VISCO-ELASTIC EFFECTS ON FREE CONVECTIVE MHD HEAT AND MASS TRANSFER FLOW PAST A SEMI-INFINITE VERTICAL MOVING PLATE WITH TIME DEPENDENT SUCTION IN PRESENCE OF RADIATION AND CHEMICAL REACTION

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Abstract **- An analysis of the free convective MHD heat and mass transfer flow of an incompressible, chemically reacting, radiating, visco-elastic fluid past a semi-infinite vertical permeable moving plate in the presence of a uniform transverse magnetic field with time dependent suction has been considered. The governing non-linear partial differential equations are non-dimensionalized and are solved by using perturbation technique. Analytical solutions for velocity, temperature and concentration field have been derived. The expressions for velocity field, temperature field, skin friction, heat flux in terms of Nusselt number, and mass flux in terms of Sherwood number are obtained. The effects of the visco-elastic parameter on velocity profiles and shear stress with the combination of the other flow parameters are discussed graphically.**

Keywords **— Visco-elastic, MHD, Chemical reaction, Radiation, Suction, Porous medium.**

I. INTRODUCTION

One of the recent advances in the area of fluid dynamics is the analysis of visco-elastic fluid flow mechanism. The analysis of visco-elastic fluid lies on the fact that viscosity of the fluid signifies the physics of the energy dissipated during the flow and its elasticity represents the energy stored during the flow. Most of the liquids used in industrial applications particularly in polymer processing applications are of non-Newtonian in nature. The fluid flow mechanism over a stretching sheet is an important problem in engineering processes with applications in industries such as in hot rolling, wire drawing, crystal growing, continuous casting, glass fiber production, extrusion of plastics and paper production. The study of visco-elasticity is necessary for determining the quality of the final products of such processes.

The analysis of the boundary layer flow over a continuous solid surface moving with constant speed was initiated by Sakiadis (1961). The thermal radiation effect in a steady free convective flow through a porous medium bounded by a vertical infinite porous plate was investigated by Raptis (1998). Again, Raptis and Perdikis (2003) analyzed the effects of thermal radiation on moving vertical plate in the presence of mass diffusion. Jaiswal and Soundalgekar (2001) obtained a solution to the problem of an unsteady flow past an infinite vertical plate with constant suction and oscillating plate temperature in a porous medium. Bakier (2001) presented an analysis of the thermal radiation effects on stationary mixed convection from vertical surfaces in saturated porous media for both a hot and a cold surface. Muthucumaraswamy (2002) studied the effects of heat and mass transfer on a continuously moving isothermal vertical surface with uniform suction. Chamkha (2003) obtained an analytical solution for the MHD flow of a uniformly stretched vertical permeable surface with effect of heat generation/ absorption and chemical reaction. Das *et al.* (2011) analyzed the effect of mass transfer on unsteady hydromagnetic free convective flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate in presence of constant suction and heat source. The problem of free convection boundary layer flow with thermal radiation and mass transfer past a moving vertical permeable plate was studied by Makinde (2005). Choudhury and Das (2010) presented a theoretical study for hydromagnetic convection of a visco-elastic fluid over a continuously moving vertical surface with uniform suction. Cortell (2007) investigated the effects of chemical reaction on a steady laminar boundary layer flow of an electrically conducting fluid of second grade in a porous medium subject to a transverse uniform magnetic field past a semi-infinite impermeable stretching sheet. Nayak *et al.* (2013) presented an analysis of unsteady magneto hydrodynamic natural convection flow of a visco-elastic incompressible electrically conducting fluid along an infinite hot vertical porous surface with fluctuating free stream as well as suction velocity in the presence of chemical reaction. Das (2014) analyzed the effects of visco-elasticity on unsteady MHD free convection and mass transfer flow of a visco-elastic, incompressible, electrically conducting fluid past an infinite hot vertical porous plate embedded in porous medium. Singh *et al.* (2011) studied the effect of chemical reaction and radiation absorption on MHD free convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate with time dependent suction.

