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ORIGINAL ARTICLE

Chemical reaction effect on MHD free convective surface over a moving vertical plate through porous medium

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Abstract An attempt has been made to study the heat and mass transfer effect in a boundary layer flow of an electrically conducting viscous fluid subject to transverse magnetic field past over a moving vertical plate through porous medium in the presence of heat source and chemical reaction. The governing non-linear partial differential equations have been transformed into a two-point boundary value problem using similarity variables and then solved numerically by fourth order Runge–Kutta fourth order method with shooting technique. Graphical results are discussed for non-dimensional velocity, temperature and concentration profiles while numerical values of the skin friction, Nusselt number and Sherwood number are presented in tabular form for various values of parameters controlling the flow system.

1. Introduction

MHD free convection flows have significant applications in the field of stellar and planetary magnetospheres, aeronautical plasma flows, chemical engineering and electronics. The fluid flow and heat transfer through a porous medium have been extensively studied in the past because of its relevance to nuclear waste disposal, solid matrix heat exchanger, thermal insulation and other practical application. Natural convective flows are frequently encountered in physical and engineering problems such as chemical catalytic reactors, nuclear waste materials, and geothermal system. The concept of simultaneous heat and mass transfer is used in various science and engineering problems. It is used in food processing, wet-bulb thermometer and polymer solution and also in various fluids flow related engineering problems. In our daily life, the combined heat and mass transfer phenomenon is observed in the formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of fruit trees, crop damage due to freezing, and environmental pollution.

The fluid flow over a stretching sheet is important in many practical applications such as extrusion of plastic sheets, paper production, glass blowing, metal spinning, polymers in metal

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Nomenclature

u, v	velocity components	T	temperature in the fluid
C	concentration of chemical species	υ	kinematic viscosity
k'_p	permeability coefficient	C_∞	free stream concentration
U_0	plate velocity	α	thermal diffusivity
D	mass diffusivity	β_T	thermal expansion coefficient
β_c	solutal expansion coefficient	ρ	fluid density
g	gravitational acceleration	σ	fluid electrical conductivity
B_0	magnetic induction	C_p	specific heat at constant pressure
Q	dimensional heat source coefficient	K_1	chemical reaction parameter
h_f	heat transfer coefficient	T_f	temperature of the hot fluid
A	a constant	k	thermal conductivity

spring processes, the continuous casting of metals, drawing plastic films and spinning of fibers [1]. The growing need for chemical reaction and hydrometallurgical industries requires the study of heat and mass transfer with chemical reaction. There are many transport processes that are governed by the combined action of buoyancy forces due to both thermal and mass diffusion in the presence of chemical reaction effect. These processes are observed in the nuclear reactor safety and combustion systems, solar collectors, as well as metallurgical and chemical engineering. Chamkha and Khaled [2] investigated the problem of coupled heat and mass transfer by magnetohydrodynamic free convection from an inclined plate in the presence of internal heat generation or absorption.

Simultaneous heat and mass transfer from different geometries embedded in porous medium has many engineering and geophysical applications also 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. Ishak et al. [3] investigated theoretically the unsteady mixed convection boundary layer flow and heat transfer due to a stretching vertical surface in a quiescent viscous and incompressible fluid. Mahapatra and Gupta [4,5] considered the stagnation flow on a stretching sheet. Sammer [6] investigated the heat and mass transfer over an accelerating surface with heat source in the presence of magnetic field. Wang [7] studied the stagnation flow toward a shrinking sheet.

Naseem and Khan [8] investigated boundary layer flow past a stretching plate with suction, heat and mass transfer and with variable conductivity. Elbashbeshy and Bazid [9] studied flow and heat transfer in a porous medium over a stretching surface with internal heat generation and suction/blowing. Cortell [10] also reported the flow and heat transfer of a fluid through porous medium over a stretching surface with internal heat generation. Anjali Devi and Ganga [11] have studied the viscous dissipation effect on nonlinear MHD flow in a porous medium over a stretching porous surface.

