MULTIVARIATE CONVECTIVE HEAT AND MASS TRANSFER PAST A VERTICAL PLATE THROUGH A POROUS MEDIUM IN CONDUCTING FIELD.

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ABSTRACT

In this manuscript, an attempt is made to study the Multivariate convective heat and mass transfer past a vertical plate through a porous medium in conducting field . The expressions for velocity, temperature and concentration distribution, skin-friction, rate of heat and mass transfer coefficients at the plate are obtained using perturbation technique. The effect of various physical parameters occurring into the problem on velocity, temperature and concentration fields are discussed with the help of graphs.

Key words: MHD, Chemical reaction, Radiation, Visco-elastic, Radiation absorption, Skin-friction.

1. INTRODUCTION

MHD is a fluid dynamics of a plasma which can carry an electric current. The interaction with this current and the magnetic field generated by the current, as well as externally imposed magnetic fields, give MHD its rich character which adds to underlying fluid dynamics. Although the plasma can carry a current, it remains electrically neutral throughout the course of its dynamics. The ideas of fluid dynamics in general are presented in heuristic detail, with emphasis on the conservation properties. At this point the electrons and positive ions which make up a completely ionized, neutral plasma are treated as separate, ideal (dissipation-free) fluids. Then, the conditions under which the plasma may be treated as a single, current-carrying fluid are listed, and the system of equations that make up ideal MHD is presented.

The important properties of ideal MHD are conservation of magnetic flux, the concept of a flux tube, essential dynamics of magnetic pressure and shear waves, or Alfv\'en waves. The relevant time and spatial scales are derived, and then the validity of MHD is addressed in terms of these parameters. One important parameter, the so-called "plasma beta", which is the ratio of fluid pressure to magnetic field pressure, is discussed at length. Finally, the effect of introducing electrical resistivity is addressed: resistivity is a dissipative momentum transfer between electrons and ions which acts as a magnetic diffusivity, relaxing the flux conservation property especially at very small scales.

Unsteady MHD Convective flow of Rivlin-Ericksen Fluid over an Infinite Vertical Porous Plate with Absorption Effect and Variable Suction was studied by Veera Sankar et al. [1]. Sharmilaa [2] Steadied Mhd Mixed Convective Flow in Presence of Inclined Magnetic Field and Thermal Radiation With Effects of Chemical Reaction and Soret Embedded in A Porous Medium . Unsteady MHD Mixed Convection Flow of Jeffrey Fluid Past a Radiating Inclined Permeable Moving Plate in the Presence of Thermophoresis Heat Generation and Chemical Reaction was discussed by Venkateswara raju et al. [3]. Unsteady MHD Free Convection Flow of a Viscoelastic Fluid Past a Vertical Porous Plate. International Journal of Dynamics of Fluids was studied by Gurivi Reddy [4]. Reddy [5] studied MHD boundary layer flow, heat and mass transfer analysis over a rotating disk through porous medium saturated by Cuwater and Ag-water nanofluid with chemical reaction. Magnetohydrodynamic (MHD) mixed convection flow of micropolar liquid due to nonlinear stretched sheet with convective condition was discussed by Waqas et al. [6]. Rashad et al, [7] studied by MHD mixed convection of localized heat source/sink in a nanofluid-filled lid-driven square cavity with partial slip.

Chemical reaction engineering (reaction engineering or reactor engineering) is a specialty in chemical engineering or industrial chemistry dealing with chemical reactors. Frequently the term relates specifically to catalytic reaction systems where either a homogeneous or heterogeneous catalyst is present in the reactor. Sometimes a reactor per se is not present by itself, but rather is integrated into a process, for example in reactive separations vessels, retorts, certain fuel cells, and photocatalytic surfaces. The issue of solvent effects on reaction kinetics is also considered as an integral part. Reactor Design uses information, knowledge and experience from a variety of areas - thermodynamics, chemical kinetcs, fluid mechanics, heat and mass transfer and economics. Chemical Reaction Engineering is the synthesis of all these factors with the aim of properly designing a Chemical Reactor.

Effects of Chemical Reaction on Unsteady MHD Casson Fluid flow past a moving Infinite Inclined Plate through Porous Medium was studied by Balakrishna et al. [8]. Rama Mohan et al. [9] Studied chemical reaction and thermal radiation effects on unsteady MHD free convection flow past an inclined moving plate with TGHS. Arifuzzaman et al. [10] was discussed chemically reactive and naturally convective high speed MHD fluid flow through an oscillatory vertical porous plate with heat and radiation absorption effect. Chemical reaction effect on MHD boundary-layer flow of two-phase nanofluid model over an exponentially stretching sheet with a heat generation was discussed by Eid [11]. Muthuraj et al.[12] was studied influences of chemical reaction and wall properties on MHD Peristaltic transport of a Dusty fluid with Heat and Mass transfer. Chemical Reaction and radiation absorption effects on MHD convective heat and mass transfer flow of a viscoelastic fluid past an oscillation porous plate with heat generation/absorption studied by Ramaiah et al.[13].

Researchers use radioactive atoms to determine the age of materials that were once part of a living organism. The age of such materials can be estimated by measuring the amount of radioactive carbon they contain in a process called radiocarbon dating. Similarly, using other radioactive elements, the age of rocks and other geological features (even some man-made objects) can be determined; this is called Radiometric dating. Environmental scientists use radioactive atoms, known as tracer_atoms, to identify the pathways taken by pollutants through the environment. Radiation is used to determine the composition of materials in a process called neutron activation analysis. In this process, scientists bombard a sample of a substance with particles called neutrons. Some of the atoms in the sample absorb neutrons and become radioactive. The scientists can identify the elements in the sample by studying the emitted radiation.

Radiation and dufour effects on laminar flow of a rotating fluid past a porous plate in conducting field was studied by Ananda Reddy et al.[14]. Venkateswara raju et al.[15] studied thermal diffusion and radiation effects on magnetocasson fluid flow past a vertical porous plate. Hari Krishna et al.[16] discussed by the effects of Radiation and Chemical Reaction on MHD Flow Past an Oscillating Inclined Porous Plate with Variable Temperature and Mass Diffusion. Recently researchers [17-20] shown interest in this area.

The aim of the present investigation is to study the Multivariate convective heat and mass transfer past a vertical plate through a porous medium in conducting field. The dimensionless governing equations are solved using the perturbation technique.

2. Formulation of the Problem

Continuity equation:

$$\frac{\partial v^*}{\partial y^*} = 0 \qquad (1)$$

Momentum equation:

$$\frac{\partial u^*}{\partial t^*} + V^*\frac{\partial u^*}{\partial y^*} = \vartheta\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta\,(T^* - T_\infty) + gB^*(C^* - C_\infty) - K_1'\frac{\partial^3 u^*}{\partial y^{*2}\,\partial t^*} - \frac{\sigma B_0^2}{\rho}u^* - \frac{\vartheta}{K_0}u^* \qquad (2)$$

Energy equation:

$$\frac{\partial T^*}{\partial t^*} + V^*\frac{\partial T^*}{\partial y^*} = \frac{K}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^*} - \frac{S^*}{\rho C_p}(T^* - T_\infty) - \frac{R^*}{\rho C_p}(C^* - C_\infty) \qquad (3)$$

Concentration equation

$$\frac{\partial C^*}{\partial t^*} + V^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K^*(C^* - C_\infty) \qquad (4)$$

The relevant boundary conditions are given as follows

$$u^* = U_0(1+\varepsilon e^{i\omega^* t^*}), \quad T^* = T_w + \varepsilon(T_w - T_\infty)e^{i\omega^* t^*},$$
$$C^* = C_w + \varepsilon(C_w - C_\infty)e^{i\omega^* t^*}, \quad \text{at} \quad y^* = 0$$
$$u^* \to 0,\ T^* \to T_\infty, \quad C^* \to C_\infty \quad \text{as } y^* \to \infty \qquad (5)$$

Where U_0 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, ω -the constant.

