Numerical Solution of MHD Heat and Mass Transfer of Power- Law fluids

Manisha Patel and M.G.Timol

Abstract— **A time-independent 3-D MHD forced convection and mass transfer flow past a semi-infinite flat surface in the presence of heat generation is discussed power-law fluids .The partial differential equations of the flow problem are reduced to a system of an ODE using similarity techniques. The transformed equations of similarity are then solved numerically and the results are presented graphically.**

Index Terms— **convection, mass transfer, non-Newtonian, power - law fluids, similarity transformation.**

MSC 2010 Codes **—34BXX, 76XX**

Nomenclature

u , v, w- Stream Velocity in X, Y, Z directions respectively
τ_{ij} - stress tensor
U, W- Main stream velocities in X and Z directions
e_{ij} - Rate of strain
τ_{yx} - stress tensor in the direction of X-axis normal to Y-axis
τ_{yz} - stress tensor in the direction of Z-axis normal to Y-axis
μ - Viscosity, t- time
m- Physical constant
n- Flow behavior indices
B_y - Imposed magnetic field
T_w – Variable Wall temperature
T_∞- ambient fluid temperature
C_w- Variable Wall concentration
C_∞- ambient fluid concentration
MHD- Magneto hydro dynemics
S_1,S_2 –Magnetic field strength
R_e - Reynolds number
k-Thermal conductivity
T- Temperature
C-Concentration
D- Diffusion coefficient
ρ -field density
C_p-Specific heat
ψ - Stream function
η - Variable of similarity
ξ - Function of x ; unknown
f_1 , f_2 ,g_1,g_2- Functions of similarity
P_r- Prandtl number
Sc- generalised Schmidt number
M- Magnetic parameter - $\dfrac{\sigma B_0^{\,2}}{\rho}$
V- Velocity
B- Magnetic induction

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I. INTRODUCTION

NOWADAYS, due to the renascence interest in study of Magneto hydrodynamic boundary layer flow, it is important to extend many of the viscous hydrodynamic solutions to include the effect of magnetic field for those cases of electrically conducted viscous fluid. The Magneto hydrodynamic boundary layer flow past a flat plate was discussed (probably first time) by Rossow (1957) in detailed. He had considered two cases namely, magnetic fluid is fixed relative to fluid and magnetic field is fixed relative to play. Heat transfer of this case was discussed by Rossow (1957), Greenspan and Carrier (1959), and Afzal (1972). Carrier et al. have considered the effect of a longitudinal magnetic field whereas Rossow has studied transverse magnetic field effect on the velocity and the temperature distribution but all these cases are limited to the geometry of 2-D flows.

Heat and mass transfer through a vertical plate having many interesting applications such as cooling systems, heat exchangers , thermal power and electronic equipment etc.. Here the buoyancy force induced by the temperature difference between the flow of fluid and the plate affects the heat transfer rate by either opposing or assisting the forced flow. On the other side many industrial fluids such as polymer melt, molten plastic, some slurries exhibits the behaviour of non-Newtonian fluid, and hence the study of heat and mass transfer for non-Newtonian fluids is of more practical important.

From the Newton's law of viscosity, the shearing stress and the rate of change in strain are directly proportional through a proportionality constant called viscosity;

$$\tau = \mu \frac{\partial u}{\partial y}. \tag{1}$$

A fluid that obeys this law of viscosity, and which is characterized by the presence of a shear stresses that vary linearly with velocity gradients indicative of local rates of strain / deformation are called Newtonian e.g. water, air. A fluid that does not obey it is called non–Newtonian. The non-linear relationship between shearing stresses and rates of strain is there in non-Newtonian fluids e.g. drilling mud, saliva ,molten plastic etc.

One particular non-Newtonian model which has been widely studied uses the following nonlinear relationship between the stress component τ_{ij} and the component of rate of deformation e_{ij}.

$$\tau_{ij} = \mu \left| \left(\sum_{m=1}^{3} \sum_{l=1}^{3} e_{ml} \quad e_{lm} \right)^{\frac{1}{2}} \right|^{n-1} e_{ij}$$

where m and n are called the physical constant and flow behaviour indices respectively. If the value of n is less than 1, the fluid is called pseudo plastic/ shear thinning fluid and if n is greater than 1, it is called dilatants/shear thickning fluid since the apparent viscosity increase or decreases with the increase shear rate according as n is greater than 1 or n is less than 1, if n is equal to 1 the fluid will be Newtonian.

