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Steady MHD boundary free convective heat and mass transfer flow over an inclined porous plate with variable suction and Soret effect in presence of hall current

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Abstract

In this paper an attempt is made to study the Hall effects on the steady MHD free convective flow of an incompressible fluid, heat and mass transfer over an inclined porous plate with variable suction and Soret effect. The flow is considered under the influence of a uniform magnetic field. The magnetic field is applied normally to the flow. The governing partial differential equations are transformed into ordinary differential equations by using similarity transformation and stretching variable. The governing momentum boundary layer, thermal boundary layer and concentration boundary layer equations with the boundary conditions are transformed into a system of first order ordinary differential equations which are then solved numerically by using Runge-Kutta fourth-fifth order method along with shooting iteration technique. The effects of the flow parameters on the primary and secondary velocities, temperature and species concentration are computed, discussed and have been graphically represented in figures for various value of different parameters.The results presented graphically illustrate that primary velocity field decrease due to increasing of magnetic parameter, permeability parameter, Grashof number, Dufour number and suction parameter and reverse trend arises for the increasing values of Hall parameter and modified Grashof number. The secondary velocity increase for increasing values of magnetic parameter, Hall parameter and permeability parameter and reverse trend arise for Grashof number, modified Grashof number and Suction parameter. The temperature field increases for the increasing values of magnetic parameter, Suction parameter, Soret number,Grashof number and modified Grashof number, Prandtl number whereas there is no effects of permeability parameter on temperature profile. Again, concentration profile decreases for increasing the values of magnetic parameter, Grashof number, modified Grashof number, and Schmidt number and the effect of the remaining entering parameter, the concentration increases up to certain interval of eta and then decreased. Alsothe numerical solutions for the skin friction [$f''(0)$], secondary skin friction [$g_0''(0)$] and local Sherwood number [$-\varphi'(0)$] have been shown in Table I.

Key words: Hall effect; MHD; Porous media; Suction; Inclinedplate

Nomenclature

MHD	Magnetohydrodynamics
c_p	Specific heat of with constant pressure Concentration susceptibility
g	Acceleration due to gravity
	Secondary Velocity Velocity Profile
m	Hall parameter
ν	Kinematic viscosity
γ	Inclination of the Plate
η	Similarity variable
α	Thermal diffusivity
β	Thermal Expansion Coefficient
β^*	Coefficient of expansion with concentration
ρ	Density
θ	Dimensionless temperature
φ	Dimensionless concentration
u	Velocity component in x-direction
v	Velocity component in y-direction
w	Secondary Velocity
V	Suction velocity
T	Temperature
D	Thermal moleculardiffusivity
f_w	Dimensionless suction velocity
C	Concentration
C_∞	Concentration of the fluid outside the boundary layer
k^*	Permeability of the porous medium
B_0	Constant magnetic field intensity
T_w	Temperature at the Plate
T_∞	Temperature of the fluid outside the boundary layer
k	Thermal conductivity
T_m	The mean fluid temperature
K_T	The thermal diffusion ratio

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Subscripts

w Quantities at the wall
∞ Quantities at the free stream

Introduction

In recent years MHD flow problems have become in view of its significant applications in industrial manufacturing processes such as plasma studies, petroleum industries Magnetohydrodynamics power generator cooling of clear reactors, boundary layer control in aerodynamics. Many authors have studied the effects of magnetic field on mixed, natural and force convection heat and mass transfer problems. This problem has also an important bearing on metallurgy where magnetohydrodynamic (MHD) techniques have recently been used. The study of effects of porous media is a topic of rapidly growing interest on heat and mass transfer due toof its many engineering applications in the field of chemical, geophysical sciences, geothermal reservoirs, thermal insulation engineering, exploration of petroleum and gas fields, water movements in geothermal reservoirs, etc. Permeable porous plates are used in the filtration processes and also for a heated body to keep its temperature constant and to make the heat in solution of the surface more effective. Previous studies deals with the studies concerning non-Newtonian flows and heat transfer in the absence of magnetic fields, but presently we find several industrial applications such as polymer technology and metallurgy,where the magnetic field is applied in the visco-elastic fluid flow.Many researchers are investigated to the unsteady free convective flow past infinite or semi-vertical plates due to its important technological applications. Chim *et al.,* (2007). obtained numerical results for the steady mixed convection boundary layer flow over a vertical impermeable surface embedded in a porous medium when the viscosity of the fluid varies inversely as a linear function of the temperature. G. V. Ramana Reddy *et al.* (2011). was studied unsteady MHD free convective mass transfer flow past an infinite vertical porous plate with variable suction and Soret effect. Hayat and Co-workers (Hayat *et al.,* 2010). analyzed a mathematical model in order to study the heat and mass transfer characteristics in mixed convection boundary layer flow about a linearly stretching vertical surface in a porous medium filled with a visco-elastic fluid, by taking into account the diffusion thermo (Dufour) and thermal-diffusion (Soret) effects. Mukhopadhyay (Mukhopadhyay, 2009). performed an analysis to investigate the effects of thermal radiation on unsteady mixed convection flow and heat transfer over a porous stretching surface in porous medium. Pal and Co-workers (Pal and Talukdar, 2010). analysed the combined effect of mixed convection with thermal radiation and chemical reaction on MHD flow of viscous and electrically conducting fluid past a vertical permeable surface embedded in a porous medium is analysed. Rahman and Co-workers (Rahman and Sattar, 2006) studied MHD convective flow of a micro-polar fluid past a continuously moving vertical porous plate in the presence of heat generation/absorption. The objective of the present paper is to study the Hall & MHD effect as well as Soret effects on the steady free convective mass transfer flow an inclined porous plate with variable suction, where the plate temperature oscillates with the same frequency as that of variable suction velocity. Seddek and Co-workers (Seddek and Salama, 2007) studied the effect of temperature dependent viscosity and thermal conductivity on unsteady MHD convective heat transfer past a semi-infinite vertical porous plate. Sharma (2004) studied unsteady effect on MHD free convective and mass transfer flow through porous medium with constant suction and constant heat flux in rotating system. But these papers thermal diffusion effects have been neglected. The unsteady free convection flow of a viscous incompressible fluid past an infinite vertical plate with constant heat flux is considered on taking into account viscous dissipative heat, under the influence of a transverse magnetic field studied by Srihari and Co-Workers (Srihari. K *et al.,* 2006). Suneetha and Co-workers (Suneetha *et al.,* 2009). examined the problem of radiation and mass transfer effects on MHD free convection flow past an impulsively started isothermal vertical plate with dissipation. So the present work focused on steady free convective heat and mass transfer over an inclined porous plate with variable suction and magnetic field in presence of Hall current.