Eq.(1) gives that $V^* = \text{Constant} = -V_0$ (6) Where V_0 is the constant suction velocity normal to the plate

On introducing the following non-dimensional quantities,

$$u=\frac{u*}{U_0},w=\frac{\upsilon w*}{U_0^2},\lambda=\frac{U_0^2K_1'}{\rho\upsilon^2},\ y=\frac{U_0\ y*}{\vartheta},\ t=\frac{t*U_0^{\ 2}}{\vartheta}\ \theta=\frac{T*-T_\infty}{T_w-T_\infty},\qquad \phi=\frac{C*-C_\infty}{C_w-C_\infty},$$

$$\Pr=\frac{\mu C_p}{K},\ Sc=\frac{\vartheta}{D},\ M^2=\frac{\sigma_e B_0^2\vartheta}{\rho U_0^{\ 2}},Gr=\frac{\vartheta g\beta\ (T_W-T_\infty)}{U_0^3},\quad Gm=\frac{\vartheta g\beta^*(C_w-C_\infty)}{U_0^3} \tag{7}$$

$$K_p=\frac{K_0U_0^2}{\vartheta^2},V_0=\frac{v_0}{U_0},\ K_r=\frac{\vartheta K*}{U_0^2},R=\frac{4I^*\vartheta^2}{KU_0^2},\ S=\frac{S*v^2}{KU_0^2},R_1=\frac{R*\vartheta^2(C_w-C_\infty)}{KU_0^2(T_w-T_\infty)},$$

In view of the above non-dimensional quantities and the equation (6) the Equations(2) to (4) after dropping the asterisks reduce to the following dimensionless form.

$$\frac{\partial u}{\partial t}-V_0\frac{\partial u}{\partial y}=\frac{\partial^2u}{\partial y^2}+Gr\theta+Gm\phi-M_1u-\lambda_1\frac{\partial^3u}{\partial y^2\partial t} \tag{8}$$

$$\Pr\frac{\partial\theta}{\partial t}-\Pr V_0\frac{\partial\theta}{\partial y}=\frac{\partial^2\theta}{\partial y^2}+\alpha\theta-R_1\phi \tag{9}$$

$$Sc\frac{\partial\phi}{\partial t}-ScV_0\frac{\partial\phi}{\partial y}=\frac{\partial^2\phi}{\partial y^2}-ScK_r\phi \tag{10}$$

Where $M_1=M^2+1/K_p$ $\alpha=R-S$

The corresponding boundary conditions are :

$$u=1+\varepsilon e^{i\omega t},\ \theta=1+\varepsilon e^{i\omega t},\phi=1+\varepsilon e^{i\omega t}\quad at\quad y=0$$
$$u\to 0,\qquad \theta\to 0,\qquad \phi\to 0\quad \text{s}\quad y\to\infty \tag{11}$$

3.Solution of the problem:

To solve the nonlinear equations (8) to (10) with the boundary conditions (11),

$$u(y,t)=u_0(y)+\varepsilon u_1(y)e^{i\omega t} \tag{12}$$
$$\theta(y,t)=\theta_0(y)+\varepsilon\theta_1(y)e^{i\omega t}$$
$$\phi(y,t)=\phi_0(y)+\varepsilon\phi_1(y)e^{i\omega t}$$

Substituting equation (12) into the equations (8), (9) and (10) and equating the harmonic and non-harmonic terms, neglecting the terms of $\in^2$, we get

Zero order terms:

$$u_0''+V_0u_0'=-\mathrm{Gr}\,\theta_0-\mathrm{Gm}\,\phi_0+\mathrm{M_1u_0} \tag{13}$$
$$\theta_0''+\Pr V_0\theta_0'+\alpha\theta_0=\mathrm{R_1}\,\phi_0 \tag{14}$$
$$\phi_0''+Sc\ V_0\phi_0'-\mathrm{ScK}_r\phi_0=0 \tag{15}$$

First order terms :

$$N_1u_1''+V_0u_1'=-\mathrm{Gr}\,\theta_1-\mathrm{Gm}\,\phi_1+N_2\mathrm{u_1} \tag{16}$$
$$\theta_1''+\Pr V_0\theta_1'+(\alpha-\Pr(\mathrm{i}\omega)\,\theta_1=\mathrm{R_1}\,\phi_1 \tag{17}$$
$$\phi_1''+ScV_0\phi_1'-Sc(K_r+i\omega)\phi_1=0 \tag{18}$$

Where $N_1=1-\lambda_1(i\omega)$ $N_2=M_1+i\omega$

The corresponding boundary conditions are

$u_0=1,\ u_1=1,\quad \theta_0=1,\ \theta_1=1,\quad \phi_0=1,\ \phi_1=1\quad$ at $y=0$

$u_0\to 0,\ u_1\to 0,\quad \theta_0\to 0,\ \theta_1\to 0,\quad \phi_0\to 0,\ \phi_1\to 0\quad$ as $y\to\infty$ (19)

Solving equations (14) – (18) under the boundary conditions (19), the following solutions are obtained

$$u_0(y) = b_5 e^{-m_1 y} + b_6 e^{-m_3 y} + b_7 e^{-m_5 y} \quad (20)$$

$$u_1(y) = b_8 e^{-m_2 y} + b_9 e^{-m_4 y} + b_{10} e^{-m_6 y} \quad (21)$$

$$\theta_0(y) = b_1 e^{-m_1 y} + b_2 e^{-m_3 y} \quad (22)$$

$$\theta_1(y) = b_3 e^{-m_2 y} + b_4 e^{-m_4 y} \quad (23)$$

$$\phi_0(y) = e^{-m_1 y} \quad (24)$$

$$\phi_1(y) = e^{-m_3 y} \quad (25)$$

Substituting equations (20) – (25) in equation (12) we obtain the velocity temperature and concentration field

$$u(y,t) = (b_5 e^{-m_1 y} + b_6 e^{-m_3 y} + b_7 e^{-m_5 y}) + \varepsilon(b_8 e^{-m_2 y} + b_9 e^{-m_4 y} + b_{10} e^{-m_6 y}) e^{i\omega t} \quad (26)$$

$$\theta(y,t) = (b_1 e^{-m_1 y} + b_2 e^{-m_3 y}) + \varepsilon(b_3 e^{-m_2 y} + b_4 e^{-m_4 y}) e^{i\omega t} \quad (27)$$

$$\phi(y,t) = e^{-m_1 y} + \varepsilon\, e^{-m_2 y} e^{i\omega t} \quad (28)$$

Skin Friction:

The non-dimensional skin friction at the surface is given by

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$\tau = [m_1 b_5 + m_3 b_6 + m_5 b_7] + \varepsilon[m_2 b_8 + m_4 b_9 + m_6 b_{10}] e^{i\omega t} \quad (29)$$

Nusselt Number :

The rate of heat transfer in terms of the Nusselt number is given by

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$Nu = [m_1 b_1 + m_3 b_2] + \varepsilon[m_2 b_3 + m_4 b_4] e^{i\omega t} \quad (30)$$

Sherwood Number :

The rate of mass transfer on the wall in terms of Sherwood number is given by

$$Sh = -\left(\frac{\partial \phi}{\partial y}\right)_{y=0}$$

$$Sh = m_1 + \varepsilon\, m_2\, e^{i\omega t} \quad (31)$$

4. RESULTS AND DISCUSSION

In order to get a physical insight into the problem numerical calculations are carried out for the Velocity, Temperature and concentration profiles and the following discussion is set out.

Throughout the computations we employ, V_0 =1,Sc=0.22,Pr=0.71,Gr=1,Gm=1,S=2,K_r=1, K_p =1,M=1, E=0.01, t=3,R=1,R_1=1, **ω=π/6, λ_1**=1.

