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Heat and Mass Transfer Effects on MHD Mixed Convective Flow of a Vertical Porous Surface in the Presence of Ohmic Heating and Viscous Dissipation

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ABSTRACT

The present paper addresses the combined effects of thermal radiation and chemical reaction on steady MHD mixed convective flow of heat and mass transfer past a vertical surface under the influence of Joule and viscous dissipation. The governing system of the partial differential equations is transformed into the dimensionless equations using dimensionless variables. The dimensionless equations are solved numerically using two term perturbation technique and numerical solution as in graphically. The effects of the various parameters entering the problem on the dimensionless velocity, temperature and concentration fields within the boundary layer are discussed qualitatively. The velocity increases with an increase in Grashof number Gr, permeability parameter and solutal Grashof number Gm but decreases in magnetic parameter.

1. Introduction

The study of boundary layer heat and mass transfer characteristics over an inclined plate has generated much interest from astrophysical, renewable energy systems and the hypersonic aerodynamics researchers for a number of decades. In recent years, MHD flow problems have come in view of its significant applications in industrial manufacturing processes such as plasma studies, petroleum industries, Magneto hydrodynamics, power generator cooling of clear reactors and boundary layer control in aerodynamics. Many authors have studied the effects of magnetic fields on the mixed, natural and force convection of the heat and mass transfer problems. Heat transfer considerations arise due to chemical reactions and often due to the very nature of the process.

MHD free convection fluid-flows frequently occur in the natural world. Fluid passing through porous medium is of great interest nowadays and many researchers are attracted towards the

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applications in the fields of science and technology, namely in the area of agriculture engineering to know about ground water resources, in technology to study the moment of natural gas, oil and water through the oil reservoirs. The effects of the mixed convection flow an unsteady stagnation point flow of a viscous fluid with a variable free stream velocity. The mass transfer effects on an unsteady flow past an accelerated vertical porous plate have been noticed by Das *et al.,* [1]. Sattar [2] has investigated the free convection and mass transfer flow, past an infinite vertical porous plate with time dependent temperature and concentration. Chen *et al.,* [3] examined heat and mass transfer in MHD flow by natural convection from a permeable, inclined surface with variable wall temperature and concentration. Masood *et al.,* [4] used HAM to formulate the MHD mixed convection Falkner–Skan flow with convective boundary conditions. The MHD conjugative heat transfer problem from vertical surfaces embedded in saturated porous media was discussed by Duwairi and Al-Kablawi [5]. Nasir Uddin *et al.,* [6] discovered the effect of conjugate heat and mass transfer on magneto hydrodynamic mixed convective flow past inclined plate in a porous medium. The skin friction in the MHD mixed convection stagnation point with mass transfer was studied by Abdelkhalek [7]. The number of investigations of natural convection flow with thermal radiation has increased greatly during the past few decades due to its importance in many practical situations. When natural convection flows occur at high temperature, radiation effects on the fluid flow become significant. Radiation effects on the natural convection flow are important in the context of furnace design, electric power generation, thermo-nuclear fusion, glass production, casting and levitation, plasma physics, cosmic flights, propulsion systems, solar power technology, spacecraft re-entry, aerothermodynamics, etc. It is worth noting that unlike convection/conduction, taking the governing equations into account the effects of radiation become quite complicated. Hence, many difficulties arise while solving such equations. However, some reasonable approximations are proposed to solve the governing equations with radiative heat transfer.

The influence of magnetic field on the flow of an electrically conducting viscous fluid with mass transfer and radiation absorption is also useful in planetary atmosphere research. Kinyanjui *et al.,* [8] investigated simultaneous heat and mass transfer in unsteady free convection flow with radiation absorption past an impulsively started infinite vertical porous plate subjected to a strong magnetic field. Soret and Dofour effects on MHD flow with heat and mass transfer past a permeable stretching sheet in the presence of the thermal radiation studied by Sreedevi *et al.,* [9]. Suneetha [10] noticed the problem of radiation and mass transfer effects on MHD free convection flow past an impulsively started isothermal vertical plate with dissipation. Aydin and Kaya [11] proposed the MHD mixed convective heat transfer about a semi-infinite inclined plate in the presence of magneto and thermal radiation effects. Reddy [12] noticed that Soret and Dofour effects on MHD free convective flow past a vertical porous plate in the presence of heat generation. Israel Cookey *et al.,* [13] noticed the influence of viscous dissipation and radiation on unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium with time dependent suction. Ogulu [14] examined the influence of radiation absorption on unsteady free convection and mass transfer flow of a polar fluid in the presence of uniform magnetic field. Rajesh [15] has investigated radiation effects on MHD free convection flow near a vertical plate with ramped wall temperature. Sivaiah *et al.,* [16] noticed that the heat and mass transfer effects on MHD free convective flow past a vertical porous plate. Radiation effects on mixed convection along an isothermal vertical plate were investigated by Hossain and Takhar [17]. Raptis and Perdiki [18] discovered the effects of thermal radiation and free convection flow past a moving vertical plate.

