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Thermal Diffusion and Chemical Reaction Effects on Unsteady MHD Dusty Viscous Flow

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Abstract
We analysed the soret, radiation and chemical reaction effects on laminar convective flow of a dusty viscous fluid of non conducting walls in presence of transverse magnetic field. The governing equations of the flow are solved by Perturbation Technique. Further, the effects of all physical parameters on the velocities of fluid phase and dust phase, temperature and concentration are analysed and discussed through graphs.
Keywords: Dusty Fluid, Laminar flow, MHD, Chemical Reaction, Soret.

1. Introduction

In the recent years the attention of many researchers has been diverted to the study of dusty fluids. The Dusty fluid is combination of fluid and dust particles .The effect of dust particles on convective flow of fluids in presence of magnetic field and chemical reaction has vital importance in various areas like environmental pollution, cooling effects of air conditioners, magneto hydrodynamic generators, pumps, accelerators and flow meters. The study of dusty fluids has its applications also in petroleum and crude oil industries. The presence of dust particles in combustion MHD generators and their effect on performance of such devices leads to study of effect of volume fraction of dust particles in non conducting walls.

Many investigations on the flow of dusty viscous fluids in presence of various physical parameters have been carried out.Thermal diffusion and diffusion-thermo effects have been found to appreciably influence the flow field in free convection boundary layer over a vertical isothermal surface embedded in a porous medium was discussed by (Postelnicu ,2004). The main aspects occurring in the modeling of a chemical reaction in a porous medium are discussed by (Nield and Bejan ,1999). (Sandeep et. al 2014) discussed aligned Magnetic Field, Radiation, and Rotation Effects on Unsteady Hydromagnetic Free Convection Flow Past an Impulsively Moving Vertical Plate in a Porous Medium. (Saffman ,1962) has discussed the stability of laminar flow of a dusty gas in which dust particles are uniformly distributed. He formulated the basic equations of the dusty fluid. (Ezzat et al. ,2012) studied space approach to the hydro magnetic flow of a dusty fluid through a porous medium by using Laplace transformation technique. (Sandeep and Sugunamma ,2013) discussed the effect of inclined magnetic field on unsteady free convection flow of a dusty viscous fluid between two infinite flat plates filled by a porous medium. (Chakrabarti ,1974) analysed the boundary layer in a dusty gas. (Datta and Mishra,1972) have investigated the boundary layer flow of a dust fluid over a semi infinite flat plate .(Mohan Krishna et al. 2013) studied the Magnetic field and chemical reaction effects on convective flow of a dusty viscous fluid. In this study they used transverse magnetic field. (Anurag Dubey and Singh ,2012) discussed effect of dusty viscous fluid on unsteady laminar free convective flow through porous media with thermal diffusion. (Sandeep et al. ,2012) analysed the effect of radiation and chemical reaction on transient MHD free convective flow over a vertical plate through porous media. (Mishra et. al, 2005) have studied the two-dimensional transient conduction and radiation heat transfer with temperature dependent thermal conductivity. (Attia ,2006) studied the unsteady couettee flow with heat transfer on dusty fluid with variable physical properties.

Some researchers like (Anjali Devi and Jothimani,1996) have discussed the heat transfer in unsteady MHD oscillatory flow. Further, (Malashetty et al. ,2001) have investigated the convective magnetohydrodynamic two phase flow and heat transfer of a fluid in an inclined channel. (Palani and Ganesan ,2007) have discussed the heat transfer effects on dusty gas flow past a semi infinite inclined plate. (Ibrahimsaidu at al. ,2010) analysed the MHD effects on convective flow of dusty viscous fluid with volume fraction of dust particles in the absence of soret number, radiation, heat absorption and chemical reactions.

In continuation of this study and with the help of above cited papers we have studied the effect of soret number on laminar convective flow of a dusty viscous fluid with non conducting walls and volume fraction, radiation, chemical reaction along with transverse magneticfield are taken into consideration. The governing equations of the flow are solved by using Perturbation Technique. Further we analyzed effects of various physical parameters on the fluid phase as well as dust particles phase and also studied the effects on temperature and concentration with the help of graphs.

2. Mathematical Formulation

Consider an unsteady laminar flow of a dusty, incompressible, Newtonian, electrically conducting, viscous fluid of uniform cross section h, when one wall of the channel is fixed and the other is oscillating with time about a constant non-zero mean. Initially at $t \le 0$, the channel wall as well as the fluid is assumed to be at the same temperature T_0 and concentration C_0. When $t>0$, the temperature of the channel wall is instantaneously raises to T_w and concentration raises to C_w , which oscillates with time and is thereafter maintained constant. Let the fluid flow is along the x- axis at the fixed wall and y- axis is perpendicular to it. As per above assumptions the governing equations of the flow are given by

$$(1-\phi)\frac{\partial u}{\partial t}=(1-\phi)\left[\frac{-1}{\rho}\frac{\partial p}{\partial x}+\upsilon\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_0)+g\beta^*(\mathrm{C}-C_0)\right]$$

$$+\frac{KN_0}{\rho}(v-u)-\frac{KN_0\sigma\mu_c^2 H_0^2}{\rho}u \qquad 1)$$

$$N_0 m\frac{\partial v}{\partial t}=\phi\left[-\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial y^2}+\rho g\beta(T-T_0)+\rho g\beta^*(\mathrm{C}-C_0)\right]+KN_0(u-v) \qquad (2)$$

$$\frac{\partial T}{\partial t}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \qquad (3)$$

$$\frac{\partial C}{\partial t}=D_M\frac{\partial^2 C}{\partial y^2}-K_l(\mathrm{C}-C_0)+\mathrm{D}_T\frac{\partial^2 T}{\partial y^2} \qquad (4)$$

The boundary conditions of the problem are given by

$$\begin{aligned} &t\le 0; u(y,t)=\mathrm{v(y,t)}=0, && \mathrm{T(y,t)=C(y,t)=0\ for\ 0\le y\le 1}\\ &t>0; u(y,t)=\mathrm{v(y,t)}=0, && \mathrm{T(y,t)=C(y,t)=0}\ at\ y=0\\ &u(y,t)=\mathrm{v(y,t)}=1+\varepsilon e^{\mathrm{int}}, && \mathrm{T(y,t)=C(y,t)}=1+\varepsilon e^{\mathrm{int}}\ at\ y=1 \end{aligned} \qquad (5)$$

Where $\mathrm{u(y,t)}$ is the velocity of the fluid and $\mathrm{v(y,t)}$ is velocity of the dust particles, ϕ is the volume fraction of the dust particle, β is the volumetric coefficient of the thermal expansion, K is the Stoke's resistance coefficient, $\mathrm{N_0}$ is the number density of the dust particles, μ_{C} is the magnetic permeability, σ is the electrical conductivity of the fluid, m is the mass of each dust particle, T is the temperature, $\mathrm{T_0}$ is the initial temperature, $\mathrm{T_w}$ is the raised temperature, C is the concentration, $\mathrm{C_0}$ is the initial concentration, $\mathrm{C_w}$ is the raised concentration, $\mathrm{H_0}$ is the magnetic field induction, $\mathrm{C_p}$ is the specific heat at constant pressure, k is the thermal conductivity, K_l is chemical reaction parameter, D_M is the coefficient of chemical molecular diffusivity, D_T is the coefficient thermal diffusivity.

