: \quad u = 0, \quad \theta = 0, \quad \phi = 0 \quad \text{at} \quad y = 0
\]

\[
t > 0: \quad u = 1, \quad \theta = 1, \quad \phi = 1 \quad \text{at} \quad y = 0
\]

\[
u \rightarrow 0, \quad \theta \rightarrow 0, \quad \phi \rightarrow 0 \quad \text{as} \quad y \rightarrow \infty
\]  

(13)

3. METHOD OF SOLUTION:

The unsteady, non-linear coupled equations (10)-(12) using conditions (13), are solved by using finite difference method. Let us consider a rectangular region with \( y \) varying from 0 to \( y_{\text{max}} (=40) \), where \( y_{\text{max}} \) represents to \( y=\infty \). The region to be examined in \((y,t)\) space is covered by a rectangular grid with sides parallel to axes with \( \Delta y \) and \( \Delta t \), the mesh sizes along \( y \)-direction and time \( t \)-direction, respectively. The equivalent finite difference schemes of equations for (10)-(12) are as follows:

\[
\left( \frac{u_{i,j+1} - u_{i,j}}{\Delta t} \right) - S \left( \frac{u_{i+1,j} - u_{i,j}}{\Delta y} \right) = \left( \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{(\Delta y)^2} \right) - \left( M + \frac{1}{Da} \right) u_{i,j}
\]  

\[
+ Gr \theta_{i,j} + Gm \phi_{i,j} - \frac{Fs}{Da} u_{i,j}^2
\]  

(14)
Here, index $i$ refer to $y$ and $j$ refer to time $t$. The mesh system is divided by taking $\Delta y = 0.1$. The initial and boundary conditions from (13) are expressed in finite difference form as follows:

\[
\begin{align*}
(u(i,0) &= 0, \quad \theta(i,0) = 0, \quad \phi(i,0) = 0 \quad \text{for all } i \\
u(0,j) &= 1, \quad \theta(0,j) = 1, \quad \phi(0,j) = 0 \quad \text{for all } j \\
u(i_{\text{max}},j) &= 0, \quad \theta(i_{\text{max}},j) = 0, \quad \phi(i_{\text{max}},j) = 0 \quad \text{for all } j
\end{align*}
\]

Here $i_{\text{max}}$ was taken as 200. First the velocity at the end of time step viz, $u(i, j+1)$, ($i=1$ to 201) is computed from eqn. (14) in terms of velocity, temperature and concentration at points on the earlier time-step. Then $\theta(i, j+1)$ is computed from eqn. (15) and $C(i, j+1)$ is computed from eqn. (16). The procedure is repeated until $t = 0.05$ (i.e. $j = 500$). During computation, $\Delta t$ was chosen as 0.001.

It is now important to calculate the physical quantities of primary interest, which are the local wall shear stress, the local surface heat and mass flux.

### 3.1 The Skin friction:

Given the velocity field in the boundary layer, we can now calculate the local wall shear stress (i.e., skin friction) is given by and in dimensionless form,

\[
\tau = \frac{\tau_w}{\rho U_0^2} = -\left(\frac{\partial u}{\partial y}\right)_{y=0}
\]

where $\tau_w$ is the skin friction.
3.2 **Rate of heat transfer (Nusselt number):**

The dimensionless local surface heat flux (i.e., Nusselt number) is obtained as

\[
Nu(\bar{x}) = -\bar{x} \frac{\left( \frac{\partial \bar{T}}{\partial \bar{y}} \right)_{\tau=0}}{\left( \bar{T}_c - \bar{T}_w \right)}
\]

and on simplification Nusselt number is given by

\[
NuRe_{\bar{x}}^{-1} = -\left( \frac{\partial \theta}{\partial \bar{y}} \right)_{y=0}
\]  

(19)

3.3 **Rate of mass transfer (Sherwood Number):**

The definition of the local mass flux and the local Sherwood number are respectively given by with the help of these equations, one can write

\[
Sh = -\bar{x} \frac{\left( \frac{\partial \bar{C}}{\partial \bar{y}} \right)_{\tau=0}}{\left( \bar{C}_\infty - \bar{C}_w \right)}
\]

and on simplification Sherwood number is given by

\[
ShRe_{\bar{x}}^{-1} = -\left( \frac{\partial \phi}{\partial \bar{y}} \right)_{y=0}
\]  