In many chemical engineering processes, chemical reactions occur between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications viz., polymer production, manufacturing of ceramics or glassware and food processing. The effect of chemical reaction on unsteady MHD flow through an impulsively started semi-infinite vertical plate was examined by Muthucumaraswamy *et al.,* [19]. Dulal Pal *et al.,* [20] analyzed Perturbation Analysis of unsteady magneto hydrodynamic convective heat and mass transfer in a boundary layer slip, flow past a vertical permeable plate with thermal radiation and chemical reaction. Recently, Kumar *et al.,* [21] investigated the effects of chemical reaction and radiation on MHD free convection flow past an exponentially accelerated vertical plate. Anjali Devi and Kandasamy [22] have discovered the effects of chemical reaction, heat and mass transfer on MHD flow past a semi-infinite plate. Ibrahim *et al.,* [23] have examined the effects of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Effects of chemical reaction and radiation absorption on MHD flow of dusty viscoelastic fluid is analysed by Prakash *et al.,* [24]. The chemical and radiation absorption effects on MHD convective heat and mass transfer flow past a semi-infinite vertical moving porous plate with time dependent suction was proposed by Ramana Reddy *et al.,* [25]. Sudheer Babu *et al.,* [26] investigated the effects of thermal radiation and chemical reaction on MHD convective flow of a polar fluid past a moving vertical plate with viscous dissipation. Saritha and Satya Narayana [27] investigated thermal diffusion and chemical reaction effects on unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate. For the problem of coupled heat and mass transfer in MHD free convection, the effect of Ohmic heating has not been considered in the above investigations. However, it is more realistic to include this effect to explore the impact of the magnetic field on the thermal transport in the boundary layer. With this awareness, the effect of Ohmic heating on the MHD free convection heat transfer has been examined on a Newtonian fluid by Hossain [28].

Chaudhary *et al.,* [29] have discovered the radiation effect with simultaneous thermal and mass diffusion in MHD mixed convection flow from a vertical surface with Ohmic heating. The effect of Ohmic heating on the MHD free convection heat transfer has been studied on a Newtonian fluid by Hossain [30]. The problem of combined heat and mass transfer of an electrically conducting fluid in MHD natural convection, adjacent to a vertical surface with Ohmic heating was analyzed by Chen [31]. The effect of Ohmic heating and viscous dissipation on MHD mixed convection heat and mass transfer about a vertical plate are analyzed by Aydin and Kaya [32]. Babu and Reddy [33] have discovered the mass transfer effects on MHD mixed convective flow from a vertical surface with ohmic heating and viscous dissipation. Sibanda and Makinde [34] proposed the effects of magnetic fields on heat transfer on a rotating disk in a porous medium with Ohmic heating and viscous dissipation.

For the problem of coupled heat and mass transfer in MHD free convection, the effect of both viscous dissipation and Ohmic heating are not studied in the above investigations. However, it is more realistic to include these two effects to explore the impact of the magnetic field on the thermal transport in the boundary layer. With this awareness, the effect of Ohmic heating on the MHD free convection heat transfer has been studied for a Newtonian fluid. The effect of Dufour and chemical reaction on an unsteady magneto hydrodynamics flow past an exponentially moving plate, the effect of radiation and viscous dissipation using the Galerkin method over a vertical porous plate with variation in temperature, and the effect of viscous dissipation and chemical reaction on the flow of MHD nanofluid, also the effects of chemical reaction and thermal radiation on MHD free convective flow of micro polar fluid past an infinite moving vertical porous plate with viscous dissipation. Thermal and concentration effects of unsteady flow of non-Newtonian fluid over an oscillating plate and transport phenomenon in a third-grade fluid over an oscillating surface. Cattaneo–Christov heat flux on MHD flow of hybrid nanofluid across stretched cylinder with radiations and Joule heating effects. Combined effects of viscous dissipation and magnetohydrodynamic on periodic heat transfer along a cone embedded in porous. An analysis of mixed convective stagnation points flows of hybrid nanofluid over sheet with variable thermal conductivity and slip conditions. Investigation of entropy generation in the existence of heat generation and nanoparticle clustering on porous Riga plate during nanofluid flow. Significance of mixed convective double diffusive MHD stagnation point flow of nanofluid over a vertical surface with heat generation has investigated and analysed the researchers [35- 45].