In the present study, an attempt has been made to extend the problem studied by Singh *et al.* (2011) to the case of visco-elastic fluid characterized by second-order fluid.

II. FORMULATION OF THE PROBLEM

Consider an unsteady, two-dimensional, MHD free convective heat and mass transfer flow of a laminar, incompressible, radiating visco-elastic fluid past a semi-infinite vertical porous moving plate embedded in a porous medium. It is assumed that there exists a first order chemical reaction between the fluid and the fluid species concentration. A magnetic field of uniform strength B_0 is applied perpendicular to the plate. The magnetic Reynolds number of flow is taken to be sufficiently small enough, so that the induced magnetic field can be neglected. The $\bar{x}$-axis is taken vertical directed along the plate and the $\bar{y}$-axis is taken normal to it. Due to the semi-infinite plate assumption, the physical variables are function of $\bar{y}$ and the time $\bar{t}$ only. The constitutive equation for the incompressible second-order fluid is

$$S = -pI + \mu_1 A_1 + \mu_2 A_2 + \mu_3 (A_1)^2 \tag{1}$$

where S is the stress tensor, p is the hydrostatic pressure, I is the unit tensor, A_n, n=1,2 are the kinematic Rivlin-Ericksen tensors, μ_1, μ_2, μ_3 are the material coefficients describing the viscosity, visco-elasticity and cross-viscosity respectively, where μ_1 and μ_3 are positive and μ_2 is negative (Coleman and Markovitz (1964)). The Eq. (1) was derived by Coleman and Noll (1960) from that of the simple fluids by assuming that the stress is more sensitive to the recent deformation than to the deformation that occurred in the distant past.

Under the above assumptions, the flow is governed by the following equations:

Continuity equation:

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0. \tag{2}$$

Equation of motion:

$$\rho\left(\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}}\right) = \rho g \beta\left(\bar{T} - \bar{T}_\infty\right) + \rho g \bar{\beta}\left(\bar{C} - \bar{C}_\infty\right) + \mu_1 \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \mu_2\left(\frac{\partial^3 \bar{u}}{\partial \bar{y}^2 \partial \bar{t}} + \bar{v}\frac{\partial^3 \bar{u}}{\partial \bar{y}^3}\right) - \sigma_1 B_0^2 \bar{u} - \frac{\mu \bar{u}}{\bar{K}}. \tag{3}$$

Equation of energy:

$$\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \frac{\kappa}{\rho C_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{Q_0}{\rho C_p}\left(\bar{T} - \bar{T}_\infty\right) + Q_1\left(\bar{C} - \bar{C}_\infty\right). \tag{4}$$

Equation of mass diffusion:

$$\frac{\partial \bar{C}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{C}}{\partial \bar{y}} = D\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} - K_r\left(\bar{C} - \bar{C}_\infty\right). \tag{5}$$

The boundary conditions are

$$\begin{aligned} &\bar{y} = 0 : \bar{u} = u_p, \bar{T} = \bar{T}_w, \bar{C} = \bar{C}_w \\ &\bar{y} \to \infty : \bar{u} \to \bar{U}(\bar{t}), \bar{T} \to \bar{T}_\infty, \bar{C} \to \bar{C}_\infty \end{aligned} \tag{6}$$

where $\bar{u}$, $\bar{v}$ are velocity components along $\bar{x}$ and $\bar{y}$-axis respectively, ρ is the fluid density, g is the acceleration due to gravity, β is coefficient of volume expansion for heat transfer, $\bar{\beta}$ is coefficient of volume expansion for mass transfer, $\bar{C}$ is species concentration, $\bar{C}_\infty$ is species concentration in the free stream, $\bar{C}_w$ is species concentration near the surface, σ_1 is Stefan-Boltzmann constant, $\bar{K}$ is porous permeability parameter, Q_0 is heat absorption coefficient, $\bar{Q}_1$ is radiation coefficient, C_p is specific heat at constant pressure, $\bar{T}$ is fluid temperature, $\bar{T}_w$ is fluid temperature at the surface, $\bar{T}_\infty$ is fluid temperature in the free stream, K_r chemical reaction parameter and D is chemical molecular diffusivity.