Mathematical formulation of the problem

Consider a two dimensional steady laminar MHD viscous incompressible electrically conducting fluid along an inclined plate with an acute angle γ. X direction is taken along the leading edge of the inclined plate and y is normal to it and extends parallel to x-axis. A magnetic field of strength B_0 isintroduced to the normal to the direction to the flow. The uniform plate temperature T_w ($>T_\infty$), where T_∞ is the temperature of the fluid far away from the plate. Let u, v and w be the velocity components along the x and y axis and secondary velocity component along the z axis respectively in the boundary layer region. The fluid pressure is constant and induced magnetic field is small in comparison tothe applied magnetic flied, therefore it is neglected.

Under the above assumptions and usual boundary layer approximation, the dimensional governing equations of are themagnetic parameter, porosity parameter, Grashof number, modified Grashof number, Prandtl number, Schmidt number,Soret and Dufour number respectively.

continuity, momentum, concentration and energy under the influence of externally imposed magnetic field are:

Equation of continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

Momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}$$

$$=\nu\frac{\partial^2 u}{\partial y^2}+g\beta\left(T-T_\infty\right)\cos\alpha+g\beta^*\left(C-C_\infty\right)\cos\alpha-\frac{\sigma B_0^2\left(u+mw\right)}{\rho\left(1+m^2\right)}-\frac{\nu}{k^*}u \quad (2)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}=\nu\frac{\partial^2 w}{\partial y^2}+\frac{\sigma B_0^2\left(mu-w\right)}{\rho\left(1+m^2\right)}-\frac{\nu}{k^*}w \quad (3)$$

Energy Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{DK_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} \quad (4)$$

Concentration Equation:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{DK_T}{T_m}\frac{\partial^2 T}{\partial y^2} \quad (5)$$

Boundary conditions are:

$$u=0,\ v=V,\ w=0,\ \frac{\partial T}{\partial y}=-\frac{q}{K_T},\ C=C_w \quad \text{at} \quad y=0$$

$$u=0,\ w=0,\ T=T_\infty,\ C=C_\infty \quad \text{as} \quad y\to\infty \quad (6)$$

To convert the governing equations into a set of similarity equations, we introduce the following similarity transformation:

$$\psi=\sqrt{2\nu Ax}\ f(\eta),\ \eta=y\sqrt{\frac{A}{2\nu x}},\ w=Ag_0(\eta),\ T-T_\infty$$

$$=\sqrt{\frac{2\nu x}{A}}\frac{q}{K_T}\theta(\eta),\ \varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}$$

We introduce the steam function $\psi\,(x,y)$ as defined by

$$u=\frac{\partial\psi}{\partial y} \quad \text{and} \quad v=-\frac{\partial\psi}{\partial x}.$$

From the above transformations, the non-dimensional, nonlinear and coupled ordinary differential equations are obtained as

$$f'''+ff''+Gr\theta\cos\alpha+Gm\varphi\cos\alpha-2Kf'-\frac{M}{1+m^2}f'-\frac{Mm}{1+m^2}g_0=0 \quad (7)$$

$$g_0''+fg_0'-2Kg_0-\frac{M}{1+m^2}g_0+\frac{Mm}{1+m^2}f'=0 \quad (8)$$

$$\theta''+Prf\theta'-Prf'\theta+S_0\varphi''=0 \quad (9)$$

$$\varphi''+Scf\varphi'+D_f\theta''=0 \quad (10)$$

The transform boundary conditions:

$$f=-f_w,\ f'=0,\ g_0=0,\ \theta'=-1,\ \varphi=1 \ \text{at} \ \eta=0,$$

$$f'=0,\ g_0=0,\ \theta=\varphi=0 \ \text{as} \ \eta\to\infty \quad (11)$$

Where f', g_0, θ and φ are the dimensionless primary velocity, secondary velocity temperature and concentration profile respectively, η is the similarity variable, the prime denotes differentiation with respect to η. Also

$$M=\frac{2x\sigma B_0^2}{\rho A},\ K=\frac{\nu x}{k^*A},\ Gr=\frac{2xg\beta\sqrt{2\nu x}}{A^{\frac{5}{2}}K_T}q,$$

$$Gm=\frac{2xg\beta^*\left(C_w-C_\infty\right)}{A^2},\ Pr=\frac{\mu c_p}{k},\ \text{and}\ Sc=\frac{\nu}{D}$$

$$S_0=\sqrt{\frac{A}{2\nu x}}\frac{K_T^2D\left(C_w-C_\infty\right)}{c_s c_p\alpha q},\ D_f=\sqrt{\frac{2\nu x}{A}}\frac{q}{T_m\left(C_w-C_\infty\right)}$$

Methodology

The governing momentum boundary layer equations (2) and (3) , thermal boundary layer equation (4) and concentration boundary layer equation (5), with the boundary conditions (6) are transformed into a system of first order ordinary differential equations which are then solved numerically by using Runge-Kutta fourth-fifth order method along with shooting iteration technique.First of all, higher order non–linear differential equations are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem applying the shooting technique. Once the problem is reduced to initial value problem, then it is solved using Runge -Kutta fourth order technique. The effects of the flow parameters on the velocity, temperature, species concentration, shearing stress, rate of heat transfer, and rate of concentration are computed, discussed and have been graphically represented in figures and tables for various value of different parameters. Now defining new variables by the equations.

