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# Effects of thermal diffusion and chemical reaction on MHD transient free convection flow past a porous vertical plate with radiation, temperature gradient dependent heat source in slip flow regime

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**Abstract**

An analytical investigation is conducted to study the unsteady free convection heat and mass transfer flow through a non-homogeneous porous medium with variable permeability bounded by an infinite porous vertical plate in slip flow regime while taking into account the thermal radiation, chemical reaction, the Soret number, and temperature gradient dependent heat source. The flow is considered under the influence of magnetic field applied normal to the flow. Approximate solutions for velocity, temperature, and concentration fields are obtained using perturbation technique. The expressions for skin-friction, rate of heat transfer, and rate of mass transfer are also derived. The effects of various physical parameters, encountered in the problem, on the velocity field, temperature field, and concentration field are numerically shown through graphs, while the effects on skin-friction, rate of heat, and mass transfer are numerically discussed by tables.

## 1. Introduction

Natural or free convection flows which are caused by buoyancy or reduced gravity [1, 2] are due to spatial temperature variations that give rise to the corresponding variations in the density of fluids (both gases and liquids). It is known that buoyancy induced flow within fluid-saturated porous media is encountered in a wide range of thermal engineering applications such as geothermal systems, oil extraction, ground water pollution, thermal insulation, heat exchangers, storage of nuclear wastes, packed bed catalytic reactors, as well as atmospheric and oceanic circulation. Comprehensive discussions and/or reviews are found in the literature [3-5].

The phenomenon of magneto hydrodynamic flow with heat and mass transfer has been a subject of growing interest because if its

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possible applications in many branches of science, technology, and industry. The study of effects of magnetic field on free convection flow is often important in liquid metals, electrolytes, and ionized gasses. Chamaka [6] studied heat and mass transfer effects on MHD free convection flow from a permeable surface embedded in a fluid saturated porous medium. MHD flow of viscous fluid through a porous medium bounded by an oscillating porous plate in slip flow regime was investigated by Gupta and Sharma [7]. Kim [8] considered effect of heat transfer on unsteady MHD convective flow past a semi-infinite vertical porous moving plate with variable suction. Raju and Varma [9] discussed unsteady MHD free convection oscillatory coquette flow embedded in a porous medium in the presence of periodic wall temperature. MHD free convection heat and mass transfer flow through a porous medium bounded by an infinite vertical porous plate with constant heat flux was proposed by Raptis and Kafousias [10].

The effect of radiation on MHD flow and heat transfer problems has become industrially more important. Many engineering processes occur at high temperatures; hence, the knowledge of radiation heat transfer is essential for designing the appropriate equipment. Nuclear power plants, gas turbines, and various propulsion devices for air craft, missiles, and satellites are examples of such processes [11]. When radiative heat transfer takes place, the involved fluid can be electrically conducting, since it is ionized due to the high operating temperature. Ghaly [12] developed the radiation effects on a certain MHD free convection flow. Ahmed and Sarmah [13] investigated the effect of thermal radiation on the transient MHD flow heat and mass transfer past an impulsively infinite vertical plate. The effect of radiation on magnetohydrodynamic flow past a plate was studied by Raptis and Massalas [14]. Poonia and Chaudary [15] presented the influence of thermal radiation on MHD oscillating flow in a planner channel with a slip condition. The effects of thermal radiation on different free convective flows in the presence of various situations have been investigated by several research scholars [16-19].

In the above-mentioned studies, the heat source/sink effect is ignored. Due to its great applicability to ceramic tile production problems, the study of heat transfer in the presence of a heat source/sink has acquired newer dimensions. A number of analytical studies have been done for various forms of heat generation (Ostrach [20], Raptis [21]). Singh [22] analyzed MHD free convection and mass transfer flow with heat source and thermal diffusion. Sexena and Dubey [23] investigated MHD free convection heat and mass transfer flow of viscoelastic fluid embedded in a porous medium with variable permeability and radiation effect and heat source in slip flow region. Mohammed Ibrahim and Bhaskar Reddy [24] studied the mass transfer and radiation effects on MHD free convection flow along a stretching surface with viscous dissipation and heat generation. Effects of heat generation and thermal radiation on MHD flow near a stagnation point on a linear stretching sheet in porous medium with variable thermal conductivity and mass transfer were studied by Mohammed Ibrahim and Suneetha [25]. Ghalambaz and Noghrehabadi [26] proposed heat generation effect on the natural convection of nanofluids over the vertical plate embedded in porous medium.

