MHD Mixed Convection from a Horizontal Plate Embedded in a Porousmedium with a Convective Boundary Condition

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Abstract

The heat and mass transfer from a horizontal plate embedded in a porous medium experiencing a first-order chemical reaction and exposed to a transverse magnetic field was studied using an analytical approach. A convective boundary condition is used instead of the commonly used conditions of constant surface temperature or constant heat flux, making this study unique and the results more realistic and practically useful. The momentum, energy, and concentration equations are solved analytically and thoroughly tested as coupled second-order ordinary differential equations. Graphic representations of the effects of Biot number, thermal Grashof number, permeability parameter, Hartmann number, Eckert number, Sherwood number, and Schmidt number on velocity, temperature, and concentration profiles are provided. The local temperature is proportional to the temperature of the plate surface.

Keywords: local skin friction; MHD flows; Horizontal plate.

1. Introduction

The study of hydromagnetic boundary layer flow with heat and mass transfer over a vertical surface embedded in a porous medium is important in many engineering situations, such as concurrent buoyant upward gas-liquid flow in packed bed electrodes [1, 2], sodium oxide-silicon dioxide glass melt flows [3, 4], reactive polymer flows in heterogeneous porous media [5, 6], electrochemical generation of elemental bromine in porous electrode systems [7, 8], and the manufacture of intumesc Moreau's book [6] contains a comprehensive survey of magneto-hydrodynamic studies and their technological applications. Several interesting computational studies of reactive MHD boundary layer flows with heat and mass transfer have appeared in recent years [7-12]. Chamkha and Khaled [13] reported similarity solutions forfor hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media. Merkin and Chaudhary [14] used an asymptotic analysis to study natural convection boundary layer flow on a vertical surface with exothermic catalytic chemical reaction and concluded that the flow is controlled by the activation energy, the heat of reaction and Prandtl and Schmidt numbers.

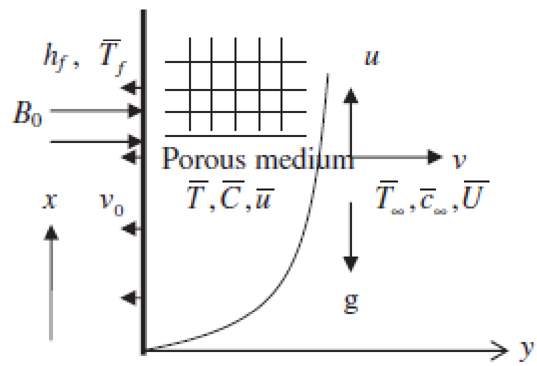

Fig. 1. Flow configuration and coordinate system [18].

Makinde [15] utilized a shooting numerical method to analyze MHD boundary-layer stream and mass exchange past a Level plate in a permeable medium with steady warm flux at the plate surface. But for a couple, of boundary layer streams have been examined utilizing either a consistent surface temperature or a consistent warm flux boundary condition. Aziz [16] has as of late examined the Blassius stream over a level plate with a convective warm boundary condition and set up the condition which the convection warm exchange coefficient must meet for a likeness sort arrangement to exist. In a contemporaneous think about, Bataller [17] considered the boundary layer stream over a convectively heated flat plate with a radiation term within the vitality condition. Since the convective boundary condition is more common and reasonable particularly with regard to a few designing and mechanical forms like transpiration cooling handle, fabric drying, etc., it appears suitable to utilize the convective boundary condition.

This paper considers MHD mixed convection from a Horizontal plate with heat and mass transfer and a convective boundary condition at the plate. It is assumed that the plate is embedded in a uniform porous medium and is exposed to a transverse magnetic field. The problem is solved analytically and results are presented for the velocity, temperature, and concentration profiles together with the local skin friction, theplate surface temperature and the local heat and mass transfer rates. The effect of various physical parameters is observed and analyzed over different profiles. The results are believed to be applicable to realistic engineering situations cited earlier.