In order to reveal the effects of various parameters on the dimensionless velocity fields, temperature field, concentration field, skin friction, Nusselt number and Sherwood number and the effect of the various physical parameters such as the Grashof number (Gr), the modified Grashof number (Gm),Magnetic parameter (M), Permeability parameter(K_p), Prandtl number (Pr), Heat absorption parameter(S), Radiation Parameter (R), Radiation absorption Parameter (R_1),Schmidt number(Sc) and Chemical reaction parameter(K_r) on velocity, temperature and concentration we draw a number of figures marked as figs. 1-19 and study these by choosing arbitrary values. The influence of these parameters on skin friction, Nusselt number and Sherwood number is also shown in Tables 1 – 3.

Figs. 1 – 10 demonstrate the variations of the fluid velocity under the effects of different parameters. In Fig.1, we represent the velocity profile for different values of Grashof number(Gr). From this figure it is noticed that, velocity increases with increases in Gr. In Fig.2 the effect of modified Grashof number (Gm) on velocity is presented. As Gm increases, velocity also increases. In Fig. 3, velocity profiles are displayed with the variation in magnetic parameter (M). From this figure it is noticed the velocity gets reduced by the increase of magnetic parameter (M). Fig.4, depicts the variations in velocity profiles for different values of permeability parameter (K_p). From where it is noticed that, velocity increases as K_p increases. Fig.5, depicts the variations in velocity profiles for different values of Prandtl number (Pr) which shows that velocity decreases as Pr increases. In Fig.6 the effect of Radiation parameter(R) on velocity is presented. As R increases, velocity also decreases. In Fig.7 the effect of Heat absorption parameter(S) on velocity is presented. As S increases, velocity also increases. In Fig. 8, velocity profiles are displayed with the variation in Radiation absorption parameter (R_1). From this figure it is noticed the velocity gets reduced by the increase of Heat absorption parameter(S).In Fig. 9, velocity profiles are displayed with the variation in Schmidt number(Sc) From this figure it is noticed the velocity gets reduced by the increase of Schmidt number(Sc).A similar effects are noticed from fig.10, in the presence of chemical reaction parameter(K_r) which is also decreases the fluid velocity.