(20)

4. **RESULTS AND DISCUSSIONS:**

In this paper, numerical values are assigned to the embedded parameters in the system, in order to report the fluid flow structure with respect to velocity, temperature, and concentration profiles. Numerical results for velocity, temperature, and concentration profiles are presented on graphs, while the skin-friction coefficient, Nusselt number, and Sherwood number are shown in tabular form. In the current study, we have chosen the Prandtl number value is \(Pr=0.71\), which corresponds to the air at \(20^\circ C\) and 1 atmospheric pressure and the value of \(Sc=0.22\). we chosen positive large values of \(Gr\) and \(Gm\), due to convection problem, which corresponds to cooling plate. Extensive computations were performed. Default values of the thermo physical parameters are specified as follows: \(M = 3\), \(Gr = 5\), \(Gm = 5\), \(Da = 0.5\), \(Fs = 0.09\), \(S = 0.2\), \(R = 1\), \(Q = 3\), \(Ra = 1\), \(Ec = 0.01\), \(Sr = 1\), \(Cr = 1\). All graphs therefore correspond to these values unless otherwise indicated.

The velocity profiles for different values of magnetic parameter \(M\), thermal Grashof number \(Gr\), and solute Grashof number \(Gm\) are plotted in Figures 2 – 4. It can be
seen that the velocity profile decreases as $M$ increases, while the opposite trend is observed as increasing of $Gr$ and $Gm$. The influence of Suction parameter $S$ and Darcy number $Da$ on the velocity profile is presented in Figure 5 and 6 respectively. It is evident from figures that, the velocity profile decreases as the value of $S$ increases, whereas the opposite trend observed with increase the values of $Da$. The effects of Prandtl number $Pr$, Radiation parameter $R$, heat source parameter $Q$, Radiation absorption parameter $Ra$, and Eckert number $Ec$ on the velocity profile is exemplified in Figures 7 – 11 respectively. As a result, it can be observed that the velocity profile decreases when $Pr$ and $R$ increases. But, the reverse results are found as the values of $Q$, $Ra$ and $Ec$ increases. Figures 12-14, shows the influence of Schmidt number $Sc$, Soret number $Sr$ and chemical reaction parameter $Cr$ on the velocity profiles. It is seen that as $Sc$, $Cr$ increases, there is a decrease in the velocity profile in the boundary layer region, but there is a monotonic increase throughout the boundary layer regime as the value of $Sr$ increases.

The influence of suction parameter $S$ on the temperature profile is depicted in Figure 15. From the figure, it is observed that the temperature profile decreases with an increase of suction parameter. The temperature profiles for different values of Prandtl number $Pr$, and thermal radiation parameter $R$ are plotted in Figures 16 and 17. Here, as the values of $Pr$, $R$ increases the temperature profile decreases. A rise in heat source parameter $Q$, radiation absorption parameter $Ra$ and Eckert number $Ec$ effect increases the temperature profile as shown in Figures 18-20 respectively. The effect of chemical reaction parameter $Cr$ on temperature profile is displayed in Figure 21. From figure, it is observed that increasing the values of $Cr$ decreases the temperature profiles.

The behavior of concentration profiles according to the variation of suction parameter $S$ and Schmidt number $Sc$ are plotted in Figures 22 and 23. It is interesting to observe that the concentration boundary layer strongly decreases with increasing of suction parameter and Schmidt number. Figure 24 presents the concentration profiles for different values of Soret number $Sr$. It is seen from this figure that the concentration profile increases with an increase of Soret number $Sr$. The concentration profile for different values of chemical reaction parameter $Cr$ and radiation absorption parameter $Ra$ are given by Figures 25 and 26, which shows that the concentration profile slightly decreases with increase of both $Cr$ and $Ra$ respectively. The effect of heat source parameter $Q$ and viscous dissipation parameter, that is, Eckert number $Ec$ on concentration profile is displayed in Figures 27 and 28 respectively. It is noticed from the figures that the concentration profile decreases near the plate and increases far away from the plate with an increasing the values of $Q$ and it is increased with an increasing values of $Ec$.