2. Mathematical formulation

We consider a steady, laminar, hydromagnetic coupled heat and mass transfer by mixed convection flow of a cold fluid at temperature T_∞ over an infinite Horizontal plate embedded in a porous medium. It is assumed that the left surface of the plate is heated by convection from a hot fluid at temperature T_f which provides a heat transfer coefficient h_f. The cold fluid on the right side of the plate is assumed to be Newtonian and electrically conducting. Except for the density, all other fluid properties are assumed to be independent of temperature and chemical species concentration. A uniform magnetic field of strength B_0 is imposed normal to the plate (along the y-axis) as shown in Fig. 1. Since the magnetic Reynolds number is very small for most fluid used in industrial applications, we assume that the induced magnetic field is negligible. Under the Boussinesq and boundary-layer approximations, the momentum, energy balance and concentration equations can be written in as [10,15-17],

$$-v_o \frac{\partial \bar{u}}{\partial \bar{y}} = \nu \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + g\,\beta(\bar{T}-\bar{T}_\infty) + g\,\bar{\beta}\,(\bar{C}-\bar{C}_\infty) + \frac{\nu}{K}(\bar{U}-\bar{u}) + \frac{\sigma B_0^2}{\rho}(\bar{U}-\bar{u}) \tag{1}$$

$$-v_o \frac{\partial \bar{T}}{\partial \bar{y}} = \frac{k}{\rho C_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{\nu}{C_p}\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right)^2 + \frac{\sigma B_0^2}{\rho C_p}(\bar{U}-\bar{u})^2 \tag{2}$$

$$-v_o \frac{\partial \bar{C}}{\partial \bar{y}} = D\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} + \frac{\nu}{C_p}\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right)^2 - \gamma\,(\bar{C}-\bar{C}_\infty) \tag{3}$$

where $\bar{x}$ and $\bar{y}$ are, respectively, the directions along and perpendicular to the surface, $\bar{u}$ is the velocity component along the plate, $\bar{U}$ is the uniform free-stream velocity, v_o is the constant suctionvelocity, g is the acceleration due to gravity, ρ, v, k and σ are, thefluid density, kinematic viscosity, the thermal conductivity and theelectrical conductivity, respectively. The local temperature is $\overline{T}, \overline{C}$ isthe species concentration and the subscript∞ denotes free-streamconditions. The other parameters are the coefficient of volumeexpansion for heat transfer β, the coefficient of volumetric expansionwith respect to species concentration $\overline{\beta}$, the molecular diffusivity$D$, and the reaction rate coefficient γ. The appropriateboundary conditions for this flow are

$$\overline{u} = 0, \quad -k\frac{\partial \overline{T}}{\partial \overline{y}} = h_f\,(\overline{T}_f - \overline{T}), \quad \overline{C} = \overline{C}_w, \quad \overline{y} = 0 \tag{4}$$

$$\overline{u} = \overline{U}, \quad \overline{T} \to \overline{T}_\infty, \overline{C} \to \overline{C}_\infty \quad \text{as} \quad \overline{y} \to \infty \tag{5}$$

where the convective heating process at the plate is characterized by the hot fluid temperature T_f and the heat transfer coefficient h_f. Introducing the following dimensionless quantities,

The dimensionless variables are introduced as follows:

$$y = \frac{v_0\,\overline{y}}{v}, \quad u = \frac{\overline{u}}{v_0}, \quad U = \frac{\overline{U}}{v_0}, \quad \theta = \frac{\overline{T} - \overline{T}_\infty}{\overline{T}_f - \overline{T}_\infty}, \quad \phi = \frac{\overline{C} - \overline{C}_\infty}{\overline{C}_w - \overline{C}_\infty}, \quad Sc = \frac{v}{D},$$
$$Gr = \frac{g\,\beta(\overline{T}_f - \overline{T}_\infty)\,v}{v_0^3}, \quad \Pr = \frac{\rho\, v\, C_p}{k}, \quad Gc = \frac{g\,\overline{\beta}\,(\overline{C}_w - \overline{C})\,v}{v_0^3}, \quad \lambda = \frac{\gamma\, v^2}{D\, v_0^2}, \tag{6}$$
$$M = \frac{\sigma B_0^2 v}{\rho v_0^2}, \quad Bi = \frac{h_f\, v}{k\, v_0}, \quad K = \frac{v_0^2\,\overline{K}}{v^2}, \quad Ec = \frac{v_0^2}{C_p(\overline{T}_f - \overline{T}_\infty)}$$

Eqs. (1)-(5) may be written in dimensionless form as follows.