2. Formation of the Problem

We consider the mixed convection flow of an incompressible and electrically conducting viscous fluid such that x^* - axis which is taken along the plate in upward direction and y^* - axis is normal to it. A transverse constant magnetic field is applied in the direction y^* - axis. Since the motion is two dimensional and length of the plate is large, therefore all the physical variables are independent of x^*. Let u^* and v^* be the components of velocity in x^* and y^* directions respectively, taken along and perpendicular to the plate (see Figure 1).

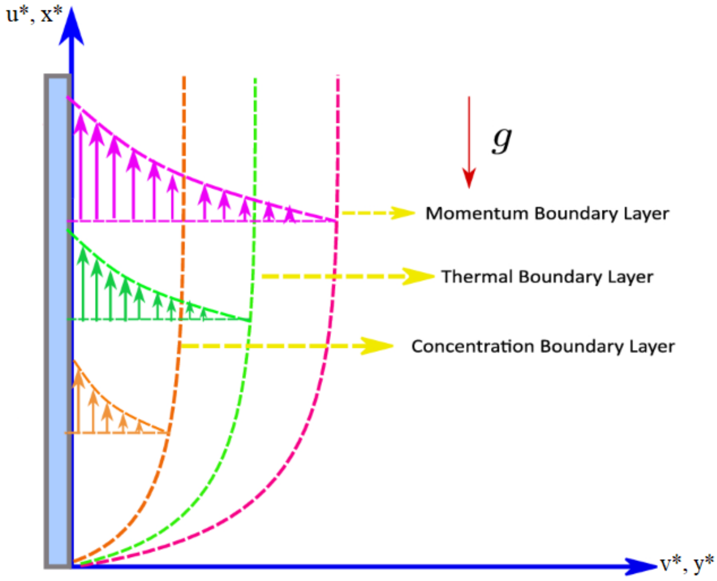

Fig. 1. Physical model and coordinate system

The governing equations of continuity, momentum, and energy for a flow of an electrically conducting radiation is given by:

$$\frac{\partial v^*}{\partial y^*} = 0 \Rightarrow v^* = -v_0 \text{ (constant)} \tag{1}$$

$$\frac{\partial p^*}{\partial y^*} = 0 \Rightarrow P^* \text{ is independent of } y^* \tag{2}$$

$$\rho v^* \frac{\partial u^*}{\partial y^*} = \mu \frac{\partial^2 u^*}{\partial y^{*2}} + \rho g \beta \left(T^* - T_\infty^*\right) + \rho g \beta^* \left(C^* - C_\infty^*\right) - \sigma B_0^2 u^* - \frac{\nu u^*}{K^*} \tag{3}$$

$$\rho C_p v^* \frac{\partial T^*}{\partial y^*} = k\frac{\partial^2 T^*}{\partial {y^*}^2} + \mu\left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{\partial {q_r}^*}{\partial y^*} + \sigma {B_0}^2 u^{2*} \tag{4}$$

$$v^* \frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial {y^*}^2} - R^*\left(C^* - {C_\infty}^*\right) \tag{5}$$

Here, g is the due to gravity, T^* - the temperature of the fluid near the plate, ${T_\infty}^*$ - the free stream temperature, c^* - the concentration, β - the coefficient of thermal expansion, k - the thermal conductivity, P^* - the pressure, C_p - the specific heat of constant pressure, B_0 - the magnetic field coefficient, μ - the viscosity of the fluid, ${q_r}^*$ - the radiative heat flux, ρ - the density, σ - the magnetic Permeability of the fluid, v_0 - the constant suction velocity, ν - the kinematic viscosity and D - molecular diffusivity.

The radiative heat flux is given by

$$\frac{\partial q_r}{\partial y^*} = 4\left(T^* - {T_\infty}^*\right)I' \tag{6}$$

Where $\int_0^\infty K_{\lambda w}\left(\frac{de_{b\lambda}}{dT^*}\right)_w d\lambda,$ $K\lambda w$ is the absorption coefficient at wall and $e_{b\lambda}$ is Planck's function.

