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Chemical Reaction Effects on an Unsteady MHD Free Convection Fluid Flow past a Semi-Infinite Vertical Plate Embedded in a Porous Medium with Heat Absorption

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ABSTRACT

In the present paper , an analysis is carried out the chemical reaction effects on an unsteady magneto hydrodynamics (MHD) free convection fluid flow past a semi-infinite vertical plate embedded in a porous medium with heat absorption was formulated. The non dimensional governing equations are formed with the help of suitable dimensionless governing parameter. The resultant coupled non dimensional governing equations are solved by a finite element method. The effect of important physical parameters on the velocity, temperature and concentration are shown graphically and also discussed the skin-friction coefficient, Nusselt number and Sherwood number are shown in tables.

Keywords: MHD, Free convection, Heat absorption, Vertical plate, FEM.

1. INTRODUCTION

The present trend in the field of chemical reaction analysis is to give a mathematical model for the system to predict the reactor performance. A large amount of research work has been reported in this field. In particular, the study of heat and mass transfer with chemical reaction is of considerable importance in chemical and hydrometallurgical industries. Chemical reaction 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. Frequently the transformations proceed in a moving fluid, a situation encountered in a number of technological fields. A common area of interest in the field of aerodynamics is the analysis of thermal boundary layer problems for two-dimensional steady and incompressible laminar flow passing a wedge. Simultaneous heat and mass transfer from different geometrics embedded in porous media has many engineering and geophysical applications such as geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors, and underground energy transport. A very significant area of research in radiative heat transfer, at the present time is the numerical simulation of combined radiation and convection/conduction transport processes. The effort has arisen largely due to the need to optimize industrial system such as furnaces, ovens and boilers and the interest in our environment and in non conventional energy sources, such as the use of salt-gradient solar ponds for energy collection and storage. In particular, natural convection induced by the simultaneous action of buoyancy forces resulting from thermal and mass diffusion is of considerable interest in nature and in many industrial applications such as geophysics, oceanography, drying processes, solidification of binary alloy and chemical engineering. Frequently the transformations proceed in a moving fluid, a situation en-countered in a number of technological fields.

Heat flow and mass transfer over a vertical porous plate with variable suction and heat absorption/generation have been studied by many workers. Raji Reddy and Srihari (2009) studied numerical solution of unsteady flow of a radiating and chemically reacting fluid with time-dependent suction. Chen (2006) studied heat and mass transfer in MHD flow by natural convection from a permeable, inclined surface with variable wall temperature and concentration. Perdikis and Rapti (2006) studied the unsteady MHD flow in the presence of radiation. Rahman and Sattar (2006) analyzed the MHD convective flow of a micro polar fluid past a continuously moving vertical porous plate in the presence of heat generation/ absorption. Kim (2000) investigated unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction by assuming that the free stream velocity follows the exponentially increasing small perturb action law. Chamkha (2004) extended the problem of Kim (2000) to heat absorption and mass transfer effects. Elbashbeshy (1997) studied heat and mass transfer along a vertical plate under the combined buoyancy effects of thermal and species diffusion, in the presence of magnetic field. Soundagekar *et al.* (1979) analyzed the problem of free convection effects on stokes problem for a vertical plate under the action of transversely applied magnetic field with mass transfer.

In all these investigations, the viscous dissipation is neglected. The viscous dissipation heat in the natural convective flow is important, when the flow field is of extreme size or at low temperature or in high gravitational field. Gebhar (1962) shown the importance of viscous dissipative heat in free convection flow in the case of isothermal and constant heat flux in the plate. Soundalgekar (1972) analyzed the effect of viscous dissipative heat on the two dimensional unsteady, free convective flow past an vertical porous plate when the temperature oscillates in time and there is constant suction at the plate. Israel Cookey *et al.* (2003) investigated the influence of viscous dissipation and radiation on unsteady MHD free convection flow past an infinite heated vertical plate in porous medium with time dependent suction.

The objective of the present paper is to analyze the chemical reaction effects on an unsteady magneto hydrodynamics free convection fluid flow past a semi-infinite vertical plate embedded in a porous medium with heat absorption. The dimensional less equations of continuity, linear momentum, energy and diffusion, which govern the flow field are solved numerically by using a finite element method. The behavior of the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number has been discussed for variations in the governing parameters.