The Problem is now simplified by writing the equations in the following non dimensional form. Here the characteristic length is taken to be h and characteristic velocity is v.

$$x^*=\frac{x}{h}, y^*=\frac{y}{h}, p^*=\frac{h^2 p}{\rho\upsilon^2}, t^*=\frac{\upsilon t}{h^2}, u^*=\frac{uh}{\upsilon}, v^*=\frac{vh}{\upsilon}, T^*=\frac{T-T_0}{T_w-T_0}, C^*=\frac{C-C_0}{C_w-C_0} \qquad (6)$$

Substituting the above non dimensional parameters represented in equation (6) in the governing equations (1) – (4) then we get (after removing asterisks)

$$\frac{\partial u}{\partial t}=-\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial y^2}+GrT+GcC+\varepsilon_1(v-u)-\varepsilon_2 Mu \qquad (7)$$

$$f\frac{\partial v}{\partial t}=\phi\left[-\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial y^2}+GrT+GcC\right]+\beta(u-v) \qquad (8)$$

$$\frac{\partial T}{\partial t}=\frac{1}{\Pr}\left[(1+R)\frac{\partial^2 T}{\partial y^2}\right] \tag{9}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-K_1C+Sr\frac{\partial^2 T}{\partial y^2} \tag{10}$$

Where

$$Gr=\frac{g\beta(T_w-T_0)h^3}{\upsilon^2},Gc=\frac{g\beta^*(C_w-C_0)h^3}{\upsilon^2},\varepsilon_1=\frac{f}{\sigma_1(1-\phi)},\varepsilon_2=\frac{KN_0}{1-\phi},\sigma_1=\frac{m\upsilon}{Kh^2},Sr=\frac{D_T\rho C_p}{K},$$

$$R=\frac{16T_\infty^3\sigma^*}{3kk^*}M=\mu_c^2h^2H_0^2\frac{\sigma}{\mu},f=\frac{mN_0}{\rho}\beta=\frac{f}{\sigma_1},\Pr=\frac{k}{\mu C_p},Sc=\frac{\upsilon}{D_M},K_1=\frac{K_l h^2}{\upsilon}.$$

Here Gr is Thermal Garshof number and Gc is Mass Garshof number, M is Magnetic parameter, R is the Radiation parameter, f is Mass concentration of dust particles, β is Concentration resistance ratio, Sr is the soret number, $\Pr$ is Prandtal number, Sc is Schmidt number, K_1 is dimensionless chemical reaction parameter.

The Corresponding non-dimensional boundary conditions are:

$$\begin{aligned}
&t\le 0;u(y,t)=\mathrm{v(y,t)}=0, && \mathrm{T(y,t)=C(y,t)=0\ for\ 0\le y\le 1}\\
&t>0;u(y,t)=\mathrm{v(y,t)}=0, && \mathrm{T(y,t)=C(y,t)=0}\ at\ y=0\\
&u(y,t)=\mathrm{v(y,t)}=1+\varepsilon e^{\mathrm{int}}, && \mathrm{T(y,t)=C(y,t)}=1+\varepsilon e^{\mathrm{int}}\ at\ y=1
\end{aligned} \tag{11}$$

3. Solution of the Problem

To solve the equations (7-10) analytically by perturbation we use the below equations, which are introduced by Soundalgekar and Bhat

$$\begin{aligned}
u(y,t)&=u_0(y)+\varepsilon e^{\mathrm{int}}u_1(y)\\
v(y,t)&=v_0(y)+\varepsilon e^{\mathrm{int}}v_1(y)\\
T(y,t)&=T_0(y)+\varepsilon e^{\mathrm{int}}T_1(y)\\
C(y,t)&=C_0(y)+\varepsilon e^{\mathrm{int}}C_1(y)
\end{aligned} \tag{12}$$

Where $\frac{\partial p}{\partial x}=p$ is constant

After substituting equations (12) in equations (7) – (10), we obtain

$$u_0''(y)-(\varepsilon_1+\varepsilon_2M)u_0(y)+\varepsilon_1v_0(y)=p-GrT_0(y)-GcC_0(y) \tag{13}$$

$$u_1''(y)-(\varepsilon_1+\varepsilon_2M+in)u_1(y)+\varepsilon_1v_1(y)=-GrT_1(y)-GcC_1(y) \tag{14}$$

$$\beta v_0(y)=\beta u_0(y)+\phi\left[u_0''(y)-p+GrT_0(y)+GcC_0(y)\right] \tag{15}$$

$$(\beta+\mathrm{inf})v_1(y)=\beta u_1(y)+\phi\left[u_1''(y)+GrT_1(y)+GcC_1(y)\right] \tag{16}$$

$$(1+R)T_0''(y)=0 \tag{17}$$

$$(1+R)T_1''(y)-in\Pr T_1(y)=0 \tag{18}$$

$$C_0''(y)-Sc\,\mathrm{K}_1C_0(y)+\mathrm{Sc\,Sr}\,T_0''(y)=0 \tag{19}$$

$$C_1''(y)-Sc\left(K_1+in\right)C_1(y)+\mathrm{Sc\,Sr}\,T_1''(y)=0 \tag{20}$$

The corresponding boundary conditions becomes

$$\begin{aligned} &u_0(y)=u_1(y)=v_0(y)=v_1(y)=0, T_0(y)=T_1(y)=C_0(y)=C_1(y)=0\, at\ y=0 \\ &u_0(y)=u_1(y)=v_0(y)=v_1(y)=1, T_0(y)=T_1(y)=C_0(y)=C_1(y)=1\, at\ y=1 \end{aligned} \tag{21}$$

On solving equation (17) and (19) with the help of boundary conditions (21), we get

$$T_0(y)=y \tag{22}$$

$$C_0(y)=\frac{\sin h\, L_0 y}{\sin h\, L_0} \tag{23}$$

Substituting the equations (22) and (23) in equations (13) and (15), we get

$$u_0''(y)-(\varepsilon_1+\varepsilon_2 M)u_0(y)+\varepsilon_1 v_0(y)=p-Gry-B_1\sin h\, L_0 y \tag{24}$$

$$v_0(y)=u_0(y)+B_2\left[u_0''(y)-p+Gr\, y+B_1\sin h\, L_0 y\right] \tag{25}$$

Substituting equation (25) in (24), we obtain

$$u_0''(y)-A^2 u_0(y)=p-Gry-B_1\sin h\, L_0 y \tag{26}$$

Where

$$A^2=\frac{\varepsilon_2 M}{1+\varepsilon_1 B_2}$$

By solving equation (26) with the help of boundary conditions (21), we get

$$u_0(y)=B_5\, e^{-Ay}+B_4\, e^{Ay}-\frac{p}{A^2}+\frac{Gr}{A^2}\, y-B_6\sin h\, L_0 y \tag{27}$$

The second order partial derivative of $u_0(y)$ is given by

$$u_0''(y)=A^2\left(B_5\, e^{-Ay}+B_4\, e^{Ay}\right)-L_0^2 B_6\sinh L_0 y \tag{28}$$

Substituting the above equations (27) and (28) in equation (25), we obtain

$$v_0(y)=B_7\left[B_5\, e^{-Ay}+B_4\, e^{Ay}-\frac{p}{A^2}+\frac{Gr}{A^2}\, y\right]-B_8\sinh L_0 y \tag{29}$$

By solving equations (18) and (20) with the boundary conditions (21), we obtain

$$T_1(y)=\frac{\sinh L_1 y}{\sinh L_1} \tag{30}$$

$$C_1(y)=B_{10}\sinh L_2 y-B_9\sinh L_1 y \tag{31}$$

Substituting equations (30) and (31) in equations (14) and (16), we obtain

$$\begin{aligned} u_1''(y)-(\varepsilon_1+\varepsilon_2 M+in)u_1(y)+\varepsilon_1 v_1(y)=-Gr\frac{\sinh L_1 y}{\sinh L_1} \\ -Gc\left(B_{10}\sinh L_2 y-B_9\sinh L_1 y\right) \end{aligned} \tag{32}$$

$$v_1(y)=B_{11}u_1(y)+B_{12}\left[u_1''(y)+Gr\frac{\sinh L_1 y}{\sinh L_1}+Gc\left(B_{10}\sinh L_2 y-B_9\sinh L_1 y\right)\right] \tag{33}$$