$$-\frac{du}{dy} = \frac{d^2u}{dy^2} + Gr\,\theta + Gc\,\phi + M\,(U - u) + \frac{U - u}{K} \tag{7}$$

$$-\frac{d\theta}{dy} = \frac{1}{\Pr}\,\frac{d^2\theta}{dy^2} + Ec\left(\frac{du}{dy}\right)^2 + M\,Ec\,(U - u)^2 \tag{8}$$

$$-\frac{d\phi}{dy} = \frac{1}{Sc}\,\frac{d^2\phi}{dy^2} - \frac{\lambda}{Sc}\phi \tag{9}$$

where Bi is the Biot number, Ec is the Eckert number, Gc and Gr are the mass transfer and thermal Grashof numbers, respectively, K is the porosity parameter, M is the Hartmann number,

λ is the reaction parameter, *Pr* is the Prandtl number and *Sc* is the Schmidt number. The quantities u, θ, ϕ represent the dimensionless velocity, dimensionless temperature, and dimensionless concentration, respectively. Here, we emphasis that the Biot number (*Bi*) is the ratio of the internal thermal resistance of the plate to the boundary layer thermal resistance. When *Bi=0*, the left side of the plate with hot fluid is totally insulated and no convective heat transfer to the cold fluid on the right side takes place.

The boundary conditions are,

$$u = 0, \quad \frac{d\theta}{dy} = Bi[\theta - 1], \ \phi = 1, \quad \text{at} \quad y = 0 \tag{10}$$

$$u = U, \ \theta = \phi = 0, \quad \text{as} \quad y = \infty \tag{11}$$

Besides the velocity, temperature, and concentration data, the numerical solution also yielded the values of $\theta(0), u'(0), -\theta'(0)$ and $-\phi'(0)$ which are, respectively, proportional to the plate surface temperature, the local skin-friction coefficient, the local Nusselt number and the local Sherwood number.

3. Method of Solution: Homotopy Perturbation Method (HPM)

Consider the function

$$A(u) - f(r) = 0 \tag{12}$$

with the boundary condition of

$$B\left(u, \frac{\partial u}{\partial n}\right) = 0 \tag{13}$$

where $A(u)$ is defined as

$$A(u) = L(u) - N(u) \tag{14}$$

Homotopy Perturbation procedure is shown as:

$$H(v,p) = L(v) - L(u_0) + pL(u_0) + p\left[N(v) - f(r)\right] = 0 \tag{15}$$

or

$$H(v,p)=(1-p)\left[L(v)-L(u_0)\right]+p\left[A(v)-f(r)\right]=0 \tag{16}$$

The solution is represented by

$$u=u_0+Pu_1+P^2u_2+P^3u_3+\ldots \tag{17}$$

$$\theta=\theta_0+P\theta_1+P^2\theta_2+P^3\theta_3+\ldots \tag{18}$$

$$\phi=\phi_0+P\phi_1+P^2\phi_2+P^3\phi_3+\ldots \tag{19}$$

A homotopy perturbation method is constructed as follows

$$H(u,p)=(1-P)\left[\frac{d^2u}{dy^2}-\frac{du}{dy}-\left(M+\frac{1}{k}\right)u\right]+P\left[\frac{d^2u}{dy^2}-\frac{du}{dy}-\left(M+\frac{1}{k}\right)u+Gr\theta+Gc\phi+\left(M+\frac{1}{k}\right)U\right]=0 \tag{20}$$

$$H(\theta,p)=(1-P)\left[\frac{d^2\theta}{dy^2}+\Pr\frac{d\theta}{dy}\right]+P\left[\frac{d^2\theta}{dy^2}+\Pr\frac{d\theta}{dy}+Ec\Pr\left(\frac{du}{dy}\right)^2+M\,Ec\Pr U^2\right]=0 \tag{21}$$

$$H(\phi,p)=(1-P)\left[\frac{d^2\phi}{dy^2}+Sc\frac{d\phi}{dy}-\lambda\phi\right]+P\left[\frac{d^2\phi}{dy^2}+Sc\frac{d\phi}{dy}-\lambda\phi\right]=0 \tag{22}$$