The study of heat and mass transfer with chemical reaction is of great practical importance for engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Possible applications of this type of flow can be found in many industries like power and chemical process industries. Madhusudhana Rao et al. [27] studied the chemical reaction and heat source effects on unsteady MHD transient free convective flow past a vertical porous plate with temperature gradient in slip flow regime in the presence of thermal radiation. Ramana Reddy et al. [28] developed the similarity transformation of heat and mass transfer effects on MHD free convective dissipative fluid flow past an inclined porous surface in the presence of chemical. Sudhakar Reddy et al. [29] analyzed the chemical reaction and radiation effects on MHD free convective flow through a porous medium bounded by a vertical surface with constant heat and mass flux. Sahin [30] studied the magnetohydrodynamic and chemical reaction effects on unsteady flow as well as heat and mass transfer characteristics in a viscous, incompressible, and electrically conducting fluid over a semi-infinite vertical porous plate in a slip-flow regime.

In the above-mentioned works, the thermal diffusion (Soret) effect has not been taken into account in the species continuity equation. The flux of mass caused by temperature gradient is known as the Soret effect or thermal diffusion. The experimental investigation of the thermal diffusion effect on mass transfer related problems was first performed by Charles Soret in 1879. Thereafter, its effect has been called the Soret effect in honor of his name. In general, the Soret effect is of smaller order of magnitude than the effect described in Fick's law and is often ignored in mass transfer process. Although this effect is quite small, the devices may be arranged to produce very sharp temperature gradient so that the separation of components in mixtures is affected. Eckert and Drake [31] emphasized that the Soret effect assumes significance in the cases concerning isotope separation and in the mixtures between gases with very light molecular weight ($H_2$, He) and the medium molecular weight ($N_2$, air). Based on Eckert and Drake [31], many other investigators have carried out model studies on the Soret effect in different heat and mass transfer problems. Some of them are Dursunkaya and Worek [32], Kafoussias and Williams [33], Sattar and Alam [34], Alam et al. [35], Prakash et al. [36], etc.

However, to the best knowledge of the present authors, so far no attempts have been made to analyze the simultaneous effects of thermal diffusion and radiation on MHD transient free convective flow past a porous vertical plate with chemical reaction, temperature gradient, and heat source in slip flow regime. Hence, this problem is investigated here.

## 2. Mathematical analysis

Consider a two-dimensional unsteady free convection flow of an incompressible viscous fluid past an infinite vertical porous plate. In rectangular Cartesian coordinate system, we take $x$-axis along the plate in the direction of flow and $y$-axis normal to it. Further, the flow is considered in the presence of temperature gradient dependent heat source, radiation, the Soret number, and chemical reaction. In the analysis, the magnetic Reynolds number is taken to be small so that the induced magnetic field is neglected. Likewise, for small velocity, the viscous dissipation and Darcy's dissipation are neglected. The flow in the medium is entirely due to the buoyancy force caused by temperature difference between the porous plate and the fluid. Under the above assumptions, the equations governing the conservation of mass (continuity), momentum, energy, and concentration can be written as follows:

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\nu}{k'(t)}u' - \frac{\sigma B_0^2}{\rho}u' \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{K_T}{\rho C_P}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_P}\frac{\partial q_r}{\partial y'} + \frac{Q'}{\rho C_P}\frac{\partial T}{\partial y} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - K'_r(C' - C'_\infty) + D_1\frac{\partial^2 T'}{\partial y'^2} \tag{4}$$

The boundary conditions relevant to the problem are

$$u' = L_1\left(\frac{\partial u'}{\partial y'}\right), T' = T'_w, C' = C'_w \quad at \quad y' = 0$$

$$u' \to 0, T' \to T'_\infty, C' \to C'_\infty \; as \; y' \to \infty \tag{5}$$

where $u'$ and $v'$ are the components of velocity along $x$-axis and $y$-axis directions, $t$ is time, $g$ is acceleration due to gravity, $\beta$ and $\beta^*$ are the volumetric coefficient of thermal and concentration expansion, $\nu$ is kinematic viscosity, $k'(t)$ is the permeability of the porous medium, $\rho$ is the density of the fluid, $\sigma$ is the electrical conductivity of the fluid, $B_0$ is the uniform magnetic field, $T'$ is the temperature of the fluid, $K_T$ is thermal conductivity, $C_p$ is the specific heat at constant pressure, $q_r$ is the radioactive heat flux, $Q'$ is the coefficient of heat source parameter, $T'_w$ is the temperature of the wall of the fluid at the plate, $T'_\infty$ is the temperature of the fluid far away from the plate, $C'_\infty$ is the concentration of the fluid far away from the plate, $L_1 = \left(\frac{2-m_1}{m_1}\right)$ isbeing the mean free path where $m_1$ is the Maxwell's reflection coefficient, $C'$ is the concentration of the fluid, $C'_w$ is the concentration of the wall of the fluid at the plate, $D$ is the mass diffusivity, and $K'_r$ is chemical reaction parameter.