The boundary conditions are

$$\begin{aligned} &u^* = 0, T^* = T_w, C^* = C_w \text{ at } y^* = 0 \\ &u^* \to 0, T^* \to T_\infty, C^* \to C_\infty \text{ as } y^* \to \infty \end{aligned} \tag{7}$$

Introducing the following non–dimensional quantities are

$$\begin{aligned} &u = \frac{u^*}{v_0}, y = \frac{v_0 y^*}{\nu}, \theta = \frac{T^* - {T_\infty}^*}{T_w - T_\infty}, C = \frac{C^* - {C_\infty}^*}{C_w - C_\infty}, \Pr = \frac{\mu c_p}{k}, Sc = \frac{\nu}{D}, \\ &Gr = \frac{g\beta\nu(T_w - T_\infty)}{{v_0}^3}, Gm = \frac{g\beta^*\nu(C_w - C_\infty)}{{v_0}^3}, M = \frac{\sigma {B_0}^2 \nu}{\rho {v_0}^2}, K = \frac{{v_0}^2 K^* \rho}{\nu^2}, \\ &E = \frac{{v_0}^2}{C_p\left(T_w - T_\infty\right)}, F = \frac{4I'\nu}{\rho c_p {v_0}^2}, Kr = \frac{\nu R^*}{{v_0}^2} \end{aligned} \tag{8}$$

The non-dimensional form of the governing Eq. (3) - Eq. (5) reduce to

$$u'' + u' - \left(M + \frac{1}{K} \right) u = -\left[GrT + GmC \right] \tag{9}$$

$$T'' + \Pr T' - F \Pr T + \Pr Ec(u')^2 + \Pr EcMu^2 = 0 \tag{10}$$

$$C'' + ScC' - ScKrC = 0 \tag{11}$$

Where Gr is the Grashof number, Gm – the modified Grashof number, Pr - the Prandtl number, F- the radiation parameter, Sc- the Schmidt number, E-the Eckert number, M-the magnetic parameter, Kr-the chemical reaction.

The corresponding boundary conditions in dimensionless form are reduced to

$$\begin{aligned} &u = 0, T = 1, C = 1 \quad \text{at } y = 0 \\ &u \to 0, T \to 0, C \to 0 \quad \text{as } y \to \infty \end{aligned} \tag{12}$$

3. Solution of the Problem

To reduce the above system of the partial differential equations into system ordinary differential equations in a dimension less from, we may represent the velocity, temperature and concentration as

$$\begin{aligned} u(y) &= u_0(y) + \varepsilon u_1(y) + O(\varepsilon^2) \\ T(y) &= T_0(y) + \varepsilon T_1(y) + O(\varepsilon^2) \\ C(y) &= C_0(y) + \varepsilon C_1(y) + O(\varepsilon^2) \end{aligned} \tag{13}$$

Using Eq. (13) into the Eq. (9) - Eq. (11) and equating the coefficient of like power of ε, we have

$$u_0'' + u_0' - \left(M + \frac{1}{K} \right) u_0 = -GrT_0 - GmC_0 \tag{14}$$

$$T_0'' + \Pr T_0' - F \Pr T_0 = 0 \tag{15}$$

$$C_0'' + ScC_0{}' - ScKrC_0 = 0 \tag{16}$$

$$u_1'' + u_1' - n_1 u_1 = -GrT_1 - GmC_1 \tag{17}$$

$$T_1'' + \Pr T_1' - E \Pr T_1 + \Pr \left(u_0' \right)^2 + \Pr Mu_0{}^2 = 0 \tag{18}$$

$$C_1'' + ScC_1{}' - ScKrC_1 = 0 \tag{19}$$

The corresponding boundary conditions are:

$$\begin{aligned} &u_0 = 0, u_1 = 0, T_0 = 1, T_1 = 0, C_0 = 1, C_0 = 0 && \text{at} \quad y = 0 \\ &u_0 \to 0, u_1 \to 0, T_0 \to 0, T_1 \to 0, && \text{as} \quad y \to \infty \end{aligned} \tag{20}$$