Substituting equation (33) in equation (32), we obtain

$$u_1''(y)-B^2 u_1(y)=-B_{14}\sinh L_1 y-Gc\, B_{10}\sinh L_2 y \tag{34}$$

Where

$$B^2=\frac{\varepsilon_1+\varepsilon_2 M+in-\varepsilon_1 B_{11}}{1+\varepsilon_1 B_{12}}$$

On solving equation (34), with the help of boundary conditions (21), we get

$$u_1(y)=B_{17}\left(e^{By}-e^{-By}\right)-B_{15}\sinh L_1 y-B_{16}\sinh L_2 y \tag{35}$$

The second order partial derivative of $u_1(y)$ is

$$u_1''(y) = B^2 B_{17}\left(e^{By} - e^{-By}\right) - L_1^2 B_{15}\sinh L_1 y - L_2^2 B_{16}\sinh L_2 y \qquad (36)$$

Substituting the above equations (36) and (35) in equation (33), we obtain

$$v_1(y) = B_{20}\left(e^{By} - e^{-By}\right) + B_{19}\sinh L_2 y + B_{18}\sinh L_1 y \qquad (37)$$

Substituting the equations (27) and (35) in equation (12), we obtain the expression for velocity of the fluid phase as

$$\begin{aligned} u(y,t) = &\left(B_5 e^{-Ay} + B_4 e^{Ay} - \frac{p}{A^2} + \frac{Gr}{A^2} y - B_6 \sin h L_0 y \right) \\ &+ \varepsilon e^{\text{int}}\left[B_{17}\left(e^{By} - e^{-By}\right) - B_{15}\sinh L_1 y - B_{16}\sinh L_2 y \right] \end{aligned} \qquad (38)$$

Substituting the equations (29) and (37) in equation (12), we obtain expression for the dust phase as

$$\begin{aligned} v(y,t) = &\left[B_7\left(B_5 e^{-Ay} + B_4 e^{Ay} - \frac{p}{A^2} + \frac{Gr}{A^2} y \right) - B_8 \sinh L_0 y \right] + \\ &\varepsilon e^{\text{int}}\left[B_{20}\left(e^{By} - e^{-By}\right) + B_{19}\sinh L_2 y + B_{18}\sinh L_1 y \right] \end{aligned} \qquad (39)$$

Substituting the equations (22) and (30) in equation (12), we obtain the expression for temperature as

$$T(y,t) = y + \varepsilon e^{\text{int}}\left(\frac{\sinh L_1 y}{\sinh L_1} \right) \qquad (40)$$

Substituting the equations (23) and (31) in equation (12), we get we obtain the expression for concentration as

$$C(y,t) = \frac{\sin h L_0 y}{\sin h L_0} + \varepsilon e^{\text{int}}\left(B_{10}\sinh L_2 y - B_9 \sinh L_1 y \right) \qquad (41)$$

Appendix:

$$L_0 = \sqrt{ScK_1}\,, L_1 = \frac{in\Pr}{1+R}, L_2 = \sqrt{(K_1 + in)Sc}$$

$$B_1 = \frac{Gc}{\sinh L_0}, B_2 = \frac{\phi}{\beta}, B_3 = \frac{p}{A^2} - \frac{Gr}{A^2} + \frac{B_1 \sinh L_0}{L_0^2 - A^2}$$

$$B_4 = \frac{1 + B_3 - \frac{p}{A^2} e^{-A}}{e^{A} - e^{-A}}, B_5 = \frac{p}{A^2} - B_4,\ B_6 = \frac{B_1}{L_0^2 - A^2}, B_7 = 1 + B_2 A^2$$

$$B_8 = B_6 + B_2 L_0^2 B_6 - B_1 B_2,\ B_9 = \frac{Sc\, SrL_1^2}{\left(L_1^2 - L_2\right)\sinh L_1},\ B_{10} = \frac{1 + B_9 \sinh L_1}{\sinh L_2}$$

$$B_{11} = \frac{\beta}{\beta + \inf}, B_{12} = \frac{\phi}{\beta + \inf}, B_{13} = \frac{Gr}{\sinh L_1}, B_{14} = B_{13} + Gc\, B_9$$

$$B_{15} = \frac{B_{14}}{L_1^2 - B^2}, B_{16} = \frac{Gc\, B_{10}}{L_2^2 - B^2}, B_{17} = \frac{1 + B_{15}\sinh L_1 + B_{16}\sinh L_2}{e^{B} - e^{-B}}$$

$$B_{18} = B_{12}B_{13} - B_{11}B_{15} - B_9 B_{12} Gc - L_1^2 B_{12} B_{15},\ B_{19} = -B_{11}B_{16} + B_{10}B_{12}Gc - L_2^2 B_{12}B_{16}$$

$$B_{20} = B_{17}\left(B_{11} + B^2 B_{11}\right)$$

4. Results and Discussion

In order to study the behaviour of fluid and dust phase velocities, temperature and concentration profiles, a comprehensive numerical computation is carried out for various values of the physical parameters that describe the flow characteristics discussed through graphs.

Fig.1 depicts the variation in velocity profiles for different values of magnetic field parameter (M). It is clear that increase in magnetic field causes the increase in dust phase velocity and decrease in velocity of the fluid phase. In general increase in magnetic field causes the decrease in fluid velocity, because of induced forces acting opposite to flow of the fluid. Fig.2 shows effect of mass concentration of dust particles (f) on the flow field. It is clear that increase in mass concentration decreases the velocity profiles of both fluid and dust phase. Fig.3 shows effect of soret number (Sr) on the velocity of the fluid. It is noticed that increase in soret number increases the velocity profiles of both fluid and dust phase.Fig.4 represents the effect of mass Grashof number (Gc) on velocity profiles of fluid and dust phase. It is understood that an increase in the mass Grashof number (Gc) causes the increase in velocity of fluid and dust phase.From Fig.5 it is easy to see that an increase Radiation parameter (R) causes the increase in velocity of fluidphase as well as dust phase.Fig.6 represents the effect of volume fraction of dust particles (ϕ) on velocity profiles of fluid and dust phase. It is understood that an increase in the causes the decrease in velocity of fluid and but increase in the dust phase.

Velocity profiles for different values of thermal Grashof number (Gr) is shown in figure 7. It is evident that an increase in Grashof number leads to increase in the velocity of the fluid phase, but it is reversed in dust phase after showing some increment initially. The effect on velocity profiles for different values of Prandtl number (Pr) are shown in figure 8.It is evident that an increase in Prandtl number causes decrease in fluid phase velocity. But it helps to the dust phase velocity to decrease. Figure 9 represents velocity profiles for different values of Schmidt number (Sc). It is clear that the velocity of fluid and dust phases decreases with an increase in Schmidt number. From fig.10 it is clear that the increase in chemical reaction parameter causes the decrease in both fluid and dust phase velocities. The effect of time (t) on velocity profiles can be seen fig.11 and it is clear that an increase in time causes the decrease in fluid phase as well as dust phase velocities.

The variations in temperature for different values of Radiation parameter (R), Prandtal number (Pr) and time (t) are shown in Figs. 12, 13 and 14 respectively. Fig.12 depicts the variation of temperature for different values of Radiation parameter and it is observed that increase in this parameter causes the increase in dusty fluid temperature. Fig.13 shows that increase in prandtal number causes the decrease in dusty fluid's temperature. From fig.14 it is evident that fluid temperature decreases with an increase in time.