$$v' = -v'_0\left(1+\varepsilon e^{-nt}\right) \tag{6}$$

where $v'_0 > 0$ is the suction velocity at the plate and $n$ is a positive constant. The negative sign indicates that the suction velocity acts toward the plate.
Consider the fluid which is optically thin with the relatively low density and radioactive heat flux given by Ede [37] below:

$$\frac{\partial q_r}{\partial y'} = 4\left(T' - T'_\infty\right) I \tag{7}$$

where $I$ is the absorption coefficient at the plate. Permeability $k'(t)$ of the porous medium is considered in the following form:

$$k'(t) = k'_0 \tag{8}$$

For introducing the following dimensionless quantities and variable:

$$u = \frac{u'}{v'_0},\ y = \frac{y'v'_0}{\upsilon},\qquad n = \frac{4\upsilon n'}{v_0'^2},\qquad t = \frac{{v_0}'^2 t'}{4\upsilon}$$

$$Gr = \frac{g\beta\upsilon(T'_w - T'_\infty)}{v_0'^3},\qquad M = \frac{\sigma {B_0}^2\upsilon}{{v_0}'^{2\rho}},$$

$$Gm = \frac{g\beta^*\upsilon(C'_w - C'_\infty)}{v_0'^3}$$

$$Q = \frac{Q'\upsilon}{v_0'^2\left(T'_w - T'_\infty\right)\rho C_p}$$

$$T = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ Ko = \frac{k'_0 v_0'^2}{\upsilon^2},\ R = \frac{4\upsilon I}{\rho C_p v_0'^2}, \tag{9}$$

$$P_r = \frac{\rho C_p \upsilon}{K_T}\qquad K_r = \frac{k'_0\upsilon}{v_0'^2}\qquad Sc = \frac{\upsilon}{D}$$

$$C = \frac{C' - C'_\infty}{C'_w - C'_\infty},\quad So = \frac{D_1\left(T'_w - T'_\infty\right)}{(C'_w - C'_\infty)\upsilon}$$

In the set of Eqs. (2) - (4), we obtain the non–dimensional form of the governing equations as follows:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \left(1+\varepsilon e^{-nt}\right)\frac{\partial u}{\partial y} = GrT + GmC + \frac{\partial^2 u}{\partial y^2} - \left[M + \frac{1}{k_0}\right]u \tag{10}$$

$$\frac{1}{4}\frac{\partial T}{\partial t} - \left(1+\varepsilon e^{-nt}\right)\frac{\partial T}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial y^2} - RT + Q\frac{\partial T}{\partial y} \tag{11}$$

$$\frac{1}{4}\frac{\partial C}{\partial t} - \left(1+\varepsilon e^{-nt}\right)\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - KrC + S0\frac{\partial^2 T}{\partial y^2} \tag{12}$$

and boundary condition (5) is reduced to:

$$u = h\left(\frac{\partial u}{\partial y}\right), T = 1,\ C = 1 \quad at \ \ \text{y=0}$$

$$u \to 0,\ T \to 0,\ C \to 0\ \ as\ \ y \to \infty \tag{13}$$

where $h = \frac{L_1 v_0'^2}{\vartheta}$

### 3. Solution of the problem

To solve the ordinary partial differential equations (10), (11), and (12), we reduce them to ordinary differential equations. To obtain the solution, the following procedure given by Gersten and Gross [38] is used. Therefore, the expressions for velocity, temperature, and concentration are assumed in the following form.

$$u(y,t) = u_0(y) + \varepsilon u_1(y)e^{-nt} + O(\varepsilon^2) \tag{14}$$

$$T(y,t)=T_0(y)+\varepsilon T_1(y)e^{-nt}+O(\varepsilon^2) \quad (15)$$

$$C(y,t)=C_0(y)+\varepsilon C_1(y)e^{-nt}+O(\varepsilon^2) \quad (16)$$

By substituting the above expressions (14), (15), and (16) in Eqs. (10) - (12), equating the harmonic and non-harmonic terms, and neglecting the higher order terms of $O(\varepsilon^2)$, we obtain the following set of ordinary differential equations:

$$u_0''+u_0'-M_1u_0=-GrT_0-GmC_0 \quad (17)$$

$$u_1''+u_1'-M_2u_1=-GrT_1-GmC_1-u_0' \quad (18)$$

$$T_0''+(1+Q)\Pr T_0'-R\Pr T_0=0 \quad (19)$$

$$T_1''+(1+Q)\Pr T_1'-\left(R-\frac{n}{4}\right)\Pr T_1=-\Pr T_0' \quad (20)$$

$$C_0''+ScC_0'-ScKcC_0=-ScS_0T_0'' \quad (21)$$

$$C_1''+ScC_1'-\left(Kr-\frac{n}{4}\right)ScC_1=-ScS_0C_0'-ScS_0T_1'' \quad (22)$$

where $M_1=M+\frac{1}{k_0}$ and $M_2=M+\frac{1}{k_0}-\frac{n}{4}$

and the boundary conditions (13) are reduced to:

$$u_0=hu_0', u_1=hu_1', T_0=1, T_1=0, C_0=1, C_0=0 \quad at \quad y=0$$

$$u_0\to 0, u_1\to 0, T_0\to 0, T_1\to 0, C_0\to 0, C_1\to 0 \quad as\ y\to\infty \quad (23)$$