Mushtaq et al. [12] examined the effects of thermal buoyancy on viscoelastic flow of a second grade fluid past a vertical, continuously stretching sheet. Numerical solutions for the coupled nonlinear partial differential are generated using local non-similarity method and Keller-Box scheme. Singh and Singh [13] have discussed the MHD free convection flow and mass transfer past a flat plate. Al-Qadat and Al-Azab [14] have studied the influence of chemical reaction on transient MHD free convective flow over a moving vertical plate. Palani and Srikanth [15] have explained the mass transfer effects on MHD flow past a semi infinite vertical plate. Chaudhary and Jain [16] have analyzed the combined heat and mass diffusion in a MHD free convective flow past a surface embedded in a porous medium. Recently, we explore the flow of a Jeffery fluid [17,18] over a stretched sheet subject to power law temperature in the presence of heat source/sink. Abbasi et al. [19] have studied the peristaltic flow in an asymmetric channel with convective boundary conditions and Joule heating. Mixed convective heat and mass transfer analysis for peristaltic transport in an asymmetric channel with Soret and Dufour effects was investigated by Abbasi et al. [20]. Soret and Dufour effects on the peristaltic transport of a third-order fluid were studied by Hayat et al. [21]. Heat transfer in viscous free convective fluctuating MHD flow through porous media past a vertical porous plate with variable temperature is analyzed by Mishra et al. [22].

The aim of the present study was to analyze the effects of magnetohydrodynamic mixed convection flow of a viscoelastic fluid embedded in a porous medium over a moving vertical plate taking the radiation and mass transfer into account. We have extended the work of Makinde [23] to study the effect of porous medium and chemical reaction on the fluid flow. Using the similarity transformations, the governing equations have been transformed into a set of ordinary differential equations, and the resultant equations are solved using Runge–Kutta method along with shooting technique. The results are analyzed for various physical parameters such as viscoelasticity, permeability of the porous medium, magnetic field, Grashof number, Schmidt number, Prandtl number, heat source parameter and chemical reaction parameter on the flow, heat and mass transfer characteristics.

2. Mathematical formulation

We consider a free convective, laminar boundary layer flow and heat and mass transfer of viscous incompressible and electrically conducting viscoelastic liquid over a moving vertical plate. The flow is assumed to be in the x-direction, which is taken along the vertical plate in the upward direction, and the y-axis is taken to be normal to the plate. A uniform transverse magnetic field of strength B_0 is assumed to be applied in the positive y-direction normal to the plate and chemical reaction is also taking place in the flow. There is no applied electric field and Hall effect and Joule heating is neglected on account that the fluid is finitely conducting. It is assumed that the induced magnetic field and the electric field due to the polarization of charges are negligible. The density variation and the effects of the buoyancy are taken into account in the momentum equation and the concentration of species far from the wall is infinitesimally small and the viscous dissipation term in the energy equation is neglected (as the fluid velocity is very slow). Using Boussinesq's approximation, the governing boundary layer equations for this problem can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho}u-\frac{\upsilon u}{k_p'}+g\beta_T(T-T_\infty)+g\beta_c(C-C_\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+S'(T-T_\infty) \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-K_1(C-C_\infty) \tag{4}$$

where u and v are velocity components, T and C are the temperature and concentration of chemical species in the fluid, υ is the kinematic viscosity, k_p' is the permeability coefficient of porous medium, C_∞ is the free stream concentration, U_0 is the plate velocity, α is the thermal diffusivity and D is the mass diffusivity, β_T is the thermal expansion coefficient, β_c is the solutal expansion coefficient, ρ is the fluid density, g is gravitational acceleration, σ is the fluid electrical conductivity, B_0 is the magnetic induction, C_p is the specific heat at constant pressure, Q is the dimensional heat generation/absorption coefficient, K_1 is the chemical reaction parameter.