The solution for the velocity, temperature and concentration as follows:

$$u(y,t) = \left[A_3 e^{-m_4 y} - A_1 e^{-m_3 y} - A_2 e^{-m_1 y} \right] + \varepsilon \left[\begin{array}{l} A_{18} e^{-m_6 y} - A_{11} e^{-m_5 y} + A_{12} e^{-2m_4 y} + A_{13} e^{-2m_3 y} \\ + A_{14} e^{-2m_1 y} - A_{15} e^{-(m_4+m_3)y} + A_{16} e^{-(m_1+m_3)y} - A_{17} e^{-(m_1+m_4)y} \end{array} \right]$$

$$T(y,t) = \left(e^{-m_3 y} \right) + \varepsilon \left[\begin{array}{l} A_{10} e^{-m_5 y} - A_4 e^{-2m_4 y} - A_5 e^{-2m_3 y} - A_6 e^{-2m_1 y} \\ + A_7 e^{-(m_3+m_4)y} - A_8 e^{-(m_1+m_3)y} + A_9 e^{-(m_1+m_4)y} \end{array} \right]$$

$$C(y,t) = e^{-m_1 y}$$

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow.

Skin Friction

The non-dimensional skin friction at the plate is given by:

$$\tau = \left(\frac{\partial u}{\partial y} \right)_{y=0} = \left(-m_4 A_3 + A_1 m_3 + m_1 A_2 \right) + \varepsilon \left(\begin{array}{l} -m_6 A_{18} + A_{11} m_5 - 2m_4 A_{12} - 2m_3 A_{13} - 2A_{14} m_1 \\ +(m_3+m_4) A_{15} - (m_1+m_3) A_{16} + (m_4+m_1) A_{17} \end{array} \right)$$

Nusselt Number

The non- dimensional form of the rate of heat transfer in terms of Nusselt number at the plate is given by:

$$Nu = -\left(\frac{\partial T}{\partial y} \right)_{y=0} = m_3 - \varepsilon \left(\begin{array}{l} -m_5 A_{10} + 2A_4 m_4 + 2m_3 A_5 + 2m_1 A_6 \\ -\left(m_3+m_4\right) A_7 + \left(m_1+m_3\right) A_8 - \left(m_4+m_1\right) A_9 \end{array} \right)$$

Sherwood Number

The non- dimensional form of the rate of heat transfer in terms of Sherwood number at the plate is given by:

$$Sh = -\left(\frac{\partial C}{\partial y} \right)_{y=0} = m_1$$

Where

$$m_1 = \frac{Sc + \sqrt{Sc^2 + 4KrSc}}{2}, m_2 = \frac{Sc + \sqrt{Sc^2 + 4KrSc}}{2}, m_3 = \frac{\Pr + \sqrt{\Pr^2 + 4F\Pr}}{2}\ m_4 = \frac{1 + \sqrt{1 + 4n_1}}{2},,$$

$$m_5 = \frac{\Pr + \sqrt{\Pr^2 + 4E\Pr}}{2}, m_6 = \frac{1 + \sqrt{1 + 4n_1}}{2}, A_1 = \frac{Gr}{m_3{}^2 - m_3 - n_1}, A_2 = \frac{Gm}{m_1{}^2 - m_1 - n_1}, A_3 = A_1 + A_2$$

$$A_4 = \frac{A_3{}^2\left(m_4{}^2 + \Pr M\right)}{4m_4{}^2 - 2\Pr m_4 - E\Pr},\ A_5 = \frac{A_1{}^2\left(m_3{}^2 + \Pr M\right)}{4m_3{}^2 - 2\Pr m_3 - E\Pr},\ A_6 = \frac{A_2{}^2\left(m_1{}^2 + \Pr M\right)}{4m_1{}^2 - 2\Pr m_4 - E\Pr},$$

$$A_7 = \frac{2A_3A_1\left(m_4m_3 + \Pr M\right)}{\left(m_4 + m_3\right)^2 - \Pr\left(m_4 + m_3\right) - E\Pr},\ A_8 = \frac{2A_2A_1\left(m_1m_3 + \Pr M\right)}{\left(m_1 + m_3\right)^2 - \Pr\left(m_1 + m_3\right) - E\Pr},$$

$$A_{12} = \frac{A_4Gr}{4m_4{}^2 - 2m_4 - n_1},\ A_{13} = \frac{A_5Gr}{4m_3{}^2 - 2m_3 - n_1},\ A_{14} = \frac{A_6Gr}{4m_1{}^2 - 2m_1 - n_1},\ A_{15} = \frac{A_7Gr}{\left(m_3 + m_4\right)^2 - \left(m_3 + m_4\right) - n_1},$$

$$A_{16} = \frac{A_8Gr}{\left(m_3 + m_1\right)^2 - \left(m_3 + m_1\right) - n_1},\ A_{17} = \frac{A_9Gr}{\left(m_1 + m_4\right)^2 - \left(m_1 + m_4\right) - n_1},$$