From the Eq. (2), it is obvious that the suction velocity normal to the plate is a function of time only. The variable suction velocity normal to the plate can be taken in the form

$$\bar{v} = -V_0\left(1 + \varepsilon e^{i\bar{\omega}\bar{t}}\right), \tag{7}$$

where V_0 is the mean suction velocity, ε is a positive small parameter, and $\bar{\omega}$ is frequency of oscillation.

The following non-dimensional quantities are introduced:

$$\begin{gathered} u = \bar{u}/V_0,\ v = \bar{v}/V_0,\ y = \bar{y}V_0/\upsilon_1,\ t = \bar{t}V_0^2/\upsilon_1, \\ u_p = \bar{u}_p/V_0,\ \omega = \upsilon_1\bar{\omega}/V_0^2,\ \theta = \left(\bar{T} - \bar{T}_\infty\right)/\left(\bar{T}_w - \bar{T}_\infty\right), \\ C = \left(\bar{C} - \bar{C}_\infty\right)/\left(\bar{C}_w - \bar{C}_\infty\right),\ \Pr = \mu_1 C_p/\kappa, \\ Gr = \upsilon_1 g\beta\left(\bar{T}_w - \bar{T}_\infty\right)/V_0^3,\ Gm = \upsilon_1 g\bar{\beta}\left(\bar{C}_w - \bar{C}_\infty\right)/V_0^3, \\ M = \sigma_1 B_0^2 \upsilon_1/(\rho V_0^2),\ \alpha = \mu_2 \rho V_0^2/\mu_1^2,\ K = \bar{K}V_0^2/\upsilon_1^2, \\ Sc = \upsilon_1/D,\ \varphi = Q_0\upsilon_1/(\rho C_p V_0^2),\ \gamma = \bar{K}_r\upsilon_1/V_0^2, \\ Q_1 = \upsilon_1\bar{Q}_1\left(\bar{C}_w - \bar{C}_\infty\right)/\left((\bar{T}_w - \bar{T}_\infty)V_0^2\right),\ U(t) = \bar{U}(\bar{t})/V_0. \end{gathered} \tag{8}$$

Using (8), Eqs. (3) to (5) are reduced to the following non-dimensional form

$$\frac{\partial u}{\partial t} - \left(1 + \varepsilon e^{i\omega t}\right)\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + \alpha\left\{\frac{\partial^3 u}{\partial y^2 \partial t} - \left(1 + \varepsilon e^{i\omega t}\right)\frac{\partial^3 u}{\partial y^3}\right\} + Gr\theta + GmC - \left(M + \frac{1}{K}\right)u, \tag{9}$$

$$\frac{\partial \theta}{\partial t} - \left(1 + \varepsilon e^{i\omega t}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - \varphi\theta + Q_1 C, \tag{10}$$

$$\frac{\partial C}{\partial t} - \left(1 + \varepsilon e^{i\omega t}\right)\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - \gamma C. \tag{11}$$

The corresponding boundary conditions are

$$\begin{aligned} &\bar{y} = 0 : u = u_p, \theta = 1, C = 1 \\ &\bar{y} \to \infty : u \to U(t), \theta \to 0, C \to 0, \end{aligned} \tag{12}$$

where Gr is Grashof number for heat transfer, Gm is Grashof number for mass transfer, K is dimensionless porous permeability parameter, M is magnetic parameter, Pr is Prandtl number, Sc is Schmidt number, γ is chemical reaction parameter, α is visco-elastic parameter and Q_1 is dimensionless radiation absorption parameter.