Equations (17) - (22) are second order linear differential equations with constant coefficients. The solutions of these paired equations under the corresponding boundary conditions (23) are:

$$T_0(y)=e^{-m_1y} \quad (24)$$

$$C_0=A_2e^{-m_2y}-A_1e^{-m_1y} \quad (25)$$

$$u_0=A_5e^{-m_3y}-A_4e^{-m_2y}+A_3e^{-m_1y} \quad (26)$$

$$T_1=-A_6e^{-m_4y}+A_6e^{-m_1y} \quad (27)$$

$$C_1=A_{10}e^{-m_5y}+A_7e^{-m_4y}+A_8e^{-m_2y}-A_9e^{-m_1y} \quad (28)$$

$$u_1=A_{16}e^{-m_6y}-A_{11}e^{-m_5y}+A_{12}e^{-m_4y}+ +A_{13}e^{-m_3y}-A_{14}e^{-m_2y}+A_{15}e^{-m_1y} \quad (29)$$

where the constants are given in Appendix.

By substituting (26) and (29) in (14), the velocity field u(y, t) is:

$$u(y,t)=\left(A_5e^{-m_3y}-A_4e^{-m_2y}+A_3e^{-m_1y}\right) +\varepsilon e^{-nt}\begin{pmatrix}A_{16}e^{-m_6y}-A_{11}e^{-m_5y}+A_{12}e^{-m_4y}\\ +A_{13}e^{-m_3y}-A_{14}e^{-m_2y}+A_{15}e^{-m_1y}\end{pmatrix} \quad (30)$$

By substituting (24) and (27) in (15), the velocity field *T(y, t)* becomes:

$$T(y,t)=\left(e^{-m_1y}\right)+\varepsilon e^{-nt}\left(-A_6e^{-m_4y}+A_6e^{-m_1y}\right) \quad (31)$$

Also, by substituting (25) and (28) in (15), the velocity field C(y, t) is:

$$C(y,t)=\left(A_2e^{-m_2y}-A_1e^{-m_1y}\right)+ \varepsilon e^{-nt}\left(A_{10}e^{-m_5y}+A_7e^{-m_4y}+A_8e^{-m_2y}-A_9e^{-m_1y}\right) \quad (32)$$

Knowing the velocity field, the shearing stress at the plate can be obtained, which is given as follows in the non-dimensional form (skin-friction coefficient):

The expression for the skin–friction ($\tau$) at the plate is:

$$\tau=\left(\frac{du}{dy}\right)_{y=0}=\left(\frac{du_0}{dy}\right)_{y=0}+\varepsilon e^{-nt}\left(\frac{du_1}{dy}\right)_{y=0} =A_{17}+\varepsilon e^{-nt}A_{18} \quad (33)$$

Knowing the temperature field, the heat transfer coefficient at the plate can be obtained, which in the non-dimensional form in terms of the Nusselt number, is given by:

$$Nu=\left(\frac{dT}{dy}\right)_{y=0}=\left(\frac{dT_0}{dy}\right)_{y=0}+\varepsilon e^{-nt}\left(\frac{dT_1}{dy}\right)_{y=0} =-m_1+\varepsilon e^{-nt}A_{19} \quad (34)$$

Knowing the concentration field, the mass transfer coefficient at the plate can be obtained, which in the non-dimensional form, in terms of the Sherwood number, is given by:

$$Sh=\left(\frac{dC}{dy}\right)_{y=0}=\left(\frac{dC_0}{dy}\right)_{y=0}+\varepsilon e^{-nt}\left(\frac{dC_1}{dy}\right)_{y=0} =A_{20}+\varepsilon e^{-nt}A_{21} \quad (35)$$

## 4. Results and discussion

Effects of various parameters like the Grashof number *Gr*, modified Grashof number *Gm*, magnetic parameter $M$, permeability of porous medium $Ko$, the Prandtl number *Pr,* radiation parameter *R*, heat source parameter *Q,* the Schmidt number *Sc,* chemical reaction parameter *Kr*, the Soret number $So$, and slip parameter *h* on velocity distribution, temperature distribution, and concentration distribution are investigated in Graphs 1-10 while keeping the other parameters constant.