2. Mathematical Analysis

An unsteady two-dimensional laminar free convective boundary layer flow of a viscous, incompressible, electrically conducting and the chemical reaction effects on an unsteady magneto hydrodynamics free convection fluid flow past a semi-infinite vertical plate embedded in a porous medium with heat absorption is considered. The x'- axis is taken along the vertical plate and the y' - axis normal to the plate. It is assumed that there is no applied voltage, which implies the absence of an electric field. The transverse applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and the Hall Effect are negligible. The concentration of the diffusing species in the binary mixture is assumed to be very small in comparison with the other chemical species which are present, and hence the Soret and Dufour are negligible. Further due to the semi-infinite plane surface assumption, the flow variables are functions of normal distance y' and t' only. Now, under the usual Boussinesq's approximation, the governing boundary layer equations of the problem are:

$$\frac{\partial v'}{\partial y'} = 0 \qquad (1)$$

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

$$\frac{\partial T}{\partial t'} + v'\frac{\partial T}{\partial y'} = \frac{k}{\rho c_p}\left[\frac{\partial^2 T}{\partial y'^2} - \frac{1}{k}\frac{\partial q_r}{\partial y'}\right] + \frac{\nu}{c_p}\left(\frac{\partial u'}{\partial y'}\right)^2 - \frac{Q_0}{\rho c_p}\left(T - T_\infty\right) \qquad (3)$$

$$\frac{\partial C}{\partial t'} + v'\frac{\partial C}{\partial y'} = D\frac{\partial^2 C}{\partial y'^2} - k_r'^2 C \qquad (4)$$

Where u', v' are the velocity components in x', y' directions respectively. t' - the time, ρ -the fluid density, ν - the kinematic viscosity, c_p - the specific heat at constant pressure, g -the acceleration due to gravity, β and β^* - the thermal and concentration expansion coefficient respectively, B_0 - the magnetic induction , α - the fluid thermal diffusivity, k_p - the permeability of the porous medium, T - the dimensional temperature, C - the dimensional concentration, k -the thermal conductivity, μ - coefficient of viscosity, Q_0 -the heat absorption, D - the mass diffusivity, k_r' - the chemical reaction parameter.

The boundary conditions for the velocity, temperature and concentration fields are:

$$u' = u_p', \quad T = T_w + \varepsilon\left(T_w - T_\infty\right)e^{n't'}, \quad C = C_w + \varepsilon(C_w - C_\infty)e^{n't'} \quad at \quad y = 0$$
$$u' \to 0, \quad T \to T_\infty, \quad C \to C_\infty \quad as \quad y' \to \infty \qquad (5)$$

Where u_p' is the plate velocity, T_w and C_w are the wall dimensional temperature and concentration respectively, T_∞ and C_∞ are the free stream dimensional temperature and concentration respectively, n' - the constant. By using Rossel and approximation, the radiative heat flux q_r is given by

$$q_r = -\frac{4\sigma_s}{3K_e}\frac{\partial T^4}{\partial y'} \qquad (6)$$

Where σ_s - the Stefan-Boltzmann constant and K_e - the mean absorption coefficient. It should be noted that by using Rossel and approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are sufficient, small, then Eq. (6) can be linearised by expanding T^4 in the Taylor series about T_∞, which after neglecting higher order terms take the form

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

In the view of Eqs. (6) and (7), Eq. (3) reduces to

$$\frac{\partial T}{\partial t'} + v'\frac{\partial T}{\partial y'} = \frac{k}{\rho\, c_p}\frac{\partial^2 T}{\partial y'^2} + \frac{16\sigma_s}{3\rho\, c_p K_e}T_\infty^3\frac{\partial^2 T}{\partial y'^2} + \frac{\mu}{\rho\, c_p}\left(\frac{\partial u'}{\partial y'}\right)^2 \tag{8}$$

From the continuity Eq. (1), it is clear that suction velocity normal to the plate is either a constant or function of time. Hence, it is assumed in the form

$$v' = -V_0\left(1+\varepsilon A e^{n't'}\right) \tag{9}$$

Where A is a real positive constant, ε and εA are small values less than unity and V_0 is scale of suction velocity at the plate surface. In order to write the governing equations and the boundary condition in dimension less form, the following non- dimensional quantities are introduced.