It is interesting point to note from fig.15 that the concentration profiles increases with an increase in soret number (Sr).Fig.16 shows that an increase in prandtal number (Pr) causes the decrease in concentration. An increase in radiation parameter (R) decreases the concentration of the dusty fluid. This we can see in fig.17. From fig.18 one can observe a fact that an increase in the Schmidt number (Sc) decreases the concentration profiles of dusty fluid.

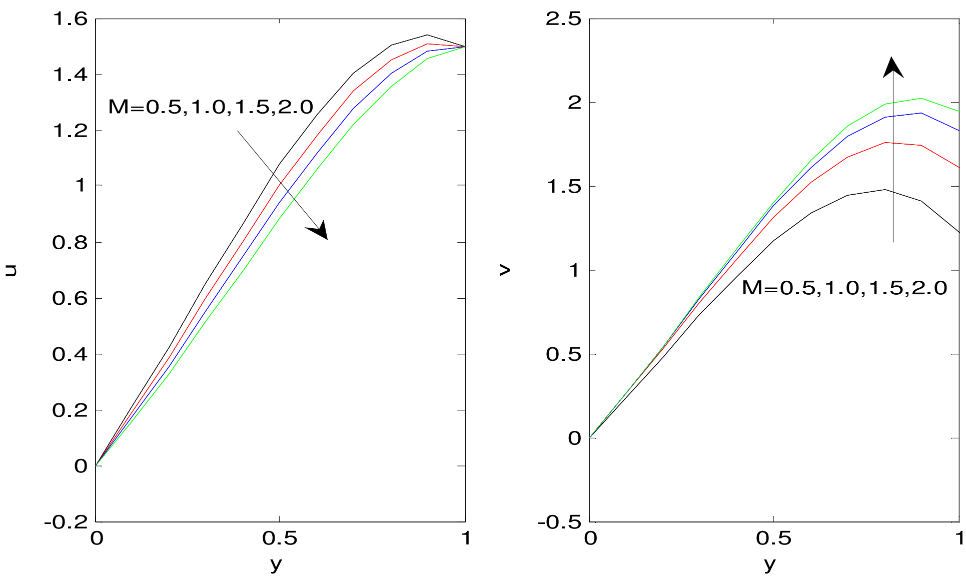

Figure 1: velocity profiles for different values of M
When Pr =0.71, Sr =2, Gr =5, Gc =5, R =2 , Sc =2, K_1 =0.5, ϕ =0.5, f =0.5.

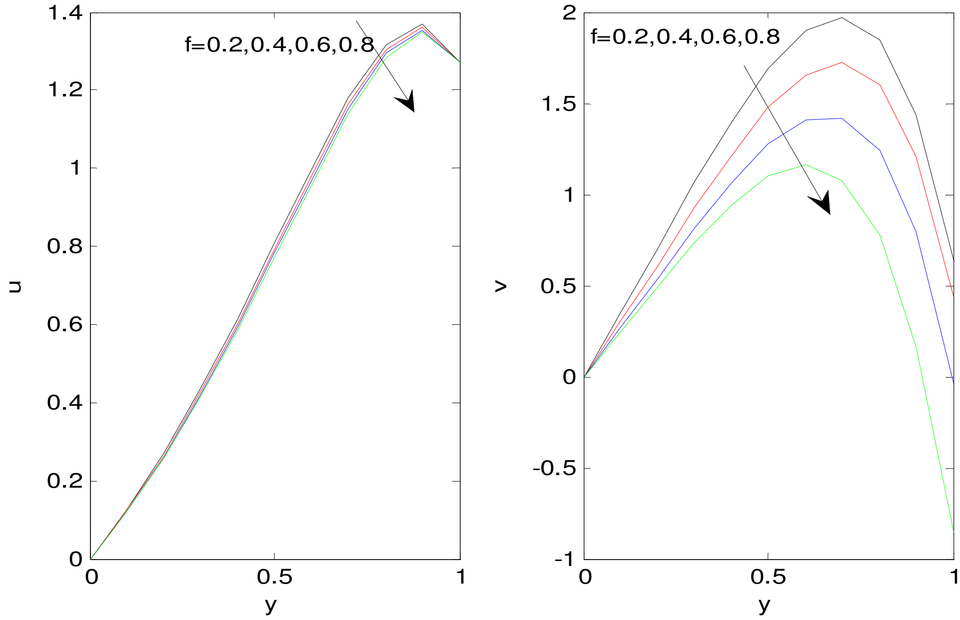

Figure 2: velocity profiles for different values of f

When $\Pr$ =0.71, Sr =2, Gr =5, Gc =5, R =2 , Sc =2, K_1 =0.5, ϕ =0.5, f =0.5.

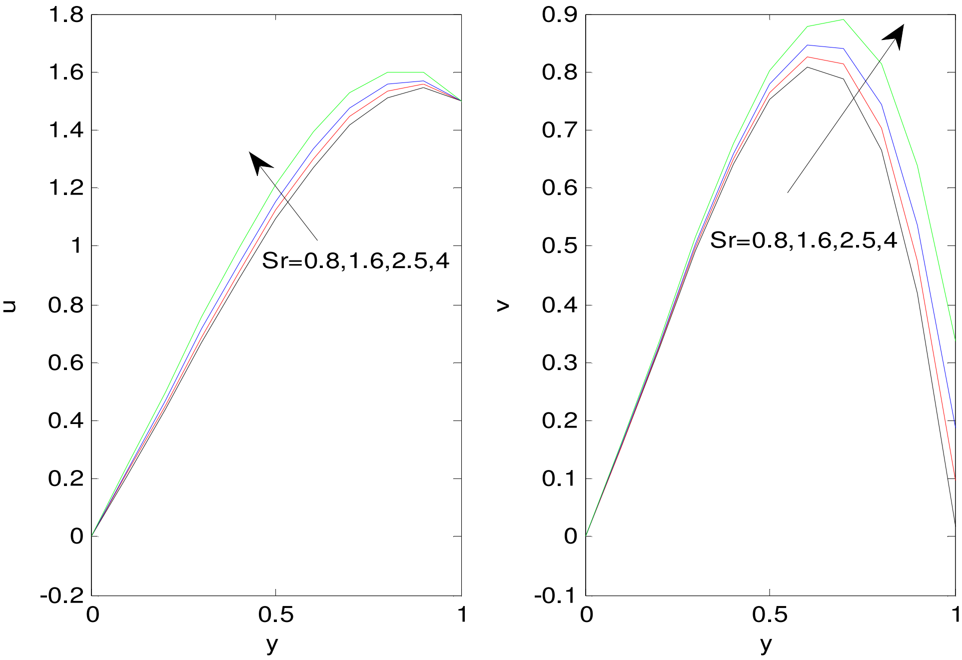

Figure 3: velocity profiles for different values of Sr

When $\Pr$ =0.71, M =2, Gr =5, Gc =5, R =2 , Sc =2, K_1 =0.5, ϕ =0.5, f =0.5.