Figure 1 exhibits the velocity profile with variation in slip in slip parameter *h*. It is observed that the significance of velocity is high near the plate and, thereafter, decreases and reaches the stationary position at the other side of the plate. As expected, velocity increases with an increase in slip parameter *h*. Figure 2 is prepared to show the influences of thermal Grashof number *Gr* and modified Grashof number *Gm* on velocity. The velocity profiles are clearly observed to be significantly enhanced with increasing *Gr* or *Gm*. The influence of magnetic field parameter *M* and permeability of porous medium *Ko* on velocity profile for the fixed values of other parameters is shown in Fig. 3. It is observed that velocity is reduced by the increase of magnetic field parameter *M*, since the applied magnetic field acts as the Lorentz force which drags velocity. Velocity increases as the permeability of porous medium *Ko* increases. According to

Figure 4, it is concluded that the velocity profile decreases with the increase in radiation parameter *R* and heat source parameter *Q*. Figure 5 shows that velocity profile decreases as the Prandtl number *Pr* or Schmidt number *Sc* increase. Figure 6 depicts the velocity profile for various values of chemical reaction parameter *Kr* and the Soret number *So*. It is noticed that velocity decreases with an increase in chemical reaction *Kr* and velocity increases with the increase in the Soret number *So*.

The influence of the Prandtl number *Pr* on temperature profile is shown in Fig. 7. It is concluded that temperature decreases with an increase in the Prandtl number *Pr*. Effect of heat source parameter *Q* and radiation parameter *R* on temperature is studied in Fig. 8. It can be observed that temperature profile decreases as radiation parameter *R* or heat source parameter *Q* increases.

Influence of the Schmidt number *Sc* and chemical reaction *Kr* on concentration field is shown in Fig. 9. It can be concluded that the concentration profile decreases with an increase in the Schmidt number *Sc* or chemical reaction parameter *Kr*. Figure 10 shows the concentration profile for different values of the Soret number *So*. It is noticed that the concentration profile decreases with an increase in the Soret number *So*.

Variations in skin-friction, rate of heat transfer in the form of the Nusselt number, and rate of mass transfer in the form of the Sherwood number are studied using Tables 1-3. It can be observed in Table 1 that the effect of increasing values of *Gr, Gm*, and *Ko* is to increase skin-friction coefficient. According to Table 2, it is noted that the Nusselt number increases with an increase in the values of *Pr* and *Q,* while it decreases with the increase of *R*. According to Table 3, the value of the Sherwood number increases as *Sc, Kr,* and *So* increase.

