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Mhd Mixed Convective Slip Flow, Heat and Mass Transfer along a Vertical Porous Plate*

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Abstract: Aim of the paper is to investigate the effects of velocity slip and thermal slip on MHD mixed convective flow along vertical porous plate in the presence of a non-uniform magnetic field. The governing nonlinear partial differential equations have been transformed into two point boundary value problem using similarity transformation and numerical solution is obtained by using Runge-Kutta fourth order scheme with shooting technique. The velocity, temperature and concentration profiles are shown through graphs and discussed numerically. The skin friction, rate of heat and mass transfer at the plate are derived, discussed numerically and presented through tables for different values of physical parameters.

Keywords: Mhd, Convective Slip Flow, Heat and Mass Transfer, Vertical Porous Plate

2010 Mathematics Classification No.: 76W05, 76S05, 76D09, 76R10.

1. Introduction

The study of magnetohydrodynamic mixed convective flows or combined free and forced convection flow over a flat plate have attracted considerable attention because of its wide industrial applications and technological uses. The non-adherence of the fluid to a solid boundary is known as velocity slip and has great importance in polishing of internal civilities, heart valves, manufacturing process of micro-electronic mechanical system etc. Jaluria[1] studied natural convection heat and mass transfer. Afzal and Hussain[2] discussed mixed convection over a horizontal plate. Yao[3] investigated two dimensional mixed convection along a flat plate. Yoshimura and Prudhomme[4] presented wall slip corrections for Couette and parallel disc viscometers. Sharma[5] considered free convection effects on the flow past an infinite vertical porous plate with constant

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suction and constant heat flux. Andersson[6] discussed slip flow past stretching surfaces. Martin and Boyd[7] studied momentum and heat transfer in laminar boundary layer with slip flow. Ariel and Hayat[8] considered the flow of an elastico-viscous fluid past a stretching sheet with partial slip. Ariel[9] presented two dimensional stagnation point flow of an elastico-viscous fluid with partial slip. Wang[10] investigated viscous flow due to a stretching sheet with surface slip and suction. Cao and Baker[11] presented slip effects on mixed convective flow and heat transfer from a vertical plate. Fang and Yao[12] studied slip MHD viscous flow over a stretching sheet. Abbas et al.[13] discussed slip effects and heat transfer in a viscous fluid over an oscillatory stretching surface. Aziz[14] presented hydrodynamic and thermal slip flow boundary layers over a flat plate with constant heat flux. Pal and Talukdar[15] considered unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Fang et al.[16] discussed viscous flow over a shrinking sheet with a second order slip flow model. MHD boundary layer slip flow and heat transfer over a flat plate have been studied by Bhattacharyya et al.[17]. Turkyilmazoglu[18] presented multiple solutions of heat and mass transfer of MHD slip flow for the viscoelastic fluid over a stretching sheet. Mukhopadhyay[19] investigated effects of slip on unsteady mixed convective flow and heat transfer past a porous stretching surface. Rohni et al.[20] discussed unsteady mixed convection boundary layer flow with suction and temperature slip effect near the stagnation point. Das[21, 22] presented slip effects on heat and mass transfer in MHD micropolar fluid over an inclined plate with thermal radiation and chemical reaction and impact of thermal radiation on MHD slip flow over a flat plate with variable fluid properties. Uddinet at.[23] investigated heat and mass transfer for combined convective slip flow. Turkyilmazaglu[24] presented multiple analytic solutions of heat and mass transfer of magnetohydrodynamic slip flow for two types of viscoelastic fluids over a stretching surface. Bhattacharyya et al.[25] studied similarity solution of mixed convective boundary layer slip flow over a vertical plate. Ellahi et al.[26] analysed series solutions of nonlinear partial differential equations with slip boundary conditions for non- Newtonian MHD fluid in porous space. Sharma and Singh[27] discussed heat and mass transfer in boundary layer flow along a vertical isothermal reactive plate near stagnation point. Mukhopadhyay and Mandal[28] studied MHD mixed convection slip flow and heat transfer over a vertical porous plate.

The aim of the paper is to investigate flow, heat and mass transfer analysis in boundary layer along a vertical porous plate in porous medium.

The governing equations of continuity, momentum, energy and mass transfer are transformed into ordinary differential equations using suitable transformations and then solved numerically for different values of dimensionless parameters involved in the problem by using Runge-Kutta fourth order method with shooting technique. The results are analysed for various physical parameters such as magnetic parameter, mixed convection parameter, velocity slip parameter, thermal jump parameter, permeability parameter, Schmidt number and Prandtl number on the flow, heat and mass transfer and presented through graphs.

