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MHD Mixed Convective Heat and Mass Transfer Flow of a Visco-Elastic Fluid over a Stretching Sheet with Chemical Reaction and Temperature Gradient Dependent Heat Sink

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Abstract:- The effect of chemical reaction on mixed convective flow with heat and mass transfer of a visco-elastic in- compressible Walter's liquid B' model and electrically conducting fluid over a stretching sheet with temperature gradient dependent heat sink in heat transfer and chemical reaction in mass transfer are investigated in a saturated porous medium in the presence of a constant transverse magnetic field. The non-linear boundary layer equations with corresponding boundary conditions are converted into a system of non-linear ordinary differential equations by similarity transformations. Further the similarity equations are solved numerically by using fourth order Runge-kutta method via shooting technique. Numerical results of the skin friction co-efficient, local Nusselt number Nu, local Shrewood number Sh as well as various temperature and concentration profiles are presented for various values of physical parameters like permeability parameter, visco-elastic parameter, magnetic parameter, Prandtl number and Schmidt number respectively.

Key words: chemical reaction term, visco-elastic parameter, stretching sheet, temperature gradient dependent heat sink / source, order of reaction

I. INTRODUCTION

Ever increasing industrial applications in the manufacture of plastic film and artificial fiber materials in recent years, has lead to a renewed interest in the study of visco-elastic boundary layer fluid flow with heat and mass transfer over a stretching sheet. The continuous surface with heat and mass transfer problem has many practical applications in electrochemistry and in polymer processing. An interesting fluid mechanical application is found in polymer extrusion processes, where the object on passing between two closely placed solid blocks is stretched into a liquid region. The stretching imparts an unidirectional orientation to the extrudate, thereby improving its mechanical properties. A number of works are presently available that follow the pioneering classical works of Sakiadis [1], Tsou et. al. [2] and Crane [3] and Rajagopal et. al., [4]. The following table lists some relevant works that pertain to visco-elastic cooling liquids. .

Authors	Types of visco-elastic fluid	Nature of study	Remarks
Rajagopal et al [5]	Second order liquid	Heat transfer considered & temp-gradient dependent heat sink not considered	Mass transfer with chemical reaction parameter not considered
Andersson et al [6]	Power law fluid	Heat transfer considered & temp-gradient dependent heat sink not considered	Mass transfer with chemical reaction parameter not considered
Siddappa & Subhas [7]	"	"	"
Rajagopal et al [8]	Second order fluid	"	"
Bujurke et al [10]	"	"	"
Chen and Char [11]	"	"	"
Dandapat & Gupta [12]	"	"	"
Chang [13]	"	"	"
Rollins & Vajravelu [14]	"	"	"
Andersson & Dandapat [15]	"	"	"
Lawrence and Rao [16]	"	"	"
Andersson [17]	Walter's liquid B' model	"	"
Kelley et al [18]	"	"	"
Maeschy et al [9]	Second order fluid	"	"
Bhatnagar et al [20]	Oldroyd-B fluid	"	"
Subhas & Veena [21]	Walter's liquid B' model	"	"
Subhas et al [22]	Weak electrically conducting Walter's liquid B'	"	"
Veena et al [23]	Walter's liquid B' model	Heat transfer not considered	Unsteady mass transfer considered
Veena et al [24]	"	Heat transfer considered with PST & PHF	Mass transfer considered with PST PHF
Veena et al [25]	"	"	Mass transfer not considered
Veena et al [26]	"	"	"
Veena et al [27]	"	Heat transfer not considered	Mass transfer considered
Veena et al [28]	"	Unsteady momentum transfer	Mass transfer not considered
Siddheshwar & Mahabaleshwar [29]	"	"	"

Besides Happel and Brenner [30] and McCormack and Crane [31] have provided comprehensive analysis on boundary layer flow including the flow caused by stretching of flat surface and between two surfaces under different physical situations.

Since then many authors including Chaim [32], Borkha Kati and Bharali [33], Wang [34], Takhar and Soundal gekar [35]; Surmadevi et al [36], Ingham [37], Hassanien and Gorla [38], Thakar and Gorla [39], Takhar et al [40], and Ajay Kumar Singh [41] have studied the boundary layer flow caused by a stretching/continuously moving sheet for different thermo-physical situations using a variety of fluid models and boundary conditions.