$$u=\frac{u'}{V_0},\ v=\frac{v'}{V_0},\ y=\frac{V_0 y'}{\nu},\ t=\frac{V_0^2 t'}{\nu},$$
$$U_p=\frac{u'_p}{V_0},\ n=\frac{\nu n'}{V_0^2},\ \theta=\frac{T-T_\infty}{T_w-T_\infty}, Sc=\frac{\nu}{D}$$
$$\varphi=\frac{C-C_\infty}{C_w-C_\infty}, M=\frac{\sigma B_0^2\nu}{\rho V_0^2},\ K=\frac{k_p V_0^2}{\nu^2},$$
$$\Pr=\frac{\nu\rho C_p}{k}=\frac{\nu}{\alpha}, Gr=\frac{g\beta\nu\left(T_w-T_\infty\right)}{V_0^3}, \tag{10}$$
$$Gm=\frac{g\beta^*\nu\left(C_w-C_\infty\right)}{V_0^3}, Ec=\frac{V_0^2}{c_p\left(T_w-T_\infty\right)},$$
$$Q=\frac{Q_0\nu}{\rho c_p V_0^2},\ K_r^2=\frac{k_r'^2\nu}{V_0^2},\ N_R=\frac{16\sigma_s T_\infty^3}{3K_e k}$$

In the view of Eqs. (6) - (9), Eqs. (2) - (4) reduced to the following dimensionless form.

$$\frac{\partial u}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gm\varphi - \left(M+\frac{1}{K}\right)u \tag{11}$$

$$\frac{\partial \theta}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial \theta}{\partial y} = \left(\frac{1+N_R}{\Pr}\right)\frac{\partial^2 \theta}{\partial y^2} + Ec\left(\frac{\partial u}{\partial y}\right)^2 - Q\theta \tag{12}$$

$$\frac{\partial \varphi}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial \varphi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \varphi}{\partial y^2} - K_r^2\varphi \tag{13}$$

Where Gr, Gm, M, K, $\Pr$, N_R, Ec, Q, Sc and K_r are the thermal Grashof number, Solutal Grashof number, Magnetic parameter, Permeability parameter, Prandtl number, thermal radiation, Eckert number, heat absorption parameter, Schmidt number and chemical reaction parameter respectively.

The corresponding boundary conditions are

$$u=U_p,\ \ \theta=1+\varepsilon e^{nt},\ \ \varphi=1+\varepsilon e^{nt} \quad at \quad y=0$$
$$u\to 0,\ \ \theta\to 0,\ \ \varphi\to 0 \quad as \quad y\to\infty \tag{14}$$

3. Solution of the Problem

The set of differential Eqs. (11) to (13) subject to the boundary conditions (14) are highly nonlinear, coupled and therefore it cannot be solved analytically. Hence, following Reddy (Reddy 1985) and Bathe (Bathe 1996), the finite element method is used to obtain an accurate and efficient solution to the boundary value problem under consideration. The fundamental steps comprising the method are as follows:

Step 1: Discretization of the domain into elements:
The whole domain is divided into finite number of *sub-domains*, a process known as discretization of the domain. Each sub-domain is termed a *finite element*. The collection of elements is designated the *finite element mesh*.

Step 2: Derivation of the element equations:
The derivation of finite element equations i.e. algebraic equations among the unknown parameters of the finite element approximation, involves the following three steps:

a. Construct the variational formulation of the differential equation.

b. Assume the form of the approximate solution over a typical finite element.

c. Derive the finite element equations by substituting the approximate solution into variational formulation.

Step 3: Assembly of element equations:
The algebraic equations so obtained are assembled by imposing the *inter-element* continuity conditions. This yields a large number of algebraic equations, constituting the *global finite element model*, which governs the whole flow domain.

Step 4: Impositions of boundary conditions:
The physical boundary conditions defined in Eq. (14) are imposed on the assembled equations.