2. Mathematical Formulation

A mixed convective two dimensional steady laminar boundary layer flow, heat and mass transfer of viscous incompressible fluid over a vertical porous plate in porous medium in the presence of non-uniform magnetic field is considered. The governing equations of continuity, momentum, energy and concentration for steady two-dimensional boundary layer flow are given by

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

(2) $$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial x}=\upsilon\frac{\partial^2 u}{\partial y^2}-\sigma\frac{B^2}{\rho}(u-U_\infty)+g\beta^*(T-T_\infty)-\frac{\upsilon u}{K_p^{'}},$$

(3) $$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\kappa\frac{\partial^2 T}{\partial y^2},$$

(4) $$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D^*\frac{\partial^2 C}{\partial y^2},$$

where physical coordinates (x,y) are chosen such that x is measured from the leading edge of the plate in upwards direction, y is measured normal to the plate, u and v are the velocity components along the x and y-axes, μ is the coefficient of viscosity, ρ is the fluid density, $\upsilon\left(=\frac{\mu}{\rho}\right)$ is the kinematic viscosity, σ is the fluid electrical conductivity, $B(=B_0/\sqrt{x})$ is the non-uniform magnetic field applied normal to the plate, B_0 is a constant, g

is acceleration due to gravity, B^* is the volumetric coefficient of thermal expansion, $K_P^{'}$ is the permeability coefficient of porous medium, T and C are the temperature and concentration of the fluid, T_∞ and C_∞ are the free stream temperature and concentration assumed constant, κ is the thermal diffusivity of the fluid, U_∞ is the free stream velocity and D^* is the mass diffusivity of the fluid.

The boundary conditions are

$$u = L_1 \frac{\partial u}{\partial y}, v = -v_w, T = T_w + D_1 \frac{\partial T}{\partial y}, C = C_w \ at \quad y = 0, \tag{5}$$

$$u = U_\infty, \ \ T = T_\infty, \ \ C = C_\infty \ \ as \ \ y \to \infty, \tag{6}$$

where C_w is the concentration of the fluid at the plate $(C_w > C_\infty)$, $T_w = T_\infty + \frac{T_0}{x}$ is the plate temperature which is variable $(T_w > T_\infty)$, T_0 being a constant. v_w represents the permeability of the porous plate where its sign indicates suction (<0) or blowing (>0), L_1 and D_1 are velocity and thermal slip factors as given by $L_1 = L(\mathrm{Re}_x)^{1/2}$ and $D_1 = D(\mathrm{Re}_x)^{1/2}$, where L and D are initial values of velocity and thermal slip factor.

3. Method of Solution

Introducing stream function ψ such that

$$u = \frac{\partial \psi}{\partial y}, \ \ v = -\frac{\partial \psi}{\partial x} \ \text{and} \ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \ \theta(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \tag{7}$$

into the equations (2) to (4), we get

$$\frac{\partial \psi}{\partial y}\frac{\partial^2 \psi}{\partial x \partial y} - \frac{\partial \psi}{\partial x}\frac{\partial^2 \psi}{\partial y^2} = \upsilon \frac{\partial^3 \psi}{\partial y^3} - \sigma \frac{B^2}{\rho}(\frac{\partial \psi}{\partial y} - U_\infty) + g\beta^*(T_w - T_\infty)\theta - \frac{\upsilon}{K_p^{'}}\frac{\partial \psi}{\partial y}, \tag{8}$$

$$\frac{\partial \psi}{\partial y}\left(\frac{\partial \theta}{\partial x} - \frac{\theta}{x}\right) - \frac{\partial \psi}{\partial x}\frac{\partial \theta}{\partial y} = \kappa \frac{\partial^2 \theta}{\partial y^2}, \tag{9}$$

$$\frac{\partial \psi}{\partial y}\frac{\partial \phi}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial \phi}{\partial y} = D^* \frac{\partial^2 \phi}{\partial y^2}. \tag{10}$$

Hence, the equation of continuity (1) is automatically satisfied.
The boundary conditions are reduced to

(11) $$\frac{\partial\psi}{\partial y}=L_1\frac{\partial^2\psi}{\partial y^2},\ \frac{\partial\psi}{\partial x}=v_x,\ \theta=1+\frac{DU_\infty}{\upsilon}\theta',\ \phi=1\ at\ y=0.$$

(12) $$\frac{\partial\psi}{\partial y}=U_\infty,\ \theta=0,\ \phi=0,\ as\ y\to\infty.$$

Applying similarity solution technique by introducing $\eta=y\sqrt{\frac{U_\infty}{\upsilon x}}$ and $\psi=\sqrt{U_\infty \upsilon x}\,f(\eta)$ into the equations (8) to (10), we get

(13) $$f'''+\frac{1}{2}ff''-M(f'-1)+\lambda\theta-\frac{1}{K_p}f'=0,$$

(14) $$\frac{1}{\Pr}\theta''+\frac{1}{2}f\theta'+f'\theta=0,$$

(15) $$\phi''+\frac{1}{2}Scf\theta'=0,$$

where prime denotes the differentiation with respect to η, $M\left(=\frac{\sigma B_0^2}{\rho U_\infty}\right)$ is the magnetic parameter, $\lambda\left(=g\beta^*\frac{T_0}{U_\infty^2}\right)$ is the mixed convection parameter, $K_p\left(=\frac{K_p' U_\infty}{\upsilon x}\right)$ is the permeability parameter, $\Pr\left(=\frac{\upsilon}{\kappa}\right)$ is the Prandtl number and $Sc\left(=\frac{\upsilon}{D^*}\right)$ is the Schmidt number.