Various paper in this field have been studied by many authors. Hansen with his co-worker (1956, 1967, 1968) are probably first to derive similarity analysis for 3-D boundary layer flows of Newtonian fluids systematically. The main concept of boundary layer was applied to power-law fluids by Schowalter (1960). Timol et al.(1987) have developed the equations of motion for three-dimensional, incompressible viscous Newtonian fluid flowing over a semi-infinite plate under the influence of a magnetic field and a pressure gradient .They have used group theoretic method to obtained similarity solutions. Similarity solutions of 3-D MHD boundary layer flows of a class of non-Newtonian fluids were investigated by Timol and Kalthia (1986) and Patel and Timol (2008). Desai and Timol (1998) had derived equations for MHD non-Newtonian fluids. They had applied group theoretic technique and then solve similarity equations numerically. Attai (2003) studied the equation for hydro magnetic stagnation point flow for Newtonian fluids with heat transfer over a permeable surface. He applied quasi-linearization technique to convert equation of momentum in linear form, and solved the equation of momentum and energy numerically using finite difference. Patel and Timol (2009) gave Numerical analysis for steady 2-D MHD forward stagnation-point flow using Crocco independent variables with Galerkin's method. A steady 2-D MHD free convection and mass transfer flow past and inclined semi-infinite surface in the presence of heat generation has been discusse and solved numerically using 6th order Runge-Kutta integration scheme by Alam et al. (2006). Chaim (1999) has studied a steady 2-D incompressible flow of a conducting power-law fluid past a flat surface in the presence of transverse magnetic field with the influence of a pressure gradient. He had use Crocco variables to convert the transformed similarity equations into a different form and then find a numerical solution. Jumeh and Majumdar (2000) studied natural convectin coupled heat and mass transfer for non-Newtonian power-law fluids over a vertical flat surface embeded in a porous mediam saturated by a fluid. They have been applied similarity transformation on the boundary layer equations and then solved the similarity equations using finite difference method.

Considering the presence of non-uniform magnetic field and the effect of Hall currents, the forced convective heat and mass along a semi infinite flat surface is investigated for power law fluidst by Affify et al. (2005). But the stress strain relationship for power law fluids taken by them in equations of momentum is incorrect so the error accoured throughout in the paper. In the present paper, the general the stress strain relationship for power law fluid is derived first and similarity analysis is obtained for 3-D steady MHD forced convective heat and mass transfer of power law fluid past a semi infinite flat surface.

II. GENERAL STRESS-STRAIN RELATIONSHIP FOR POWER-LAW FLUID

The familiar model of power-law fluid is phenomenological purely; It is very much useful in describing a great number of non-Newtonian fluids. It can be represented in the mathematical form as;

$$\overline{\overline{\tau}} = -\left\{ m \left| \frac{1}{2} \overline{\overline{\Delta}} : \overline{\overline{\Delta}} \right|^{\frac{n-1}{2}} \right\} \overline{\overline{\Delta}}$$

where the physical constant and the flow indices i.e. m and n are differ for different fluids and can be determined experimentally.

Now,

$$\overline{\overline{\Delta}}\,\overline{\overline{\Delta}} = \sum_{l=1}^{3} \sum_{m=1}^{3} e_{lm} \; e_{ml}$$

$$\overline{\overline{\Delta}} = e_{ij} \text{ and } \overline{\overline{\tau}} = \tau_{ij}$$

Hence ;

$$\overline{\overline{\Delta}} : \overline{\overline{\Delta}} = (e_{11})^2 + (e_{22})^2 + (e_{33})^2 + 2(e_{12})^2 + 2(e_{23})^2 + 2(e_{13})^2$$

where;

$$e_{11} = \frac{\partial u'}{\partial x'} + \frac{\partial u'}{\partial x'}; \; e_{22} = \frac{\partial v'}{\partial y'} + \frac{\partial v'}{\partial y'}; \; e_{33} = \frac{\partial w'}{\partial z'} + \frac{\partial w'}{\partial z'};$$

$$e_{12} = \frac{\partial u'}{\partial y'} + \frac{\partial v'}{\partial x'} = e_{21} \ldots.etc$$

and

$$\tau_{ij} \Rightarrow \tau'_{x'x'}, \quad \tau'_{y'y'}, \quad \tau'_{z'z'}, \; \tau'_{x'y'} \ldots..etc$$

$$e_{ij} \Rightarrow e_{x'x'}, \quad e_{y'y'}, \quad e_{z'z'}, \; e_{x'y'} \ldots..etc$$