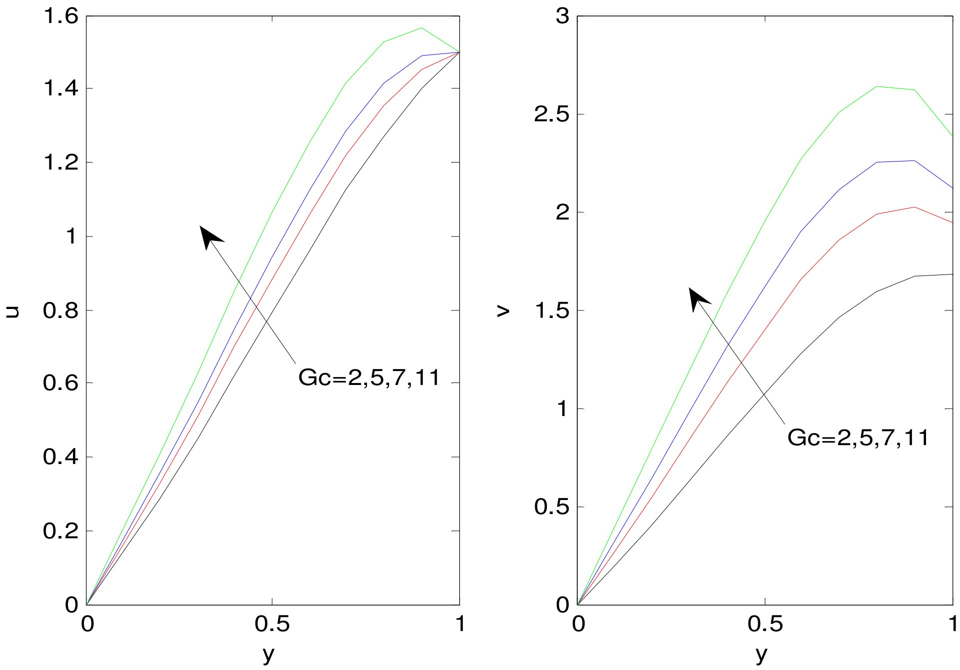

Figure 4: velocity profiles for different values of Gc
When $\Pr = 0.71, M = 2, Gr = 5, Sr = 2, R = 2, Sc = 2, K_1 = 0.5, \phi = 0.5, f = 0.5$.

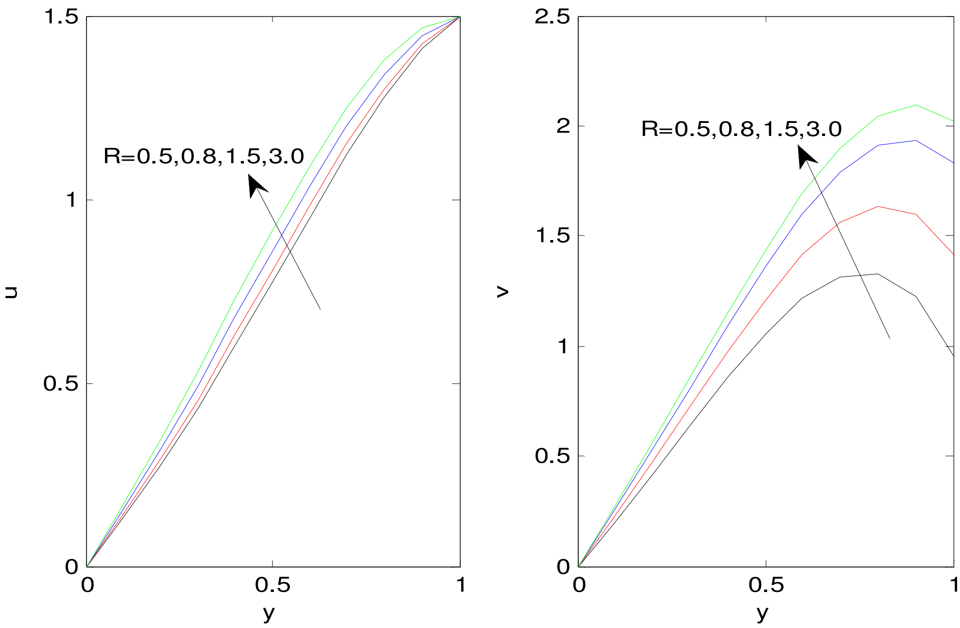

Figure 5: velocity profiles for different values of R
When $\Pr = 0.71, M = 2, Gr = 5, Gc = 5, Sr = 2, Sc = 2, K_1 = 0.5, \phi = 0.5, f = 0.5$.

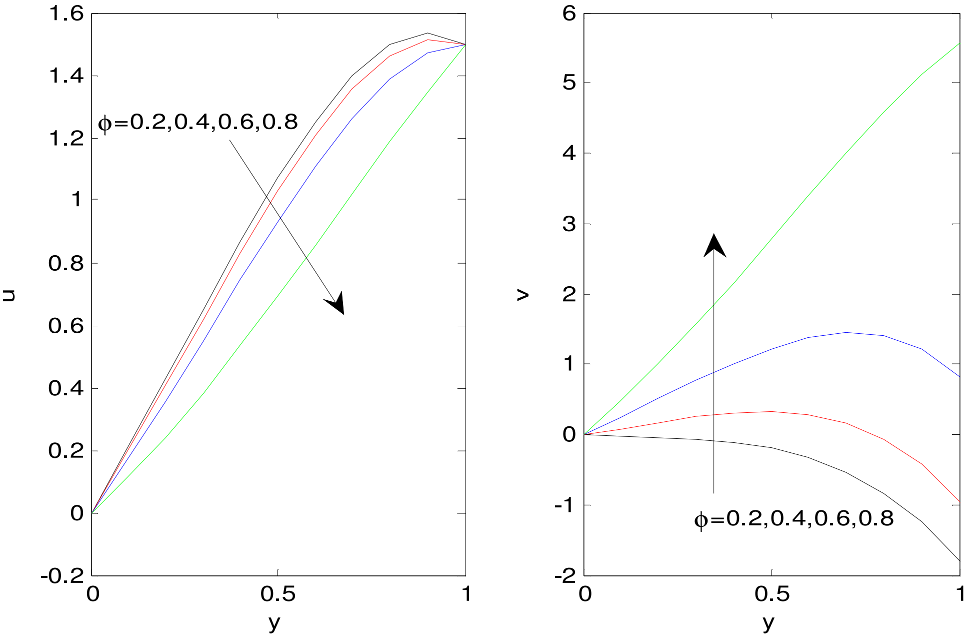

Figure 6: velocity profiles for different values of ϕ

When $\Pr=0.71, M=2, Gr=5, Gc=5, Sr=2, Sc=2, K_1=0.5, R=2, f=0.5$.

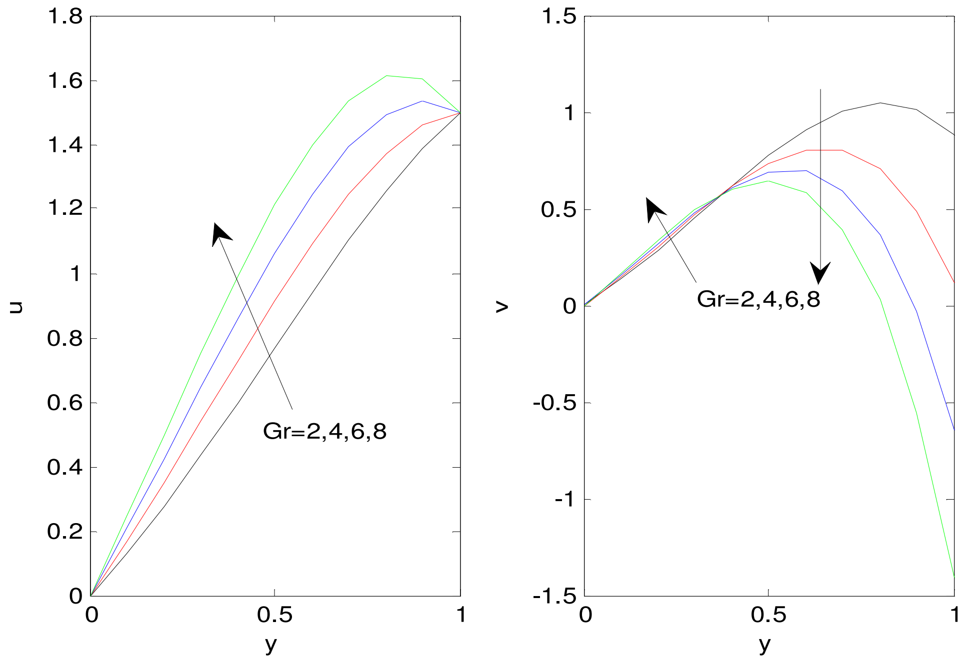

Figure 7: velocity profiles for different values of Gr

When $\Pr=0.71, M=2, \phi=0.5, Gc=5, Sr=2, Sc=2, K_1=0.5, R=2, f=0.5$.