Step 5: Solution of the assembled equations:
The final matrix equation can be solved by a direct or indirect (iterative) method. For computational purposes, the coordinate y is varied from 0 to $y_{\max}=10$, where $y_{\max}$ represents infinity i.e. external to the momentum, energy and concentration boundary layers. The whole domain is divided into a set of 100 line elements of equal width 0.05, each element being three noded. Thus after assembly of all the elements equations we obtain a matrix of order 201×201. This system of equations as obtained after assembly of the elements equations is non-linear therefore an iterative scheme has been used to solve it. The system is linearized by incorporating known functions. After applying the given boundary conditions only a system of 195 equations remains for

the solution which has been solved using Gauss elimination method. This process is repeated until the desired accuracy of 0.0005 is obtained.

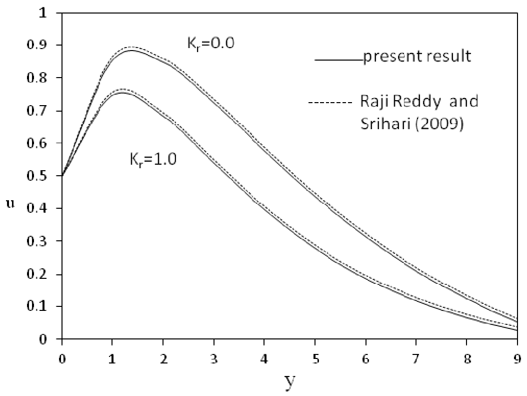

Fig. 1. Comperision of velocity profiles

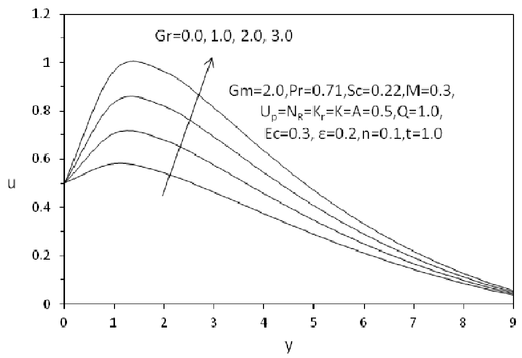

Fig. 2. velocity profiles for different values of Gr

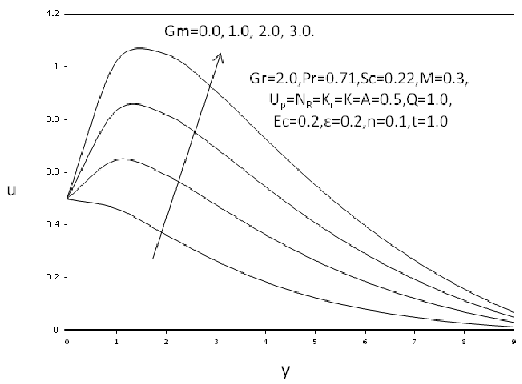

Fig. 3. velocity profiles for different values of Gm

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. The skin-friction at the plate, which in the non-dimensional form is given by

$$C_f = \frac{\tau'_w}{\rho U_0 V_0} = \left(\frac{\partial u}{\partial y}\right)_{y=0} \qquad (15)$$

The rate of heat transfer coefficient, which in the non-dimensional form in terms of the Nusselt number is given by

$$Nu = -x \frac{\left(\frac{\partial T}{\partial y'}\right)_{y'=0}}{T_w - T_\infty} \Rightarrow Nu\,\mathrm{Re}_x^{-1} = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} \qquad (16)$$

The rate of mass transfer coefficient, which in the non-dimensional form in terms of the Sherwood number, is given by

$$Sh = -x \frac{\left(\frac{\partial C}{\partial y'}\right)_{y'=0}}{C_w - C_\infty}$$

$$\Rightarrow Sh\,\mathrm{Re}_x^{-1} = -\left(\frac{\partial \varphi}{\partial y}\right)_{y=0} \qquad (17)$$

Where $\mathrm{Re}_x = \frac{V_0 x}{\nu}$ is the local Reynolds number.