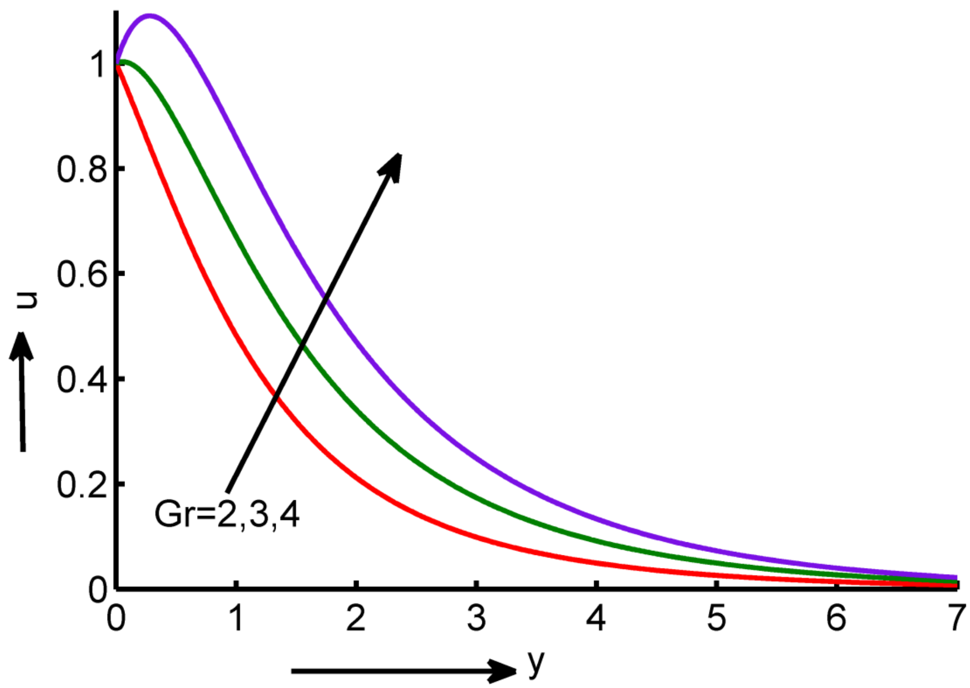

Figure 1: Effect of Thermal Grashof number on Velocity

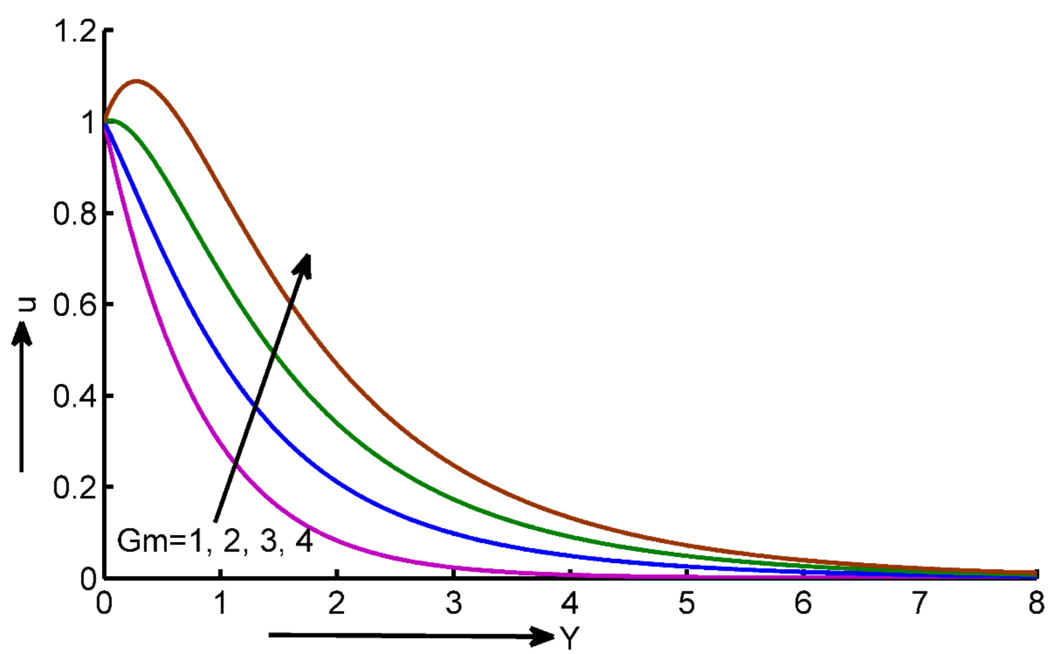

Figure 2: Effect of Modified Grashof number on Velocity

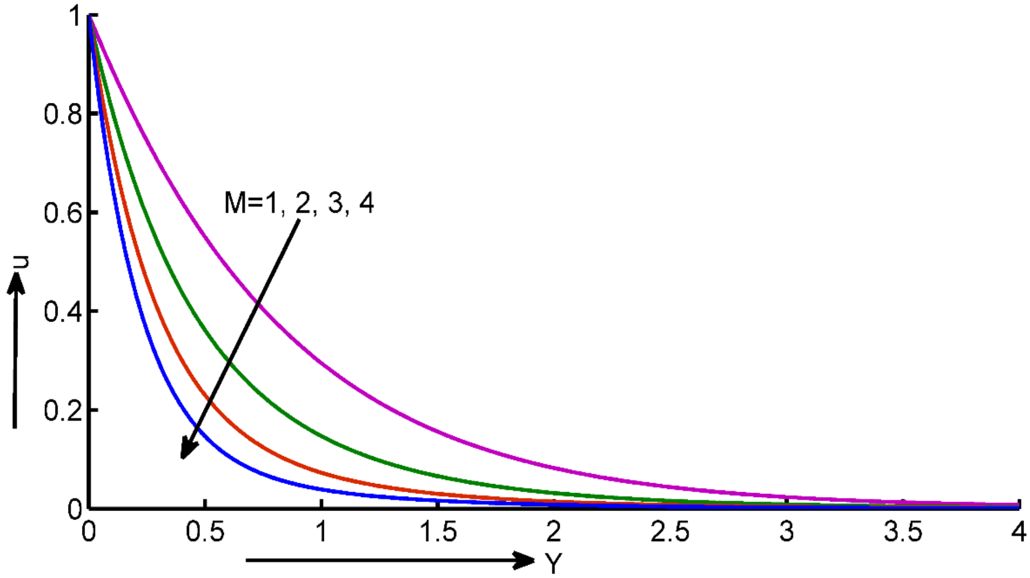

Figure 3: Effect of Magnetic parameter on Velocity

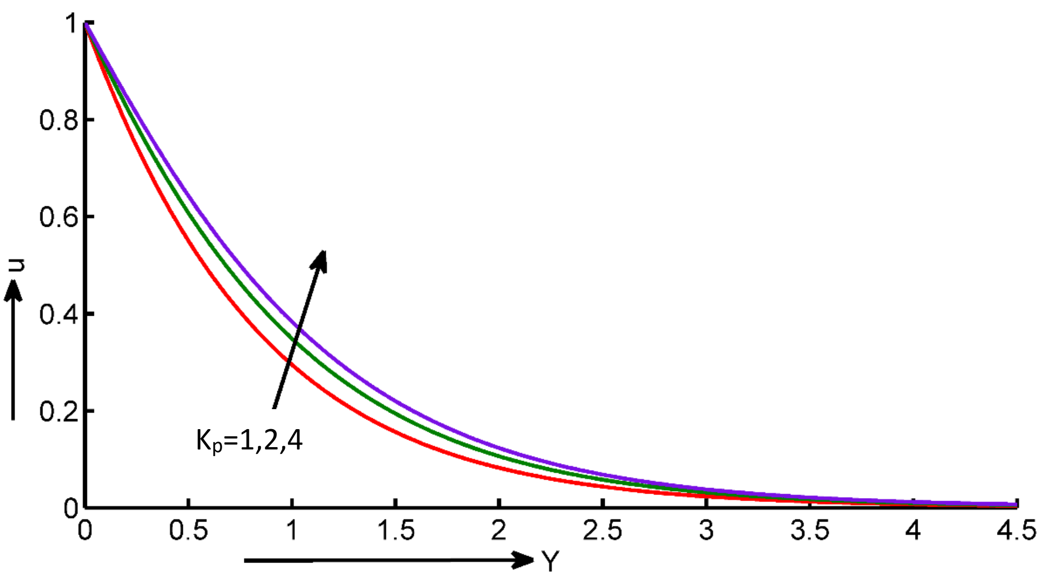

Figure 4: Effect of Permeability parameter on Velocity

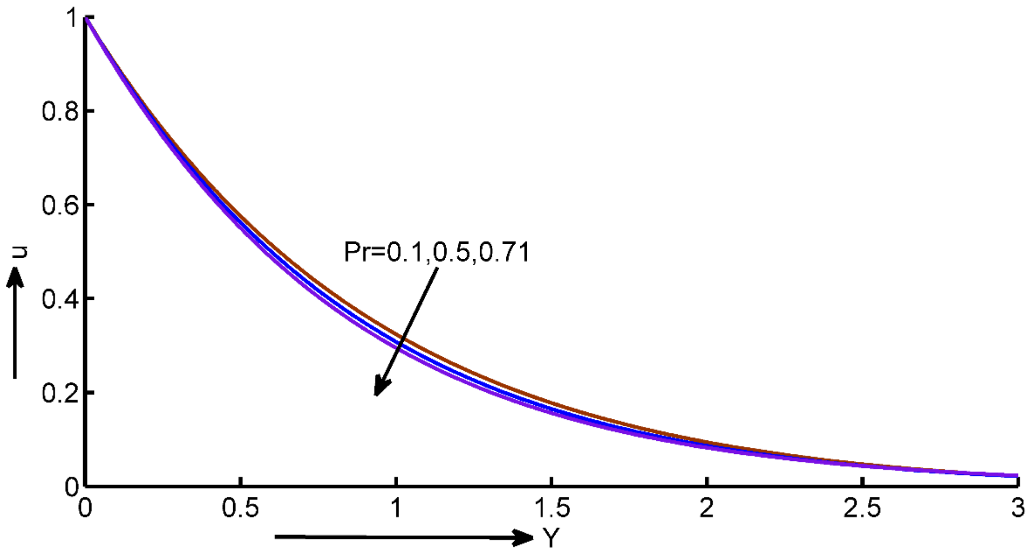

Figure 5: Effect of Prandtl number on Velocity

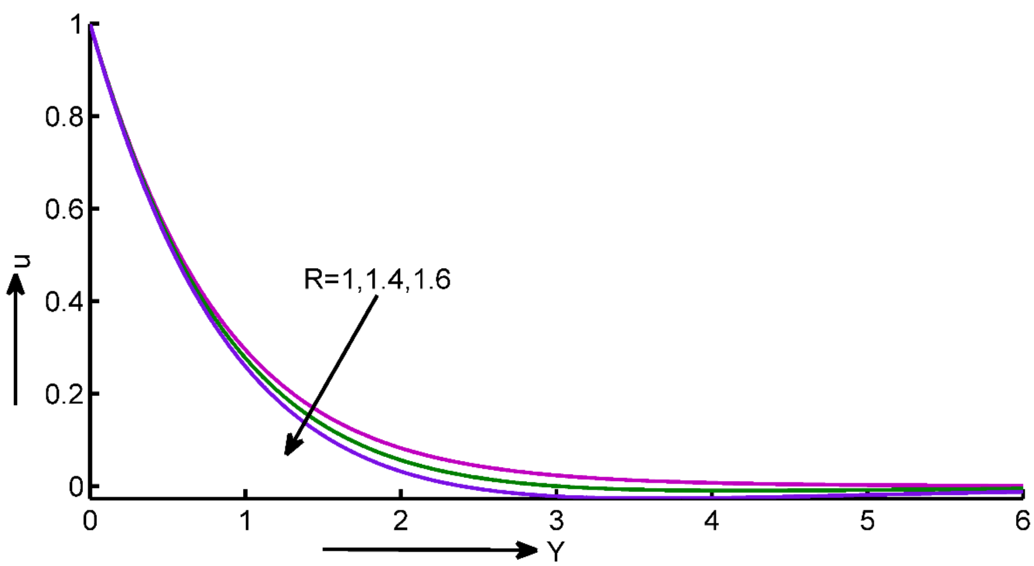

Figure 6: Effect of Radiation parameter on Velocity

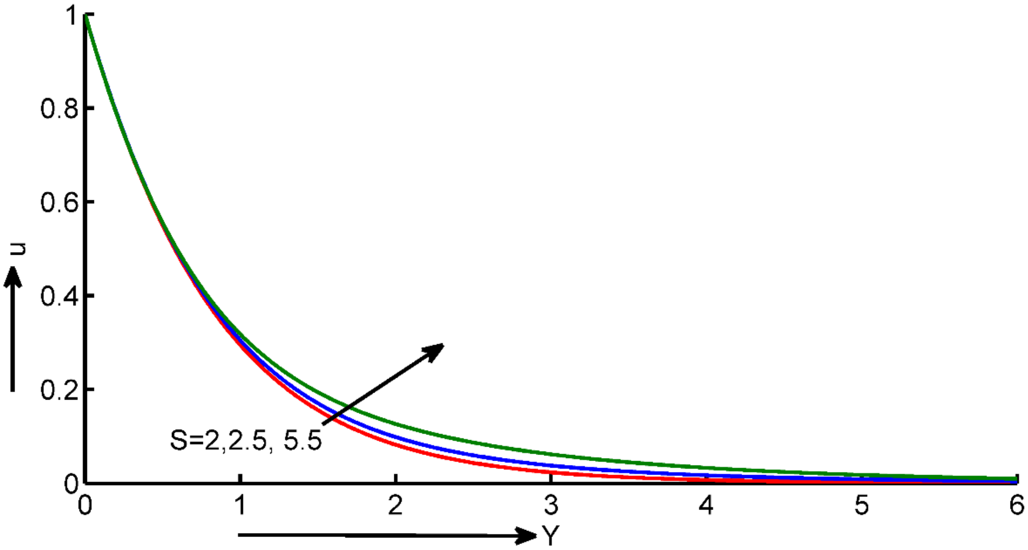

Figure 7: Effect of Heat absorption parameter on Velocity

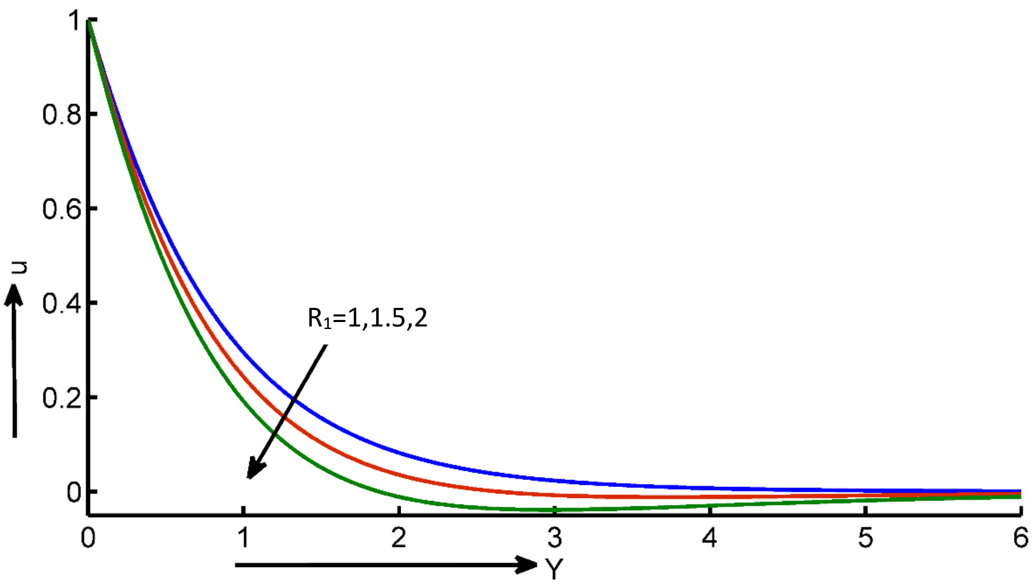

Figure 8: Effect of Radiation absorption parameter on Velocity

