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MHD FREE CONVECTION FLUID FLOW PAST A SEMI-INFINITE VERTICAL POROUS PLATE WITH HEAT ABSORPTION AND CHEMICAL REACTION

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ABSTRACT

An analysis is presented for the magneto hydrodynamics (MHD) free convection fluid flow past a semi-infinite vertical plate in a porous medium with heat absorption and chemical reaction was considered. 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.

Key words: MHD, Free convection, Heat absorption, Vertical plate, Chemical reaction.

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

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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.

Gebhart and Pera[1] studied the nature of vertical natural convection flow resulting from the combined buoyancy effects of thermal and mass diffusion. Soundalgekar and Patti[2] studied the problem of the flow past an impulsively started isothermal infinite vertical plate with mass transfer effects. Singh and Tewari[3] studied the effect of thermal stratification on non-Darcian free convection flow by using the Ergun model[4] to include the inertia effect. Lai and Kulacki[5] analyzed the effects of variable viscosity on mixed convection heat transfer along a vertical surface in a saturated porous medium considering Newtonian fluid. It is well known that there exists non-Darcian flow phenomena bodies inertia effect and solid-boundary viscous resistance. Deka et al.[6] studied the effect of the first order homogeneous chemical reaction on the process of an unsteady flow past an infinite vertical plate with a constant heat and mass transfer. Later, Kafoussian and Williams[7] investigated the effects of temperature-dependent viscosity on free-forced convective boundary layer flow past a vertical isothermal flat plate in Newtonian fluid. Pantokratoras[8] made a theoretical study to investigate the effect of variable viscosity on flow and heat transfer on a continuous moving plate. Vajravelu and Rollins[9] studied heat transfer in an electrically conducting fluid over a stretching surface by taking into account of magnetic field. Ali[10] investigated the effect of variable viscosity on mixed convection heat transfer along a moving surface. Salem[11] studied the problem of flow and heat transfer of all electrically conducting viscoelastic fluid having temperature dependent viscosity as well as thermal conductivity fluid over a continuously stretching sheet in the presence of a uniform magnetic field for the case of power-law variation in the sheet temperature. However, all these works have neglected electric field, which is also one of the important parameters to alter the momentum, heat and mass transfer characteristics in the boundary layer flow. Abel et al.[12] studied viscoelastic MHD flow and heat transfer over a stretching sheet with viscous with Ohmic dissipations in the presence of electric field.

Pal and Chatterjee[13] investigated similar problem by considering micropolar fluid. Sharma and Singh[14] analyzed the effects of variable thermal conductivity, viscous dissipation on steady MHD natural convection flow of low Prandtl number fluid on an inclined porous plate with Ohmic dissipation. In certain porous media applications such as that involving heat removal from nuclear fuel debris, underground disposal of radiative waste material, storage of food stuffs, the study of heat transfer is of much importance. Ali[15] analyzed the effect of lateral mass flux on the natural convection boundary layer induced by a heated vertical plate embedded in a saturated porous medium with an exponential decaying heat generation. It is worth mentioning that non-Darcian forced flow boundary layers from a very important group of flows, the solution of which is of great importance in many practical applications such as in biomechanical problems, in filtration transpiration cooling and geothermal. Seddeek[16] analyzed non-Darcian effect on forced convection heat transfer over a flat plate in a porous medium with temperature-dependent viscosity. Recently, Pal and Mondal[17] analyzed the effect of variable viscosity on MHD non-Darcy mixed convective heat transfer in porous medium with non-uniform heat source/sink. Muthucumaraswamy and Ganesan[18] studied effect of the chemical reaction and injection on flow characteristics in an unsteady upward motion of an isothermal plate. Chamkha[19] studied the MHD flow of a numerical of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Raptis[20] investigate the steady flow of a viscous fluid through a very porous medium bounded by a porous plate subjected to a constant suction velocity by the presence of thermal radiation. Reddy et al.[21] have studied the mass transfer and radiation effects of unsteady MHD free convective fluid flow embedded in porous medium with heat generation/absorption. Venkateswarlu et al.[22] have studied the unsteady MHD flow of a viscous fluid past a vertical porous plate under oscillatory suction velocity.

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.