4. Results and Discussion

In order to obtain a physical insight of the problem, and to observe that the effects of various physical hydrodynamics parameters on the velocity, temperature and concentration, numerical calculations have been performed for different values of magnetic parameter M, thermal Grashof number Gr, Solutal Grashof number Gm, Permeability parameter K, Eckert number Ec, heat absorption parameter Q, thermal radiation N_R, Prandtl number $\Pr$, Schmidt number Sc and chemical reaction parameter K_r. In order to ascertain the accuracy of the numerical results, the present study is compared with the previous study. The velocity profiles for

$$Gr = Gm = 2.0,$$
$$Gr = Gm = 2.0,\ M = 0.3,\ K = 0.5,\ \Pr = 0.71,$$
$$N_R = 0.5,\ Ec = 0.2,\ Q = 1.0,\ Sc = 0.22,$$
$$U_p = 0.5,\ A = 0.5, \varepsilon = 0.2,\ n = 0.1, t = 1.0$$

are compared with the available solution of Raji Reddy and Srihari (Raji Reddy and Srihari 2009), in Fig. 1. It is observed that the present results are in good agreement with that of Raji Reddy and Srihari (Raji Reddy and Srihari 2009).

For various values of the thermal Grashof number Gr and solutal Grashof number Gm, the velocity profiles 'u' are plotted in Figs. (2) and (3). The thermal Grashof number Gr signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force. Also, as Gr increases, the peak values of the velocity increases rapidly near the porous plate and then decays smoothly to the free stream velocity.

The solutal Grashof number Gm defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value. It is noticed that the velocity increases with increasing values of the solutal Grashof number.

The effect of the magnetic parameter M is shown in Fig. 4. It is observed that the tangential velocity of the fluid decreases with the increase of the magnetic field number values. The decrease in the tangential velocity as the magnetic parameter M increases is because the presence of a magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction, as in the present study. This resistive force slows down the fluid velocity component as shown in Fig. 4.

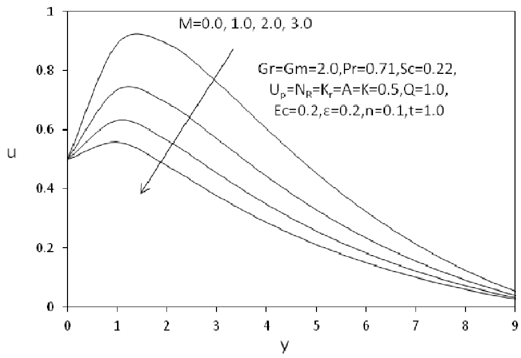

Fig. 4. Velocity profiles for different values of M

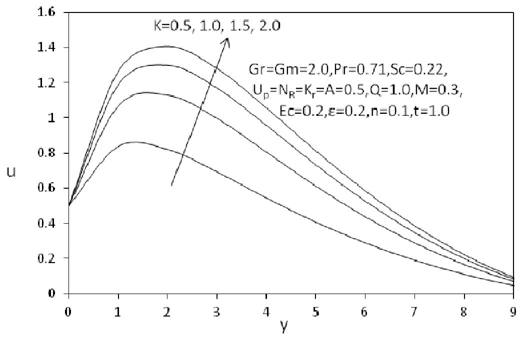

Fig. 5. Velocity profiles for different values of K

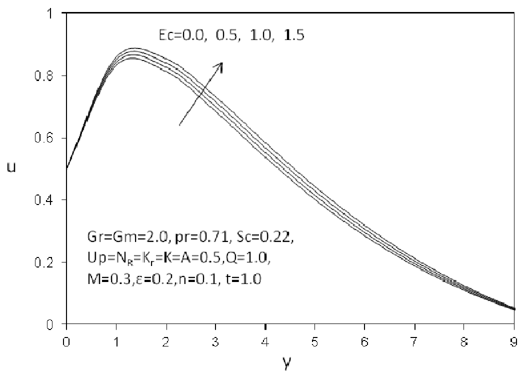

Fig. 6. Velocity profiles for different values of Ec

Figure 5 shows the effect of the permeability of the porous medium parameter K on the velocity distribution. It is found that the velocity increases with an increase in K.

For different values of the Eckert number Ec the velocity and temperature profiles are plotted in Fig. 6 and Fig. 7. It is obvious that an increase in the Eckert number Ec results in a increase in the velocity and temperature within the boundary layer.