$$A_{18} = A_{11} - A_{12} - A_{13} - A_{14} + A_{15} - A_{16} + A_{17},$$

4. Results and Discussions

In the present work, we have analyzed flow, heat and mass transfer on mixed convection flow of a viscous incompressible, electrically conducting fluid over an infinite vertical porous plate in the presence of magnetic field and thermal radiation using the classical model for the radiative heat flux. The results are obtained to illustrate the influence of the thermal Grashof number (Gr), solutal Grashof number (Gm), magnetic field parameter (M), Permeability parameter (K), radiation parameter (F), Schmidt number Sc, Prandtl number (Pr) and chemical reaction parameter (Kr) on velocity field, temperature distribution and concentration field are studied in Figure 2 - Figure 13, while keeping the other parameters as constants.

The effect of the magnetic parameter (M) and porosity parameter (K) on the dimensionless velocity is shown in the Figure 2 and Figure 3 respectively. It is observed that an increase in the magnetic parameter results in a decrease in the velocity field. This result qualitatively agrees with the expectations since the magnetic field exerts a retarding force on the flow. For different values of porosity parameter K, it can be seen that the velocity profile increases with the increase of permeability parameter the effect of Grashof number on the velocity profiles is shown in Figure 4. It is noticed that the Grashof number increases, the velocity is also increases. Figure 5 show that the dimensionless velocity for different values of solutal Grashof number. It is noticed that the velocity increases with an increasing of the solutal Grashof number.

Effects of radiation parameter (F) on velocity and temperature profiles are studied from Figure 6 and Figure 7 respectively. It is observed that the velocity and temperature profiles decrease with an increasing the radiation parameter (F). The effect of Prandtl number (Pr) on the velocity and temperature profiles is presented in Figure 8 and Figure 9 respectively. It can be seen that both the velocity and the temperature profiles decrease with an increasing of the Prandtl number.

Figure 10 and Figure 11 illustrates that the effect of Schmidt number (Sc) on the velocity and concentration profiles. It is observed that velocity and concentration decrease with an increasing the Schmidt number. Figure 12 and Figure 13 are shows that the effect of chemical reaction parameter (Kr) on the velocity and concentration profiles. It is observed that the velocity and concentration decrease with an increasing the chemical reaction parameter.

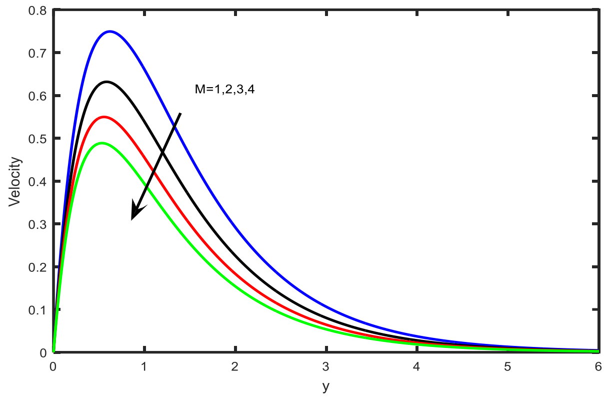

Fig. 2. Velocity profiles for different values of magnetic parameter (M)

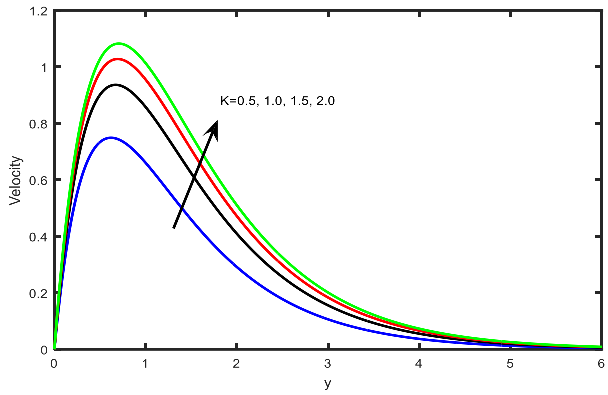

Fig. 3. Velocity profiles for different values of permeability parameter (K)