Hence we get,

$\delta^m \quad [\quad 1 \quad 1 \quad 1 \quad \frac{1}{\delta^2} \quad \frac{1}{\delta^2}$

$$\tau'_{x'x'} = -m\left\{\left(\frac{1}{2}\right)^{\frac{n-1}{2}}\left[4\left(\frac{\partial u'}{\partial x'}\right)^2 + 4\left(\frac{\partial v'}{\partial y'}\right)^2 + 4\left(\frac{\partial w'}{\partial z'}\right)^2 + 2\left(\frac{\partial u'}{\partial y'} + \frac{\partial v'}{\partial x'}\right)^2 + 2\left(\frac{\partial v'}{\partial z'} + \frac{\partial w'}{\partial y'}\right)^2 + 2\left(\frac{\partial v'}{\partial z'} + \frac{\partial w'}{\partial x'}\right)^2\right]^{\frac{n-1}{2}} 2\frac{\partial u'}{\partial x'}\right\}$$

$1 \qquad 1]$

$\delta^m \quad [\quad 1 \quad 1 \quad 1 \quad \frac{1}{\delta^2} \quad \frac{1}{\delta^2} \quad 1$

$$\tau'_{y'x'} = -m\left\{\left(\frac{1}{2}\right)^{\frac{n-1}{2}}\left[4\left(\frac{\partial u'}{\partial x'}\right)^2 + 4\left(\frac{\partial v'}{\partial y'}\right)^2 + 4\left(\frac{\partial w'}{\partial z'}\right)^2 + 2\left(\frac{\partial u'}{\partial y'} + \frac{\partial v'}{\partial x'}\right)^2 + 2\left(\frac{\partial v'}{\partial z'} + \frac{\partial w'}{\partial y'}\right)^2 + 2\left(\frac{\partial u'}{\partial z'} + \frac{\partial w'}{\partial x'}\right)^2\right]^{\frac{n-1}{2}} \left(\frac{\partial u'}{\partial y'} + 2\frac{\partial v'}{\partial x'}\right)\right\}$$

$\frac{1}{\delta}\delta]$

$\delta^m \quad [\quad 1 \quad 1 \quad 1 \quad \frac{1}{\delta^2} \quad \frac{1}{\delta^2} \quad 1$

$$\tau'_{y'z'} = -m\left\{\left(\frac{1}{2}\right)^{\frac{n-1}{2}}\left[4\left(\frac{\partial u'}{\partial x'}\right)^2 + 4\left(\frac{\partial v'}{\partial y'}\right)^2 + 4\left(\frac{\partial w'}{\partial z'}\right)^2 + 2\left(\frac{\partial u'}{\partial y'} + \frac{\partial v'}{\partial x'}\right)^2 + 2\left(\frac{\partial v'}{\partial z'} + \frac{\partial w'}{\partial y'}\right)^2 + 2\left(\frac{\partial u'}{\partial y'} + \frac{\partial w'}{\partial x'}\right)^2\right]^{\frac{n-1}{2}} \left(\frac{\partial w'}{\partial y'} + \frac{\partial v'}{\partial z'}\right)\right\}$$

$\frac{1}{\delta^2}\ \delta]$

and similarity other components of τ_{ij} can be derived.