III. METHOD OF SOLUTION

Assuming the small amplitude oscillation ($0<\varepsilon<<1$) in the neighborhood of the plate, the velocity, temperature, and concentration are represented as

$$u(y,t) = u_0(y) + \varepsilon e^{i\omega t}u_1(y), \tag{13}$$

$$\theta(y,t) = \theta_0(y) + \varepsilon e^{i\omega t}\theta_1(y),$$

$$C(y,t) = C_0(y) + \varepsilon e^{i\omega t} C_1(y)$$

and

$$U(t) = 1 + \varepsilon e^{i\omega t}.$$

Substituting Eq. (13) in Eqs. (9) to (11), equating the like powers of ε, the following equations are obtained

$$\alpha u_0''' - u_0'' - u_0' + \left(M + \frac{1}{K}\right)u_0 = Gr\theta_0 + GmC_0, \quad (14)$$

$$\alpha u_1''' - (1 + i\alpha\omega)u_1'' - u_1' + \left(M + \frac{1}{K}\right)u_1 = Gr\theta_1 + GmC_1 - \alpha u_0''' + u_0', \quad (15)$$

$$\theta_0'' + \Pr\theta_0' - \varphi\Pr\theta_0 = -Q_1 \Pr C_0, \quad (16)$$

$$\theta_1'' + \Pr\theta_1' - \Pr(i\omega + \varphi)\theta_1 = -\Pr\theta_0' - Q_1 C_1 \Pr, \quad (17)$$

$$C_0'' + ScC_0' - \gamma ScC_0 = 0, \quad (18)$$

$$C_1'' + ScC_1' - Sc(\gamma + i\omega)C_1 = -ScC_0', \quad (19)$$

where prime denotes the derivative with respect to y.

The corresponding boundary conditions are

$$\begin{gathered} y = 0 : u_0 = u_p, u_1 = 0, \theta_0 = 1, \theta_1 = 0, C_0 = 1, C_1 = 0 \\ y \to \infty : u_0 \to 1, u_1 \to 1, \theta_0 \to 0, \theta_1 \to 0, C_0 \to 0, \\ C_1 \to 0. \end{gathered} \quad (20)$$

Equations (16) to (19) are solved by using the boundary conditions (20) and their solutions are given by

$$C_0 = e^{-m_1 y}, \quad (21)$$

$$C_1 = A_1\left(e^{-m_1 y} - e^{-m_2 y}\right), \quad (22)$$

$$\theta_0 = A_3 e^{-m_3 y} + A_2 e^{-m_1 y}, \quad (23)$$

$$\theta_1 = A_{10} e^{-m_4 y} + A_9 e^{-m_3 y} + A_8 e^{-m_2 y} + A_7 e^{-m_1 y}, \quad (24)$$

where

$$m_1 = 0.5\left(Sc + \sqrt{Sc^2 + 4\gamma Sc}\right),$$
$$m_2 = 0.5\left(Sc + \sqrt{Sc^2 + 4(\gamma + i\omega)Sc}\right),$$
$$m_3 = 0.5\left(\Pr + \sqrt{\Pr^2 + 4\Pr\varphi}\right),$$
$$m_4 = 0.5\left(\Pr + \sqrt{\Pr^2 + 4\Pr(i\omega + \varphi)}\right).$$

In order to solve the Eqs. (14) and (15), we note that α which is a measure (dimensionless) of relaxation time, $|\alpha|<1$ for visco-elastic fluid with small memory, and this enables us to assume the solutions in the form

$$\begin{gathered} u_0 = u_{00} + \alpha u_{01} + O(\alpha^2), \\ u_1 = u_{10} + \alpha u_{11} + O(\alpha^2). \end{gathered} \quad (25)$$

Equating the like powers of α and neglecting the higher powers of α, the following equations are obtained

$$u_{00}'' + u_{00}' - \left(M + \frac{1}{K}\right)u_{00} = -Gr\theta_0 - GmC_0, \quad (26)$$

$$u_{01}'' + u_{01}' - \left(M + \frac{1}{K}\right)u_{01} = \alpha u_{00}''', \quad (27)$$

$$u_{10}'' + u_{10}' - \left(M + \frac{1}{K} + i\omega\right)u_{10} = u_{00}' - Gr\theta_1 - GmC_1, \quad (28)$$

$$u_{11}'' + u_{11}' - \left(M + \frac{1}{K} + i\omega\right)u_{11} = u_{10}''' - i\omega u_{10}'' - u_{01}' + u_{00}'''. \quad (29)$$