EXPERIMENTAL

Mathematical analysis

An unsteady two-dimensional laminar free convective boundary layer flow of a viscous, incompressible, electrically conducting on unsteady magneto hydrodynamics free convection fluid flow past a semi-infinite vertical plate in a porous medium with heat absorption and chemical reaction 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:

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

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

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

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

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:

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

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 Rosseland approximation, the radiative heat flux q_r is given by –

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

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

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \qquad \ldots(7)$$

In view of equations (6) and (7), equation (3) reduces to –

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

From the continuity equation (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

$$v' = -V_0\left(1 + \boldsymbol{\varepsilon}\, Ae^{n't'}\right) \qquad \ldots(9)$$

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.

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

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

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

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

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

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 –

$$\begin{aligned} &u=U_p,\quad \theta=1+\varepsilon e^{nt},\quad \varphi=1+\varepsilon e^{nt} \qquad \text{at} \qquad y=0 \\ &u\to 0,\quad \theta\to 0,\quad \varphi\to 0 \qquad as \qquad y\to\infty \end{aligned} \quad \ldots(14)$$

Solution of the problem

The set of differential Equations (11) to (13) subject to the boundary conditions (14) are highly nonlinear, coupled and therefore it cannot be solved analytically. The fundamental steps comprising the method are as follows:

Step 1: Discretization of the domain into elements:

Step 2: Derivation of the element equations:

Step 3: Assembly of element equations:

Step 4: Impositions of boundary conditions:

Step 5: Solution of the assembled equations:

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 –

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

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

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

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

$$Sh = -x \frac{\left(\frac{\partial C}{\partial y'}\right)_{y'=0}}{C_w - C_\infty} \quad \Rightarrow Sh\,\mathrm{Re}_x^{-1} = -\left(\frac{\partial \varphi}{\partial y}\right)_{y=0} \qquad \ldots(17)$$

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

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 Grash of number *Gr*, modified Grash of number *Gm*, Permeability parameter K, Eckert number Ec, heat absorption parameter *Q*, thermal radiation *N*, Prandtl number Pr, Schmidt number Sc and chemical reaction parameter K_r. The velocityprofiles for $Gr = Gm = 2.0$, $M = 0.3$, $K = 0.5$, Pr = 0.71, $N = 0.5$, $Ec = 0.2$, $Q = 1.0$, $Sc = 0.22$, $Up = 0.5$, $A = 0.5$, $\varepsilon = 0.2$, $n = 0.1$, $t = 1.0$. For various values of the thermal Grashof number *Gr* and modified number *Gm*, the velocity profiles '*u*' are plotted in Figs. 1 and 2. The thermal Grash of 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 modified Grash of 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 modified Grash of number.

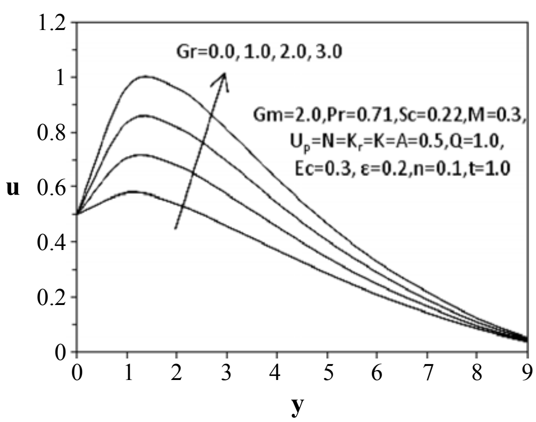

Fig. 1: Velocity profiles for different values of Gr

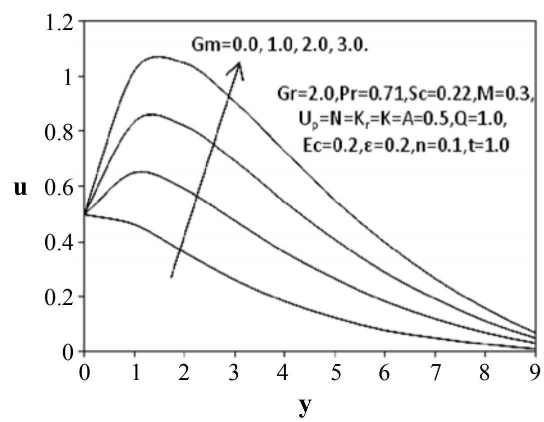

Fig. 2: Velocity profiles for different values of Gm

The effect of the magnetic parameter *M* is shown in Fig. 3. 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. 3. Fig. 4, 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*.