We assume as before $k = 0\left(\delta^m\right)$, where m is to be determined writing only the order of various terms we get the following order relation

$$0(1) = 0\left(\delta^{m-n-1}\right) + 0\left(\delta^{m-n+1}\right)$$

taking m = n + 1 we get the following non-vanishing component

$$\tau'_{y'x'} = -m\left\{\left(\frac{1}{2}\right)^{\frac{n-1}{2}}\left[2\left(\frac{\partial u'}{\partial y'}\right)^2 + 2\left(\frac{\partial w'}{\partial y'}\right)^2\right]^{\frac{n-1}{2}} \frac{\partial u'}{\partial y'}\right\} \text{ or}$$

$$\tau'_{y'x'} = -m\left\{\left[\left(\frac{\partial u'}{\partial y'}\right)^2 + \left(\frac{\partial w'}{\partial y'}\right)^2\right]^{\frac{n-1}{2}} \frac{\partial u'}{\partial y'}\right\}$$

Similarly other non-vanishing components will be

$$\tau'_{y'z'} = -m\left\{\left[\left(\frac{\partial u'}{\partial y'}\right)^2 + \left(\frac{\partial w'}{\partial y'}\right)^2\right]^{\frac{n-1}{2}} \frac{\partial w'}{\partial y'}\right\}$$

Remaining shear-stress components vanish under the boundary-layer assumption.

III. BASIC EQUATIONS

The equations of MHD and conventional fluid dynamics are different due to one additional force term in equation of momentum and a term due to Joule heating in the equation of energy. In such kind of situation the Maxwell's equations have to be satisfied in the entire flow field and in the body and interface.

In order to derive the basic equations, the following assumptions are made:

I. The considered fluid is incompressible finitely conducting with constant physical properties.
II. Electrical ,hall effect and polarization effects are ignored.
III. The induced magnetic field is not considered.
IV. The flow is laminar and time dependent.
V. The imposed magnetic field is normal to the free stream velocities.
VI. Very small magnetic Reynolds number is assumed .

Following these above assumptions, the equatuin of motion governing the velocity distribution in the presence of magnetic field as,

$$\nabla \cdot V = 0 \qquad \text{------ (1.1)}$$

$$f - \rho\frac{DV}{Dt} = \nabla P - \nabla\,\overline{\overline{\tau}} + \left(\nabla \times B\right) \times B \qquad \text{------ (1.2)}$$

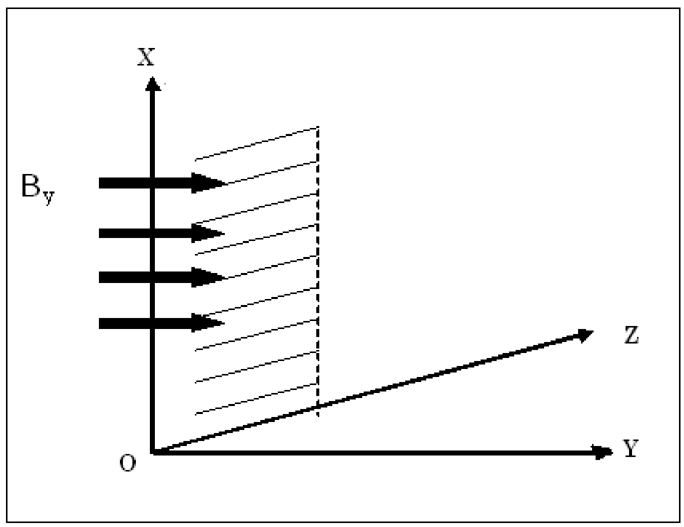

Fig. 1. Flow Geometry

IV. MATHEMATICAL FORMULATION

Consider the time-independent forced convective heat & mass transfer of a incompressible, viscous and conducting fluid over a semi-infinite flat surface in the influence of non-uniform magnetic field. The flow is parallel to the X-axis, and Y-axis perpendicular to it. A uniform strength magnetic field is introduced normal to the flow direction. For the simplicity of the problem, the variation of flow and heat transfer quantities in the Z-direction are neglected . The external electric field is assumed to be zero and the electric field due to polarization if charges are negligible. Due to the small magnetic Reynolds number, the induced magnetic field is also neglected. The temperature of the plate is kept uniform at T_w and it is greater than the ambient fluid temperature T_∞. The species concentration at the plate is also held uniform at C_w which is greater than the ambient fluid concentration C_∞. Following the above assumptions the boundary layer equation for the 3-D MHD forced convective heat & mass transfer of non-Newtonian power law fluids (with generalized Ohm's law) is governed by:(Fig.1)