However Darcy's law is valid in a certain seepage velocity domain for flows with very low Reynolds number on addition when fluid flows over a saturated porous medium, the commonly known "no slip" condition fails since the external surface may produce a tangential flow below the fluid porous interface.

The initial studies on flow through porous medium considered only momentum transfer. However, the boundary layer analysis of thermal convection in porous media became an emergent topic of research during the last three decades of twentieth century due to the interest of researchers in developing geothermal energy resources and also to accelerate the progress in chemical engineering process modeling and chemical effects such as magnetic field, thermal dispersion, chemical reaction, internal heat generation, temperature gradient dependent heat sink/ source, visco-elasticity, mass diffusivity etc. due to their applications in novel energy system technologies and in geo-nuclear repositors. In this regard Ahmadi and Manvi [21], Cheng [42] studied the free convection boundary layer in a saturated porous medium when the power law variation is wall temperature persists. Takhar et al [43] studied the effects of both homogeneous and heterogeneous chemical reactions on dispersion flows in porous medium. Angissa et al [44] provided an analysis on heat and mass transfer effect in thermally stratified porous medium for unsteady boundary layer flow. In the present century a exploration of industries using latest technologies in extrusions to manufacturing processes and melt spinning processes is taking place on these industries and in polymer industries the extradite is stretched into a filament due to the elastic property when it is drawn from the dye and solidifies in the desired shape through a controlled cooling system. Therefore many authors Siddappa et al [45], Veena et al [46], Sonth et al [47] Khan et al [48], Mahapatra et al [49] and Bhargava et al [50] have analyzed the problems on boundary layer flow, caused by a stretching sheet for different flow models. Thus in the present paper we are concerned not only with the mixed convection flow past a non-isothermal stretching sheet but also the presence of magnetic field, porous medium, mass transfer, chemical reaction rate parameter and temperature gradient dependent heat sink effects. The study involves steady and heat transfer flow of an incompressible visco-elastic Walter's liquid B'model past a porous stretching sheet. The results of the study are discussed for different numerical values of the various parameters encountered in the problem. The present work finds applications in polymer industries and material processing industries.

II. MATHEMATICAL ANALYSIS

We consider the steady free convective flow with heat and mass transfer of a visco-elastic incompressible and electrically conducting fluid over a stretching sheet. By applying two equal and opposite forces along the x-axis, the sheet is being stretched with a speed proportional to the distance from the fixed origin x = 0. The uniform transverse magnetic field Bo is imposed along the y-axis with sheet being immersed in a saturated porous medium as shown in figure 1. The induced magnetic field due to the motion of the electrically conducting fluid is negligible compared visco-elasticity of the fluid. This assumption is valid for small magnetic Reynold's number. The pressure gradient and viscous dissipation are neglected where as temperature gradient heat dependent sink effect is considered. The temperature and speices concentration are maintained at a prescribed constant values Tw and Cw at the sheet and are assumed to vanish far away.

Under the assumptions along with the Boussinesq's approximation, the governing equations for continuity, momentum, energy and diffusion of the laminar boundary layer flow can be written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=O \qquad \ldots(1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-k_1\left\{u\frac{\partial^3 u}{\partial x\partial y^2}+v\frac{\partial^3 u}{\partial y^3}-\frac{\partial^3 u}{\partial y^3}-\frac{\partial u}{\partial y}.\frac{\partial^2 u}{\partial x\partial y}+\frac{\partial u}{\partial x}.\frac{\partial^2 u}{\partial y^2}\right\}+$$

$$g\beta T+g\beta^* G-\frac{\sigma B_o^2}{\rho}u-\frac{\nu}{k'}u \qquad \ldots(2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho cp}\frac{\partial^2 T}{\partial y^2}-Q'\frac{\partial T}{\partial y} \quad \ldots(3)$$

$$u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=D\frac{\partial^2 c}{\partial y^2}-k_o c^n \quad \ldots(4)$$

The boundary conditions for this problem can be written as

$u\,(x_1 O) = bx$, $v(x, O) = O$, $T(x, O) = Tw$ $C\,(x, O) = C_w$ …(5)