A solution of Eqs. (20) to (22) can then be obtained in the form

$$u(y)=u_0(y)+pu_1(y)+p^2u_2(y)+\ldots \tag{23}$$

$$\theta(y)=\theta_0(y)+p\theta_1(y)+p^2\theta_2(y)+\ldots \tag{24}$$

$$\phi(y)=\phi_0(y)+p\phi_1(y)+p^2\phi_2(y)+\ldots \tag{25}$$

Substituting Eqs. (17) - (19) into (20) - (22), yields

$$\begin{aligned}H(u,p)=(1-P)&\left[\frac{d^2(u_0+Pu_1+...)}{dy^2}-\frac{d(u_0+Pu_1+...)}{dy}-\left(M+\frac{1}{k}\right)(u_0+Pu_1+...)\right]+\\ P&\left[\begin{aligned}&\frac{d^2(u_0+Pu_1+...)}{dy^2}-\frac{d(u_0+Pu_1+...)}{dy}-\left(M+\frac{1}{k}\right)(u_0+Pu_1+...)+\\ &Gr(\theta_0+p\theta_1+...)+Gc(\phi_0+p\phi_1+...)+\left(M+\frac{1}{k}\right)U\end{aligned}\right]=0\end{aligned} \tag{26}$$

$$\begin{aligned}H(\theta,p)=(1-P)&\left[\frac{d^2(\theta_0+p\theta_1+...)}{dy^2}+\Pr\frac{d(\theta_0+p\theta_1+...)}{dy}\right]+\\ P&\left[\frac{d^2(\theta_0+p\theta_1+...)}{dy^2}+\Pr\frac{d(\theta_0+p\theta_1+...)}{dy}+Ec\Pr\left(\frac{d(u_0+pu_1+...)}{dy}\right)^2+M\,Ec\Pr U^2\right]=0\end{aligned} \tag{27}$$

$$\begin{aligned}H(\phi,p)=(1-P)&\left[\frac{d^2(\phi_0+P\phi_1+...)}{dy^2}+Sc\frac{d(\phi_0+P\phi_1+...)}{dy}-\lambda(\phi_0+P\phi_1+...)\right]+\\ P&\left[\frac{d^2(\phi_0+P\phi_1+...)}{dy^2}+Sc\frac{d(\phi_0+P\phi_1+...)}{dy}-\lambda(\phi_0+P\phi_1+...)\right]=0\end{aligned} \tag{28}$$

Comparing the coefficients of p, p^2 and solving u_0, u_1 , θ_0, θ_1 and ϕ_0, ϕ_1

Solving the coefficients of p^0 in Eqs. (26) - (28) using boundary condition

$$u_0(y)=U\left(1-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right),\ \theta_0(y)=\frac{Bi\,e^{-\Pr y}}{(\Pr+Bi)},\ \phi_0(y)=e^{-\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}y} \tag{29}$$

Using the Eqs. (26) and (28) and boundary condition solving for the coefficients of p^1,

$$\begin{aligned}u_1=&\frac{GrBi}{(Bi-1)(A+\sqrt{\Pr}-\Pr)}\left[e^{-\Pr y}-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right]+\\ &\frac{Gc}{A-\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}-\left(\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}\right)^2}\left[e^{-\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}y}-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right]+U\left[1-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right]\end{aligned} \tag{30}$$

$$\theta_1 = \frac{Ec\,\Pr U^2(\sqrt{4A+1}+1)}{2(\Pr-(\sqrt{4A+1}+1))}\left[e^{-(\sqrt{4A+1}+1)y} - e^{-\Pr y}\right] - M\,EcU^2\,y \tag{31}$$

We obtain the solution the Eqs.(30) and (31),

$$u(y) = u_0 + u_1 = U\left(1-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right) + \frac{GrBi}{(Bi-1)(A+\sqrt{\Pr}-\Pr)}\left[e^{-\Pr y} - e^{-\frac{\sqrt{4A+1}+1}{2}y}\right] +$$
$$\frac{Gc}{A-\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}-\left(\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}\right)^2}\left[e^{-\frac{\sqrt{4\lambda+Sc^2}+Sc}{2}y} - e^{-\frac{\sqrt{4A+1}+1}{2}y}\right] + U\left[1-e^{-\frac{\sqrt{4A+1}+1}{2}y}\right] \tag{32}$$

$$\theta(y) = \overline{\theta}_0 + \overline{\theta}_1 = \frac{Bi\,e^{-\Pr y}}{(\Pr+Bi)} + \frac{Ec\,\Pr U^2(\sqrt{4A+1}+1)}{2(\Pr-(\sqrt{4A+1}+1))}\left[e^{-(\sqrt{4A+1}+1)y} - e^{-\Pr y}\right] - M\,EcU^2\,y \tag{33}$$