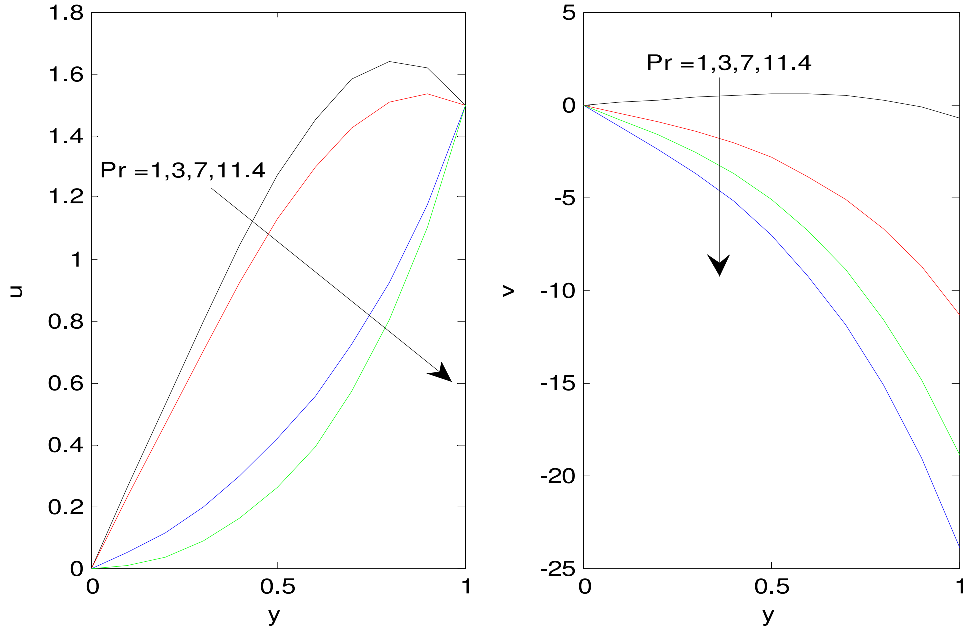

Figure 8: velocity profiles for different values of $\Pr$
When Gc =0.71, M =2, ϕ=0.5, Gc =5, Sr =2 , Sc =2, K_1 =0.5, R =2, f =0.5.

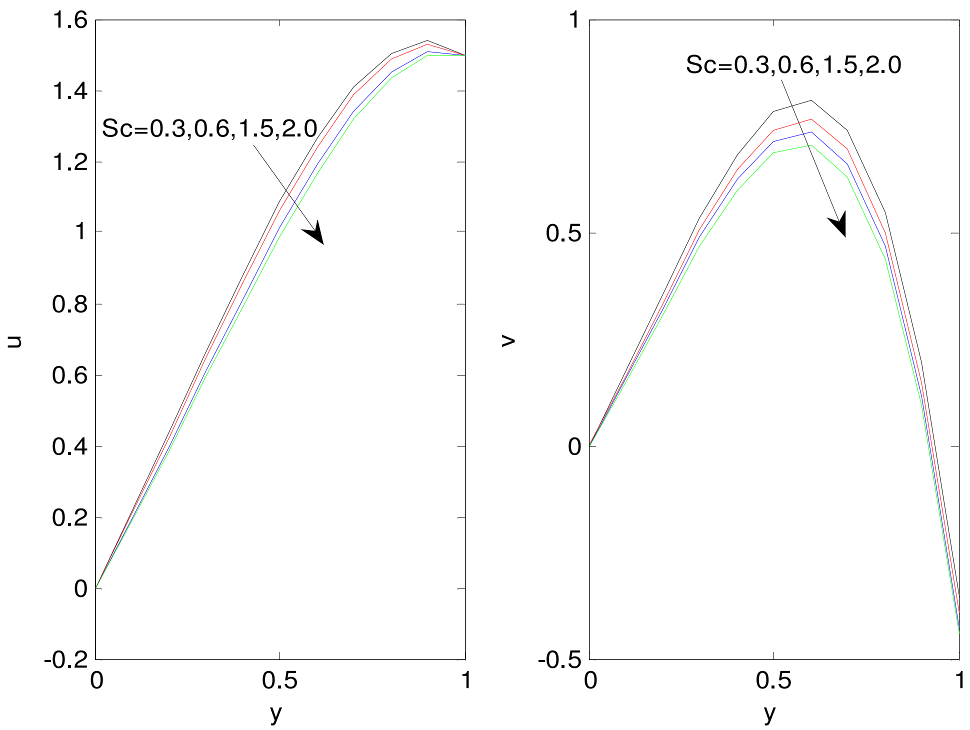

Figure 9: velocity profiles for different values of Sc
When $\Pr$ =0.71 Gc =0.71, M =2, ϕ=0.5, Gc =5, Sr =2 , K_1 =0.5, R =2, f =0.5.

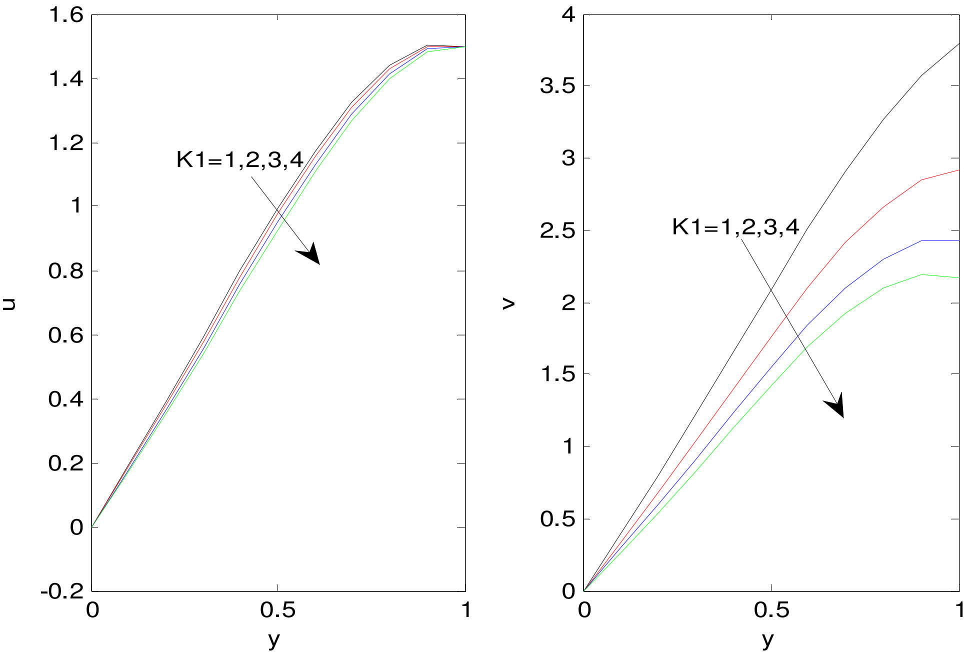

Figure 10: velocity profiles for different values of K_1

When $\Pr=0.71\, Gc=0.71, M=2, \phi=0.5, Gc=5, Sr=2, Sc=2, R=2, f=0.5$.