The boundary conditions at the plate surface and far into the cold fluid may be written as

$$\begin{gathered}u(x,0)=U_0, v(x,0)=0, -k\frac{\partial T}{\partial y}(x,0)=h_f[T_f-T(x,0)],\\ C_w(x,0)=Ax^\lambda+C_\infty, u(x,\infty)=0, T(x,\infty)=T_\infty, C(x,\infty)=C_\infty\end{gathered} \tag{5}$$

where C_w is the species concentration at the plate surface, λ is the plate surface concentration exponent. The continuity equation (1) is satisfied by the Cauchy-Riemann equations

$$u=\frac{\partial\psi}{\partial y}, v=-\frac{\partial\psi}{\partial x} \tag{6}$$

where $\psi(x, y)$ is the stream function.

In order to transform Eqs. (2)–(5) into a set of ordinary differential equations, the following similarity transformations and dimensionless variables are introduced Ref. [23]

$$\left.\begin{aligned}&\eta=\left(\tfrac{U_0}{\upsilon x}\right)^{1/2}y, \psi=\sqrt{\upsilon x U_0}\,f(\eta),\\ &\theta(\eta)=\tfrac{T-T_\infty}{T_f-T_\infty}, \phi(\eta)=\tfrac{C-C_\infty}{C_w-C_\infty}\end{aligned}\right\} \tag{7}$$

where $f(\eta)$ is the dimensionless stream function, θ is the dimensionless temperature, ϕ is the dimensionless concentration, η is the similarity variable.

In view of Eqs. (6) and (7), Eqs. (2)–(5) transform into

$$f'''+\frac{1}{2}ff''-\left(Ha+\frac{1}{k_p}\right)f'+Gr\theta+Gc\phi=0 \tag{8}$$

$$\theta''+\frac{1}{2}\mathrm{P}_r\,f\theta'+P_rS\theta=0 \tag{9}$$

$$\phi''+\frac{1}{2}Scf\phi'-Sck_c\phi=0 \tag{10}$$

subject to boundary conditions

$$\left.\begin{aligned}&f(0)=0, f'(0)=1, \theta'(0)=Bi[\theta(0)-1], \phi(0)=1\\ &f'(\infty)=0, \theta(\infty)=0, \phi(\infty)=0\end{aligned}\right\} \tag{11}$$

where the primes denote differentiation with respect to η. The dimensionless variables are as follows:

$Ha=\frac{\sigma B_0^2 x}{\rho U_0}$ (magnetic field parameter)	$k_p=\frac{k_p' U_0}{\upsilon x}$ (permeability parameter)
$S=\frac{S'x}{U_0}$ (source parameter)	$P_r=\frac{\upsilon}{\alpha}$ (the Prandtl number)
$Bi=\frac{h_f}{k}\sqrt{\frac{\upsilon x}{U_0}}$ (convective heat transfer parameter)	$Sc=\frac{\upsilon}{D}$ (the Schmidt number)
$Gr=\frac{g\beta_T(T_f-T_\infty)x}{U_0^2}$ (thermal Grashof number)	$k_c=\frac{K_1 x}{U_0}$ (reaction parameter)
$Gc=\frac{g\beta_c(C_w-C_\infty)x}{U_0^2}$ (solutal Grashof number)	

Here we see that all the local parameters $Bi, Ha, Gr, Gc, S, k_c, k_p$ in Eqs. (8)–(10) are functions of x. To have a similarity solution all the parameters $Bi, Ha, Gr, Gc, S, k_c, k_p$ must be constant. The physical quantities of interest are the plate surface temperature, the local skin friction coefficient, the local Nusselt number, and local Sherwood number. These are proportional to $\theta(0), f''(0), -\theta'(0)$, and $-\phi'(0)$ respectively.

3. Method of solution

The governing boundary layer Eqs. (8)–(10) subject to boundary conditions (11) are solved numerically by using shooting method. First of all higher order non-linear differential equations Eqs. (8)–(10) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique. From the process of numerical computation, the plate surface temperature, the local skin friction coefficient, the local Nusselt number, and local Sherwood number are also sorted out and their numerical values are presented in a tabular form (see Fig. 1).