The corresponding boundary conditions are

(16) $$f'=S_V f'',\ f=S,\ \theta=1+S_T\theta',\ \phi=1\ at\ \eta=0,\ \text{and}$$

(17) $$f'=1,\ \theta=0,\ \phi=0\ as\ \eta\to\infty,$$

where $S_V\left(=\frac{LU_\infty}{\upsilon}\right)$ is the velocity slip parameter, $S_T\left(=\frac{DU_\infty}{\upsilon}\right)$ is the thermal slip parameter and S is the permeability of the porous plate. For $\lambda>0$ there is buoyancy aided flow, whereas for $\lambda < 0$ there is buoyancy oppose flow in boundary layer.

Local skin friction coefficient, Nusselt and Sherwood numbers are given by

$$C_f = \frac{2\tau_w}{\rho U_\infty^2} = 2\mathrm{Re}_x^{-1/2} f''(0), Nu_x = \frac{q_w x}{\kappa(T_w - T_\infty)} = -\mathrm{Re}_x^{-1/2}\theta'(0), \text{ and}$$

(18) $$Sh_x = \frac{q_m x}{D^*(C_w - C_\infty)} = -\mathrm{Re}_x^{-1/2}\phi'(0),$$

where the wall shear stress τ_w, the heat flux q_w and the mass flux q_m are given by

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \; q_w = -\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}, \; q_m = -D^*\left(\frac{\partial C}{\partial y}\right)_{y=0} \text{ and}$$

(19) $\mathrm{Re}_x\left(=\frac{U_\infty x}{\upsilon}\right)$ is the local Reynolds number.

The set of equations subject to the boundary conditions are solved numerically using the shooting method.

Equations (13) to (15) are transformed into system of first order differential equations as given below

(20) $$f_1' = f_2, \; f_2' = f_3, \; f_3' = -\frac{1}{2} f_1 f_3 + M(f_2 - 1) - \lambda f_4 + \frac{1}{K_p} f_2, \; f_4' = f_5,$$

$$f_5' = -\Pr\left(\frac{1}{2} f_1 f_5 + f_2 f_4\right), \; f_6' = f_7, \; f_7' = -\frac{1}{2} Sc f_1 f_7,$$

where $f = f_1, \; f' = f_2, \; f'' = f_3, \; f''' = f_3', \theta = f_4, \; \theta' = f_5, \; \theta'' = f_5', \phi = f_6, \; \phi' = f_7, \; \phi'' = f_7'.$

subject to the initial conditions:

$$f_1(0) = S, \; f_2(0) = S_V s_1, \; f_3(0) = s_1, \; f_4(0) = 1 + S_T s_2, \; f_5(0) = s_2, \; f_6(0) = 1, \; f_7(0) = s_3.$$

In order to get solution, step by step integration is carried out using Runge-Kutta fourth order method with shooting technique. To start the integration, values of $f_1, f_2, f_3, f_4, f_5, f_6$ and f_7 are required at $\eta = 0$, but from the boundary condition it is clear that values of f_3, f_5 and f_7 are not known. According to shooting technique, values of f_3, f_5 and f_7 are s_1, s_2 and s_3 assumed. The accuracy of the assumed missing initial conditions are checked by comparing the calculated values of different variables at the terminal point with the given values. The calculations are carried out by using the *MATLAB* programming.

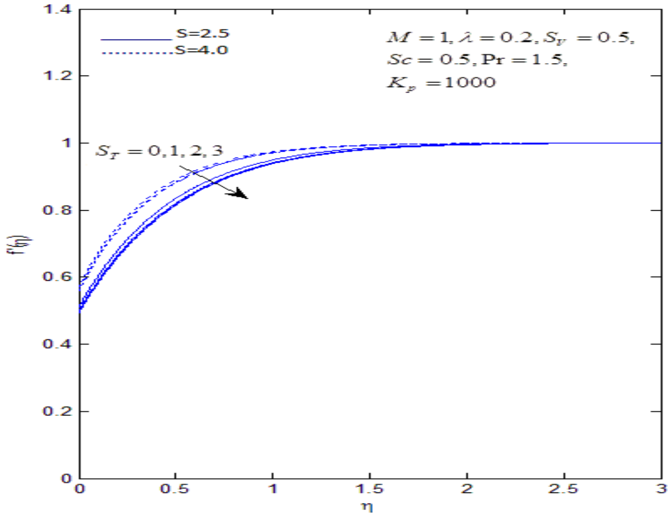

Figure 1: Velocity profiles versus η for different values of S_T.