The corresponding boundary conditions are

$$\begin{gathered} y = 0 : u_{00} = u_p, u_{01} = 0, u_{10} = 0, u_{11} = 0, \\ y \to \infty : u_{00} \to 1, u_{01} = 0, u_{10} \to 1, u_{11} = 0. \end{gathered} \quad (30)$$

Equations (26) to (29) are solved by using the boundary conditions (30) and their solutions are given by

$$u_{00} = 1 + A_{14} e^{-m_5 y} + A_{13} e^{-m_3 y} + A_{12} e^{-m_1 y}, \quad (31)$$

$$u_{01} = A_{22} e^{-m_5 y} + A_{19} e^{-m_3 y} + A_{18} e^{-m_1 y}, \quad (32)$$

$$u_{10} = 1 + A_{33} e^{-m_6 y} + A_{32} e^{-m_5 y} + A_{31} e^{-m_4 y} + A_{30} e^{-m_3 y} + A_{29} e^{-m_2 y} + A_{28} e^{-m_1 y}, \quad (33)$$

$$u_{11} = A_{47} e^{-m_6 y} + A_{45} e^{-m_5 y} + A_{44} e^{-m_4 y} + A_{43} e^{-m_3 y} + A_{42} e^{-m_2 y} + A_{41} e^{-m_1 y}, \quad (34)$$

where

$$m_5 = 0.5\left\{1 + \sqrt{1 + 4\left(M + \frac{1}{k}\right)}\right\},$$

$$m_6 = 0.5\left\{1 + \sqrt{1 + 4\left(M + \frac{1}{k} + \frac{i\omega}{4}\right)}\right\},$$

and the constants A's are not presented here for the sake of brevity.

IV. RESULT AND DISCUSSION

The purpose of this study is to bring out the effects of visco-elastic parameter α on the governing flow with the combination of the other parameters involved in the flow problem. The corresponding results for Newtonian fluid can be deduced from the above results by setting α=0, and it is worth mentioning here that these results coincide with that of Singh *et al.* (2011). The real parts of the results are considered throughout for numerical validation.

Figures 1-9 represent the pattern of velocity profiles against γ to observe the visco-elastic effects for various sets of values of the magnetic field parameter (M), Schmidt number (Sc), Prandtl number (Pr), Grashof number for mass transfer (Gm), Grashof number for heat transfer (Gr), radiation absorption parameter (Q_1), permeability parameter (K), chemical reaction parameter (γ) with fixed values of u_p=0.5, ε=0.5, t=1, φ=2, ω=0.1. It is evident from the Figs. 1-9 that the velocity distribution attains a distinctive maximum value in the vicinity of the plate and then begins to diminish till it attains a finite value at large distance from the plate for both Newtonian and non-Newtonian fluid flows. These figures illustrate that the fluid velocity decelerates with the growing effect of the absolute value of visco-elastic parameter $|\alpha|$, (α=0,-0.2,-0.4).

It is observed that velocity field increases with the increasing values of Grashof number for mass transfer (Figs. 4 and 5), Grashof number for heat transfer (Figs. 5 and 6), radiation absorption parameter (Figs. 6 and 7), permeability parameter (Figs. 7 and 8), whereas the ve

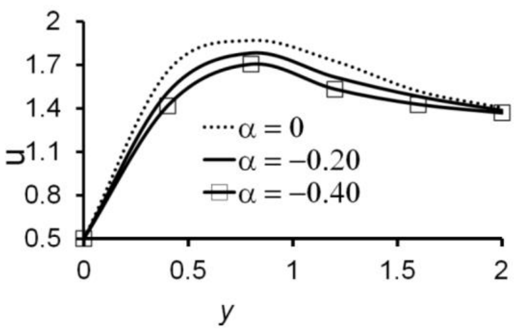

Fig. 1: Fluid velocity u against y with M=0.5, Sc=0.5, Pr=2, Gm=2, Gr=4, Q_1=2, K=2, γ=0.2.