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (2)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U\frac{\partial U}{\partial x}+\frac{n}{R_e}\frac{\partial}{\partial y}\left\{\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]^{(n-1)/2}\frac{\partial u}{\partial y}\right\}+S_1(x,t)\ [U-u] \quad (3)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}=U\frac{\partial W}{\partial x}+\frac{n}{R_e}\frac{\partial}{\partial y}\left\{\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]^{(n-1)/2}\frac{\partial w}{\partial y}\right\}+S_2(z,t)\ [W-w] \quad (4)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} \quad (5)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{D}{\rho}\frac{\partial^2 C}{\partial y^2} \quad (6)$$

The boundary conditions are:

$u = v = w = 0,\ T = T_w,\ C = C_w$ at $y = 0$ (7)

$u = U(x),\ w = W(x),\ T = T_\infty,\ C = C_\infty$ at $y \to \infty$ (8)

By introducing following dimensionless variables and parameters (using free-parameter method)

$$u=\frac{\partial \psi}{\partial y}=Uf_1'(\eta),\quad \frac{w}{U}=f_2(\eta),\quad v=-\frac{\partial\psi}{\partial x},$$

$$g_1(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\quad g_2(\eta)=\frac{C-C_\infty}{C_w-C_\infty},$$

$$\eta=R_e^{\frac{1}{n+1}}\frac{y}{\xi(x)},\quad \psi=\frac{Uf_1\xi(x)}{R_e^{\frac{1}{n+1}}},$$

Equation of continuity satisfies and the governing equations (3)-(8) reduce to:

$$\frac{\partial}{\partial\eta}\left\{\left[\left(f_1''\right)^2+\left(f_2'\right)^2\right]^{\frac{n-1}{2}}f_1''\right\}-A\left(f_1'f_1'-1\right)+B\left(f_1f_1''\right)-C\left(f_1'-1\right)=0 \quad (9)$$

$$\frac{\partial}{\partial\eta}\left\{\left[\left(f_1''\right)^2+\left(f_2'\right)^2\right]^{\frac{n-1}{2}}f_2'\right\}-A\left(f_1'f_2-1\right)+B\left(f_1f_2'\right)-C\left(f_2-1\right)=0 \quad (10)$$

$$\frac{k}{\rho c_p}\left(\frac{R_e}{\xi}\right)^2 g_1''+\left(U'+U\frac{\xi'}{\xi}\right)f_1g_1'=0 \quad (11)$$

$$D\left(\frac{R_e}{\xi}\right)^2 g_2''+\left(U'+U\frac{\xi'}{\xi}\right)f_1g_2'=0 \quad (12)$$

where,

$$A=U^{1-n}U'\xi^{n+1}\frac{1}{n},\ B=\frac{U^{2-n}\xi^{n+1}}{n}\left(\frac{U'}{U}+\frac{\xi'}{\xi}\right),\ C=SU^{1-n}\frac{\xi^{n+1}}{n},\ S=\frac{\sigma B_y^{\ 2}}{\rho} \quad (13)$$

The boundary conditions are:

$$f_1=f_2=f_1'=f_2'=0,\ g_1=g_2=1\ \text{ at }\ \eta=0 \quad (14)$$

$$f_1'=f_2'=1,\ g_1=g_2=0\quad at\quad \eta\to\infty \quad (15)$$

Let

$$U=W=\xi=x^{1/3},\ B_y=B_0x^{-1/3},\ \eta=R_e^{1/n+1}\frac{y}{x^{1/3}} \quad (16)$$

Using equation (16) , equations (9)-(12) will be converted into following equations:

$$\frac{\partial}{\partial\eta}\left\{\left[\left(f_1''\right)^2+\left(f_2'\right)^2\right]^{\frac{n-1}{2}}f_1''\right\}-\frac{1}{3n}\left(f_1'f_1'-1\right)+\frac{2}{3n}\left(f_1f_1''\right)-\frac{M}{n}\left(f_1'-1\right)=0 \quad (17)$$

$$\frac{\partial}{\partial\eta}\left\{\left[\left(f_1''\right)^2+\left(f_2'\right)^2\right]^{\frac{n-1}{2}}f_2'\right\}-\frac{1}{3n}\left(f_1'f_2-1\right)+\frac{2}{3n}\left(f_1f_2'\right)-\frac{M}{n}\left(f_2-1\right)=0 \quad (18)$$