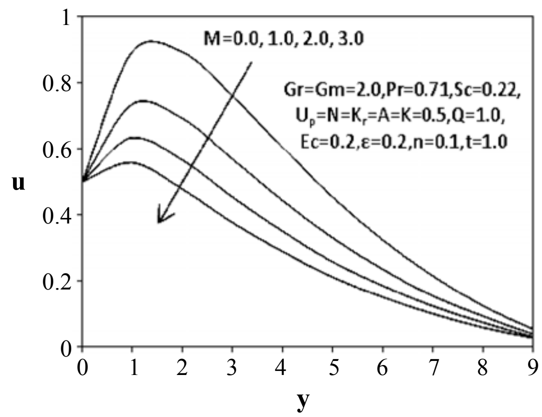

Fig. 3: Velocity profiles for different values of M

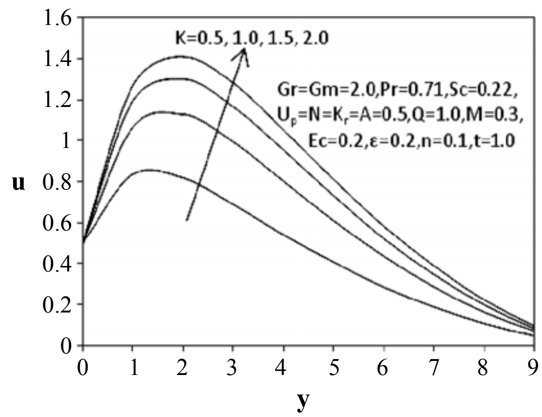

Fig. 4: Velocity profiles for different values of K

For different values of the Eckert number *Ec* the velocity and temperature profiles are plotted in Fig. 5 and Fig. 6. It is obvious that an increase in the Eckert number *Ec* results in a increase in the velocity and temperature within the boundary layer. Figs. 7 and 8 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.