$u\,(x, \infty) = O$, $u'\,(x, \infty) = O$, $T\,(x, \infty) = O$, $C\,(\infty, O) = O$ …(6)

The continuity equation (1) is satisfied by the stream function ψ (x, y) defined by

$$u=\frac{\partial\psi}{\partial y},\ v=-\frac{\partial\psi}{\partial x} \quad \ldots(7)$$

Introducing the similarity transformations

$$\psi(x_1 y)=(b\nu)^{1/2}\,x\,G(\eta),\ \eta=\left(\frac{b}{\nu}\right)^{1/2} y\,\theta=\frac{T}{T_w},\ \phi=\frac{C}{C_W} \quad \ldots(8)$$

Substituting (7) into equations (2), (3) and (4) and boundary conditions (5) and (6).
We obtain

$$G_\eta{}^2-GG_{\eta\eta}=G_{\eta\eta\eta}-k_1\left\{2G_\eta\,G_{\eta\eta\eta}-G_{\eta\eta\eta}-G\,G_{\eta\eta\eta}-G_{\eta\eta}{}^2\right\}$$

$$-\ G_r\,\theta-(k_2+M.)G_\eta \quad \ldots(9)$$

$$\theta_{\eta\eta}+P_r(1+Q)G(\eta)\theta_\eta(\eta)=0 \quad \ldots(10)$$

$$\phi''+SC\left(f\,\phi'-\nu\,\phi^n\right)=0 \quad \ldots(11)$$

where the corresponding boundary conditions are:

$$G(O)=O,\qquad G_\eta(O)=1,\qquad \theta(O)=1,\qquad \phi(O)=1 \quad \ldots(12)$$

$$G_\eta(\infty)=O,\qquad G_{\eta\eta}(\infty)=O,\qquad \theta(\infty)=O,\qquad \phi(\infty)=O \quad \ldots(13)$$

Skin friction co-efficient, Nusselt Number and Shrewood Number

i) The local wall shear stress is defined by

$$T_w=\mu\left(\frac{\partial u}{\partial y}\right)_{(x_1 o)}=\mu\left(\frac{b}{\nu}\right)^{1/2} x\,G_{\eta\eta}(O) \quad \ldots(14)$$

and the skin friction co-efficient at the wall is derived as

$$c_f=\frac{\tau_w}{\mu\left(\frac{b}{\nu}\right)^{1/2} bx}=G_{\eta\eta}(O) \quad \ldots(15)$$

ii. The rate of heat flux at the wall is defined as

$$q_w=-k\left(\frac{\partial T}{\partial y}\right)_{(x,o)}=-k\left(\frac{b}{\nu}\right)^{1/2} T_w\,\theta_\eta(O) \quad \ldots(16)$$

and the local Nusselt number is derived as

$$Nu=\frac{q_w}{k\left(\frac{b}{\nu}\right)^{1/2} T_w}=-\theta_\eta(O) \quad \ldots(17)$$

iii. The rate of mass flux at the wall is defined as follows

$$m_w=-D\left(\frac{\partial c}{\partial y}\right)_{(x,o)}=-D\left(\frac{b}{\nu}\right)^{1/2} C_w\,\phi_\eta(O) \quad \ldots(18)$$

and the local Shrewood number is

$$Sh=\frac{m_w}{D\left(\frac{b}{\nu}\right)^{1/2} C_w}=-\phi_\eta(O) \quad \ldots(19)$$

Numerical solution

Since equations (9), (10) and (11) are non-homogeneous, coupled ordinary differential equations with variable coefficients. The Runge-Kutta integration scheme via shooting techniques for the non-linear boundary value problem is similar to the linear case, except that the solution of the non-linear problem can not be simply expressed as a linear combination between the solutions of the two initial value problems. Instead we need to use sequence of suitable initial values for the derivatives such that the tolerance at the end point of the range is very small. This sequence of initial values is given by secant method. Selection of the appropriate finite value of η_∞ is the most important aspect in this method. It is important to know that for different sets of physical parameters the appropriate values of η_∞ are different.