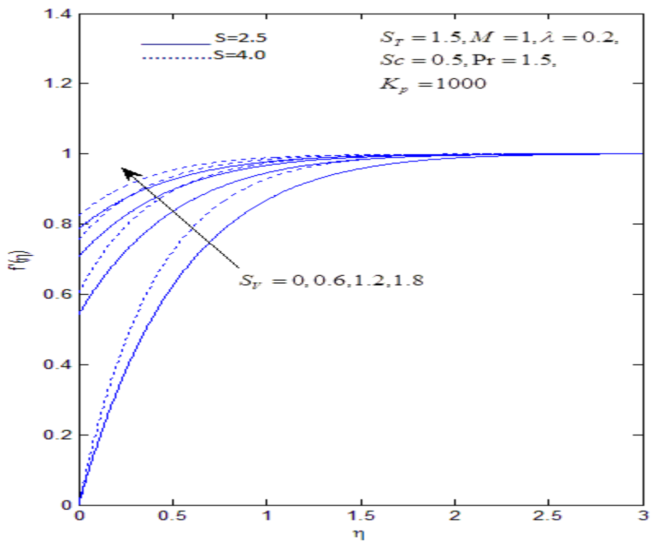

Figure 2: Velocity profiles versus η for different values of S_V.

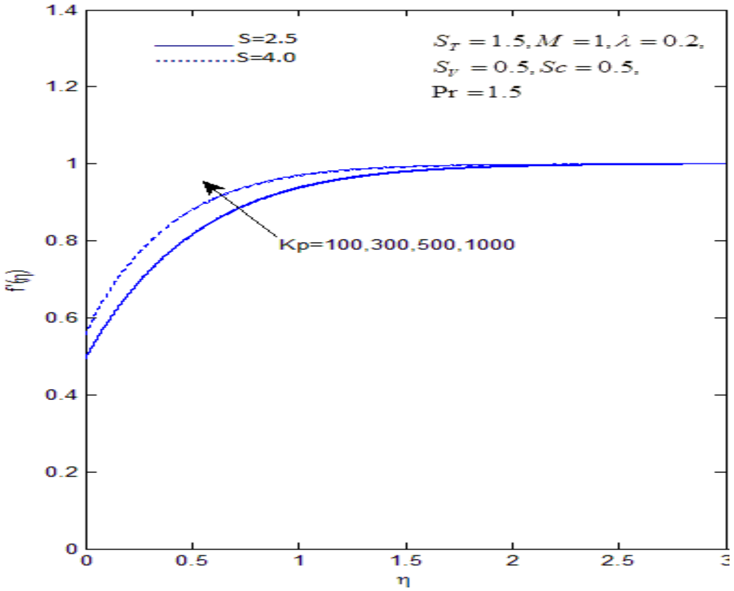

Figure 3: Velocity profilesversus η for different values of K_p.

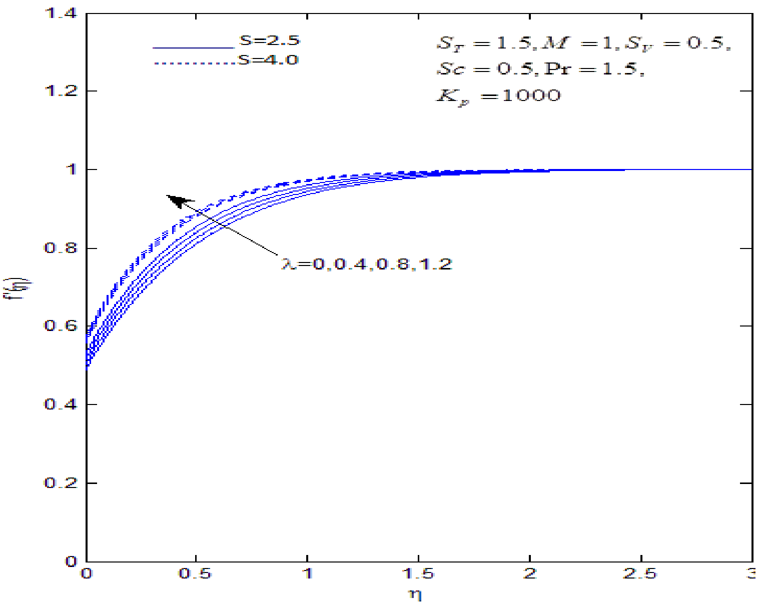

Figure 4: Velocity profilesversus η for different values of λ.