4. Results and discussion

In order to get a physical insight into the problem, a representative set of numerical results is shown graphically in Figs. 2–11, to illustrate the influence of physical parameters embedded in the flow system. The Prandtl number was taken to be

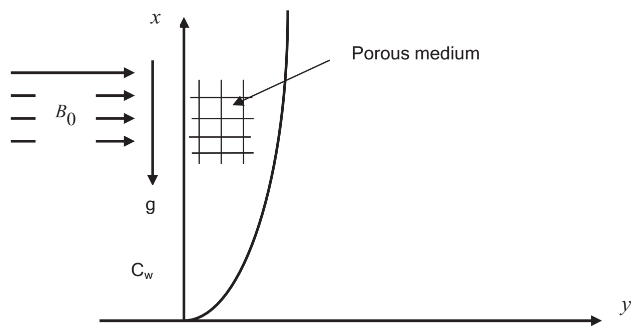

Figure 1 Flow geometry.

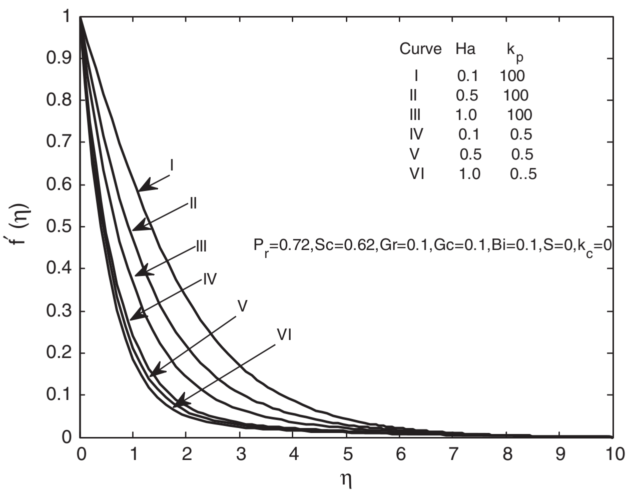

Figure 2 Velocity profile for different values of Ha and k_p.

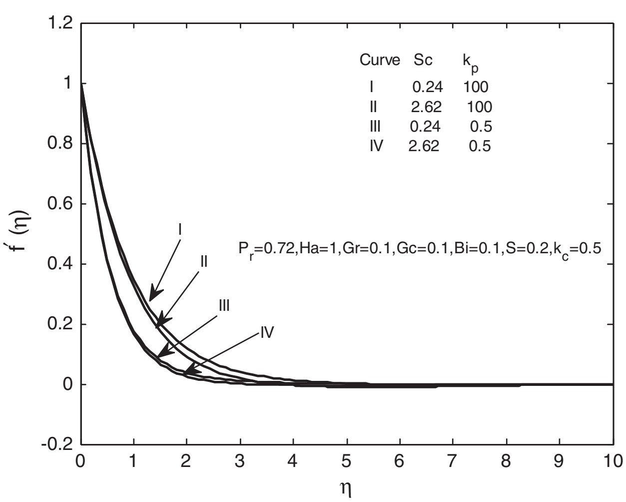

Figure 3 Velocity profiles for different values of Sc and k_p.

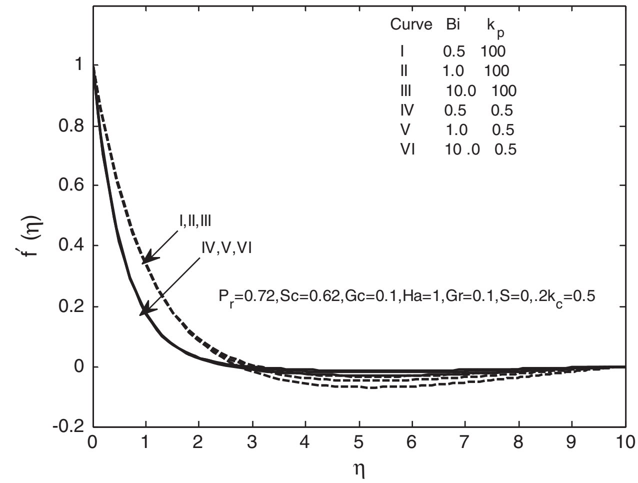

Figure 4 Velocitty profiles for different values of Bi and k_p.