$$g_1''+\Pr f_1g_1'=0 \quad (19)$$

$$g_2''+Sc\,f_1g_2'=0 \quad (20)$$

The boundary conditions are:

$$f_1=f_2=f_1'=f_2'=0,\ g_1=g_2=1;\ \eta=0 \quad (21)$$

$$f_1'=f_2'=1,\ g_1=g_2=0\quad ;\eta\to\infty \quad (22)$$

V. RESULTS & DISCUSSION

Using free parameter technique of similarity transformation to the flow problem, the governing equations with the boundaryy conditions are converted to a system of non linear ODE .thee system of similarity equations (17)-(20) with the boundaryy conditions (21 and 22) are numerically solved and presentedd graphically.

The results of the component of velocities $f_1' \& f_2$, the temperature profile g_1 and the concentration g_2 have been obtained for different values of n i.e. power-law index n (valuess are :0.85 ,1, 1.2, 1.5), the generalised Schmidt number S_c (rangee 0.1 to 5), the generalised Prandtl number P_r (range 10 to 50) thee magnetic parameter M (range 0.3 to 1).

Figure 2 and 3 show that the velocity profiles across and along the plate f_2 *and* f_1' respectively, decrease when n is increased. Figure 4 shows that the temperature profile g_1 decreases when Pr is increased. Figure 5 shows clearly that the concentration profile g_2 decreases when S_c is increased.

Fig. 6 and Fig.7 show that the temperature g_1 and the concentration g_2 increase with increase in *n.* It is clear from Fig. 8 and 9 that the velocity profiles along the plate and across the plate $f_1' \& f_2$ respectively, increase with the increase in the magnetic number M. Figures 10 and 11 show that the temperature profile g_1 and the concentration g_2 decrease when M is increased.

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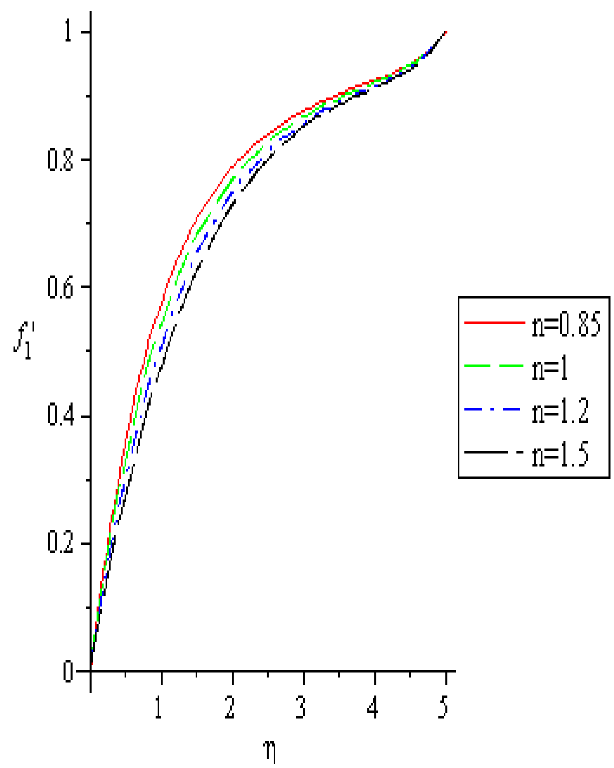

Figure:2 Velocity Profile f_1' with different values of n for Pr=10, M=0.3,Sc=0.1

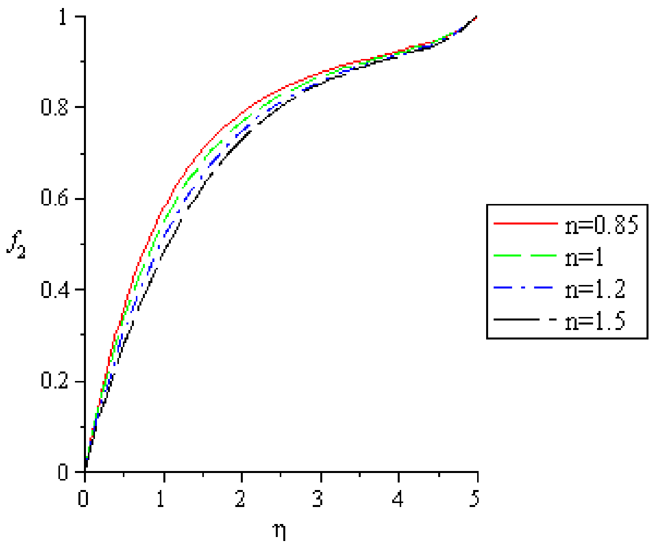

Figure 3: Velocity Profile f_2 with different values of n for Pr=10, M=0.3,Sc=0.1