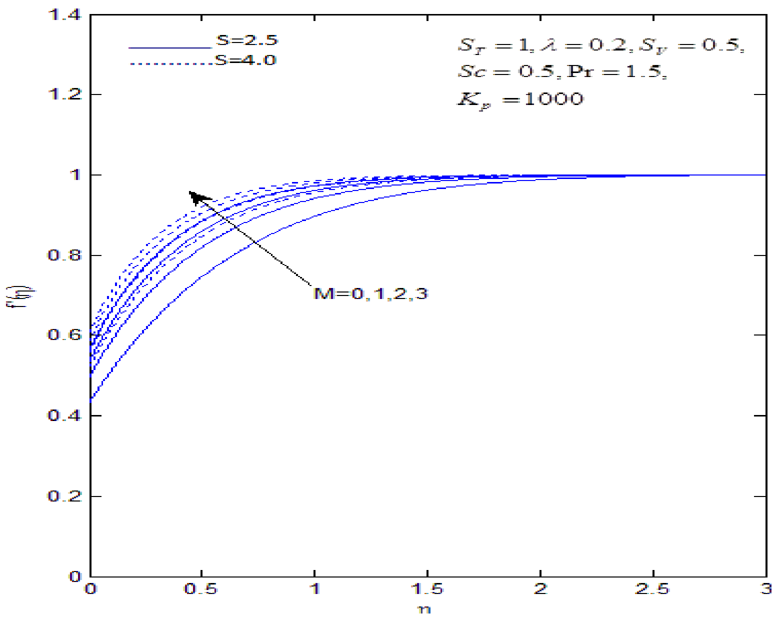

Figure 5: Velocity profilesversus η for different values of M .

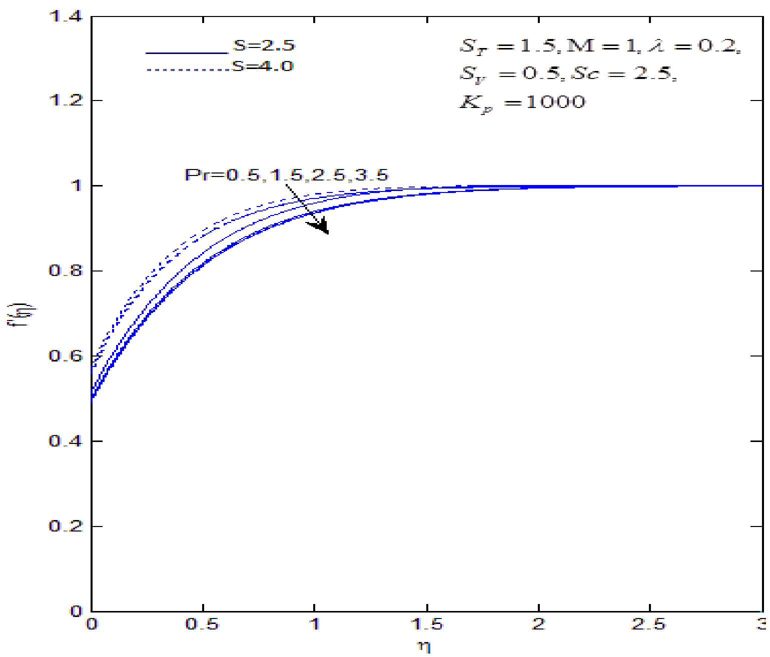

Figure 6: Velocity profilesversus η for different values of Pr .

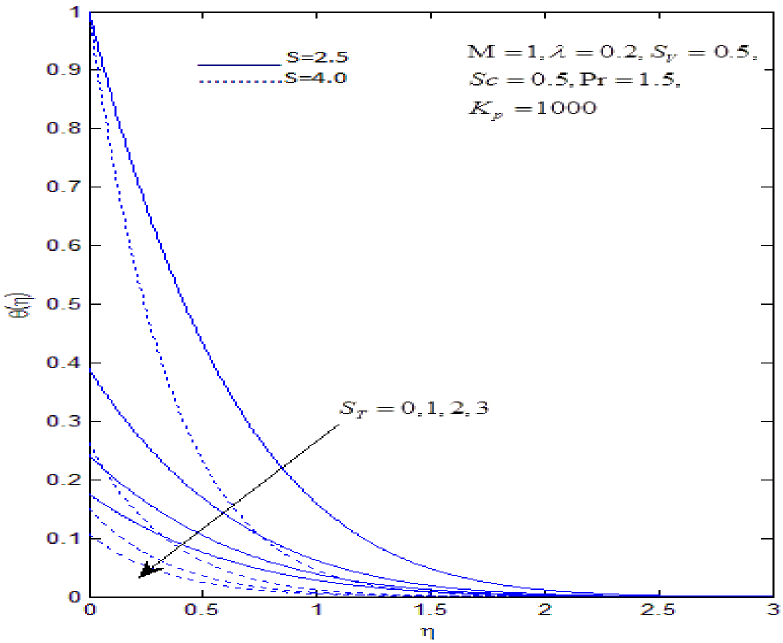

Figure 7: Temperature profiles versus η for different values of S_T .