The effects of various governing parameters on skin friction coefficient $\tau$, Nusselt number $Nu$, and Sherwood number $Sh$ is shown in Tables 1, 2 and 3. In order to
emphasize the contributions of each parameter, one parameter is varied while the remaining parameters hold default fixed values. It is observed from Table 1 that an increase in any of the parameters $Gr$, $Gm$ and $Da$ causes reduction in the skin-friction, while increasing any of the parameters $M$ and $S$ resulted in corresponding increase in the skin-friction coefficient. From Table 2, it is observed that an increase in $S$, $Pr$ and $R$ leads to a rise in Nusselt number, while increasing any of the parameters $Q$, $Ra$ and $Ec$ leads to a fall in the Nusselt number. We observed from Table 3 that an increase in $Sc$ and $Sr$ causes’ reduction in the Sherwood number, while increasing any of the parameters $S$ and $Cr$ resulted in corresponding increase in the Sherwood number.

5. CONCLUSIONS:

The effects of radiation and chemical reaction on unsteady MHD mixed convection flow over a vertical porous plate embedded in a porous medium in the presence of radiation absorption, Soret number and heat source have been studied numerically and solved using FDM technique in this paper to discuss the concentration, temperature and velocity of the fluid. The resulting partial differential equations are nondimensionalised, simplified, and solved by finite difference method. From the present investigation, following conclusions have been drawn:

- Enhancement in the value of suction parameter decreases the velocity, temperature and concentration profiles. i.e., suction stabilizes the hydrodynamic, thermal as well as concentration boundary layers growth.
- An increase in the value of radiation absorption decreases the concentration and increases the velocity and temperature profiles.
- Increasing heat source parameter the velocity and temperature profiles increases and concentration decreases near the plate and slightly increases far away from the plate
- Increasing the value of suction parameter there is an increase in the skin friction, Nusselt number and Sherwood number.
- There is increase in the skin friction coefficient with increase in the value of magnetic parameter and decrease with increases in the value of thermal Grashof number, mass Grashof number and Darcy number.
- The value of the Nusselt number has a tendency to increase the value of Prandtl number and radiation parameter and decreases with increase in the value of radiation absorption, heat source and viscous dissipation.
- The Soret number and Schmidt number have tendency to decrease the Sherwood number but it has a tendency to increase the value of chemical reaction parameter.
Fig. 2: Velocity profile for different values of $M$ with $Gr=7$.

Fig. 3: Velocity profile for different values of $Gr$.

Fig. 4: Velocity profile for different values of $Gm$.

Fig. 5: Velocity profile for different values of $S$ with $Gr=10$.

Fig. 6: Velocity profile for different values of $Da$ with $Gr=10$.

Fig. 7: Velocity profile for different values of $Pr$ with $M=1, Gr=7$. 
Fig. 8: Velocity profile for different values of $R$ with $M=1, Gr=7$.

Fig. 9: Velocity profile for different values of $Q$ with $M=1, Gr=Gm=7$.

Fig. 10: Velocity profile for different values of $Ra$ with $M=1, Gr=Gm=7$.

Fig. 11: Velocity profile for different values of $Ec$ with $Gr=7, Gm=7$.

Fig. 12: Velocity profile for different values of $Sc$ with $M=1, Gr=Gm=7$.

Fig. 13: Velocity profile for different values of $Sr$ with $Gr=Gm=7$. 
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Fig. 14: Velocity profile for different values of Cr with M=2, Gr=Gm=7.

Fig. 15: Temperature profile for different values of S with Q=Ra=5.

Fig. 16: Temperature profile for different values of Pr.

Fig. 17: Temperature profile for different values of R.

Fig. 18: Temperature profile for different values of Q.

Fig. 19: Temperature profile for different values of Ra with Q=5.
Fig. 20: Temperature profile for different values of Ec with Q=5

Fig. 21: Temperature profile for different values of Cr with Q=5

Fig. 22: Concentration profile for different values of S

Fig. 23: Concentration profile for different values of Sc with Q=5

Fig. 24: Concentration profile for different values of Sr

Fig. 25: Concentration profile for different values of Cr with Q=5
Fig. 26: Concentration profile for different values of $Ra$ with $Q=5$.