The higher order differential equations (7), (8), (9), (10) and boundary conditions (11) may be transformed to nine equivalent first order differential equations and boundary Numerical calculation for the distribution of primary velocity, secondary velocity, temperature and concentration profiles

$$y_1 = f, y_2 = f', y_3 = f'', y_4 = g_0, y_5 = g_0', y_6 = \theta,$$
$$y_7 = \theta', y_8 = \varphi, y_9 = \varphi'$$

across the boundary layer for different values of the parameters are carried out. For the purpose of our computation we have chosen $f_w = 0.6$, $M = 2.0$, $m = 0.1$, $K = 1.0$, $G_r = 0.2$, G_m=0.5, S_0 = 0.02, Df= 0.5, S_c= 0.22, P_r = 1.0 and α = 60°while the

$$dy_1 = y_2, dy_2 = y_3, dy_3$$
$$= -y_1y_3 - Gr\cos\alpha\, y_6 - Gm\cos\alpha\, y_8 + 2Ky_2 + \frac{M}{1+m^2}y_2 + \frac{Mm}{1+m^2}y_4,$$

$$dy_4 = y_5, dy_5 = -y_1y_5 + 2Ky_4 + \frac{M}{1+m^2}y_4 - \frac{Mm}{1+m^2}y_2, dy_6$$

$$= y_7, dy_7 = -\frac{Pry_1y_7}{1-D_fS_0} + \frac{Pry_2y_6}{1-D_fS_0} + \frac{ScS_0y_1y_9}{1-D_fS_0},$$

$$dy_8 = y_9, dy_9 = -\frac{Scy_1y_9}{1-D_fS_0} + \frac{D_fPry_1y_7}{1-D_fS_0} + \frac{D_fPry_2y_6}{1-D_fS_0}$$

And the boundary conditions are

$$y_1 = -f_w, y_2 = 0, y_4 = 0, y_7 = -1, y_8 = 1 \quad \text{at } \eta = 0$$
$$y_2 = 0, y_4 = 0, y_6 = 0, y_8 = 0 \quad \text{as } \eta \to \infty$$