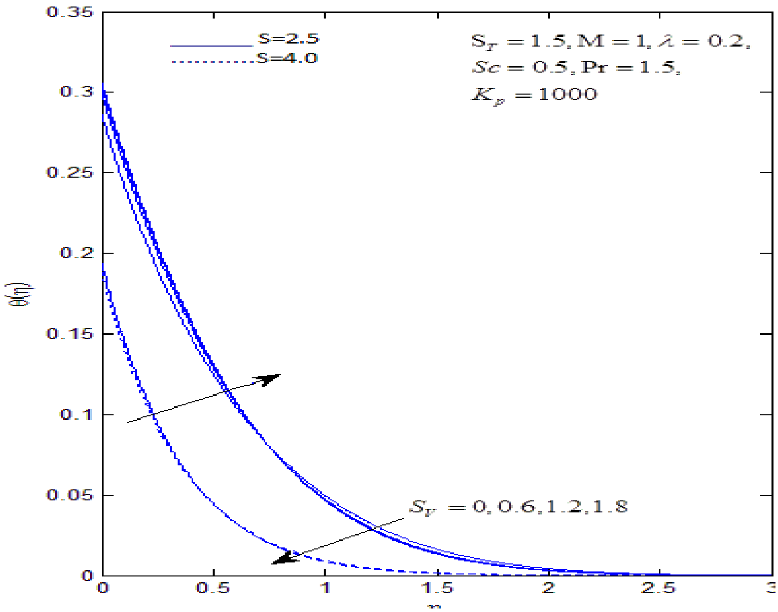

Figure 8: Temperature profiles versus η for different values of S_V .

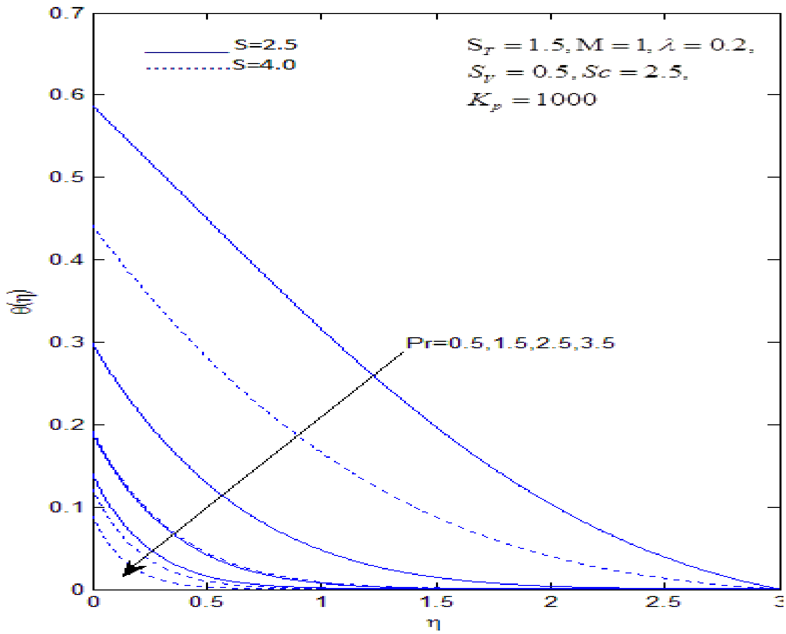

Figure 9: Temperature profilesversus η for different values of Pr .

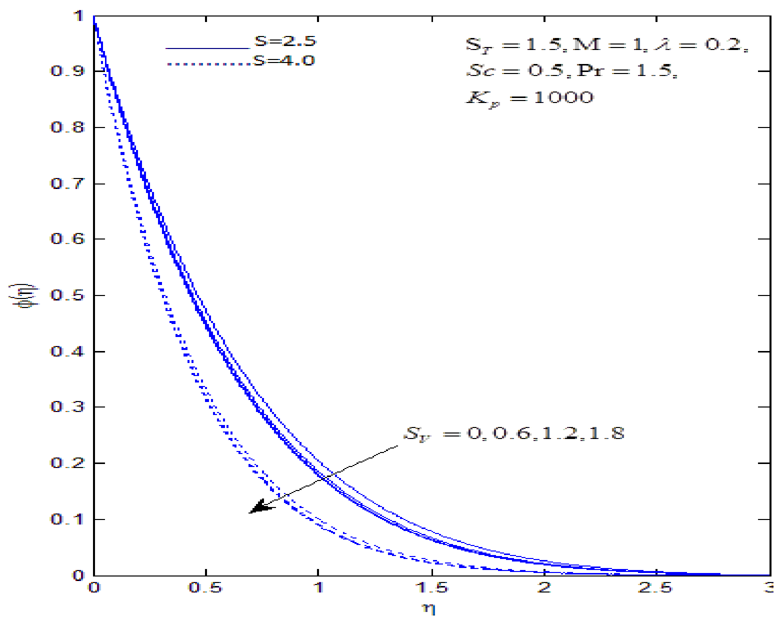

Figure 10: Concentration profiles versus η for different values of S_V .