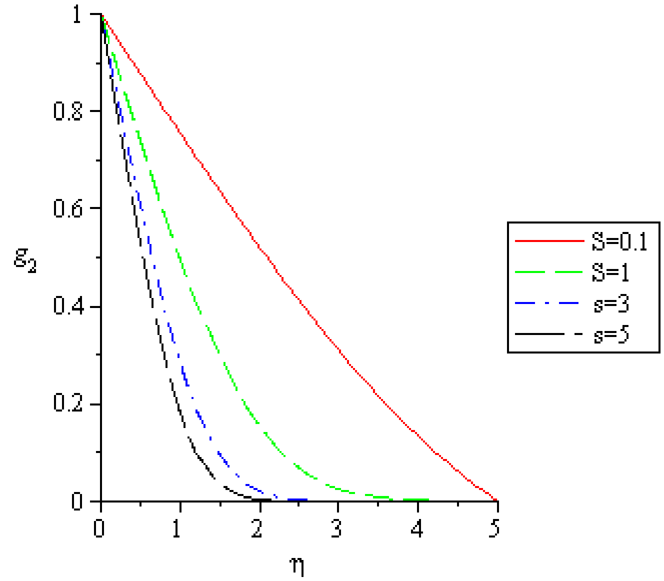

Figure 5: Concentration profile g_2 with different values of *Sc* for n=0.85, M=0.3,Pr=10

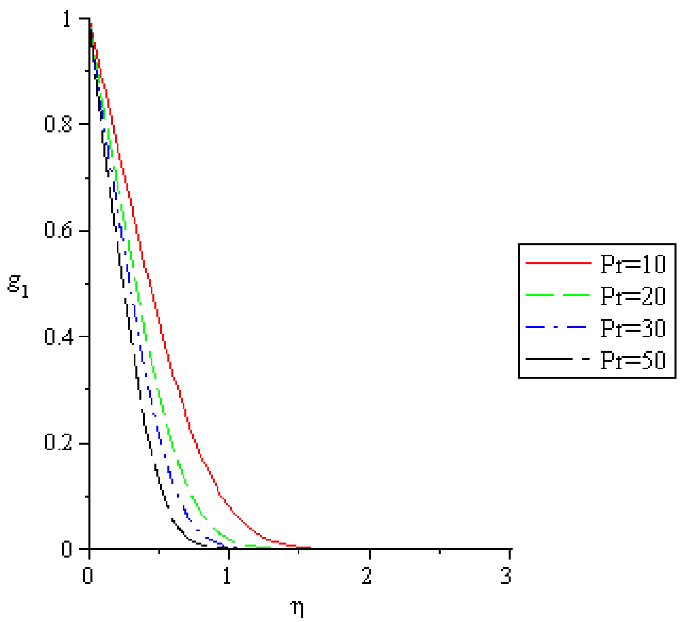

Figure 4: Temperature profile g_1 with different values of Pr for n=0.85, M=0.3,Sc=0.1

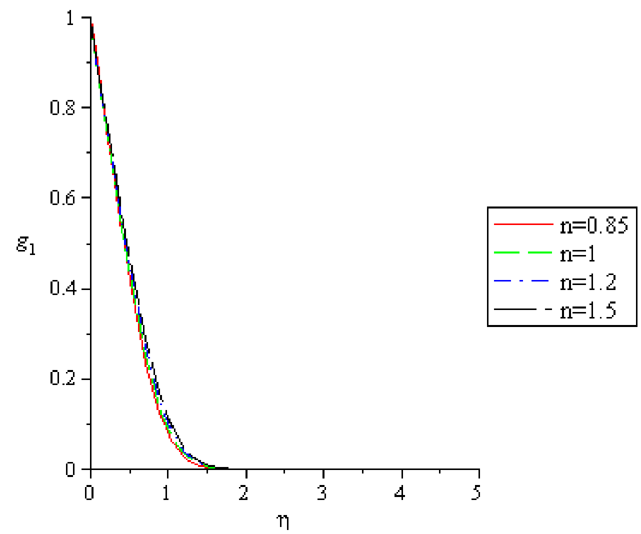

Figure 6: Temperature profile $g_1$with different values of n for Sc=0.1, M=0.3,Pr=10