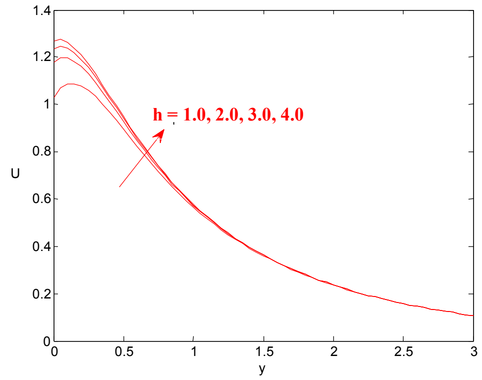


**Fig. 1.** Graph of *u* against *y* for various values of *h*.

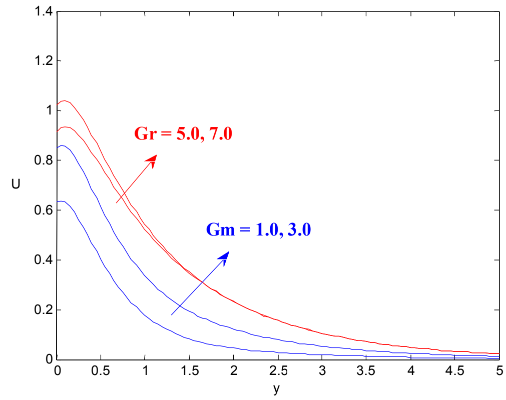


**Fig. 2.** Graph of *u* against *y* for various values of *Gr* and *Gm.*

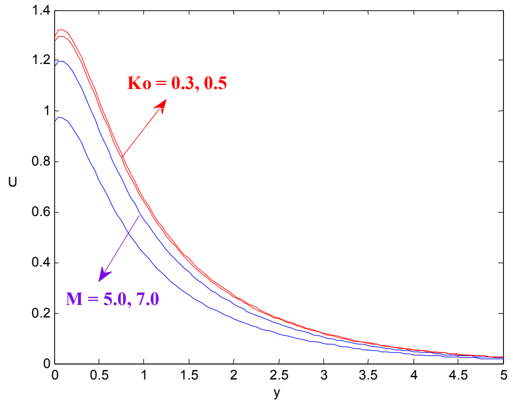


**Fig. 3.** Graph of *u* against *y* for various values of *Ko* and *M*.

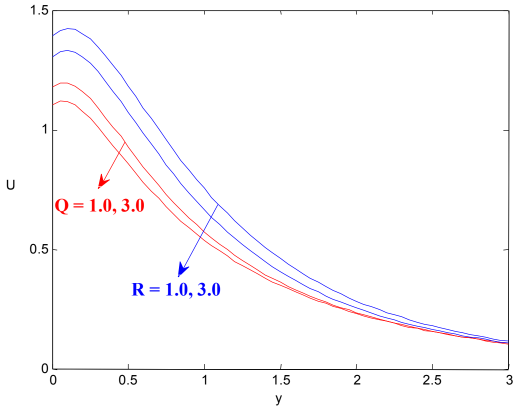


**Fig. 4.** Graph of *u* against *y* for various values of *Q* and *R*.

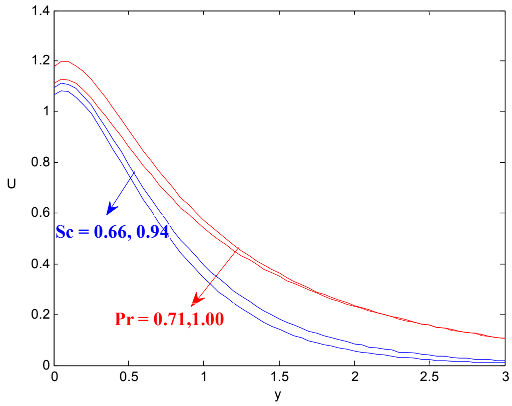


**Fig. 5.** Graph of *u* against *y* for various values of *Pr* and *Sc*.

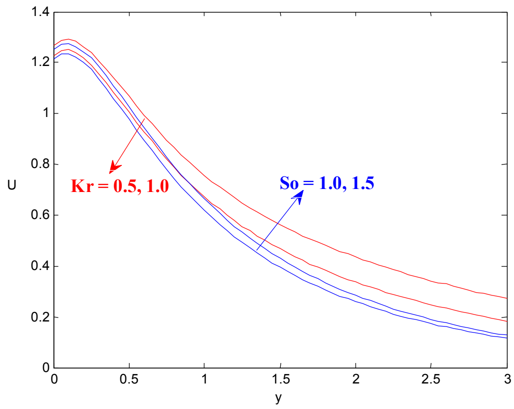


**Fig. 6.** Graph of *u* against *y* for various values of *Kr* and *So*.

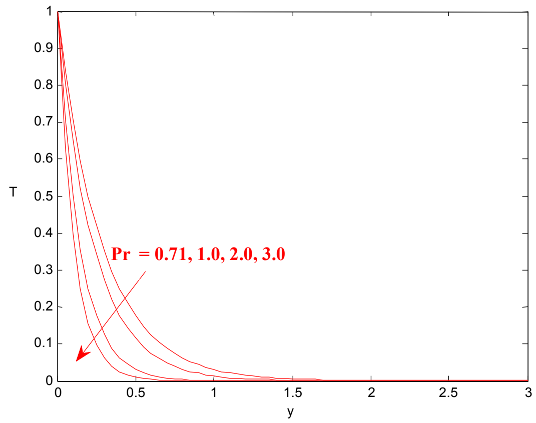


**Fig. 7.** Graph of $T$ against $y$ for various values of $Pr$.

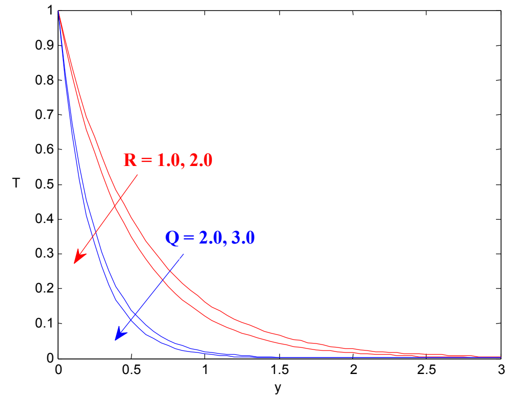


**Fig. 8.** Graph of $T$ against $y$ for various values of $R$ and $Q$.

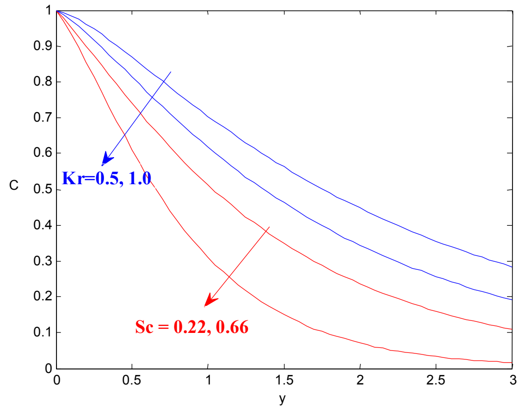


**Fig. 9.** Graph of $C$ against $y$ for various values of $Sc$ and $Kr$.

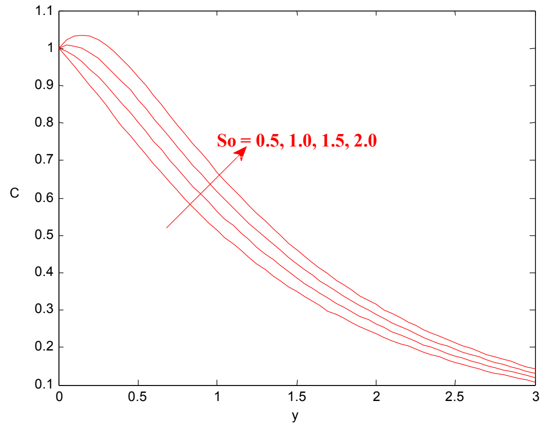


**Fig. 10.** Graph of $C$ against $y$ for various values of $So$.

**Table 1.** Effect of various physical parameters on skin-friction coefficient for $Pr = 0.71$, $Q=1.0$, $R=10$, $Sc=0.22$, $Kr=2$, and $So=0.5$.

| *Gr* | *Gm* | *M* | *Ko* | *Cf* | *Nu* | *Sh* |
|---|---|---|---|---|---|---|
| 10 | 6.0 | 5.0 | 1.0 | 0.5885 | -3.4692 | -0.4449 |
| 12 | 6.0 | 5.0 | 1.0 | 0.6407 | -3.4692 | -0.4449 |
| 14 | 6.0 | 5.0 | 1.0 | 0.6929 | -3.4692 | -0.4449 |
| 10 | 8.0 | 5.0 | 1.0 | 0.6976 | -3.4692 | -0.4449 |
| 10 | 10.0 | 5.0 | 1.0 | 0.8067 | -3.4692 | -0.4449 |
| 10 | 6.0 | 6.0 | 1.0 | 0.5287 | -3.4692 | -0.4449 |
| 10 | 6.0 | 7.0 | 1.0 | 0.4809 | -3.4692 | -0.4449 |
| 10 | 6.0 | 5.0 | 3.0 | 0.6377 | -3.4692 | -0.4449 |