Here the coupled boundary value problem of fourth order in G and second order in θ and ϕ has been reduced to a system of eight simultaneous ordinary differential equations. To solve this system we require eight initial conditions, although we have only two initial conditions on G and one each initial condition on θ and ϕ respectively. The third initial condition on G is obtained (Lawrence and Rao (1995) by applying initial conditions of (12) in (9). Further three other initial conditions are not prescribed. We employ the numerical shooting technique and secant method. Finally we use the fourth order Runge-Kutta scheme to solve the initial value problems. The value of η at infinity is fixed at 6.

The equations (9) to (11) with boundary conditions (12) and (13) were solved numerically using Runge-Kutta algorithm with a systematic guessing of $G_{\eta\eta}(O), \theta_\eta(O) \text{ and } \phi_\eta(O)$ until the boundary conditions at infinity $G\eta(O), \theta(O) \text{and} \phi(O)$ decay exponentially to zero. If the boundary conditions at infinity are not satisfied. Then the numerical routine uses a half interval method to calculate corrections to estimated values of $G_{\eta\eta}(O), \theta_\eta(O) \text{and} \phi_\eta(O)$. This process is repeated iteratively until exponentially decaying solutions in $G_\eta(\eta), \theta(\eta) \text{and} \phi(\eta)$ were obtained. Numerical results for skin friction $G_{\eta\eta\eta}(O)$, dimensionless temperature gradient - $\theta_\eta(O)$ as well as $G_\eta(\eta), \theta(\eta) \text{ and } \phi(\eta)$ were presented.

Results and discussion

Numerical computational results have been carried out various values of visco-elastic parameter (k_1), permeability parameter (k_2), magnetic parameter (M), and impermeability of the boundary wall. Results are computed for small values of Prandtl number of the range Pr = 0.71, Gc = 0.5, Gr = 0.5 which are applicable to the case of polymer solution. Kinematic viscosity ν is taken as 0.04, stretching rate b = 2.0, various values of the magnetic parameter M and k_2 ranging from 10 to 2000 schimidt number Sc in the range 0.1 < Sc < 10, internal heat generation term θ' = 0.5, three values of the chemical reaction parameter ν < 1, the first, second – and third-order reactions in n.

Figs (1a),(1b),(1c) show the non-dimensional horizontal velocity profiles for different non-dimensional parameters like visco-elastic parameter $k_{1,}$ magnetic parameter Mn and permeability parameter k_2. It is observed from the figures that the horizontal fluid velocity decreases in the boundary layer with increasing distance from the boundary. It is interesting to note that the effect of visco-elasticity (k_1) is to decrease the velocity. This result is consistent with the physical fact that introduction of tensile stress due to visco-elasticity causes transverse contraction of the boundary layer and hence velocity decreases. This phenomenon is even true in the presence of magnetic parameter (M) and permeability parameter (k_2). Fig. (2a), (2b), (2c) are depicted to present the transverse velocity distribution for various numerically computed values for Pr = 0.71, Gc = 0.5, Gr = 0.5, r < 1 and for various values of k_1, magnetic parameter M and permeability parmeter k_2. The values of Schimidt number are taken in the range 0.1 to 10 and three values of order of reaction n = 1,2,3. From the figures we observe that velocity distribution is less at the edge of the boundary layer and decrease monotonically with increase in the values of chemical reaction parameter r. Figs. (3) and (4) show that the thickness of the concentration boundary layer reduces with an increase in chemical reaction parameter. Figs. (5) explains the graph of concentration profiles for an increase in the order of reaction n. From the figure it is noticed that concentration boundary layer slightly increase with an increase in the order of reaction. Figure (6) describes the behavior of concentration boundary layer thickness how it will be dense with an increase in values of visco-elastic parameter k_1 for fixed values of Schemidt number Sc = 5.0. Figures (7a) and (7b) present the temperature distribution θ (η) and concentration distribution ϕ (η) across the boundary layer and from the figures it follows that there is thickness of the temperature boundary layer as well as concentration boundary layer θ (η) and ϕ(η) decrease to zero so as to meet the far field boundary conditions for fixed parameters, comparing the curves in each figure it is found that the temperature at fixed location increases with increase in magnetic parameter M and permeability parameter k_2 but decreases, with the prandtl number Pr and Schemidt number Sc respectively. Though magnetic and permeability parameters do not enter into the heat and mass transfer equations, directly they actually affect the velocity distribution and therefore increase the temperature and concentration profiles indirectly. The results of the local Nusselt number, -θ'(O) also decrease as the chemical reaction parameter ν and Prandtl number Pr increase. Physically it can be explained that the flow is accelerated by accelerating buoyancy force and permeability of the medium. Further more an increasing chemical reaction parameter ν or Prandtl number decelerates the flow in the boundary layer, which certainly results in a decrease in the heat flux. The local Shrewood number ϕ'(O) increase as the reaction parameter r and Schmidt number Sc increase and also - ϕ'(O) is a decreasing function of the order of reaction n. On the other hand we observed from all the tables that the skin friction co-efficient, **$G_{\eta\eta}$ (O),** the local Nusselt number, θ'(O) are not sensitive to change as the order of the reaction n, increase but they be little sensitive with increase in visco-elasti parameter $k_{1,}$ **$G_{\eta\eta}$ (O)** , -θ'(O) and - ϕ'(O) decrease for an increase in the values of visco-elastic parameter k_1. From the table it is observed that the skin friction co-efficient at the wall of **$G_{\eta\eta}$ (O)**, decreases with an increase of visco-elastic parameter k_1, chemical reaction parameter and Schemidt number Sc. These results are well in agreement with the results of Anderson et al [52] and Lia [53]. Tables of values are calculated to exhibit the results of skin friction coefficient **$G_{\eta\eta}$ (O)**, the local Nusselt number, -θ'(O) and the local Shrewood number, - ϕ'(O) for various values of visco-elastic parameter k_1, chemical reaction parameter, the order of reaction n.