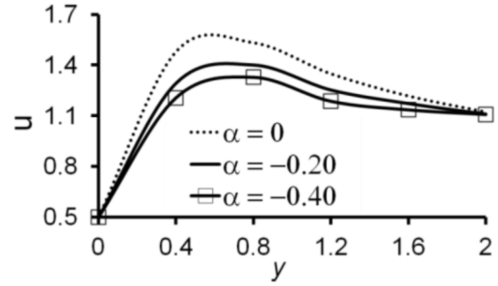

Fig. 2: Fluid velocity u against y with M=1, Sc=0.5, Pr=2, Gm=2, Gr=4, Q_1=2, K=2, γ=0.2.

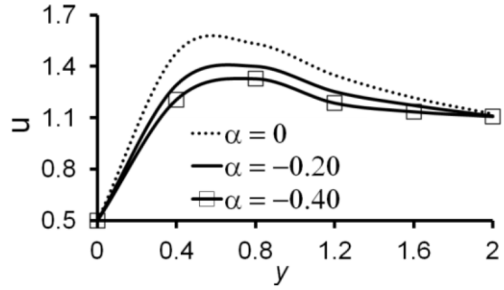

Fig. 3: Fluid velocity u against y with M=1, Sc=0.8, Pr=2, Gm=2, Gr=4, Q_1=2, K=2, γ=0.2.

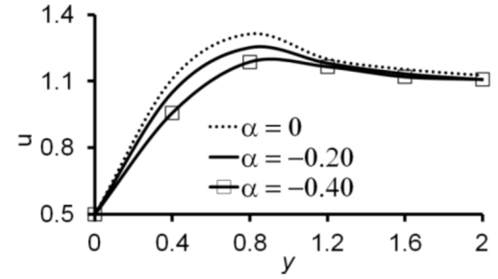

Fig. 4: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=2, Gr=4, Q_1=2, K=2, γ=0.2.

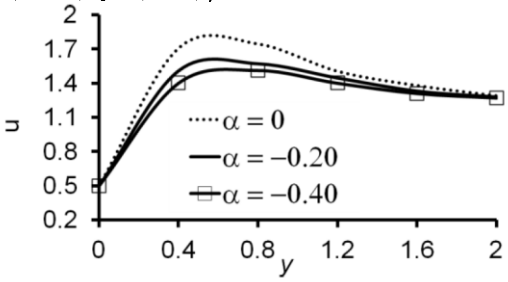

Fig. 5: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=4, Gr=4, Q_1=2, K=2, γ=0.2.

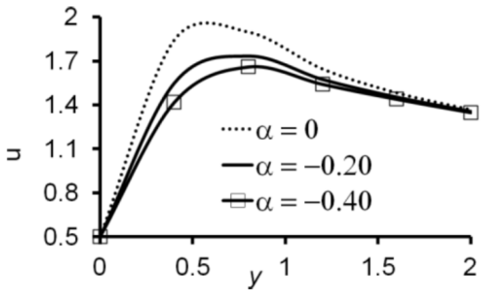

Fig. 6: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=4, Gr=6, Q_1=2, K=2, γ=0.2.

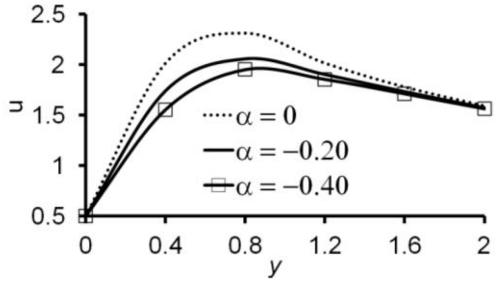

Fig. 7: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=4, Gr=6, Q_1=4, K=2, γ=0.2.

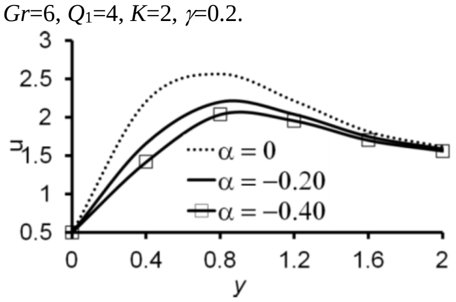

Fig. 8: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=4, Gr=6, Q_1=4, K=5, γ=0.2.