| 10 | 6.0 | 5.0 | 5.0 | 0.6486 | -3.4692 | -0.4449 |

**Table 2.** Effects of various physical parameters on the Nusselt number *Gr=10, Gm=6, M=5, Ko=1 ,Sc=0.22, Kr=2, and So=0.5.*

| *Pr* | *Q* | *R* | *Cf* | *Nu* | *Sh* |
|---|---|---|---|---|---|
| 0.71 | 1.0 | 10 | 0.5885 | -3.4692 | -0.4449 |
| 1.0 | 1.0 | 10 | 0.5553 | -4.3190 | -0.3530 |
| 1.5 | 1.0 | 10 | 0.5181 | -5.6571 | -0.2073 |
| 0.71 | 3.0 | 10 | 0.5513 | -4.4413 | -0.3397 |
| 0.71 | 5.0 | 10 | 0.5208 | -5.5434 | -0.2197 |
| 0.71 | 1.0 | 6 | 0.6174 | -2.8944 | -0.5067 |
| 0.71 | 1.0 | 8 | 0.6013 | -3.1985 | -0.4741 |

**Table 3.** Effects of various physical parameters on the Sherwood number *Gr=10, Gm=6, M=5, Ko=1, Pr = 0.71, Q=1, and R=10.*

| *Sc* | *Kr* | *So* | *Cf* | *Nu* | *Sh* |
|---|---|---|---|---|---|
| 0.22 | 2.0 | 0.5 | 0.5885 | -3.4692 | -0.4449 |
| 0.66 | 2.0 | 0.5 | 0.5473 | -3.4692 | -0.5630 |
| 0.94 | 2.0 | 0.5 | 0.5342 | -3.4692 | -0.6174 |
| 0.66 | 3.0 | 0.5 | 0.5716 | -3.4692 | -0.5997 |
| 0.66 | 4.0 | 0.5 | 0.5587 | -3.4692 | -0.7294 |
| 0.66 | 2.0 | 1.0 | 0.6071 | -3.4692 | -0.1155 |
| 0.66 | 2.0 | 1.5 | 0.6257 | -3.4692 | 0.2139 |

## 5. Conclusions

In this work, the problem of thermal diffusion and radiation effects on MHD transient free convective flow past a porous vertical plate with chemical reaction, temperature gradient dependent, and heat source in slip flow regime was investigated. The resulting governing equations were solved by the perturbation scheme and presented for the variations of major parameters. A systematic study on the effects of various parameters on flow, heat, and mass transfer characteristics was also carried out. Some of the important findings, obtained from the graphical and table representations of the results, are listed below:

- An increase in magnetic field parameter M led to decrease in the velocity distribution, while a reverse effect was noticed for the permeability of porous medium Ko.
- The presence of thermal radiation R reduced velocity as well as thermal boundary layer.
- An increase in the Schmidt number Sc or Prandtl number Pr led to a fall in velocity.
- Skin-friction coefficient decreased with an increase in M, whereas it showed a reverse effect in the case of Gr, Gm, Ko.
- The Nusselt number increased with the increase in the Prandtl number Pr.
- An increase in Sc or Kr tended to increase the Sherwood number.

It is hoped that the present investigation of the physics of flow over a porous vertical plate can be utilized as the basis for many scientific and engineering applications in order to study more complex vertical problems including the flow of electrical conducting fluids. The finding may be useful for studying movement of oil or gas and water through the reservoir of an oil or gas field in the migration of underground water and the filtration and water purification processes. The results of the problem are also of great interest in geophysics for studying the interaction of the geomagnetic field with the fluid in the geothermal region. The effect of radiation on MHD flow and heat transfer problems has become industrially more important. The study of heat and mass transfer with chemical reaction is of great practical importance for engineers and scientists because of its almost universal occurrence in many branches of science and engineering. The phenomenon of slip-flow regime has attracted the attention of a large number of scholars due to its wide ranging application. The problem of slip flow regime is very important in this era of modern science, technology, and vast ranging industrialization. In a convective fluid when the flow of mass is caused by temperature difference, one cannot neglect the thermal diffusion effect (commonly known as the Soret effect) due to its practical applications in engineering and science.

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**Appendix**

$$m_1=\frac{(1+Q)\Pr+\sqrt{(1+Q)^2\Pr^2+4R\Pr}}{2},\ m_2=\frac{Sc+\sqrt{Sc^2+4ScKr}}{2},\ m_3=\frac{1+\sqrt{1+4M_1}}{2},$$

$$m_4=\frac{(1+Q)\Pr+\sqrt{(1+Q)^2\Pr^2+4\left(R-\frac{n}{4}\right)\Pr}}{2},\ m_5=\frac{Sc+\sqrt{Sc^2+4Sc\left(Kr-\frac{n}{4}\right)}}{2},$$

$$m_6=\frac{1+\sqrt{1+4M_2}}{2},\ A_1=\frac{ScS_0m_1^2}{m_1^2-Scm_1-ScKr},\ A_2=1+A_1,\ A_3=\frac{GmA_1-Gr}{m_1^2-m_1-M_1},$$

$$A_4=\frac{GmA_2}{m_2^2-m_2-M_1},\ A_5=\frac{A_4(1+hm_2)-A_3(1+hm_1)}{(1+hm_3)},\ A_6=\frac{\Pr m_1}{m_1^2-(1+Q)\Pr m_1-\Pr\left(R-\frac{n}{4}\right)},$$

$$A_7=\frac{S_0ScA_6m_4^2}{m_4^2-Scm_4-\left(Kr-\frac{n}{4}\right)Sc},\ A_8=\frac{ScA_2m_2}{m_2^2-Scm_2-\left(Kr-\frac{n}{4}\right)Sc}\ A_9=\frac{S_0ScA_6m_1^2+Scm_1A_1}{m_1^2-Scm_1-\left(Kr-\frac{n}{4}\right)Sc}$$

,

$$A_{10}=A_9-A_8-A_7,\ A_{11}=\frac{GmA_{10}}{m_5^2-m_5-M_2},\ A_{12}=\frac{GmA_6-GmA_7}{m_4^2-m_4-M_2},\ A_{13}=\frac{m_3A_5}{m_3^2-m_3-M_2},$$

$$A_{14}=\frac{GmA_8+m_2A_4}{m_2^2-m_2-M_2},\ A_{15}=\frac{-GrA_6+GmA_9-m_1A_3}{m_1^2-m_1-M_2},$$

$$A_{16}=\frac{A_{11}(1+hm_5)-A_{12}(1+hm_4)-A_{13}(1+hm_3)+A_{14}(1+hm_2)-A_{15}(1+hm_1)}{(1+hm_6)},$$

$$A_{17}=-m_3A_5+A_4m_2-A_3m_1,$$

$$A_{18}=-m_6A_{16}+A_{11}m_5-m_4A_{12}-m_3A_{13}+A_{14}m_2-A_{15}m_1,$$

$$A_{19}=A_6m_4-m_1A_6,\qquad A_{20}=-m_2A_2+A_1m_1,\qquad A_{21}=-m_5A_{10}-m_4A_7-m_2A_8+A_9m_1.$$