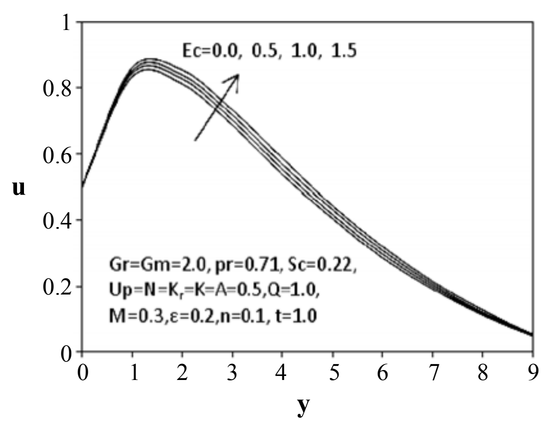

Fig. 5: Velocity profiles for different values of Ec

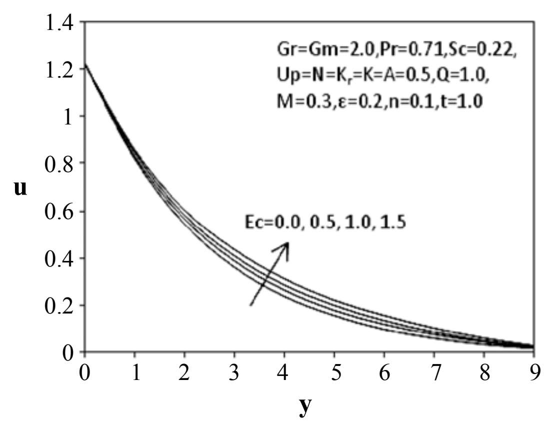

Fig. 6: Temperature profiles for different values of Ec

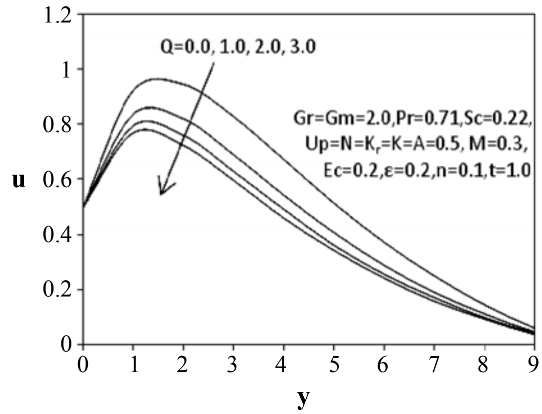

Fig. 7: Velocity profiles for different values of Q

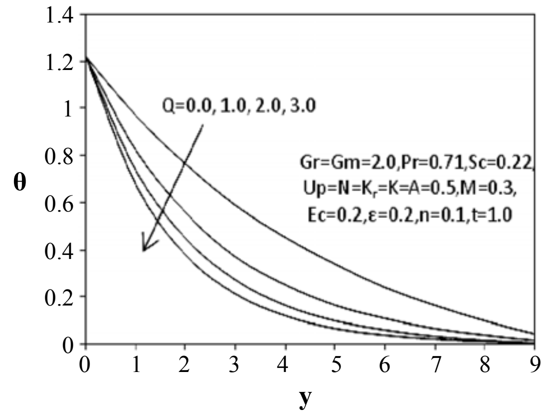

Fig. 8: Temperature profiles for different values of Q

A Fig. 9 and 10 shows 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.

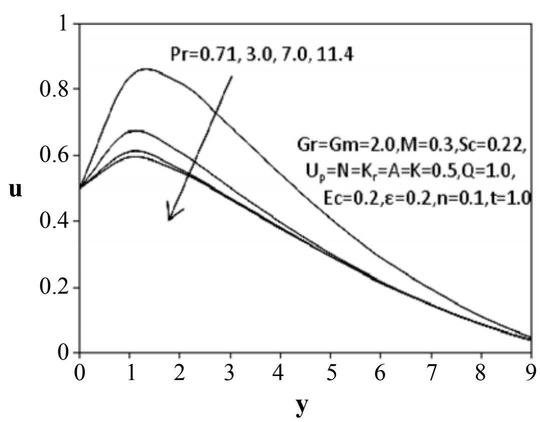

Fig. 9: Velocity profiles for different values of Pr

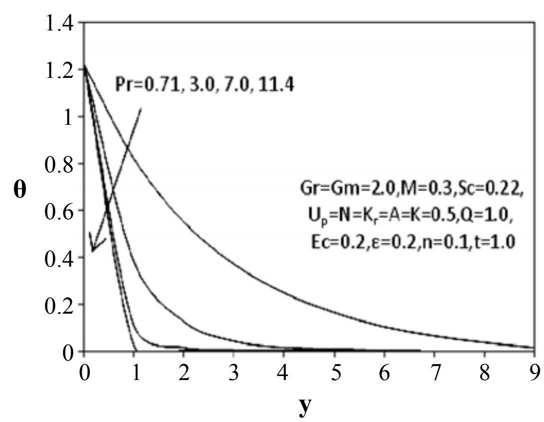

Fig. 10: Temperature profiles for different values of Pr

For different values of thermal radiation N_R the velocity and temperature profiles are shown in Figs. 11 and 12. 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. 13 and 14. 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.