Results and discussion

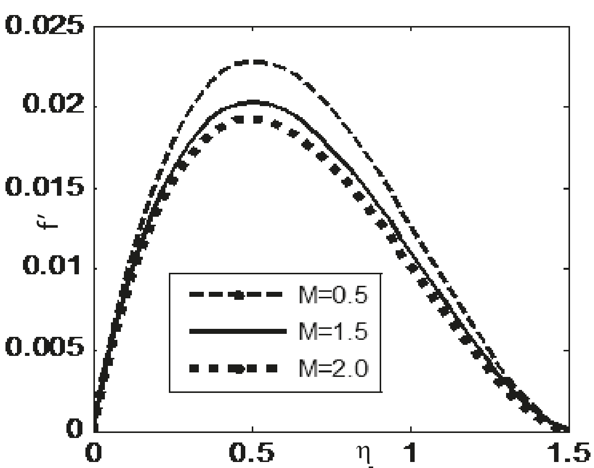

Fig. 1. Primary velocity profile for various values of M

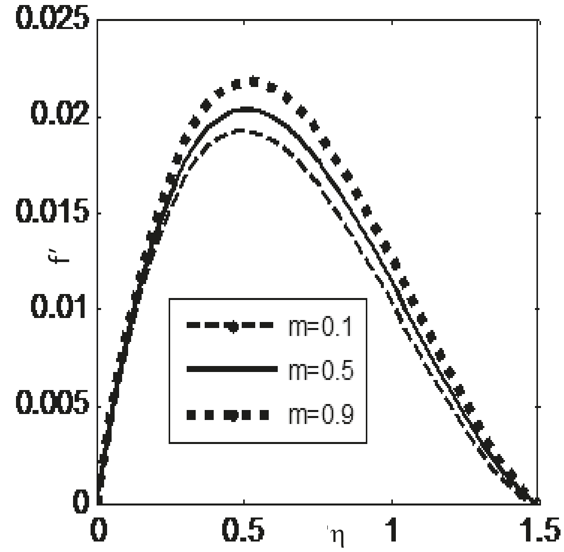

Fig. 2. Primary velocity profile for various values of m

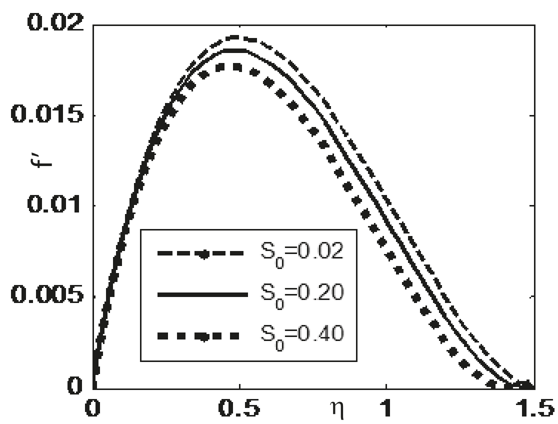

Fig. 3. Primary velocity profile for various values of S_0

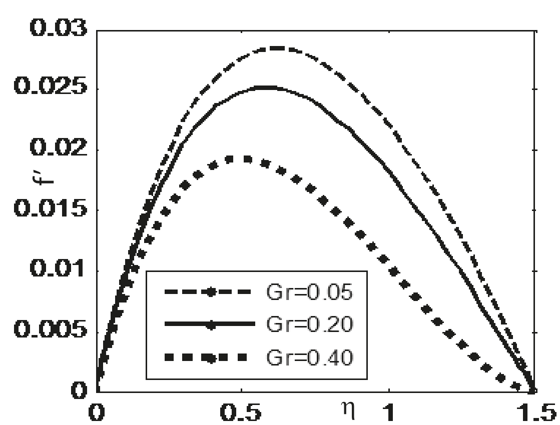

Fig. 4. Primary velocity profile for various values of Gr

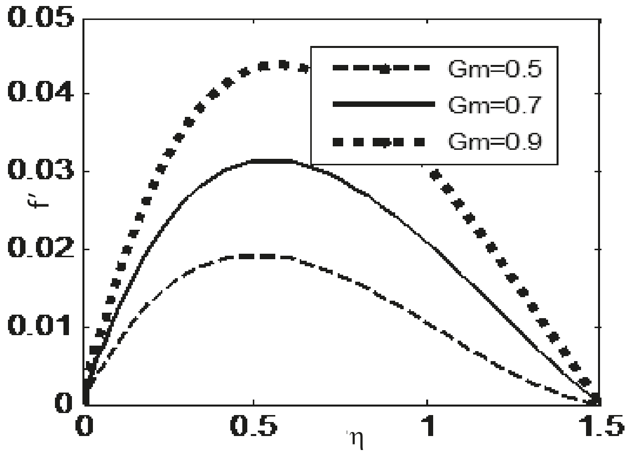

Fig. 5. Primary velocity profile for various values of Gm

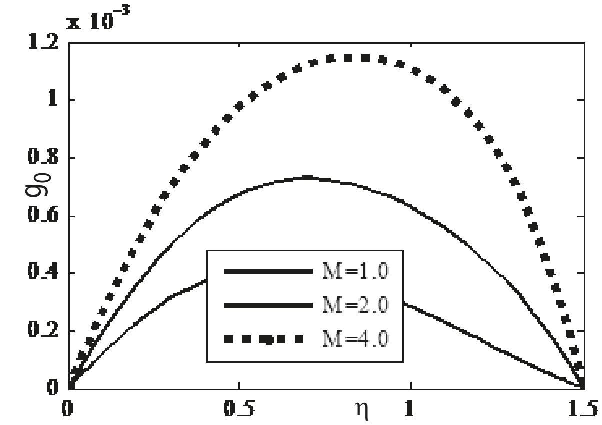

Fig. 8. Secondary velocity profile for various values of M

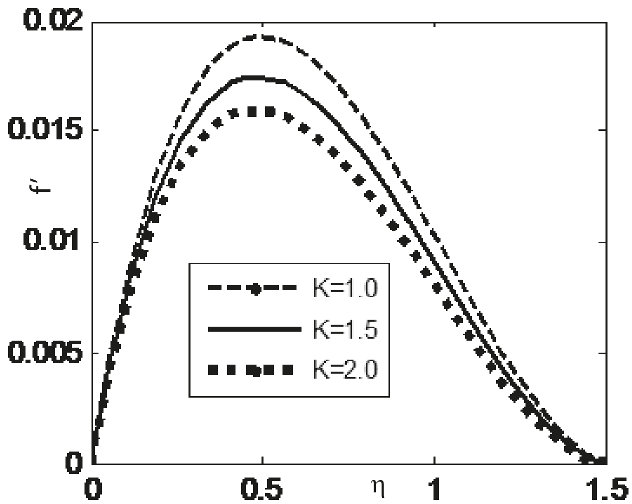

Fig. 6. Primary velocity profile for various values of K

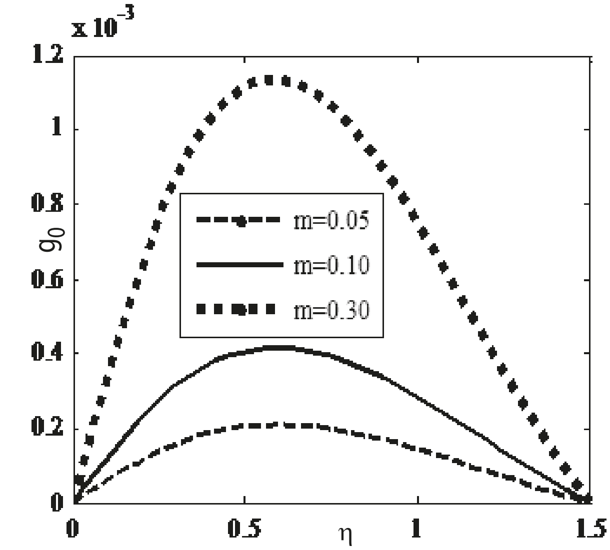

Fig. 9. Secondary velocity profile for various values of m

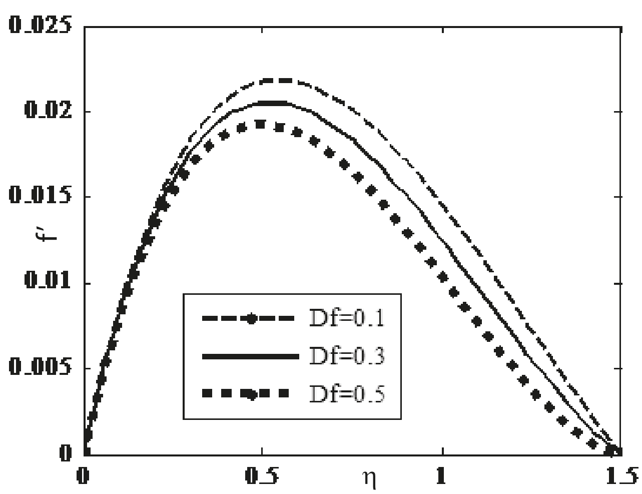

Fig. 7. Primary velocity profile for various values of Df

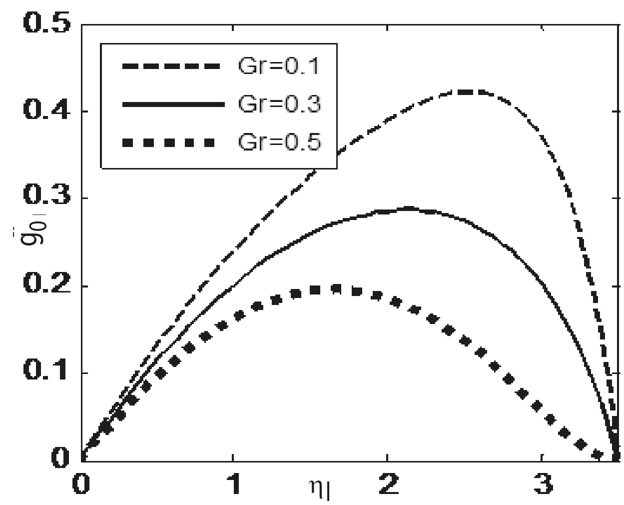

Fig. 10. Secondary velocity profile for various values of Gr

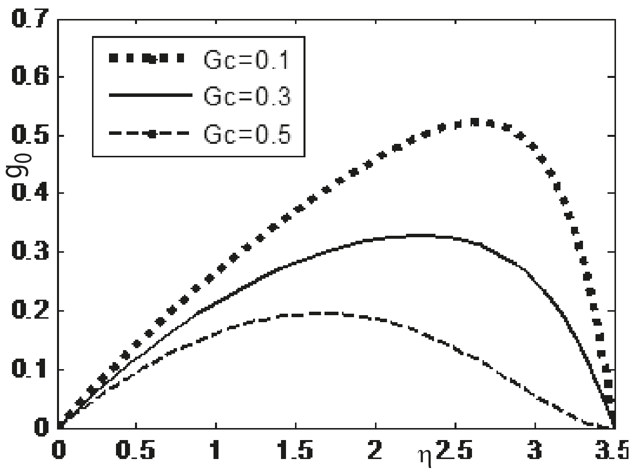

Fig. 11. Secondary velocity profile for various values of Gm

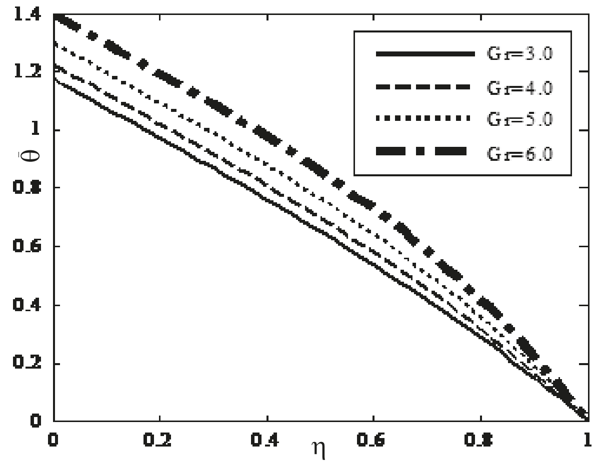

Fig. 14. Temperature profile for various values of Gr

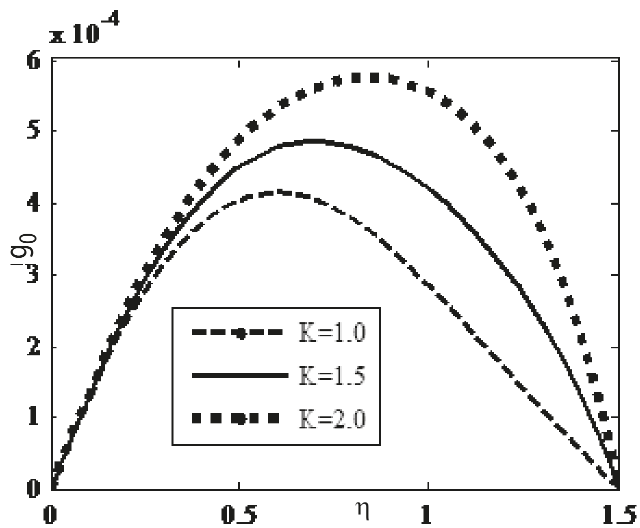

Fig. 12. Secondary velocity profile for various values of K

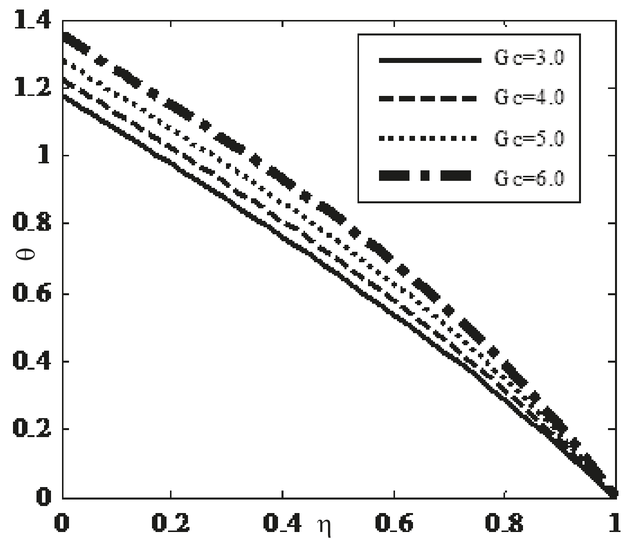

Fig. 15. Temperature profile for various values of Gm

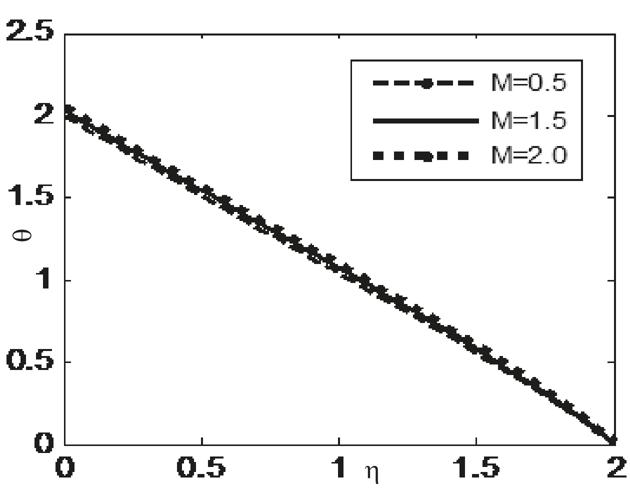