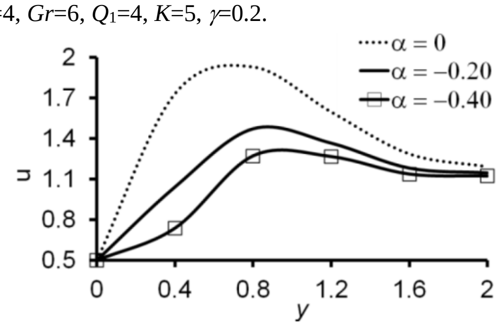

Fig. 9: Fluid velocity u against y with M=1, Sc=0.8, Pr=4, Gm=4, Gr=6, Q_1=4, K=5, γ=0.6.

locity decrease with the increasing values of magnetic field parameter (Figs. 1 and 2), Schmidt number (Figs. 2 and 3), Prandtl number (Figs. 3 and 4) and chemical reaction parameter increases (Figs. 8 and 9) for both Newtonian and visco-elastic cases. It indicates the fact that the fluid motion is retarded due to the application of the transverse magnetic field, Schmidt number, Prandtl number, chemical reaction parameter, whereas it is accelerated under the effects of mass diffusion, thermal diffusion, radiation, porous permeability parameter for both Newtonian and visco-elastic fluid.

The skin friction (wall shear stress) at the plate is given by

$$\sigma = \frac{\bar{\sigma}}{\rho V_0^2} = \left[\frac{\partial u}{\partial y} + \alpha \left\{ \frac{\partial^2 u}{\partial y \partial t} - \left(1 + \in e^{i\omega t}\right) \frac{\partial^2 u}{\partial y^2} \right\} \right]_{y=0}$$

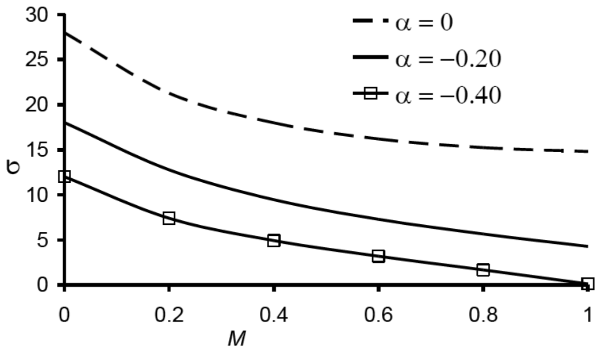

Fig. 10: Skin friction σ against M with Sc=0.2, Pr=2, Gm=2, Gr=2, Q_1=4, K=5, γ=0.2, u_p=0.5, ε=0.2, t=0.5, φ=2, ω=0.1.

Figure 10 exhibits the behaviour of the skin friction σ against M for various visco-elastic parameters. It is evident from the figure that an increase in the magnetic field parameter decreases the skin friction for both Newtonian and visco-elastic fluid. Also, it is seen that the growth of absolute value of the visco-elastic parameter $|\alpha|$, (α=0,-0.2,-0.4) reduces the skin friction.

Heat transfer coefficient in terms of Nusselt number is given by

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

Mass transfer coefficient in terms of Sherwood number is given by

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

It has also been observed that the Nusselt number and Sherwood number are not significantly affected by the visco-elastic parameter.

V. CONCLUSIONS

The above study leads to the following conclusions:

1. The velocity field has a decelerating trend with the growing effect of magnitude of the visco-elastic parameter.
2. Velocity increases with the increasing values of mass diffusion, thermal diffusion, radiation, and porous permeability parameter for both Newtonian and visco-elastic cases.
3. Velocity decreases with the increasing values of magnetic field, Schmidt number, Prandtl number, chemical reaction parameter for both Newtonian and visco-elastic cases.
4. The skin friction coefficient shows a decelerating trend with the growth of magnitude of the visco-elastic parameter.
5. Magnetic field parameter reduces skin friction coefficient for both Newtonian and visco-elastic cases.

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