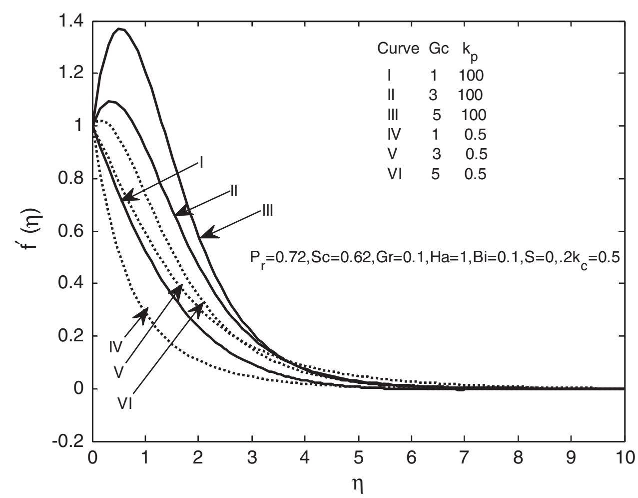

Figure 5 Velocity profiles for different values of Gc and k_p.

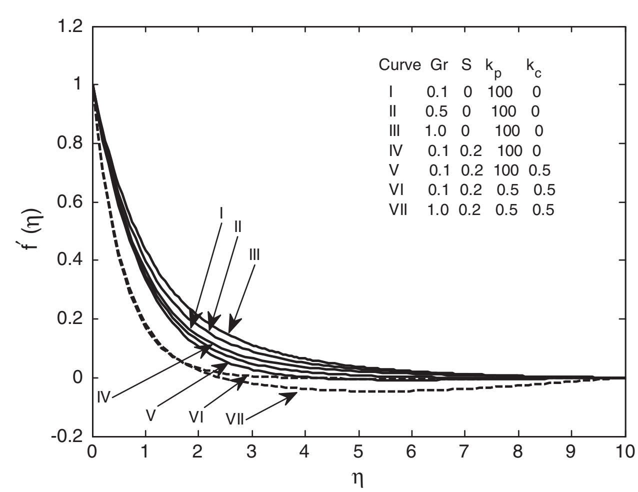

Figure 6 Velocity profiles for different values of Gr, S, k_p, k_c when $P_r = 0.72$, $Ha = 1$, $Sc = 0.62$, $Bi = 0.1$.

$P_r = 0.72$, which corresponds to air. Attention is focused on positive values of the buoyancy parameters, that is, thermal Grashof number $G_r > 0$ (which corresponds to the cooling problem) and solutal Grashof number $G_c > 0$ (which indicates that the chemical species concentration in the free stream

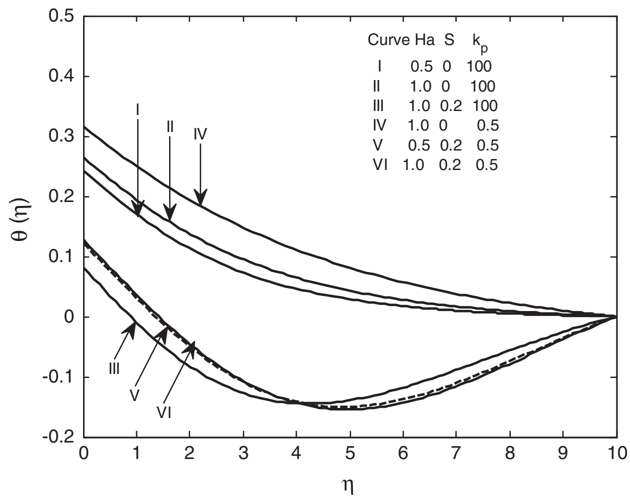

Figure 7 Temperature profiles for different values of Ha, S and k_p when P_r = 0.72, Gr = Gc = Bi = 0.1, k_c = 0.5, Sc = 0.62.