Fig. 13. Temperature profile for various values of M

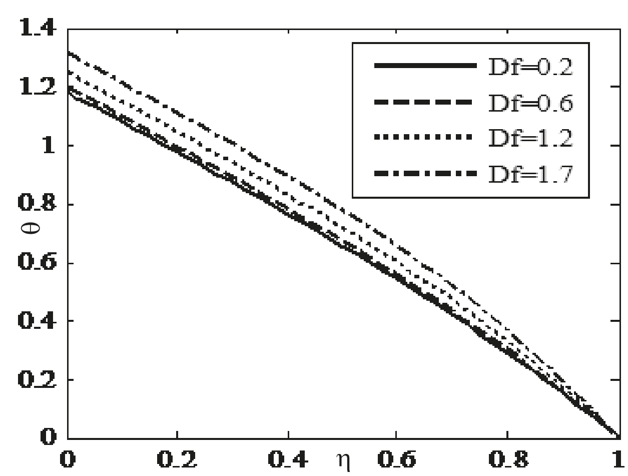

Fig. 16. Temperature profile for various values of Df

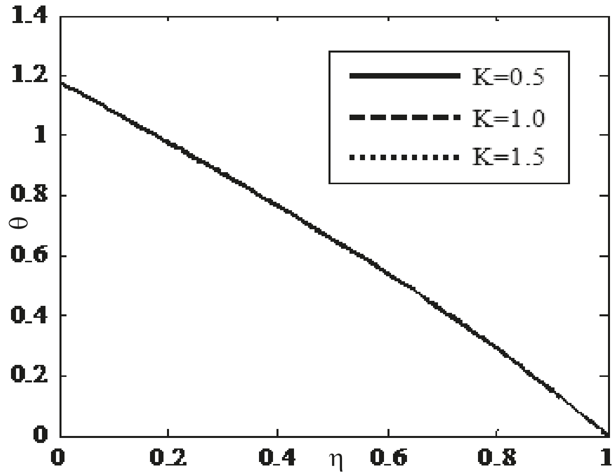

Fig. 17. Temperature profile for various values of K

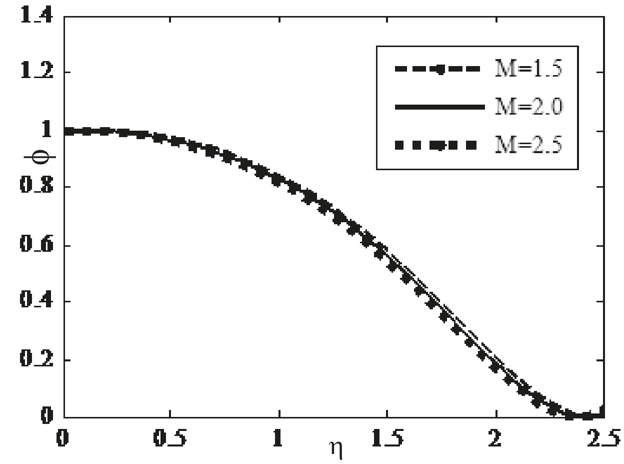

Fig. 20. Concentration profile for various values of M

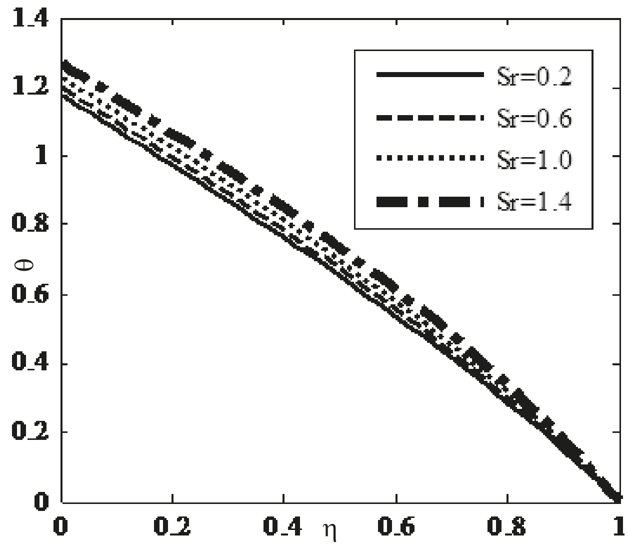

Fig. 18. Temperature profile for various values of S_0

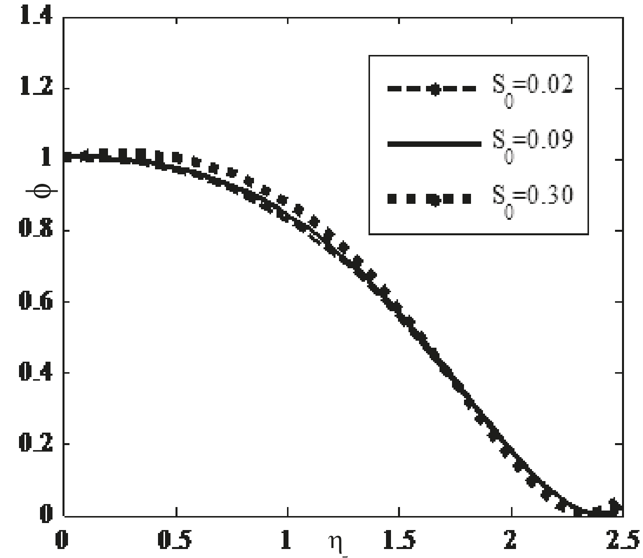

Fig. 21. Concentration profile for various values of S

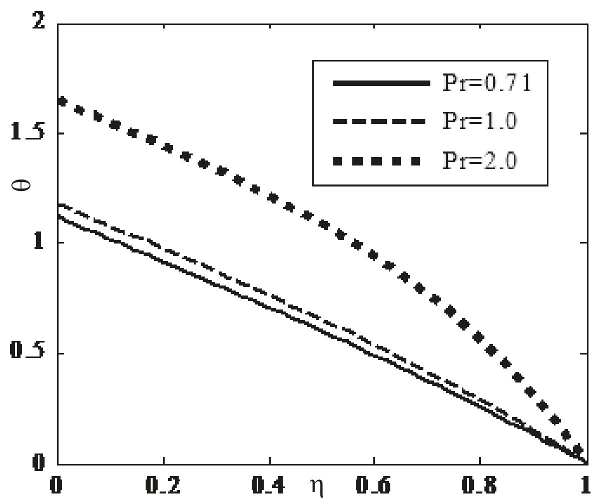

Fig. 19. Temperature profile for various values of Pr

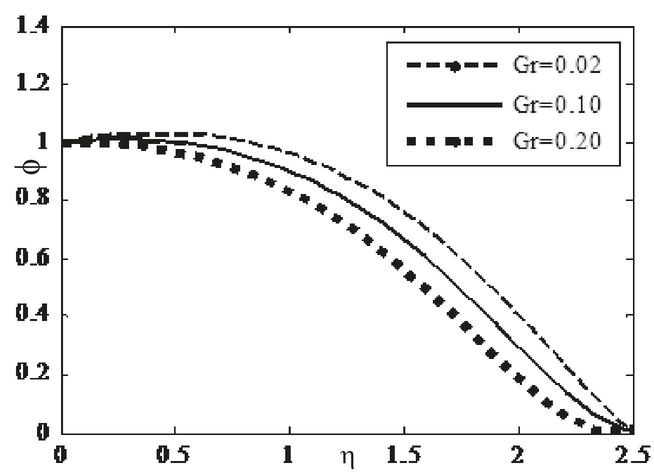

Fig. 22. Concentration profile for various values of Gr

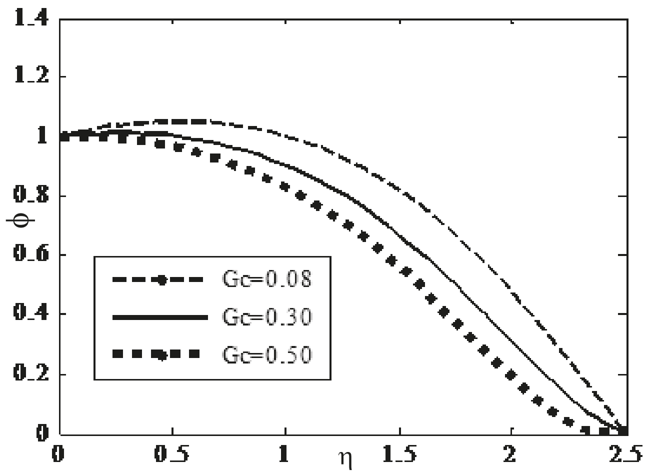

Fig. 23. Concentration profile for various values of Gm

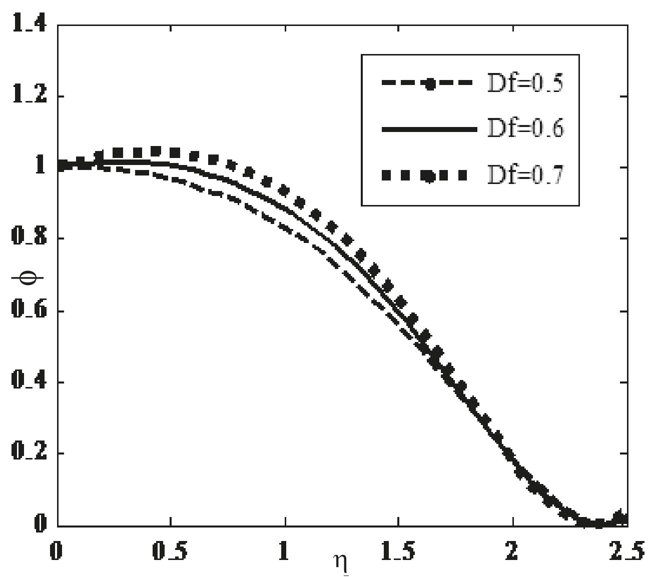

Fig. 24. Concentration profile for various values of Df

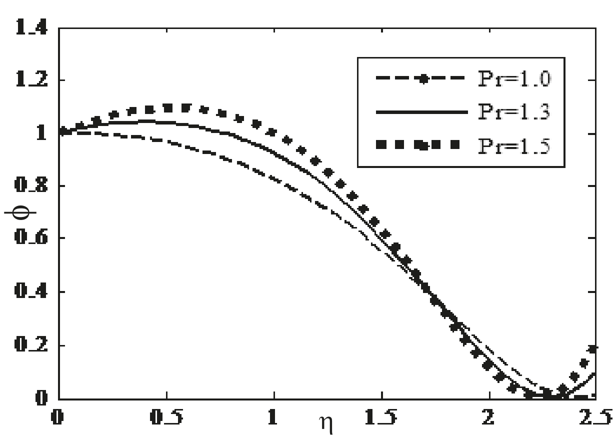

Fig. 25. Concentration profile for various values of Pr

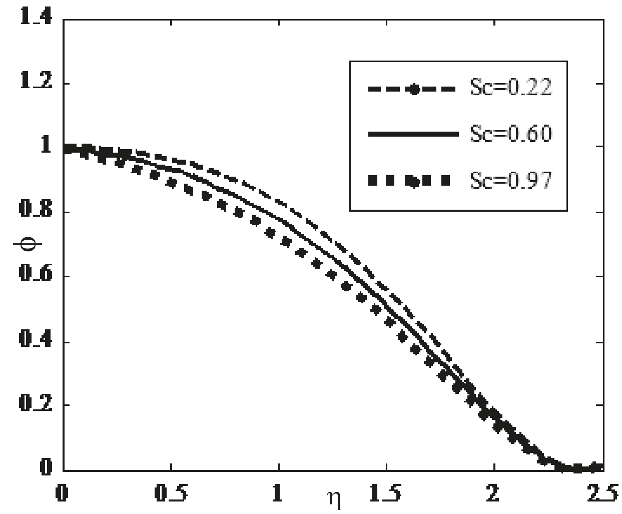

Fig. 26. Concentration profile for various values of Sc

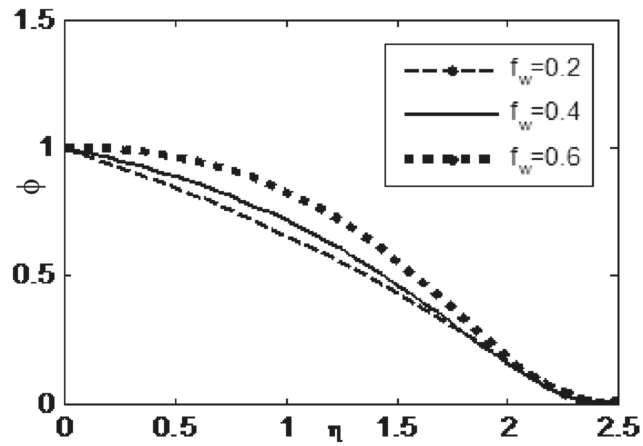

Fig. 27. Concentration profile for various values of f_w

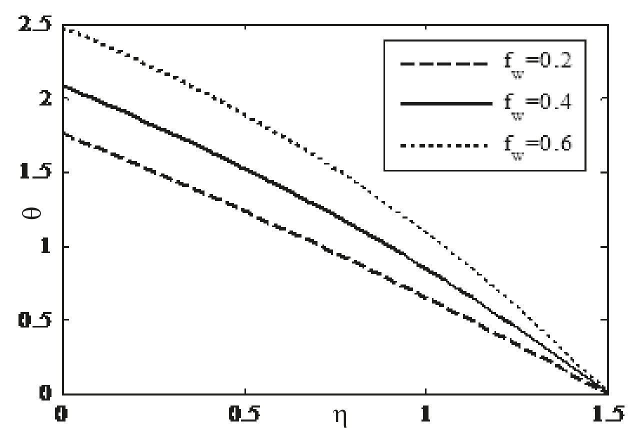

Fig. 28.Temperature profile for various values of f_w

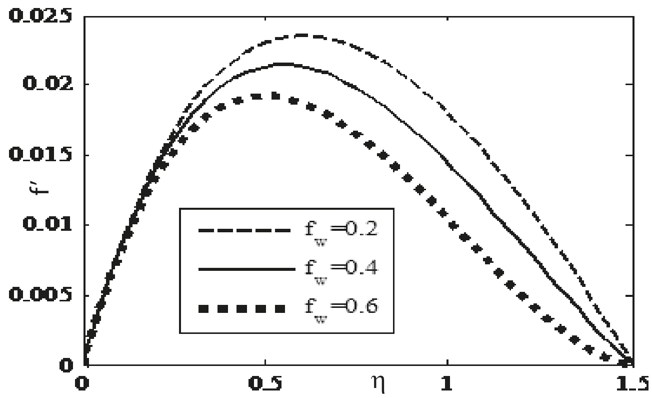

Fig. 29. Primaryvelocity profile for various values of f_w

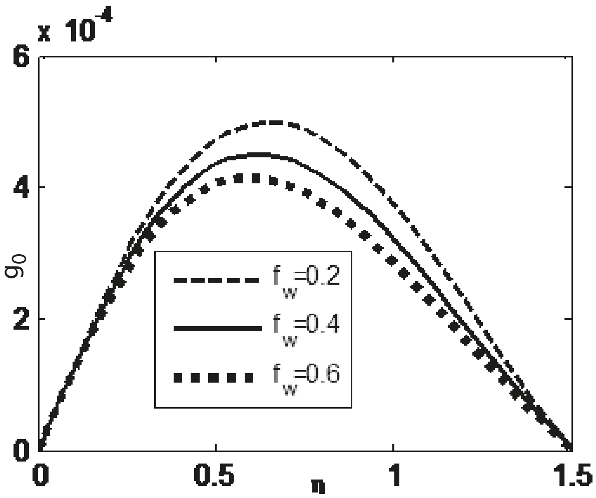