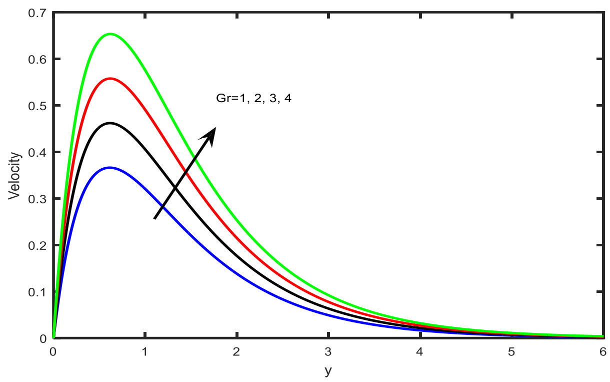

Fig. 4. Velocity profiles for different values of Grashof Number (Gr)

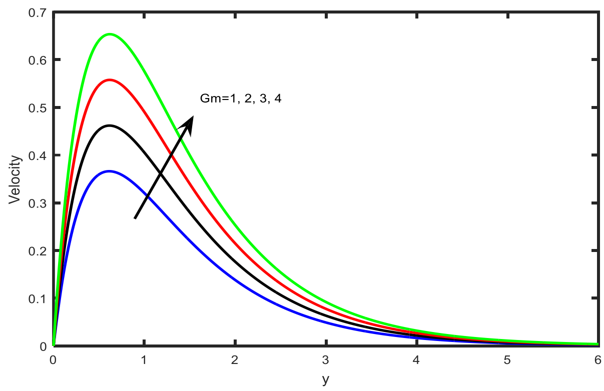

Fig. 5. Velocity profiles for different values of solutal Grashof Number (Gm)

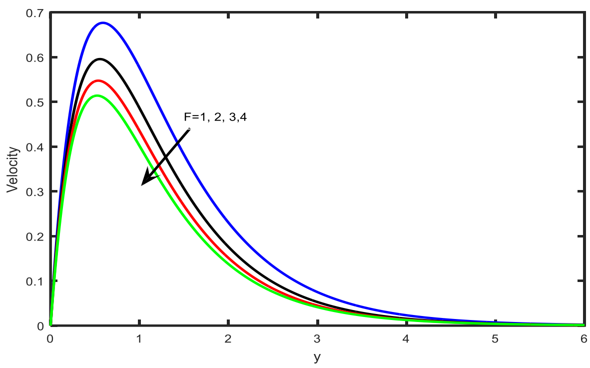

Fig. 6. Velocity profiles for different values of radiation parameter (F)

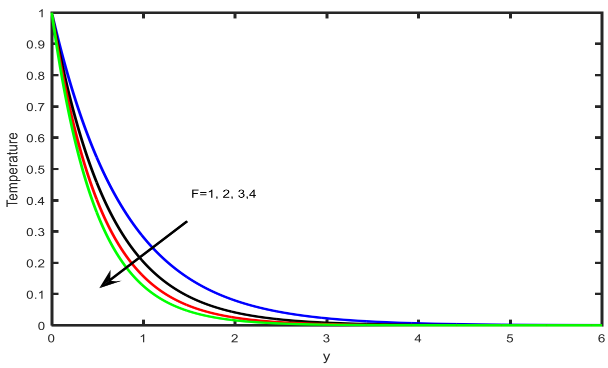

Fig. 7. Temperature profiles for different values of radiation parameter (F)

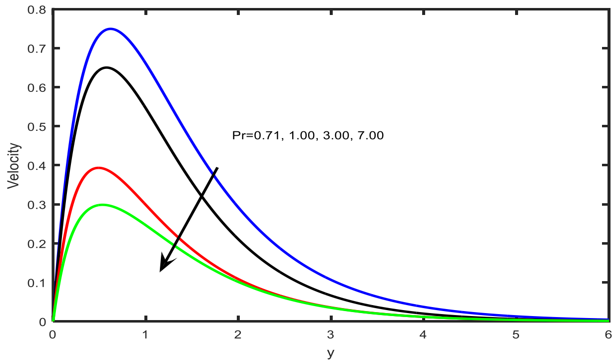

Fig. 8. Velocity profiles for different values of Prandtl number (Pr)

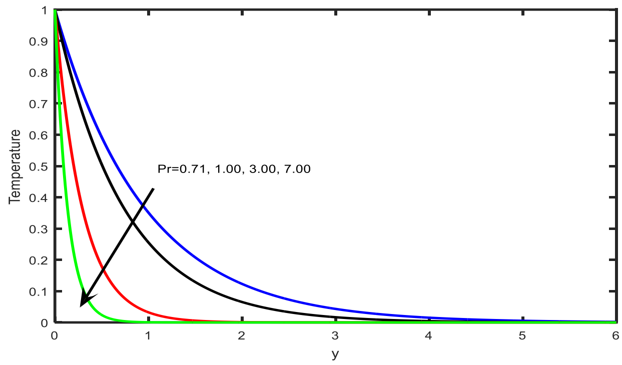

Fig. 9. Temperature profiles for different values of Prandtl number (Pr)