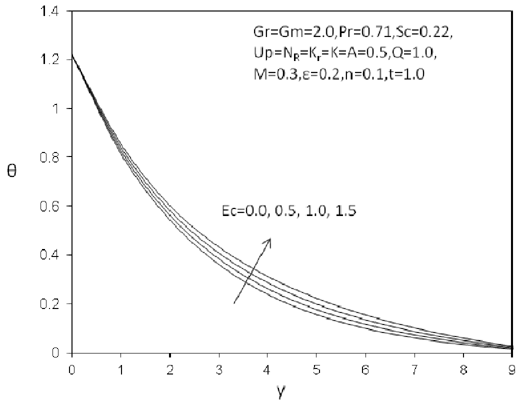

Fig. 7. Temrerature profiles for different values of Ec

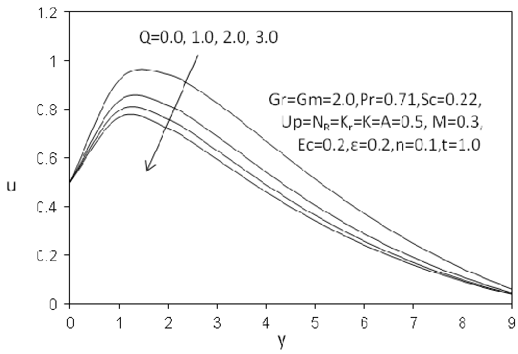

Fig. 8. Velocity profiles for different values of Q

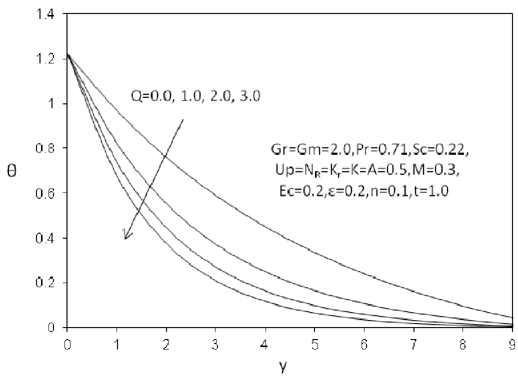

Fig. 9. Temperature profiles for different values of Q

Figures 8 and 9 illustrate the velocity and temperature profiles for different values of heat absorption parameter Q, the numerical results show that the effect of increasing values of heat absorption parameter result in a decreasing velocity and temperature.

Figures 10 and 11 show the behavior velocity and temperature for different values Prandtl number. The numerical results show that the effect of increasing values of Prandtl number results in a decreasing velocity. It is observed that an increase in the Prandtl number results a decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer. The reason is that smaller values of Pr are equivalent to increase in the thermal conductivity of the fluid and therefore, heat is able to diffuse away from the heated surface more rapidly for higher values of Pr. Hence in the case of smaller Prandtl number as the thermal boundary later is thicker and the rate of heat transfer is reduced.