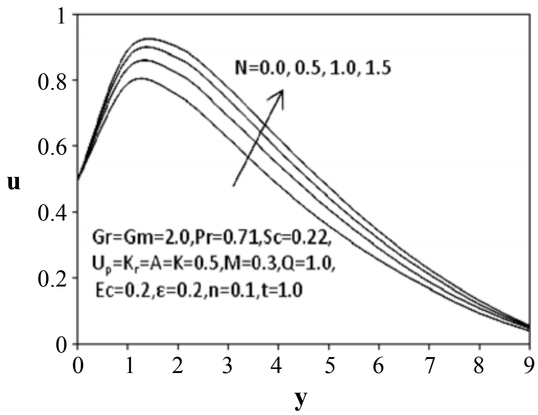

Fig. 11: Velocity profiles for different values of N

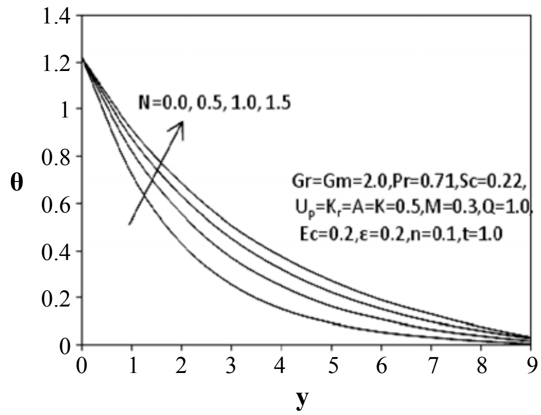

Fig. 12: Temperature profiles for different values of N

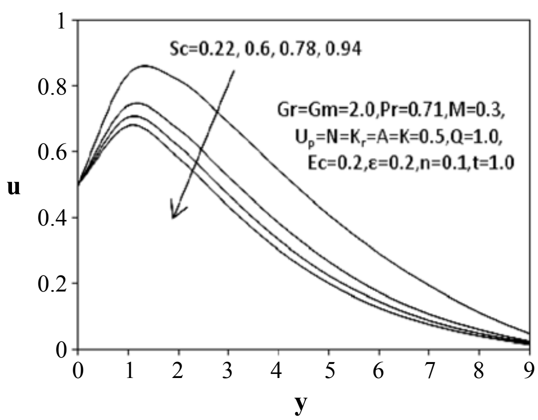

Fig. 13: Velocity profiles for different values of Sc

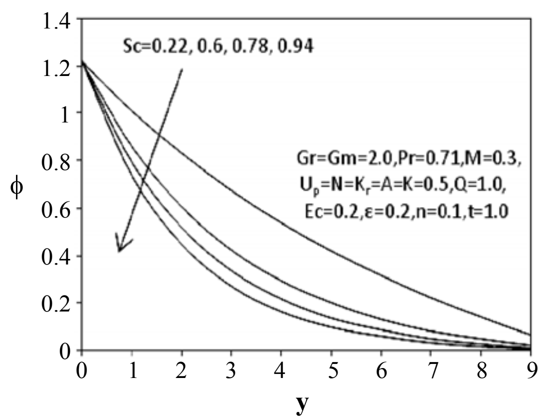

Fig. 14: Concentration profiles for different values of Sc

Figs. 15 and 16, 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.

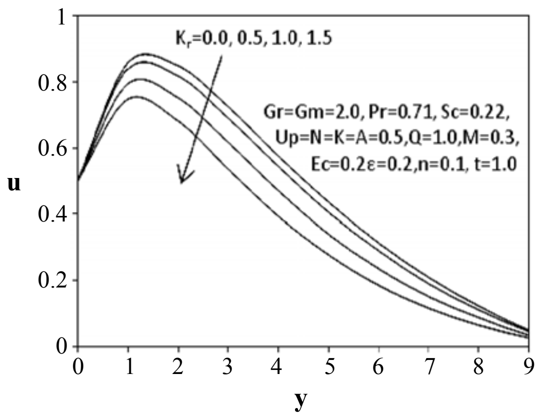

Fig. 15: Velocity profiles for different values of K_r

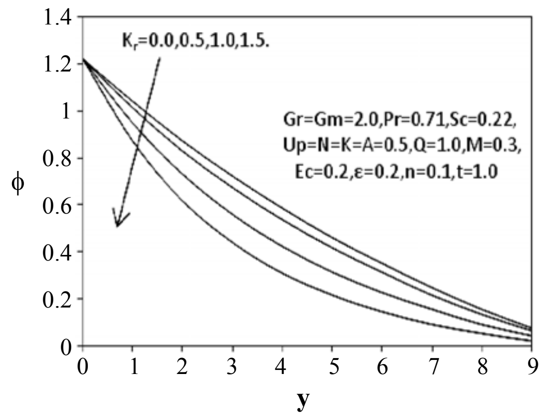

Fig. 16: Concentration profiles for different values of K_r

Tables (1), (2) and (3) show the numerical values of the skin friction coefficient, Nusselt number and Sherwood number. 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.

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	1.0606
4.0	2.0	1.0	0.5	1.9890
2.0	4.0	1.0	0.5	2.2752
2.0	2.0	2.0	0.5	0.6945
2.0	2.0	1.0	1.0	1.5921

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	1.1106
1.0	0.71	0.5	1.0	1.5070	0.9270
0.5	7.0	0.5	1.0	0.6338	5.5109
0.5	0.71	1.0	1.0	1.4499	1.0501
0.5	0.71	0.5	2.0	1.2886	1.4206

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	1.4072	0.5509
0.60	0.5	1.1211	1.0095
0.22	1.0	1.2801	0.7436

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.

CONCLUSION

The numerical study has been performed on the 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:

(a) The velocity increases with the increase in thermal Grashof number and modified Grashof number.

(b) The velocity decreases with an increase in the magnetic parameter.

(c) The velocity increases with an increase in the permeability of the porous medium parameter.

(d) An increase in the Eckert number increases the velocity and temperature.

(e) An increase in the Prandtl number decreases the velocity and temperature.

(f) An increase in the thermal radiation leads to increase in the velocity and temperature.

(g) Increasing the heat absorption parameter reduces both velocity and temperature.

(h) The velocity as well as concentration decreases with an increase in the Schmidt number.

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

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