III. CONCLUSIONS

The effects of temperature gradient dependent heat sink and chemical reaction parameter on mixed convective flow with heat and mass transfer of a visco-elastic and electrically conducting fluid over a stretching sheet has been studied. The governing equations with prescribed boundary conditions have been converted into a system of non-linear ordinary differential equations with the appropriate boundary conditions by applying similarity transformations. Numerical solutions of the similarity equations have also been obtained by using a fourth order Runge-kutta method via shooting technique. From the result findings, the following conclusions are drawn.

1. The velocity profiles decrease owing to an increase in visco-elastic parameter and chemical reaction parameter where as the temperature and concentration boundary layer decrease with increase in values of chemical reaction parameter.
2. The velocity and temperature distribution is more but the concentration boundary layer decrease owing to an increase in order of reaction.
3. The velocity distribution decrease but the temperature distribution and concentration distribution increase with increase in magnetic and permeability parameters.
4. The velocity and concentration profiles decrease but the temperature boundary layer increases with an increase in Schimidt number Sc.
5. Skin friction co-efficient and the rate of heat transfer are sensitive to change owing to increase in visco-elastic parameter but not sensitive to change owing to an increase in chemical reaction parameter and the order of reaction where as local Shrewood number decreases, with increase in the order of reaction n.
6. Skin friction co-efficient increases and the rate of heat and mass transfer co-efficients decrease with an increase in the values of magnetic and permeability parameters.

Table 1: Values of skin friction $G_{\eta\eta}$ (O) for different values of M, k_1 and k_2 and reaction order n:

M	k_1	k_2	n	$G_{\eta\eta}$ (O)
0.0	0.20	0.0	0	1.292
0.5	0.4	0.5	1	1.8201
1.0	0.6	1.0	2	2.2854
1.5	0.8	1.5	3	2.0137

Table 2: The results at the sheet θ_η (O) for different values of M, k_1, k_2

M	k_1	k_2	Pr	θ_η(O)	Q
0	0	0	6.7	-3.0003	0.0
0.5	0.05	0.5	6.7	-2.9516	0.05
1.0	0.05	1.0	6.7	-2.9015	0.15
5.0	0.1	5	6.7	-2.6341	0.10
10	0.5	10	6.7	-2.4131	0.5
20	0.8	20	6.7	-2.0152	0.5