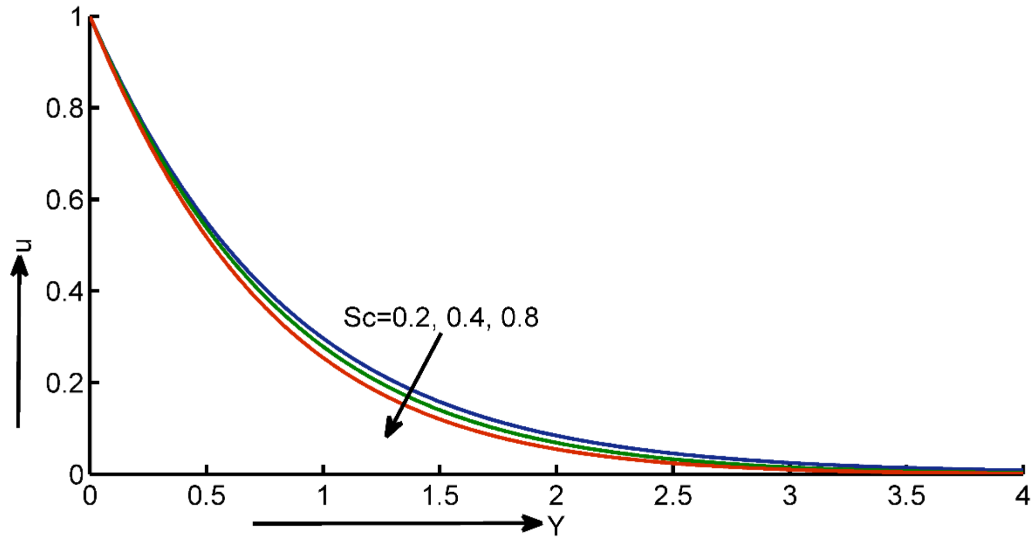

Figure 9: Effect of Schmidt number on Velocity

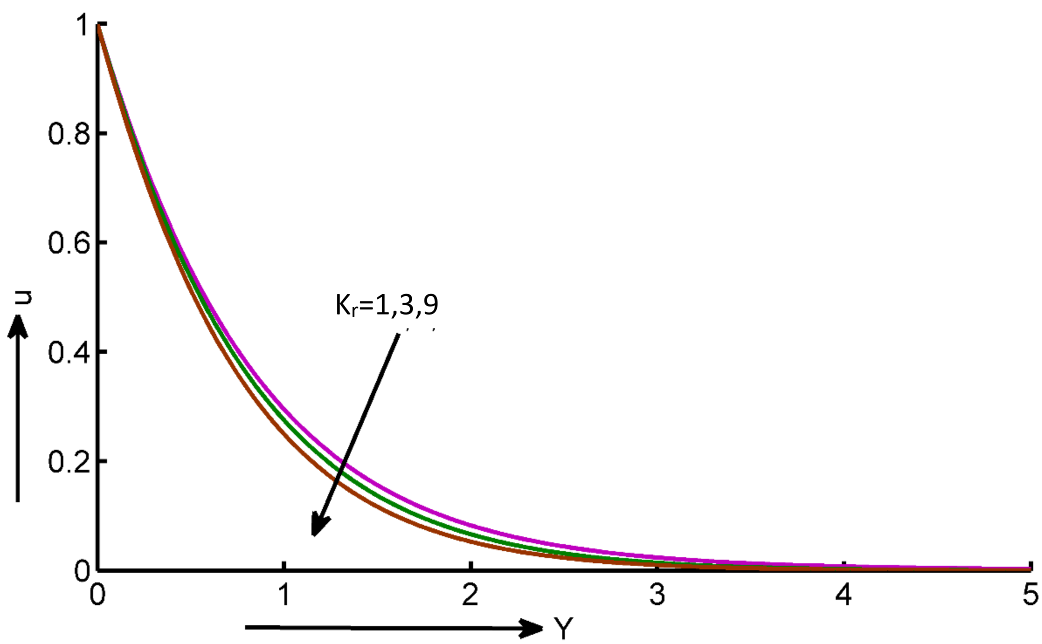

Figure 10: Effect of Chemical Reaction Parameter on Velocity

Figures 11– 17, display the variations of the fluid temperature under the effects of different parameters. From Fig11-14, it is clear that temperature decreases with the increase in Radiation absorption Parameter (R_1), Heat absorption parameter(S),Prandtal number (Pr) and Radiation Parameter (R), In Fig15-17, the effect of Chemical reaction parameter(K_r), Heat absorption parameter(S) and Schmidt number(Sc) are shown on the temperature profile. From these figures are observed that temperature increases with an increase values in K_r, S and Sc.