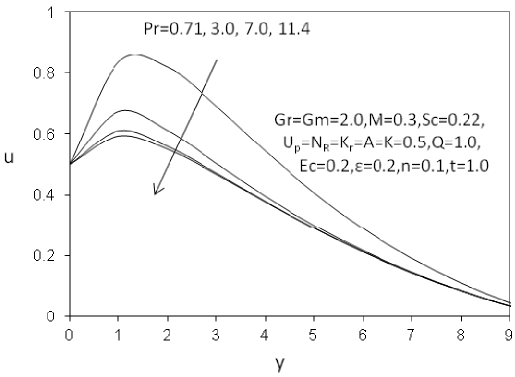

Fig. 10. velocity profiles for different values of Pr

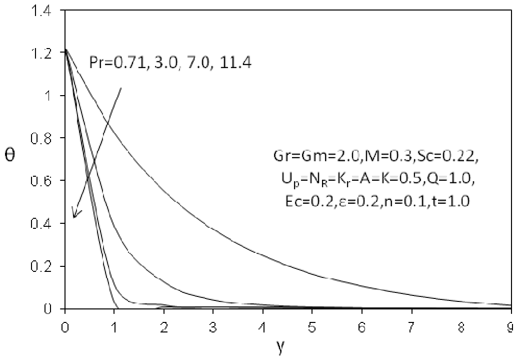

Fig. 11. Temperature profiles for different values of Pr

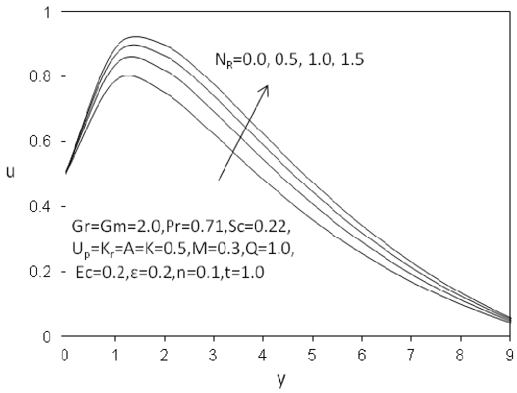

Fig. 12. velocity profiles for different values of N_R

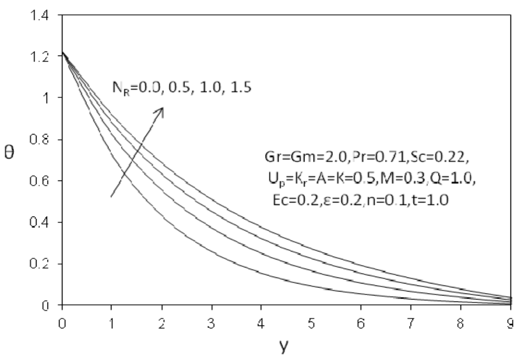

Fig. 13. Teperature profiles for different values of N_R

For different values of thermal radiation N_R the velocity and temperature profiles are shown in Figs. 12 and 13. It is noticed that an increase in the thermal radiation results a increase in the velocity and temperature within the boundary layer. The effect of the Schmidt number Sc on the velocity and concentration are shown in Figs. 14 and 15. As the Schmidt number increases, the velocity and concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. Reductions in the velocity and concentration distributions are accompanied by simultaneous reductions in the velocity and concentration boundary layers.

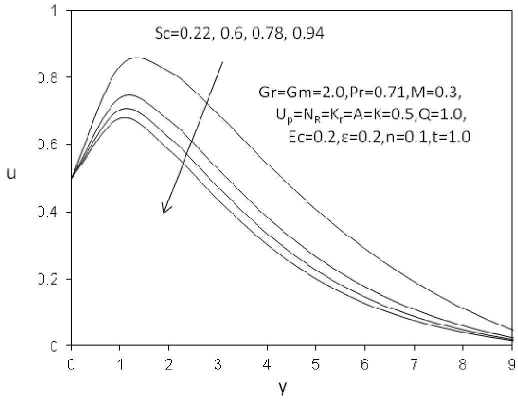

Fig. 14. velocity profiles for different values of Sc

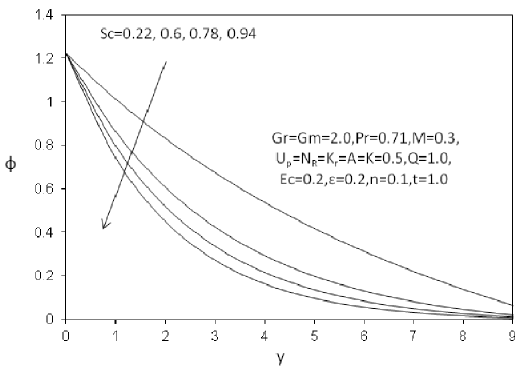

Fig. 15. Concentration profiles for different values of Sc

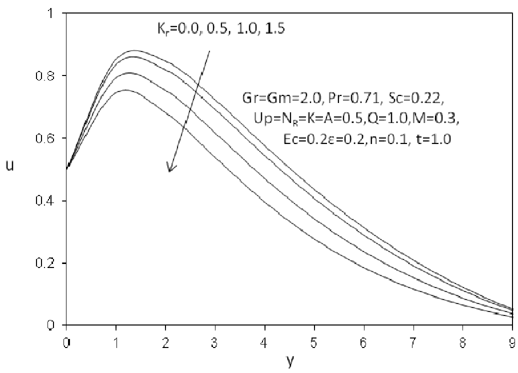

Fig. 16. Velocity profiles for different values of K_r

Figures 16 and 17, illustrates the behavior velocity and concentration for different values of chemical reaction parameter K_r. It is observed that an increase in leads to a decrease in both the values of velocity and concentration. The numerical calculations have been computed to understand the physical aspect of the problem. Tables 1, 2 and 3 show the numerical values of the skin friction coefficient, Nusselt number and Shear wood number.