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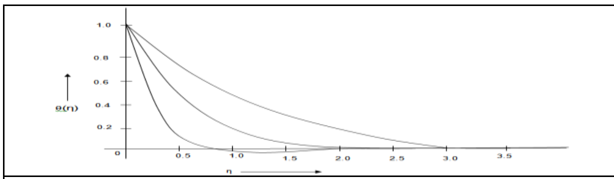
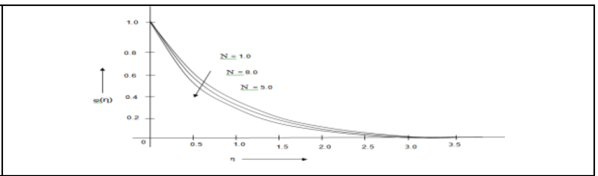
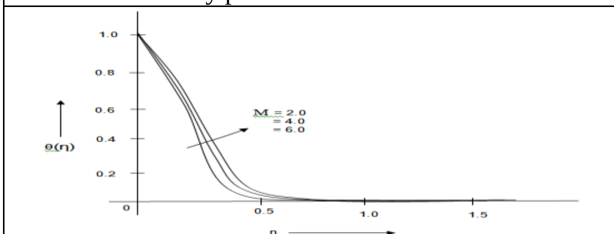


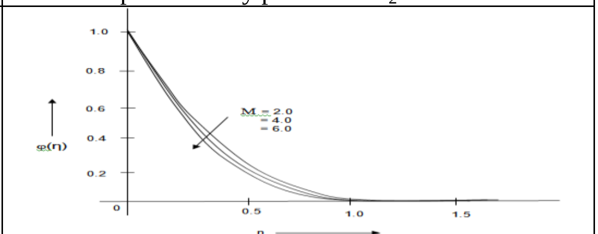
Fig(1a) Effect of visco-elastic parameter k_1 on horizontal velocity profiles.



Fig(1b) Horizontal velocity profiles for different values of permeability parameter k_2



Fig(1c) Horizontal velocity profiles for different values of magnetic parameter M and for fixed values



Fig(2a) Graph of transverse velocity distribution G(η) versus η for different values of visco-elastic