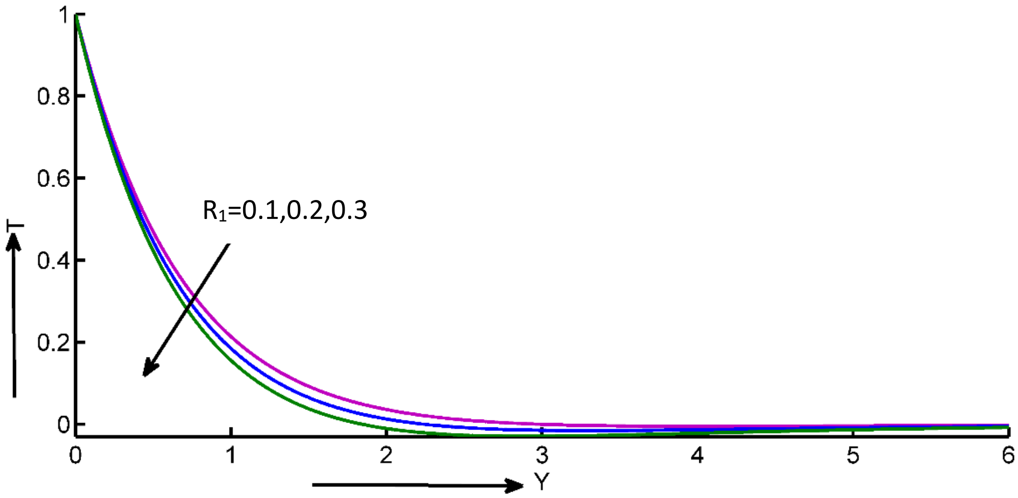

Figure 11: Effect of Radiation absorption parameter on Temperature

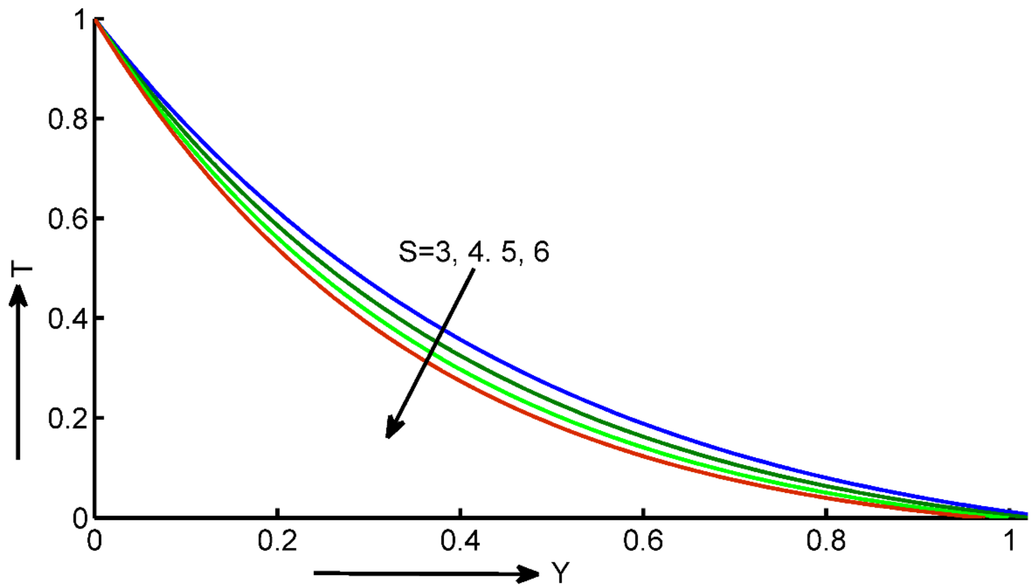

Figure 12: Effect of Heat absorption parameter on Temperature

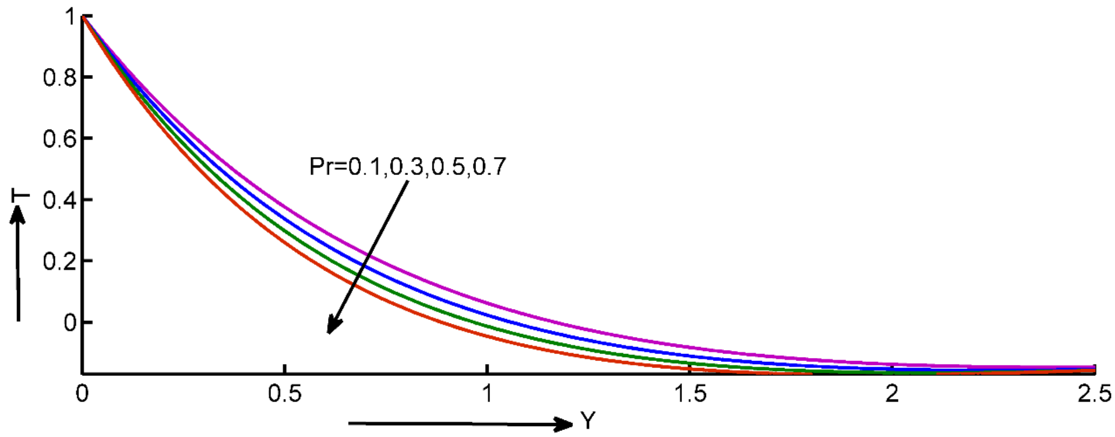

Figure 13: Effect of Prandtl number on Temperature

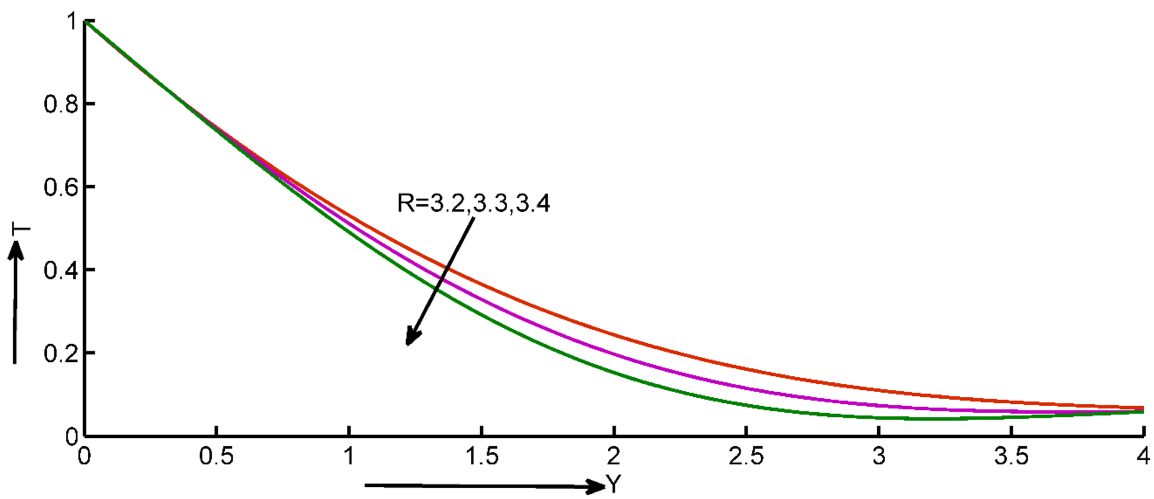

Figure 14: Effect of Radiation parameter on Temperature

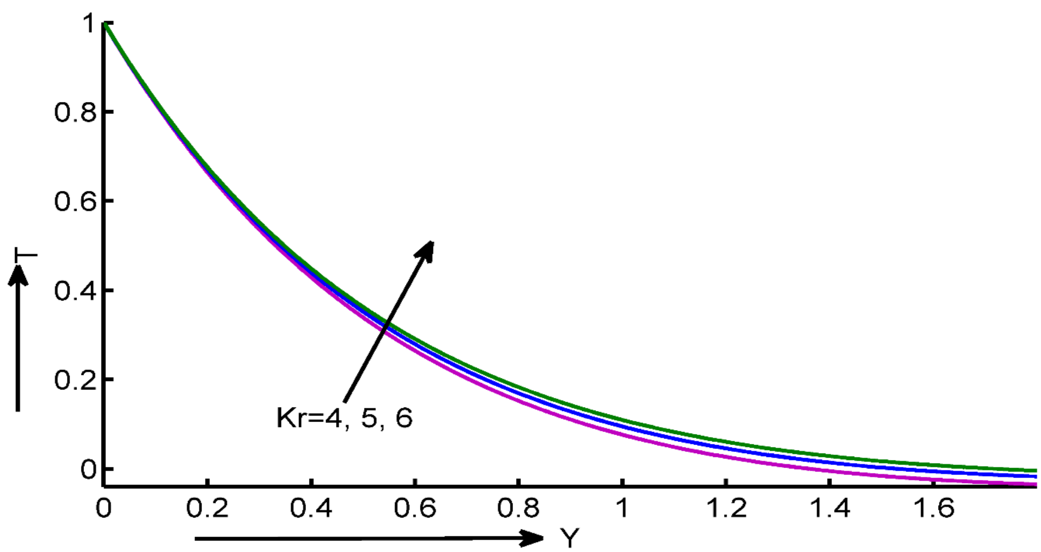

Figure 15: Effect of Chemical Reaction Parameter on Temperature