where

$$A = M + \frac{1}{k} \tag{34}$$

The velocity, temperature, and concentration data, the homotopy perturbation method using analytically. Also yielded the values of $\theta(0), u'(0), -\theta'(0)$ and $-\phi'(0)$ which are, respectively, proportional to the plate surface temperature, the local skin-friction coefficient, the local Nusselt number and the local Sherwood number as follows:

$$\theta(0) = -\frac{Bi\Pr}{\Pr+Bi} + \frac{Ec\ \Pr\ U^2\,(\sqrt{4A+1}+1)\ ((-\sqrt{4A+1}-1)+\Pr)}{2\Pr-2\sqrt{4A+1}-2} - M\,Ec\,U^2 \tag{35}$$

$$u'(0) = \frac{U\,(\sqrt{4A+1}+1)}{2} + \frac{Gr\ Bi\left(-\Pr+\frac{\sqrt{4A+1}}{2}-\frac{1}{2}\right)}{(Bi-1)\ (A+\sqrt{\Pr}-\Pr)}$$
$$+\frac{Gc\left(\sqrt{Sc^2+4\lambda}+Sc-\sqrt{4A+1}+1\right)}{(Sc+1)\sqrt{Sc^2+4\lambda}+Sc^2+Sc+2\lambda-2A} + \frac{U\,(\sqrt{4A+1}-1)}{2} \tag{36}$$

$$-\theta(0) = \frac{Bi\Pr}{\Pr+Bi} - \frac{Ec\ \Pr\ U^2\,(\sqrt{4A+1}+1)\ ((-\sqrt{4A+1}-1)+\Pr)}{2\Pr-2\sqrt{4A+1}-2} + M\,Ec\,U^2 \tag{37}$$