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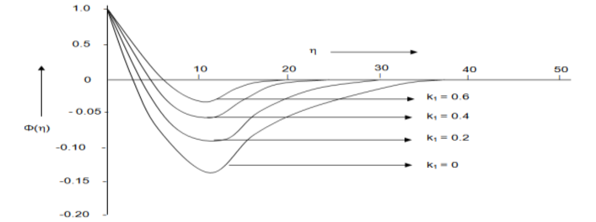
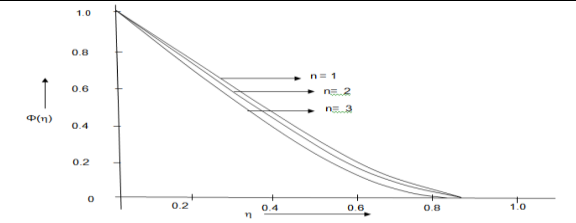
<tr><td>
</td><td>
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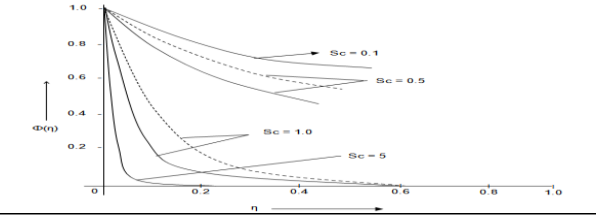
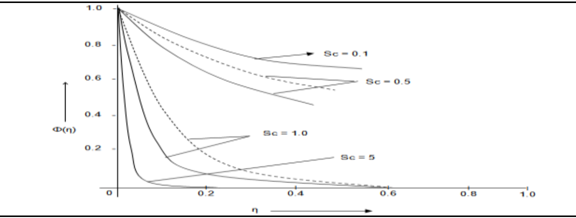
<tr><td>Fig(2b). Transverse velocity profiles G(η) versus η for different values of magnetic parameter M</td><td>Fig(2c). Transverse velocity proprofiles for different values of permeability parameter k_2 and for fixed $M = 2$, $k_1 = 0.2$</td></tr>
<tr><td>
</td><td>
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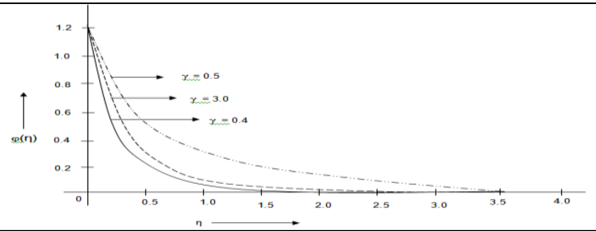
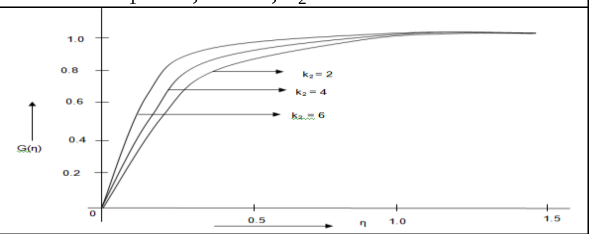
<tr><td>Fig(3) Effect of chemical reaction parameter over the concentration profiles</td><td>Fig(4). Graph of Concentration profiles Φ(η) vs η with Schimidt number as a parameter for fixed values of $k_1 = 0$, $M = 2$, $k_2 = 2$</td></tr>
<tr><td>
</td><td>
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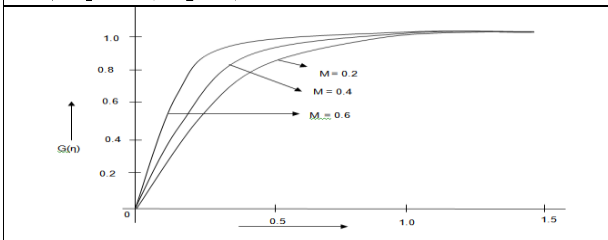
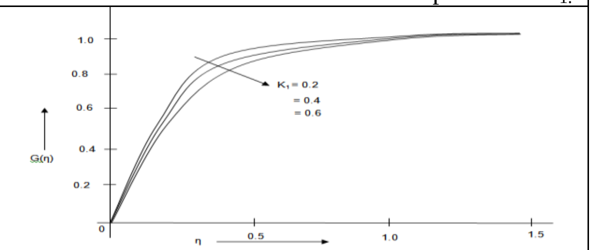
<tr><td>Fig (5). Graph of concentration profiles Φ(η) Vs η for destructive reactions of different orders n when Sc = 1.0, $k_1 = 0.2$, $k_2 = 2$, $M = 2$</td><td>Fig(6). Concentration profiles Φ(η) Vs η for generative first order reaction with $n = 1$, $k_2 = 0$, $M = 0$ for different values of visco-elastic parameter k_1.</td></tr>
<tr><td>
</td><td>
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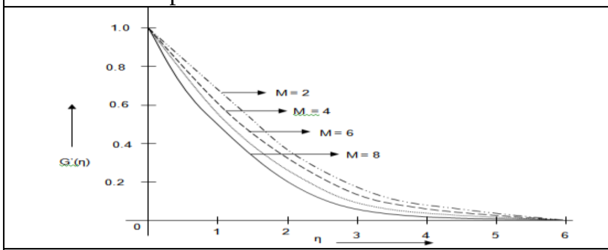
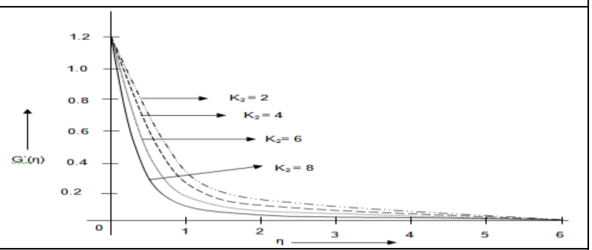
<tr><td>Fig(7a). Influence of magnetic field over the concentration profiles</td><td>Fig(7b). Effect of magnetic field on temperature field.</td></tr>
<tr><td>
</td><td>
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<tr><td>Fig(8a). Buoyancy ratio over concentration profiles</td><td>Fig(8b). Buoyancy ratio over the temperature profiles.</td></tr>
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