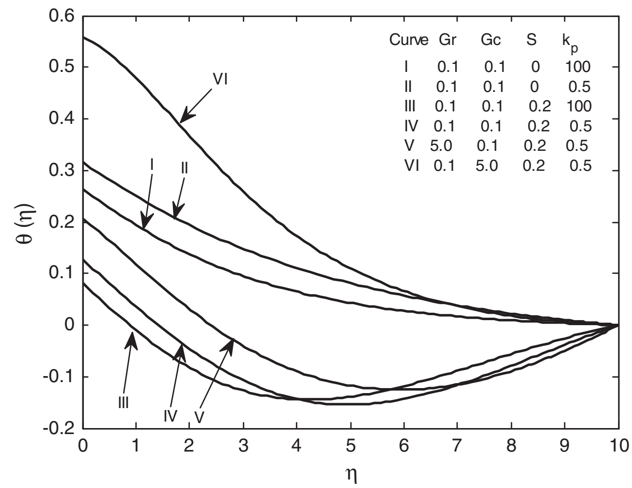

Figure 9 Temperature profiles for different values of Gr, Gc, S and k_p when P_r = 0.72, Ha = 1, Bi = 0.1, k_c = 0.5, Sc = 0.62.

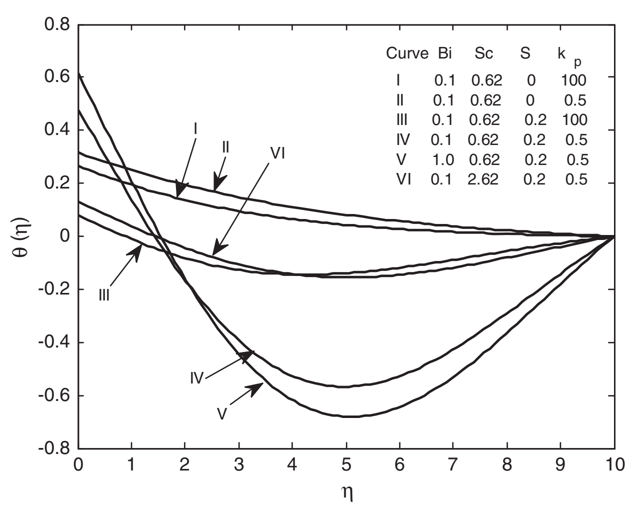

Figure 8 Temperature profiles for different values of Bi, Sc, S and k_p when P_r = 0.72, Ha = 1, Gr = 0.1 = Gc, k_c = 0.5.

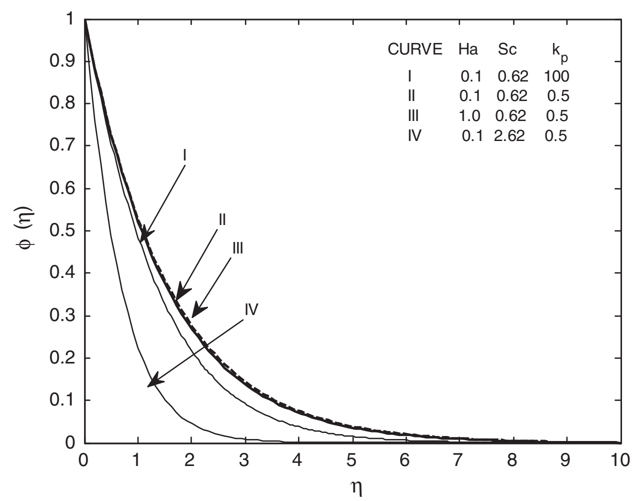

Figure 10 Concentration profiles for different values of Ha, Sc and k_p when P_r = 0.72, Gr = Gc = Bi = 0.1, k_c = 0.5, S = 0.2.