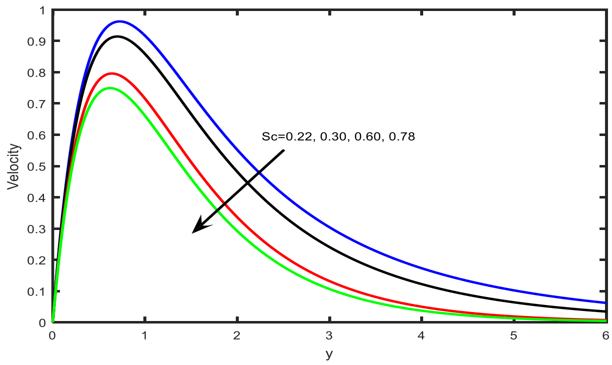

Fig. 10. Velocity profiles for different values of Schmidt number (Sc)

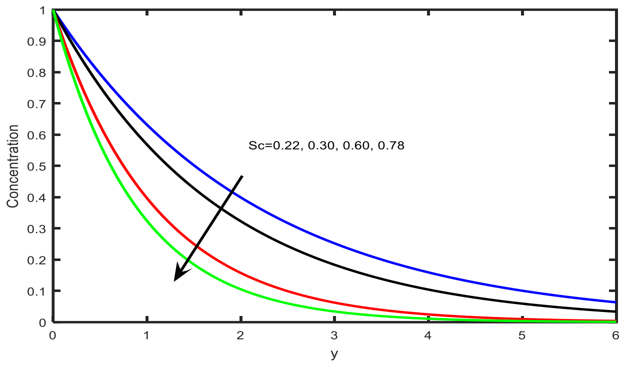

Fig. 11. Concentration profiles for different values of Schmidt number (Sc)

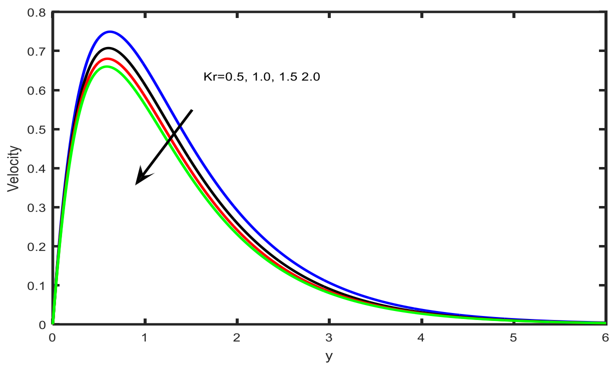

Fig. 12. Velocity profiles for different values of chemical reaction parameter (Kr)

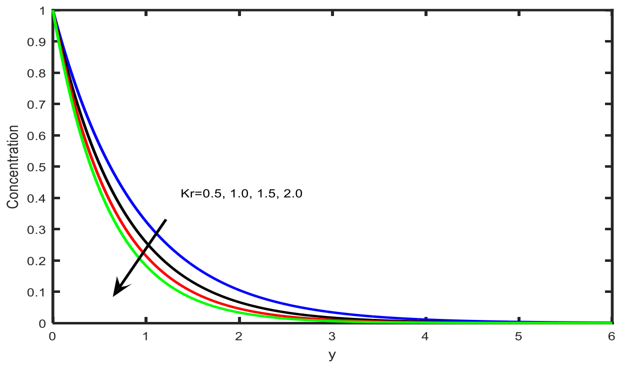

Fig. 13. Concentration profiles for different values of chemical reaction parameter (Kr)

5. Conclusion

The notable points of the study are as follows:

i. The velocity increases with an increase in Grashof number Gr and solutal Grashof number Gm.
ii. The velocity decreases with an increase in the magnetic parameter M.
iii. The velocity increases with an increase in the porosity parameter K.
iv. An increase in the Prandtl number Pr, decreases the velocity and the temperature field.
v. An increase in the Radiation parameter F, decreases the velocity and the temperature field.

vi. The velocity as well as concentration decreases with an increase in the Schmidt number Sc and Chemical reaction Kr.

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