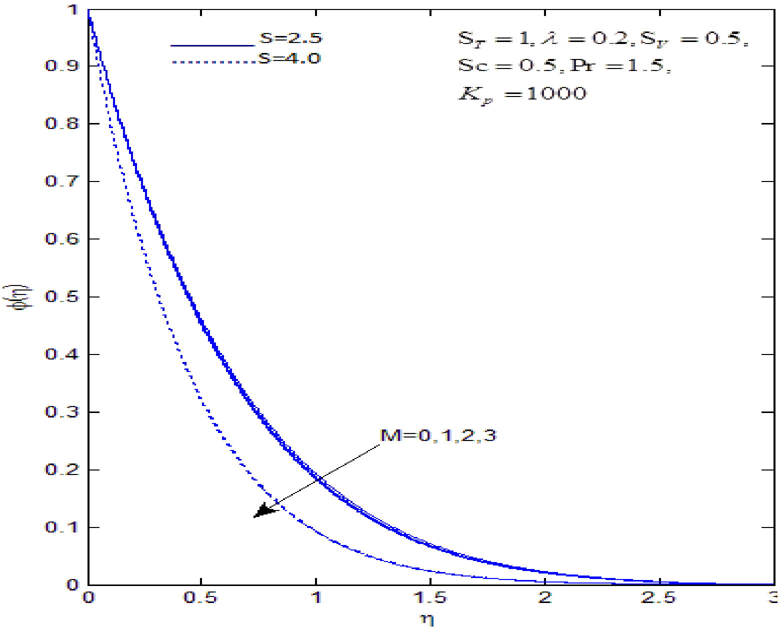

Figure 11: Concentration profilesversus η for different values of M .

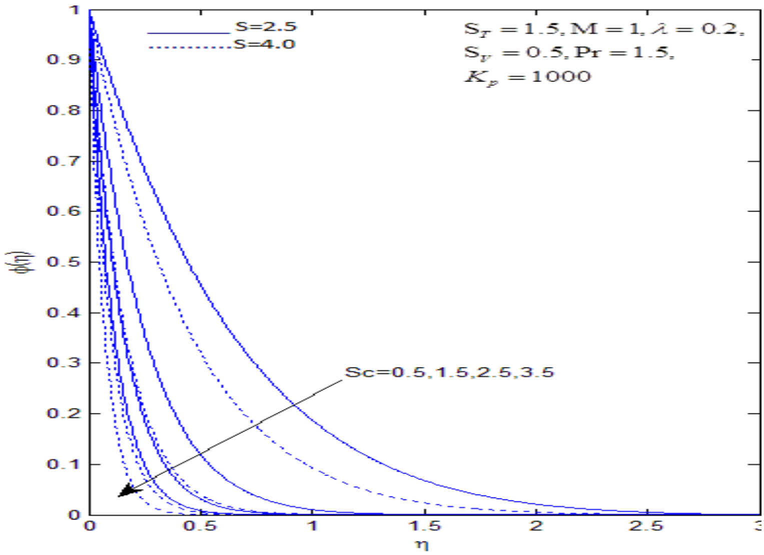

Figure 12: Concentration profilesversus η for different values of Sc .

4. Results and Discussion

Figure 1 shows that fluidvelocity decreases slightly with an increase in thermal slip parameter (S_T) and it increases as similarity variable (η) increases. From figure 2 and 3, it is clear that fluid velocity increases with the increase in the values of velocity slip parameter (S_V) or permeability parameter (K_p). It is observed from figure 4 that fluid velocity increases with an increase in mixed convection parameter (λ). Figure 5 depicts that fluid velocity significantly enhanced with increasing values of magnetic parameter (M). Figure 6 shows that fluid velocity decreases with the increase of the Prandtl number $(\Pr)$.

Figure 7 represents that an increase in thermal slip parameter (S_T) results in significant decrease in fluid temperature. Figure 8 depicts that near the plate fluid temperature increases with the increase in the values of velocity slip parameter (S_V) but there reverse effect is seen far away from the plate. The fluid temperature is significantly diminishes with increases values of Prandle number the plate. The fluid temperature is significantly diminishes with increasing values of Prandtl number $(\Pr)$ as noted from figure 9.Figure 10 to 12 depict that the concentration decreases with the increasing values of velocity slip parameter (S_V), magnetic parameter (M) and Schmidt number (Sc), respectively.

Table 1 depicts that skin friction coefficient increases due to increase of magnetic parameter (M), mixed convection parameter (λ) or permeability parameter (K_p), while it decreases due to increase of thermal slip parameter (S_T), velocity slip parameter (S_V) or Prandtl number $(\Pr)$. Nusselt number increases due to increase of Prandtl number $(\Pr)$ and it decreases when velocity slip parameter (S_V), mixed convection parameter (λ), magnetic parameter (M) or thermal slip parameter (S_T) increase.