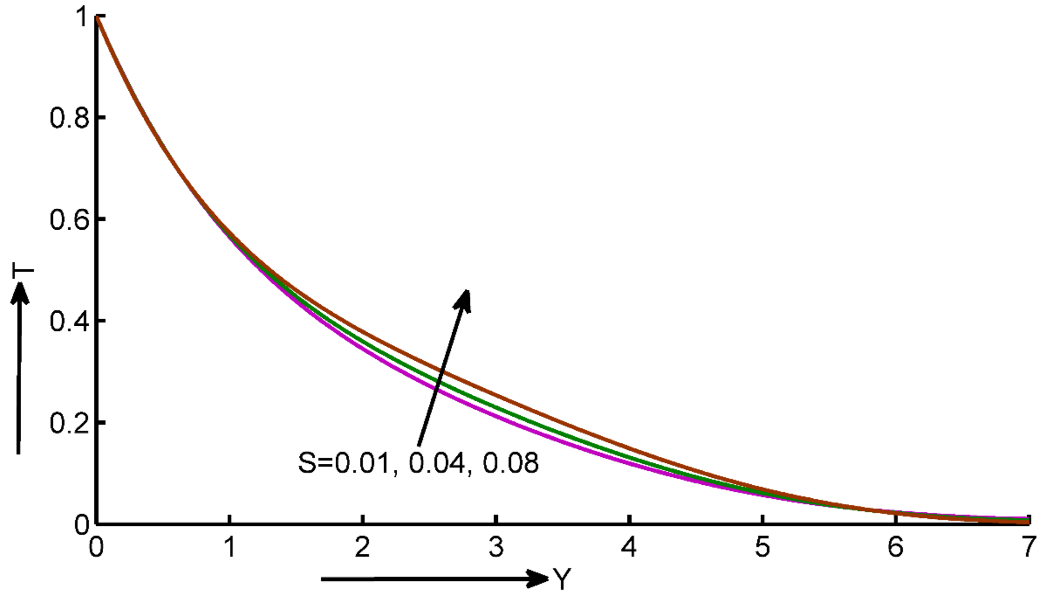

Figure 16: Effect of Heat absorption parameter on Temperature

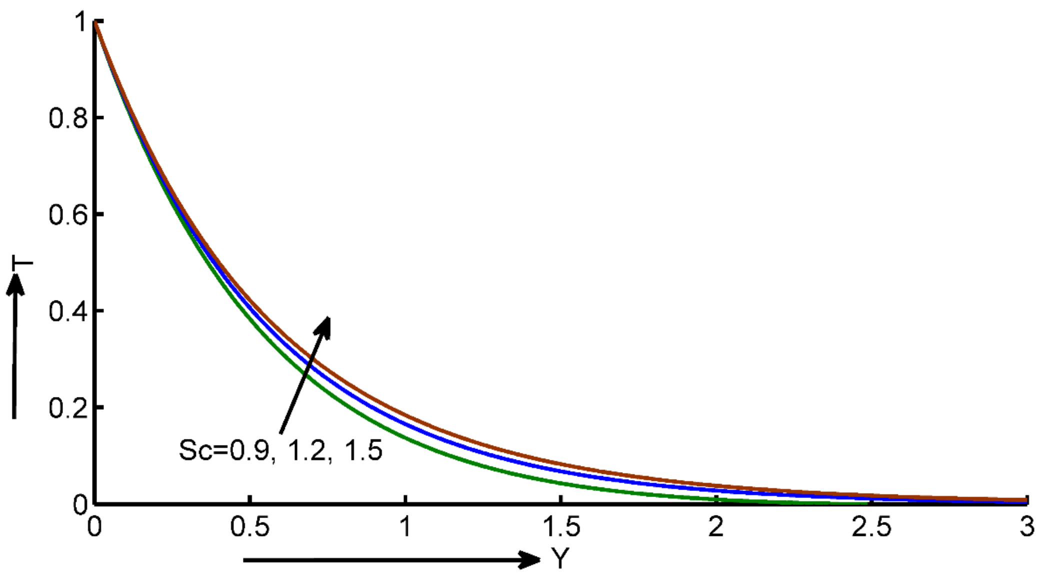

Figure 17: Effect of Schmidt number on Temperature

To analyze the effect of Schmidt parameter(Sc) on the concentration profile in Fig.18. The result shows that the concentration field decreases when increases Sc. Fig.19 depicts the variations in Concentration profile for different values of Chemical Reaction Parameter(K_r). From this figure it is noticed that, Concentration decreases when K_r increases.