Fig. 27: Concentration profile for different values of $Q$.

Fig. 28: Concentration profile for different values of $Ec$ with $Gr=Gm=7$. 
Table 1: Values of Skin friction coefficient $\tau$ for various values of $M, Gr, Gm, Da, S$ with fixed values of $Fs=0.09, Pr=0.71, R=1, Q=3, Ra=1, Ec=0.01, Sc=0.22, Sr=1$ and $Cr=1$.

<table>
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<th>Gr</th>
<th>Gm</th>
<th>Da</th>
<th>S</th>
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<td>5.0</td>
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Table 2: Values of Nusselt number $Nu$ for various values of $S, Pr, R, Q, Ra$ and $Ec$ with fixed values of $M=3, Gr=Gm=5, Da = 0.5, Fs=0.09, Sc=0.22, Sr=1$ and $Cr=1$.

<table>
<thead>
<tr>
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<th>Ra</th>
<th>Ec</th>
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<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
<td>0.50</td>
<td>3.7229</td>
</tr>
</tbody>
</table>

Table 3: Values of Sherwood number $Sh$ for various values of $S, Sc, Sr$ and $Cr$ with fixed values of $M=3, Gr=Gm=5, Da = 0.5, Fs=0.09, Pr=0.71, R=1, Q=3, Ra=1$ and $Ec=0.01$.

<table>
<thead>
<tr>
<th>S</th>
<th>Sc</th>
<th>Sr</th>
<th>Cr</th>
<th>$Sh$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.22</td>
<td>1.0</td>
<td>1.0</td>
<td>3.4711</td>
</tr>
<tr>
<td>0.4</td>
<td>0.22</td>
<td>1.0</td>
<td>1.0</td>
<td>3.5552</td>
</tr>
<tr>
<td>0.2</td>
<td>0.30</td>
<td>1.0</td>
<td>1.0</td>
<td>3.3087</td>
</tr>
<tr>
<td>0.2</td>
<td>0.22</td>
<td>3.0</td>
<td>1.0</td>
<td>3.1013</td>
</tr>
<tr>
<td>0.2</td>
<td>0.22</td>
<td>1.0</td>
<td>3.0</td>
<td>3.5241</td>
</tr>
</tbody>
</table>

**NOMENCLATURE**

- $\bar{u}, \bar{v}$: Darcian velocity components in the $\bar{x}$ and $\bar{y}$ directions respectively
- $\bar{t}$: Time
- $g$: Acceleration due to gravity
\( \bar{K}r \)  Darcy Permeability

b empirical constant

\( B_0 \) magnetic induction

\( T \) Dimensional temperature of the fluid

\( \bar{T}_{\infty} \) Temperature of the fluid at the plate

\( \bar{T}_{\infty} \) Temperature of the fluid far away from the plate

\( k \) Thermal conductivity

\( q_r \) Radiative heat flux

\( \bar{Q} \) Dimensional heat source

\( \bar{Q}_t \) Dimensional radiation absorption parameter

\( c_p \) Specific heat at constant pressure

\( c_s \) Concentration susceptibility

\( T_m \) Mean fluid temperature,

\( k_f \) Thermal diffusion ratio,

\( \bar{C} \) Dimensional concentration of the solute

\( \bar{C}_w \) Concentration of the solute at the plate

\( \bar{C}_\infty \) Concentration of the solute far from the plate

\( D_m \) Coefficient of mass diffusivity

\( D_r \) Thermal diffusion ratio and

\( \bar{C}r \) Chemical reaction parameter

\( U_o \) Constant velocity of the plate

\( \sigma_1 \) Stefan–Boltzmann constant

\( k_i \) Mean absorption coefficient.
Greek Symbols

\( \nu \)  
Kinematic viscosity

\( \rho \)  
Density

\( \beta \)  
Volumetric coefficient of thermal expansion

\( \bar{\beta} \)  
Volumetric coefficient of concentration expansion

\( \sigma \)  
electric conductivity

REFERENCES:


[19]. M. A. Mansour, N. F. El-Anssary, and A. M. Aly, “Effect of chemical reaction and viscous dissipation on MHD natural convection flows saturated in porous