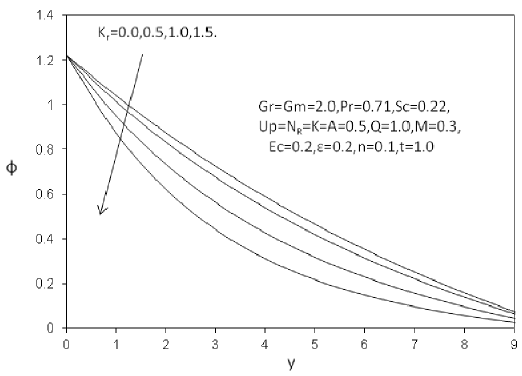

Fig. 17. Concentration profiles for different values of K_r

Table 1 Effect of Gr, Gm, M and K on C_f
(N_R=0.5, Pr=0.71, Ec=0.2, Q=1.0, Sc=0.22, K_r=0.5)

Gr	Gm	M	K	C_f
2.0	2.0	1.0	0.5	1.0608
4.0	2.0	1.0	0.5	1.9892
2.0	4.0	1.0	0.5	2.2753
2.0	2.0	2.0	0.5	0.6947
2.0	2.0	1.0	1.0	1.5923

Table 2 Effect of N_R, Pr, Ec and Q on C_f and Nu
(Gr=2.0, Gm=2.0, M=0.3, K=0.5, Sc=0.22, K_r=0.5)

N_R	Pr	Ec	Q	C_f	Nu
0.5	0.71	0.5	1.0	1.4229	1.1105
1.0	0.71	0.5	1.0	1.5169	0.9271
0.5	7.0	0.5	1.0	0.6341	5.5109
0.5	0.71	1.0	1.0	1.4498	1.0500
0.5	0.71	0.5	2.0	1.2884	1.4207

Table 3 Effect of Sc and K_r on C_f and Sh
(Gr=2.0, Gm=2.0, M=0.3, K=0.5, N_R=0.5, Pr =0.71, Ec=0.2, Q=1.0)

Sc	K_r	C_f	Sh
0.22	0.5	1.4073	0.5506
0.60	0.5	1.1212	1.0094
0.22	1.0	1.2800	0.7438

The effects of where Gr, Gm, M, K, Pr, N_R, Ec, Q, Sc and K_r on the skin-friction C_f, Nusselt number Nu, Sherwood number Sh are shown in Tables 1 to 3. From Table 1, it is observed that as Gr or Gm or K increases, the skin-friction coefficient increases, where as the skin-friction coefficient decreases as M increases. From Table 2, it is noticed that as N_R or Ec increases, the skin-friction coefficient increases while the Nusselt number decreases and Pr or Q increases, the skin-friction coefficient decreases while the Nusselt number increases. From Table 3, it is found that as Sc or K_r increases, the skin-friction coefficient decreases while the Sherwood number increases.

5. CONCLUSION

In this paper, an unsteady two dimensional radiations and MHD free convection viscous dissipative past a moving vertical porous plate with chemical reaction was considered. The non- dimensional governing equations are solved with the help of finite element method. The conclusions of the study are as follows:

1. The velocity increases with the increase in thermal Grashof number and solutalGrashof number.
2. The velocity decreases with an increase in the magnetic parameter.
3. The velocity increases with an increase in the permeability of the porous medium parameter.
4. An increase in the Eckert number increases the velocity and temperature.
5. An increase in the prandtl number decreases the velocity and temperature.
6. An increase in the thermal radiation leads to increase in the velocity and temperature.
7. Increasing the heat absorption parameter reduces both velocity and temperature.
8. The velocity as well as concentration decreases with an increase in the Schmidt number.

The velocity as well as concentration decreases with an increase in the chemical reaction parameter.

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