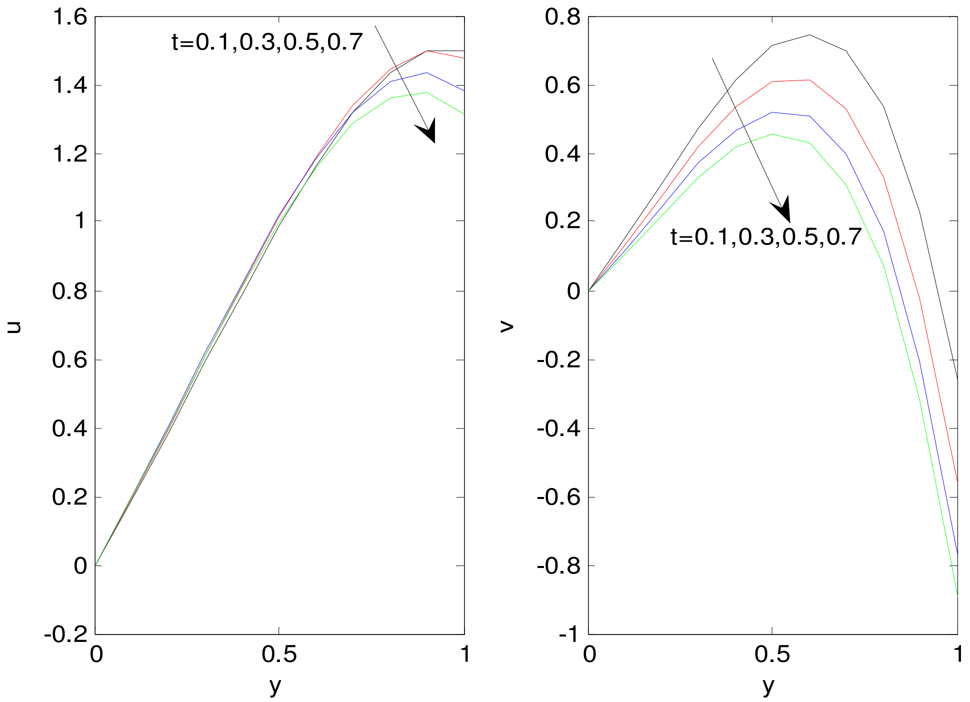

Figure 11: velocity profiles for different values of t

When $\Pr=0.71\, Gc=0.71, M=2, \phi=0.5, Gc=5, Sr=2, Sc=2, R=2, f=0.5$.

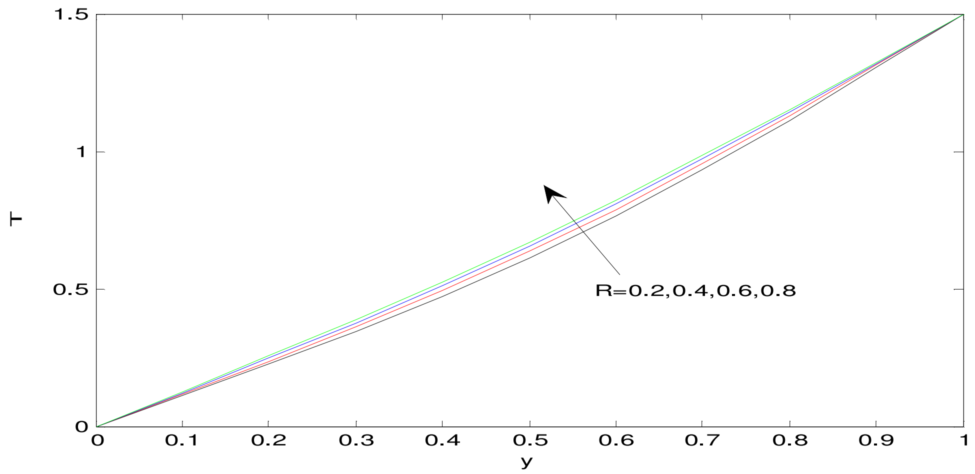

Figure 12: Temperature profiles for different values of R When $\Pr = 0.71$, $t = 0.1$.

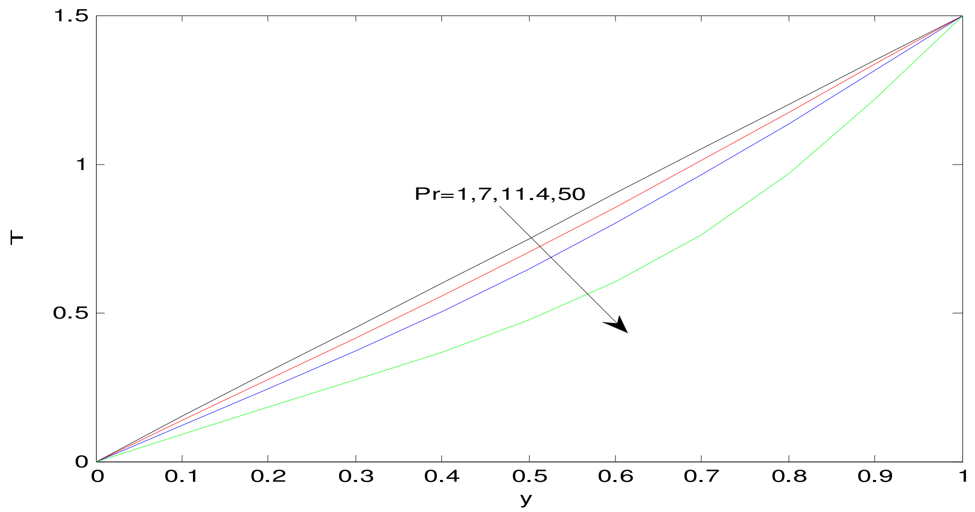

Figure 13: Temperature profiles for different values of R When $R = 2$, $t = 0.1$.

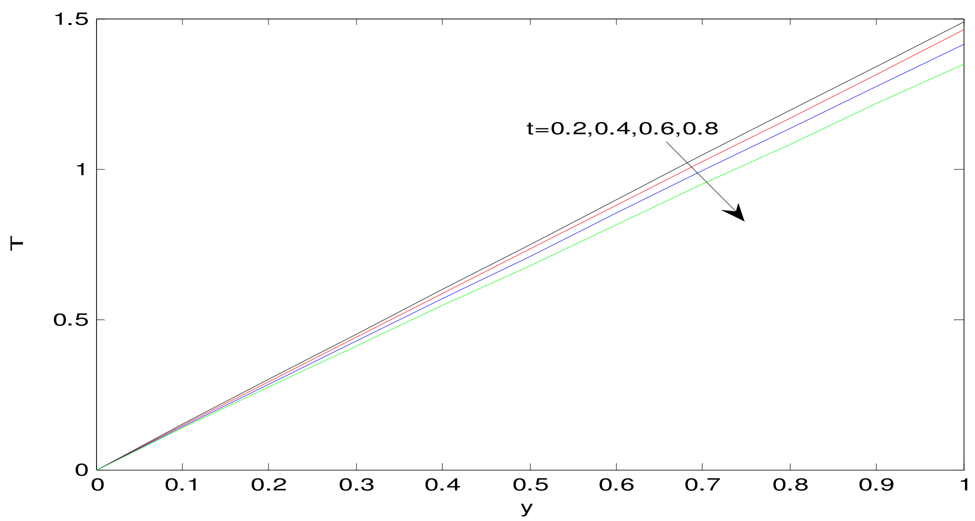

Figure 14: Temperature profiles for different values of R When $\Pr = 0.71$, $R = 2$.