$$-\phi'(0) = -\frac{(\sqrt{Sc^2+4\lambda}+Sc)^2}{4} \tag{38}$$

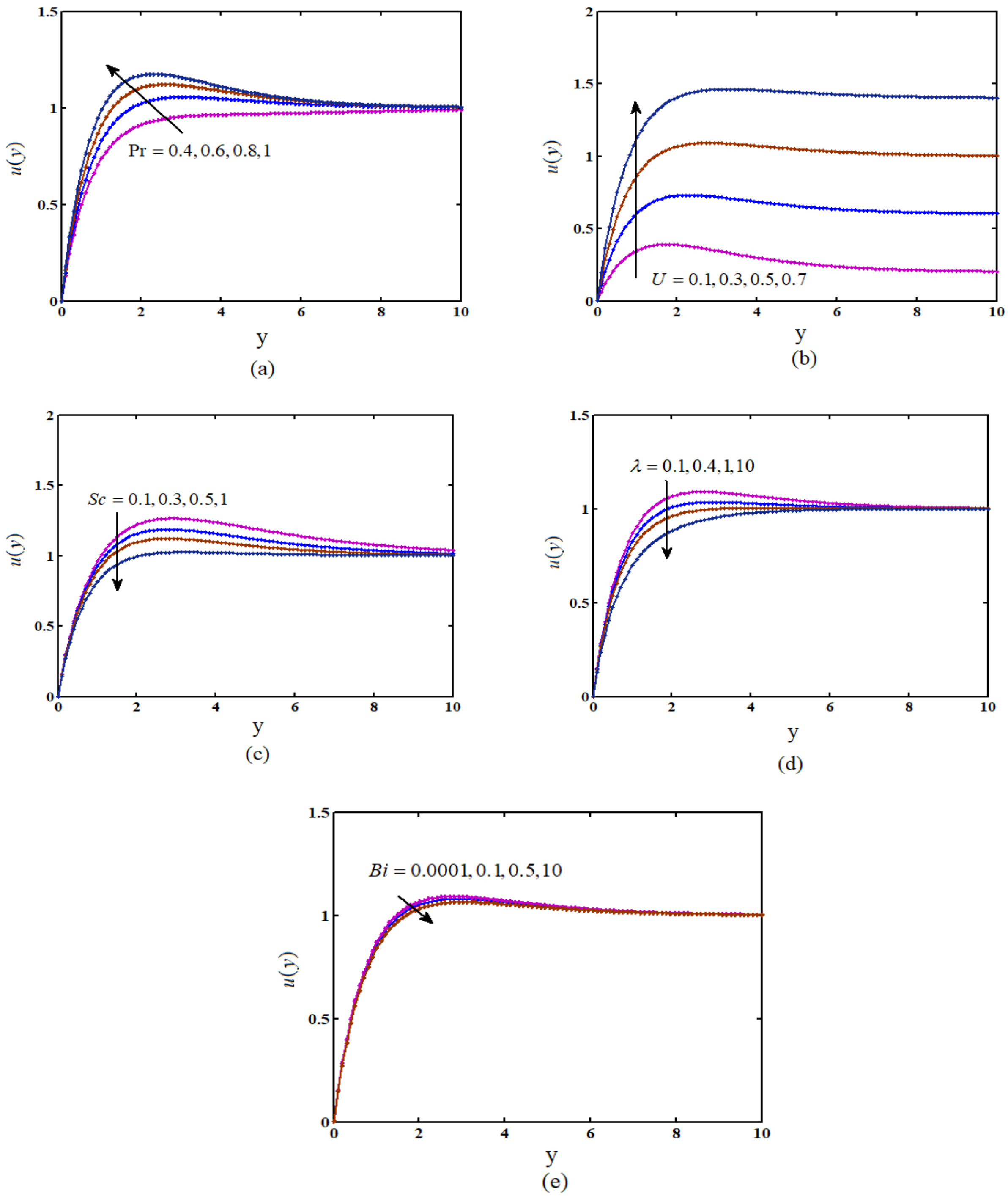

Fig. 2. Velocity profiles for Sc=0.62, Gr=1, Gc=1, k=1, Ec=0.1, M=0.1, λ=0.1, Bi=0.5, Pr=0.7, U=0.5.

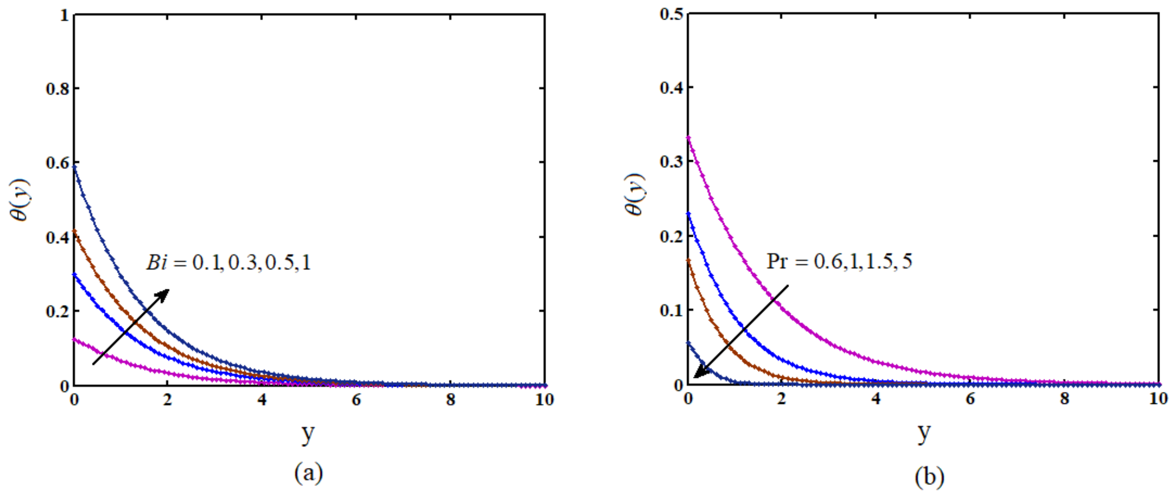

Fig.3: Temperature profiles for Gr=3, Gc=0.01, k=1, Ec=0.1, M=0.0008, Bi=.3, Pr=0.7, U=0.5.