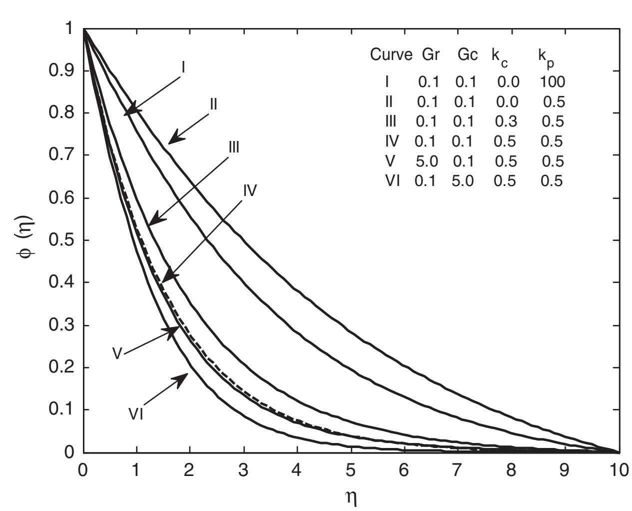

Figure 11 Concentration profiles for different values of Gr, Gc, k_c and k_p when P_r = 0.72, Ha = 1, Bi = 0.1, Sc = 0.62, S = 0.2.

region is less than the concentration at the boundary surface). Fig. 2 represents the effect of local magnetic field parameter and permeability parameter on the velocity field. It is obvious that an increase in the local magnetic parameter Ha results in a decrease in the velocity at all points. Application of a transverse magnetic field to an electrically conducting fluid gives rise to a resistive-type of force called the Lorentz force. This force has the tendency to slow down the motion of the fluid in the boundary layer. Curves I, II, III of the figure represents the effect of Ha on velocity in the absence of permeability and it is seen that it is in good agreement with the work of Makinde [23]. It is also seen in Fig. 2 that the velocity profiles decrease with the increase of permeability parameter k_p. The effect of the k_p on velocity profile decreases with increase in it.

Fig. 3 shows a slight decrease in the fluid velocity with an increase in Schmidt number. The decrease is more in the presence of porous medium. Similar trend is observed in the fluid

Table 1 Skin friction coefficient ($\tau(0)$), Nusselt number ($-\theta'(0)$) and Sherwood number ($-\phi'(0)$) for $P_r = 0.72$.

Gr	Gc	Sc	Bi	Ha	Kp	S	Kc	$\tau(0)$	$-\theta'(0)$	$-\phi'(0)$
0.1	0.1	0.62	0.1	0.1	100	0.0	0.0	−0.41149	0.078572	0.332445
0.1	0.1	0.62	0.1	0.1	100	0.0	0.1	−0.42154	0.078421	0.418468
0.1	0.1	0.62	0.1	0.1	100	0.2	0.1	−0.49909	0.115024	0.403805
0.1	0.1	0.62	0.1	0.1	0.5	0.2	0.1	−1.44774	0.089083	0.34164
0.1	0.1	0.62	0.1	1.0	100	0.2	0.1	−1.01798	0.093304	0.364954
0.1	0.1	0.62	1.0	0.1	100	0.2	0.1	−0.48079	0.433276	0.39389
0.1	0.1	2.62	0.1	0.1	100	0.2	0.1	−0.52689	0.103249	0.928141
0.1	1.0	0.62	0.1	0.1	100	0.2	0.1	0.338455	0.07163	0.480505
1.0	0.1	0.62	0.1	0.1	100	0.2	0.1	−0.37737	0.080417	0.393572
1.0	0.1	0.62	0.1	0.1	0.5	0.2	0.1	−1.39241	0.08534	0.339513
0.1	1.0	0.62	0.1	0.1	0.5	0.2	0.1	−0.74255	−0.24165	0.407709
0.1	0.1	0.62	0.1	1.0	0.5	0.2	0.1	−1.72765	0.08777	0.330435

velocity (Fig. 4) with an increase in the local convective heat transfer parameter (Bi).

Fig. 5 shows the effect of local solutal Grashof number (Gc) on velocity. It is noticed that the velocity profiles increase with the increase in Gc. Fig. 6 shows the effect of local thermal Grashof number (Gr) on velocity both in the presence and absence of porous medium. It is observed that an increase in the Gr results in a decrease in the velocity. Physically $Gr > 0$ means heating of the fluid or cooling of the boundary surface, $Gr < 0$ means cooling of the fluid or heating of the boundary surface and $Gr = 0$ corresponds to the absence of free convection current.