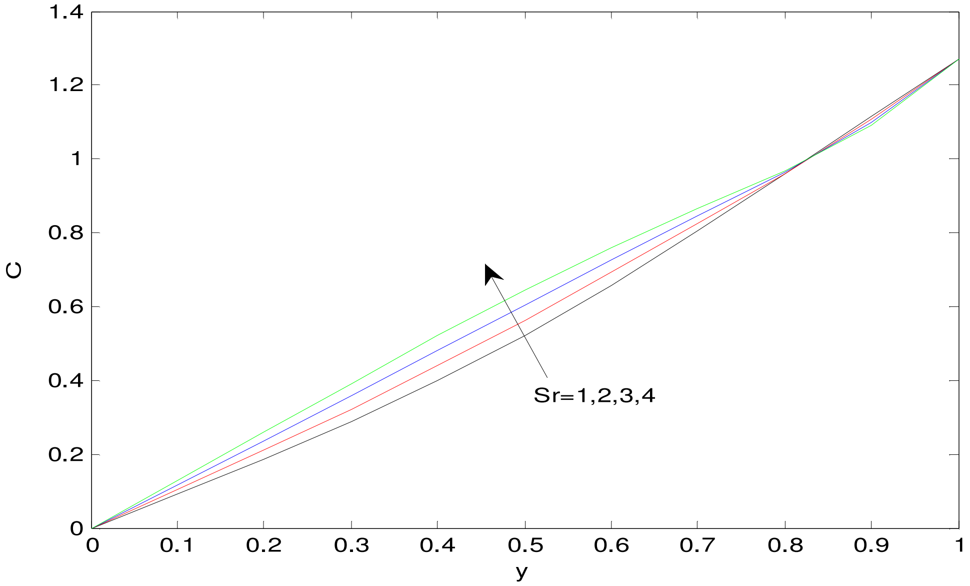

Figure 15: Concentration profiles for different values of Sr
When $\Pr$ =0.71, t =0.1, R =2, Sc =2, K_1 =0.5.

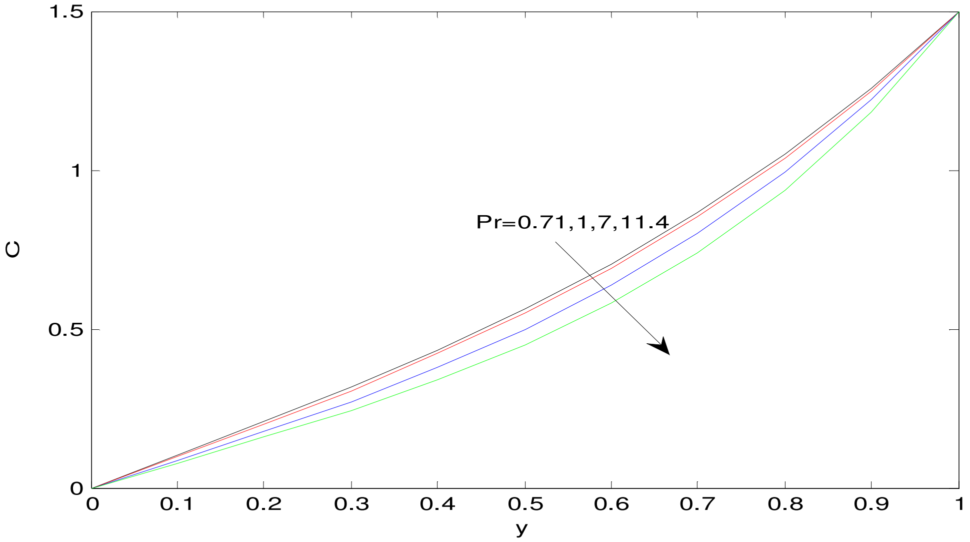

Figure 16: Concentration profiles for different values of $\Pr$
When R =2, t =0.1, Sr =2, Sc =2, K_1 =0.5.

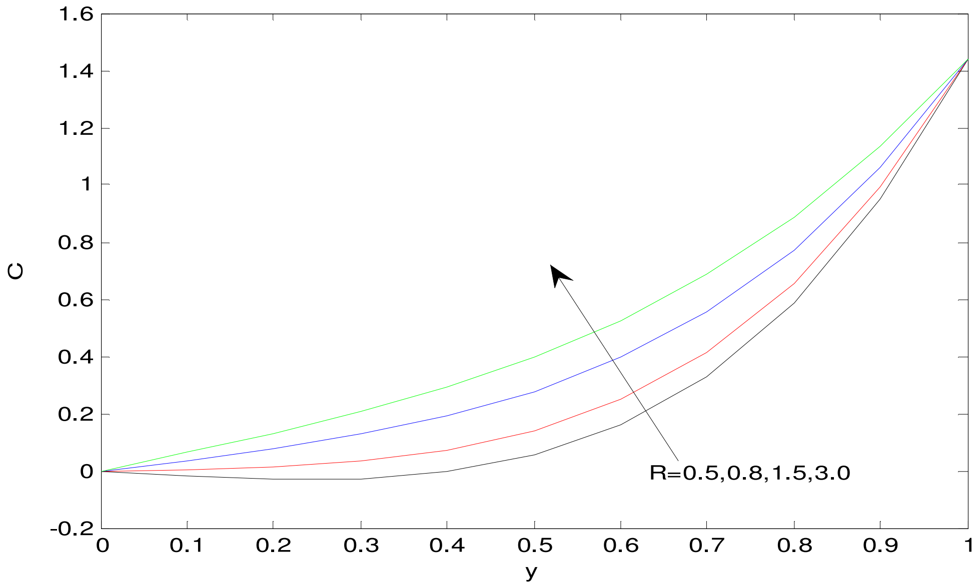

Figure 17: Concentration profiles for different values of R
When $\Pr = 0.71$, $t = 0.1$, $Sr = 2$, $Sc = 2$, $K_1 = 0.5$.

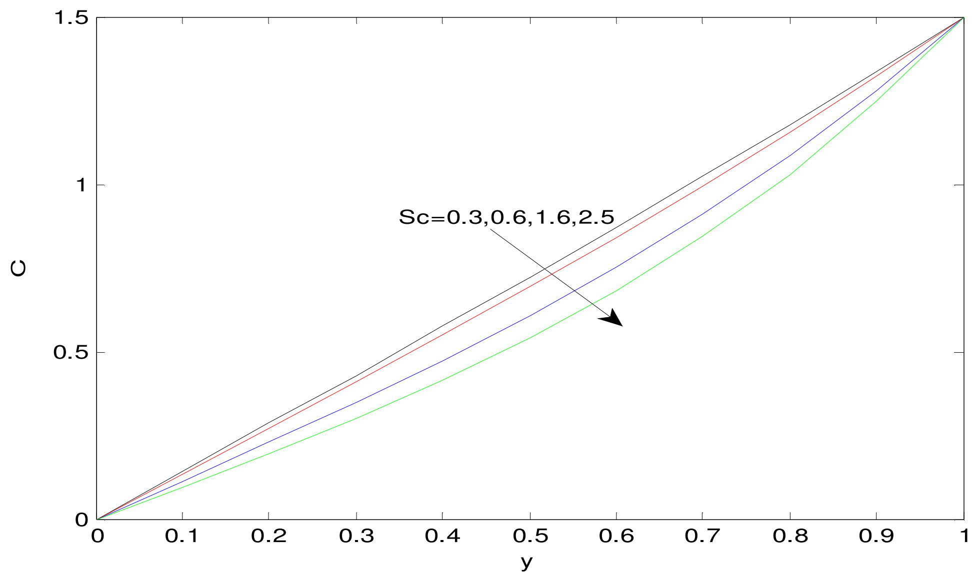

Figure 18: Concentration profiles for different values of Sc
When $\Pr = 0.71$, $t = 0.1$, $Sr = 2$, $R = 2$, $K_1 = 0.5$.

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