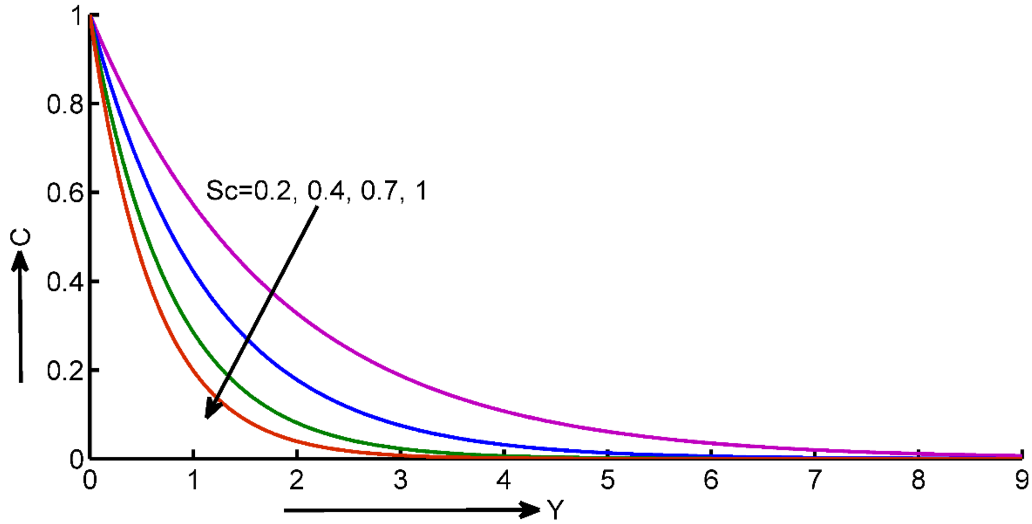

Figure 18: Effect of Schmidt number on Concentration

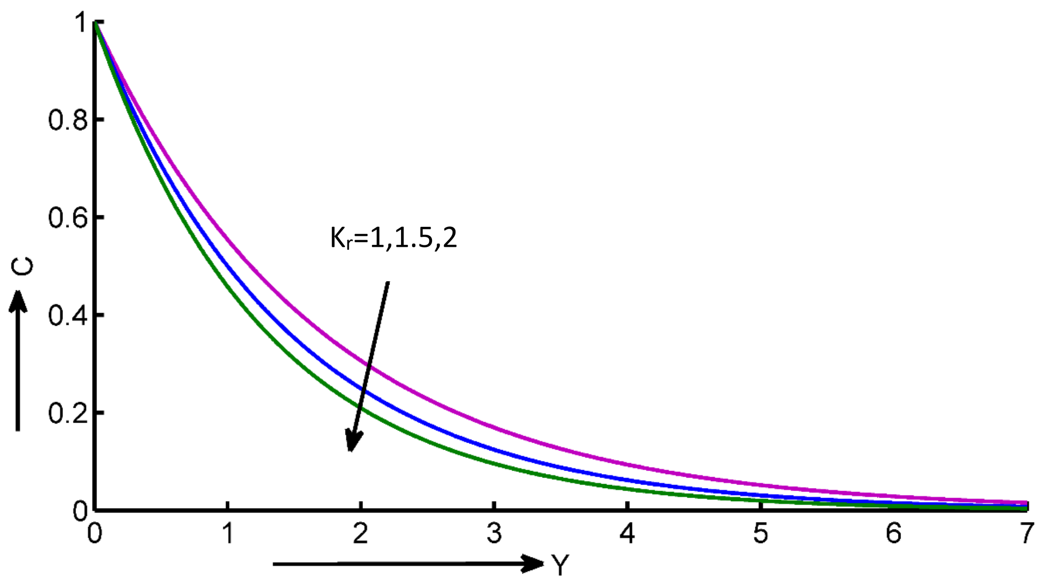

Figure 19: Effect of Chemical Reaction Parameter on Concentration

Table – 1, shows numerical values of skin-friction for various of Grashof number (Gr), modified Grashof number (Gm), Magnetic parameter (M), Permeability parameter (K_p) and Visco elastic parameter(λ) From table 1, we observe that the skin-friction decreases with an increase in Grashof number (Gr), modified Grashof number (Gm), Permeability parameter (K_p) where as it increases under the influence of magnetic parameter and visco elastic parameter.

Table-1:
Variations in Skin Friction

Gr	Gm	M	K_p	λ	τ
1.5	1	1	1	1	1.0513
2	1	1	1	1	0.9445
2.5	1	1	1	1	0.8376
3	1	1	1	1	0.7308
1	1	1	1	1	1.1582
1	1.2	1	1	1	1.0324
1	1.4	1	1	1	0.9067
1	2	1	1	1	0.5296
1	1	0.5	1	1	0.7715
1	1	1	1	1	1.1582
1	1	1.5	1	1	1.6434
1	1	2	1	1	2.1609
1	1	1	0.5	1	1.5568
1	1	1	1	1	1.1582
1	1	1	1.2	1	1.0808
1	1	1	1.6	1	0.9780
1	1	1	1	1	1.1582
1	1	1	1	2	1.1589
1	1	1	1	3	1.1595
1	1	1	1	4	1.1601

Table – 2 demonstrates the numerical values of Nusselt number (Nu) for different values of Prandtl number (Pr), Radiation parameter (R), Heat absorption parameter (S) and Radiation absorption parameter (R_1). From table 2, we notice that the Nusselt number increases with an increase in Prandtl number, Heat absorption parameter (S) and Radiation absorption parameter (R_1) where as it decreases under the influence of Radiation parameter (R).

Table-2:
Variations in Nusselt Number

Pr	R	S	R_1	Nu
0.11	1	2	1	1.7066
0.21	1	2	1	1.7806
0.31	1	2	1	1.8572
0.41	1	2	1	1.9362
0.71	1	2	1	2.1866
0.71	2	2	1	2.4001
0.71	3	2	1	0.6094
0.71	4	2	1	0.4769
0.71	5	2	1	0.4346
0.71	1	2.2	1	2.2268
0.71	1	2.4	1	2.2696
0.71	1	2.6	1	2.3137
0.71	1	2.8	1	2.3583
0.71	1	2	1	2.1866
0.71	1	2	2	2.9572
0.71	1	2	3	3.7278
0.71	1	2	4	4.4985

Table – 3 shows numerical values of Sherwood number (Sh) for the distinction values of Schmidt number (Sc), Chemical reaction parameter (K_r). It can be noticed from Table - 3 that the Sherwood number enhances with rising values of Schmidt number, and the Chemical reaction parameter.

Table-3:

Variations in Sherwood Number

Sc	Kr	Sh
0.1	1	0.3701
0.3	1	0.7178
0.5	1	0.9998
0.7	1	1.2567
0.22	1	0.5917
0.22	2	0.7823
0.22	3	0.9297
0.22	4	1.0544

5. CONCLUSIONS

In this problem, we have studied the multivariate convective heat and mass transfer past a vertical plate through a porous medium in conducting field. In the analysis of the flow the following conclusions are made:

1. Velocity increases with an increase in Grashof number and as well as modified Grashof number, Permeability parameter and Heat absorption parameter of the porous medium while, it decreases in the existence of magnetic parameter, Radiation parameter, Radiation absorption parameter, Schmidt number, Prandtl number and chemical reaction parameter.
2. Temperature increases in the presence of Schmidt number and Heat absorption parameter while it decreases in the presence of Radiation absorption parameter, Heat absorption parameter, Prandtl number, chemical reaction parameter and radiation parameter.
3. Concentration decreases with an increase in Schmidt number and chemical reaction parameter.
4. As significant decrease in seen in skin friction for Grashof number, modified Grashof number and permeability parameter while a increase is seen in the presence of magnetic parameter and visco elastic parameter.
5. The rate of heat transfer increases with Prandtl number, heat absorption parameter and Radiation absorption paremeter where as it decreases with an increase in radiation parameter.
6. The rate of mass transfer increases with Schmidt number and Chemical reaction parameter.

APPENDIX

$$M_1 = \mathrm{M}^2 + 1/\mathrm{Kp} \quad \alpha = \mathrm{R} - \mathrm{S}, \quad \mathrm{N}_1 = 1 - \lambda_1 (\mathrm{i}\omega) \quad \mathrm{N}_2 = \mathrm{M}_1 + \mathrm{i}\omega,$$

$$m_1 = \frac{ScV_0 + \sqrt{Sc^2V_0^2 + 4K_r Sc}}{2} \qquad m_2 = \frac{ScV_0 + \sqrt{Sc^2V_0^2 + 4Sc(K_r + i\omega)}}{2}$$

$$m_3 = \frac{\Pr V_0 + \sqrt{\Pr^2 V_0^{\,2} + 4\alpha}}{2} \qquad m_4 = \frac{\Pr V_0 + \sqrt{\Pr^2 V_0^{\,2} - 4(\alpha - \Pr(i\omega)}}{2}$$

$$m_5 = \frac{V_0 + \sqrt{V^2{}_0 + 4M_1}}{2} \qquad m_6 = \frac{V_0 + \sqrt{V^2{}_0 + 4N_1N_2}}{2}$$

$$b_1 = \frac{R_1}{m_1^2 - \Pr V_0 m_1 + \alpha} \qquad b_2 = 1 - b_1 \qquad b_3 = \frac{R_1}{m_2^2 - \Pr V_0 m_2 + (\alpha - \Pr(i\omega))}$$

$$b_4 = 1 - b_{31} \qquad b_5 = \frac{-(b_1 Gr + Gm)}{m_1^2 - V_0 m_1 - M_1} \qquad b_6 = \frac{-b_2 Gr}{m_3^2 - V_0 m_3 - M_1} \qquad b_7 = 1 - (b_5 + b_6)$$

$$b_8 = \frac{-(b_3 Gr + Gm)}{N_1 m_2^2 - V_0 m_2 - N_2} \qquad b_9 = \frac{-b_4 Gr}{N_1 m_4^2 - V_0 m_4 - N_2} \qquad b_{10} = 1 - (b_8 + b_9)$$

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