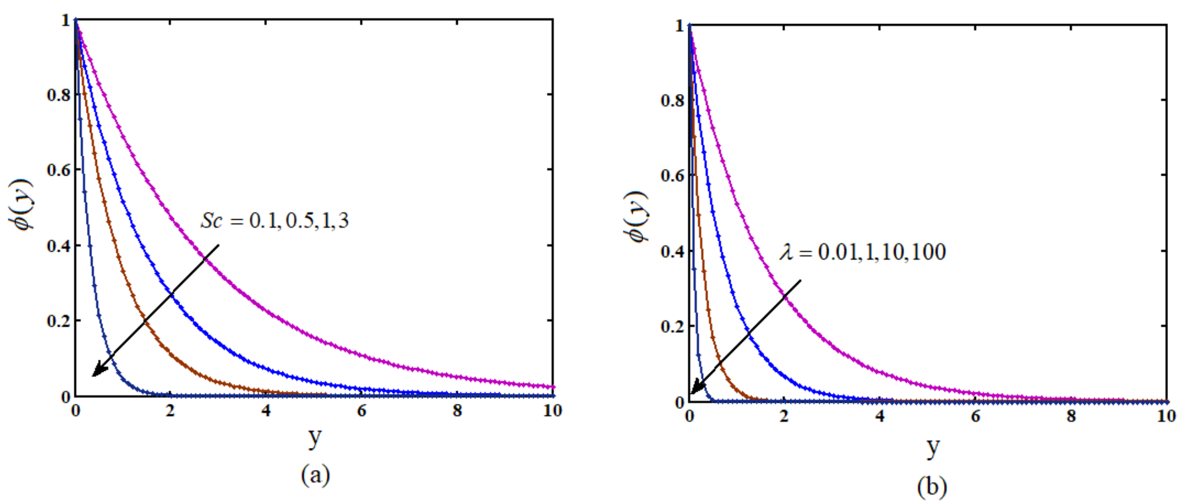

Fig.4: Concentration profiles for Sc=0.62, Gr=1, Gc=1, k=1, Ec=0.1, M=0.1,

Bi=0.5, Pr=0.7, U=0.5.

4. Results and Discussions

In this study, MHD mixed convection from a Horizontal plate embedded in a porous medium with a convective boundary condition has been investigated for velocity profile and temperature distribution and Concentration profiles. The governing equation which is a pair ordinary differential equations were solved analytically by using the homotopy perturbation method.

Figures 2(a) and 2(b), shows the effect of Prandtl number and free stream velocity. From this figures, we observed that the Velocity increases as the increasing value of a particular Prandtl number 'Pr ' and free stream 'U'. The vertical velocity also decreases when the Schmidt number Sc is increased as illustrated in Fig. 2(c). Since Sc is proportional to the density of the diffusing species, the diffusion of heavier species in air tends to retard the upward flow velocity. Figure 2(d), illustrates different values of reaction rate parameter parameter 'λ' observed that the Velocity increases with the increasing of reaction rate.

Fig.2(e) shows the velocity profile with or without Biot number. It is interesting to note that without Biot number the peak velocity is low. As the convection Biot number decreases, the plate thermal resistance increases. Consequently, the peak velocity and the velocities in the neighbourhood of the peak decrease significantly.

Figures 3(a), it can be represented that the Biot number of the temperature increases when the 'Bi' decrease. The effects of the Prandtl number 'Pr' on the temperature profile shown in Fig. 3(b), where it is noticed that an decrease in 'Pr' leads to an increase in the Prandtl number.

In Figures 4(a) and 4(b) represented the effects of the concentration increases, the varies values of the Schmidt number 'Sc' and reaction rate parameter 'λ' is reducing. Analytical results for proportional to the plate surface temperature, the local skin-friction coefficient, the local Nusselt number and the local Sherwood number is presented.

5. Conclusion

The influence of convective boundary condition on hydromagnetic mixed convection with heat and mass transfer past a Horizontal plate embedded in a porous medium is solved analytically in this work. The left surface of the plate is heated by convection from a hot fluid while the cold fluid on the right side of the plate is assumed to be Newtonian and electrically conducting. A table containing the numerical data showing the effects of various parameters controlling the system on the plate surface temperature, the wall shear stress, and the local

Nusselt and Sherwood numbers is also provided. Our results reveal among others that both the fluid velocity and temperature increase with an increase in the convective heat transfer parameter i.e. the Biot Number (Bi). Physical significance and application of Biot number with respect to boundary layer flow problems can be found in several engineering and industria processes such as drying of material, transpiration cooling, etc. Proportional to the plate surface temperature, the local skin-friction coefficient, the local Nusselt number and the local Sherwood number solved analytically presented.

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