Fig. 30. Secondary velocity profile for various values of f_w

parameters are varied over range as shown in the figures. Fig.1 clearly demonstrates that the primary velocity starts from maximum value at the surface and then decreasing until it reaches to the minimum value at the end of the boundary layer for all the values M. It is interesting to note that the effect of magnetic field is more prominent at the point of peak value, because the presence of M in an electrically conducting fluid introduces a force like Lorentz force which acts against the flow if the magnetic field is applied in the normal direction as in the present problem. As a result velocity profile is decreased. Similar effect is also observed in Fig.3, Fig.4, Fig.6, Fig.7 and Fig.29 with increasing values of S_0, Gr, K, Df and f_w but reverse trend arise for increasing values of m and Gm which are shown in Fig.2 and Fig.5. From Fig.8, Fig.9 and Fig.12 it is observed that secondary velocity increases for increasing values of M, m and K but reverse trend arise for the effect of Gr, Gm and f_w are shown in Fig.10, Fig.11 and Fig.30. In Fig.13-Fig.19 and Fig.28 show the effect of temperature profile for various values of entering parameters. From Fig.19 it is clearly demonstrates that the thermal boundary layer thickness increases as the P_r increases implying lower heat transfer. It is due to the fact that higher values of P_r means decreasing thermal conductivity and therefore it is