Sherwood number increases due to increase of magnetic parameter (M), mixed convection parameter (λ), velocity slip parameter (S_V) or Schmidt number (Sc), while it decreases due to increase of thermal slip parameter (S_T).

Table1: Numerical values of skin friction coefficient, Nusselt number and Sherwood number at the surface of the plate for various values of physical parameters andsuction parameter $S=4.0$

S_T	M	λ	S_V	Sc	Pr	K_p	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.0	1.0	0.2	0.5	0.5	1.5	1000	1.14085	2.80500	2.17094
1.0	1.0	0.2	0.5	0.5	1.5	1000	1.12183	0.73730	2.16930
2.0	1.0	0.2	0.5	0.5	1.5	1000	1.11894	0.42437	2.16900
3.0	1.0	0.2	0.5	0.5	1.5	1000	1.11780	0.29790	2.16890
1.5	1.0	0.2	0.0	0.5	1.5	1000	2.49040	0.54136	2.11570
1.5	1.0	0.2	0.6	0.5	1.5	1000	1.00811	0.53850	2.17320
1.5	1.0	0.2	1.2	0.5	1.5	1000	0.62976	0.53770	2.18730
1.5	1.0	0.2	1.8	0.5	1.5	1000	0.45771	0.53740	2.19350
1.5	1.0	0.2	0.5	0.5	1.5	100	1.11560	0.53870	2.16860
1.5	1.0	0.2	0.5	0.5	1.5	300	1.11885	0.53870	2.16900
1.5	1.0	0.2	0.5	0.5	1.5	500	1.11950	0.53870	2.16900
1.5	1.0	0.2	0.5	0.5	1.5	1000	1.12000	0.53870	2.16900
1.5	1.0	0.0	0.5	0.5	1.5	1000	1.11500	0.53870	2.16860
1.5	1.0	0.4	0.5	0.5	1.5	1000	1.12494	0.53870	2.16940
1.5	1.0	0.8	0.5	0.5	1.5	1000	1.13495	0.53860	2.17030
1.5	1.0	1.2	0.5	0.5	1.5	1000	1.14490	0.53860	2.17120
1.0	0.0	0.2	0.5	0.5	1.5	1000	1.04640	0.73790	2.16260
1.0	1.0	0.2	0.5	0.5	1.5	1000	1.12180	0.73729	2.16930
1.0	2.0	0.2	0.5	0.5	1.5	1000	1.17511	0.73680	2.17370
1.0	3.0	0.2	0.5	0.5	1.5	1000	1.21622	0.73660	2.17700
1.5	1.0	0.2	0.5	2.5	0.5	1000	1.14065	0.37220	10.15900
1.5	1.0	0.2	0.5	2.5	1.5	1000	1.12000	0.53870	10.15600
1.5	1.0	0.2	0.5	2.5	2.5	1000	1.11700	0.58560	10.15540
1.5	1.0	0.2	0.5	2.5	3.5	1000	1.11610	0.60730	10.15600
1.5	1.0	0.2	0.5	0.5	1.5	1000	1.12000	0.53870	2.16900
1.5	1.0	0.2	0.5	1.5	1.5	1000	1.12000	0.53870	6.16200
1.5	1.0	0.2	0.5	2.5	1.5	1000	1.12000	0.53870	10.15600
1.5	1.0	0.2	0.5	3.5	1.5	1000	1.12000	0.53870	14.15300

5. Conclusions

Steady two dimensional boundary layer flow of a viscous incompressible fluid along a vertical porous plate is investigated in the presence of non-uniform magnetic field, velocity slip and thermal jump. Numerical calculations are carried out for various values of the physical parameters and the following conclusions are made:

1. Fluid velocity profile increases and concentration decreases due to increase in magnetic parameter (M) or velocity slip parameter (S_V).
2. Fluid velocity profile and temperature both decreases with increasing values of thermal slip parameter (S_T) or Prandtl number $(\Pr)$.
3. Fluid velocity increases due to increase in mixed convection parameter (λ) or permeability parameter (K_p).
4. Fluid mass profile decreases with increase in Schmidt number (Sc).
5. Skin friction coefficient increases with increasing values of magnetic parameter (M), mixed convection parameter (λ) or permeability parameter (K_p), while it decreases due to increase of thermal slip parameter (S_T), velocity slip parameter (S_V) or Prandtl number $(\Pr)$.
6. Nusselt number increases due to increase of Prandtl number $(\Pr)$ and it decreases with increasing values velocity slip parameter (S_V), mixed convection parameter (λ), magnetic parameter (M) or thermal slip parameter (S_T).
7. Sherwood number increases with increasing values of magnetic parameter (M), mixed convection parameter (λ), velocity slip parameter (S_V) or Schmidt number (Sc), while it decreases due to increase of thermal slip parameter (S_T).

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