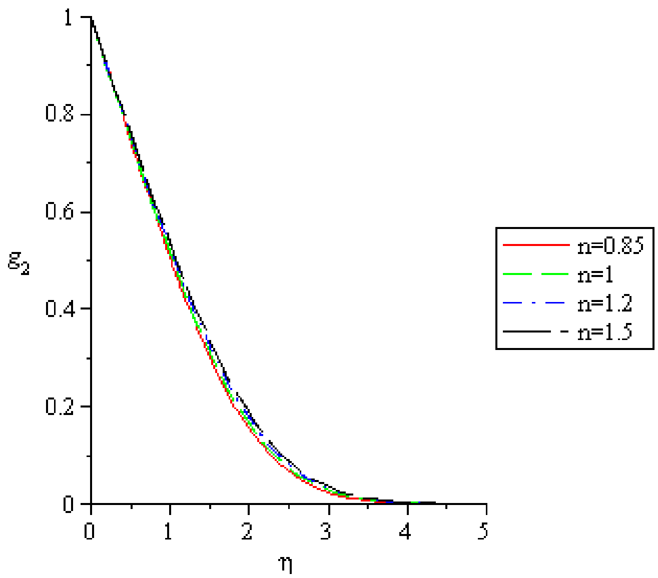

Figure 7: Concentration profile g_2 with different values of ***n*** for Sc=1, M=0.3,Pr=10

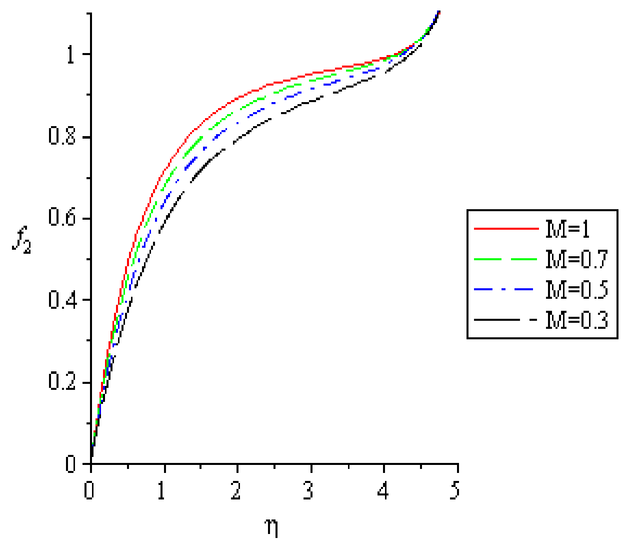

Figure 9: Velocity Profile f_2 with different values of M for Pr=10, n=0.85,Sc=0.1

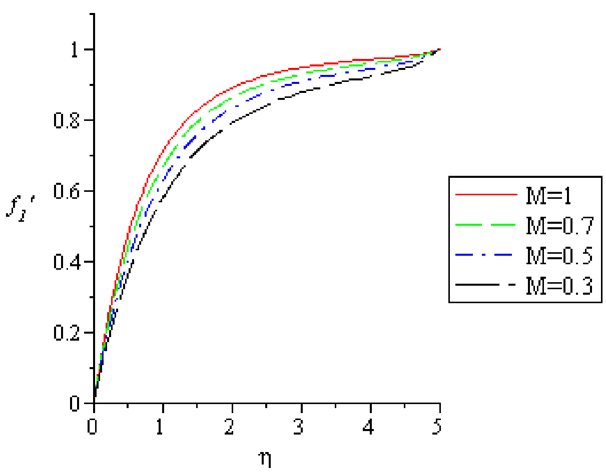

Figure 8: Velocity Profile f_1' with different values of M for Pr=10, n=0.85,Sc=0.1