able to diffuse away from the plate more slowly than lower values of P_r, hence the rate of heat transfer is increased as a result the heat of the fluid in the boundary layer decreases. Similar result has been found for the effect of M, Gr, Gm, Df, S_0 and f_w but there is no effect of K on temperature profile. Fig20 - Fig.27 show the concentration profiles obtained by the numerical simulation for various values of entering non-dimensional parameters. From Fig.20, Fig.22, Fig.23 and Fig.26, it is observed that the concentration profile decreases for the effect of M, Gr, Gm and Sc but in a certain interval of η

Table I. The primary skin friction, secondary skin friction, and rate of Concentration for various values of M, m, S_0, K, f_w and taking G_r = 0.2, Gm = 0.5, α = 60°, S_c=0.22, Pr = 1.0, Df = 0.5.

M	m	S_0	K	f_w	f "(0)	$g_0(0)$	φ'(0)
0.5	0.1	0.02	1.0	0.6	0.105227	0.001295	-
1.5	0.1	0.02	1.0	0.6	0.0973	0.002017	0.0279
2.0	0.1	0.02	1.0	0.6	0.093849	0.0027596	0.014
2.0	**0.1**	0.02	1.0	0.6	0.093849	0.0006527	-
2.0	**0.5**	0.02	1.0	0.6	0.09707	0.001295	-
2.0	**0.9**	0.02	1.0	0.6	0.10127	0.00359	-
2.0	0.1	**0.02**	1.0	0.6	0.093849	-	0.014
2.0	0.1	**0.20**	1.0	0.6	0.09242	-	-
2.0	0.1	**0.40**	1.0	0.6	0.0904859	-	-
2.0	0.1	0.02	**1.0**	0.6	0.093849	0.001295	-
2.0	0.1	0.02	**1.5**	0.6	0.08794	0.001345	-
2.0	0.1	0.02	**2.0**	0.6	0.0830	0.001379	-
2.0	0.1	0.02	1.0	**0.2**	0.09599	0.0013445	-0.289
2.0	0.1	0.02	1.0	**0.4**	0.09542	0.001316	-0.173
2.0	0.1	0.02	1.0	**0.6**	0.093849	0.001295	0.014

the concentration profile is increased and the decreased which are shown in Fig.21, Fig.24, Fig.25, and Fig.27. Further the numerical solutions for the skin friction [f "(0)], secondary skin friction [$g_0(0)$] and local Sherwood number [φ'(0)] have been shown in Table I.

Conclusions

Following are the conclusions made from above analysis:

- The magnitude of velocity decreases with increasing magnetic parameter because the presence of M in an electrically conducting fluid introduces a force like Lorentz force which acts against the flow but reverse trend arise for the effect of m whereas in both of M and m, the secondary velocity is increased.
- In case of suction, the primary and secondary velocities are decreased and reverse trend arises in temperature profile whereas the concentration profile is increased up to certain interval of η and then decreased.
- The thermal boundary layer thickness increases for the increasing values of P_r means lower heat transfer. It is due to the fact that higher values of P_r means decreasing thermal conductivity and therefore it is able to diffuse away from the plate more slowly than lower values of P_r, hence the rate of heat transfer is increased as a result the heat of the fluid in the boundary layer decreases.
- Increase in Schmidt number results decrease in concentration and similar trend arises for the effects of M.

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