The numerical results for the temperature profiles for variation in Ha, S and k_p are shown in Fig. 7. It is interesting to note that the thermal boundary layer thickness increases with an increase in the intensity of magnetic field (curves I and II) in the absence of source and porous medium. The result agrees well with the one reported by Makinde [23]. But the presence of source decreases the thermal boundary layer. Again it is observed that the presence of porous medium increases the thermal boundary layer. But increase in Ha, in the presence of both source and porous medium decreases the temperature profile. It is observed that effect of source is dominant and it reduces the thermal boundary layer.

Fig. 8 presents the variation of Bi, Sc, S and k_p on the temperature profile with the fixed values of the parameter $P_r = 0.72, H_a = 1, G_r = 0.1, G_c = 0.1$ and $k_c = 0.5$. It is observed that in the absence of source parameter as well as porous medium ($S = 0, k_p = 100$) the temperature profile becomes linear. The presence of porous matrix ($k_p = 0.5$) enhances the temperature at all points (Curve I and II). The presence of source decelerates the temperature profile in both presence and absence of porous matrix. Increase in Bi decreases the thermal boundary layer in the presence of source and porous matrix. It is also observed that increase in Sc increases the thermal boundary layer. The variation of G_r and G_c is remarked in the presence of S and k_p in Fig. 9 with the fixed values of $P_r = 0.72, H_a = 1, Bi = 0.1, k_c = 0.5$ and $S_c = 0.62$. The thermal buoyancy parameter decelerates the temperature boundary layer whereas the mass buoyancy accelerates it in the presence of porous matrix.

Fig. 10 shows the effect of Ha and Sc on the concentration profile in the presence and absence of porous matrix with fixed values of $P_r = 0.72, H_a = 1, Bi = 0.1, k_c = 0.5, Gr = 0.1, Gc = 0.1$ and $S = 0.2$. Application of a transverse magnetic field to an electrically conducting fluid gives rise to a resistive-type of force called the Lorentz force. But Lorentz force enhances the concentration profile at all points and presence of porous matrix also. The increase of Sc lower down the thermal boundary layer and the temperature field becomes asymptotic in nature over the boundary layer.

The effect of chemical reaction parameter, k_c in the absence/presence of porous matrix is observed in Fig. 11 keeping the parameter $P_r = 0.72, H_a = 1, Bi = 0.1, Sc = 0.62$ and $S = 0.2$. It is noticed that in the absence of k_c ($k_c = 0$) the porosity enhances the temperature field at all points. In the presence of porous matrix the concentration boundary layer became thinner and thinner as the chemical reaction parameter increases. It is observed that the concentration profile is asymptotic in nature. The result well agrees with Makinde [23].

The numerical computation of skin friction coefficient, Nusselt number and Sherwood number is obtained and presented in Table 1. It is observed that S_c, H_a, K_p, S, K_c decreases the skin friction coefficient whereas it increases due to increase in buoyancy parameters, G_r, G_c and Bi. It is also noticed that in the absence of K_p, S, K_c the result is in good agreement with Makinde [23]. With increase in the parameters Bi, S, the Nusselt number increases but for the other parameters it decreases. A significant increase is remarked incase of Sherwood number when there is an increase in the value of the parameters G_c, K_c, S_c but the reverse trend is well marked from the table. However, the result well agrees with the result of Makinde [23].

5. Conclusion

- Increase in the local magnetic parameter Ha results in a decrease in the velocity.
- The thermal and mass boundary layer thickness increases with an increase in the intensity of magnetic field.
- The temperature profile becomes linear in the absence of source parameter as well as porous medium.
- Thermal buoyancy parameter decelerates the temperature boundary layer.
- The porosity enhances the temperature field at all points but the presence of source parameter decreases the temperature profile.
- Concentration boundary layer decreases in the presence of porous matrix.

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