HEAT AND MASS TRANSFER OF MHD VISCO-ELASTIC OSCILLATORY FLOW THROUGH AN INCLINED CHANNEL WITH HEAT GENERATION/ ABSORPTION IN PRESENCE OF CHEMICAL REACTION

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Abstract— **The purpose of this work is to investigate the unsteady hydromagnetic oscillatory flow of a fluid through an inclined channel between two parallel flat plates under the influence of magnetic field and first-order chemical reaction with heat transfer including heat generating sources or heat absorbing sinks, while one of these two plates is adiabatic. The fluid is assumed to be visco-elastic (second-order), incompressible and electrically conducting. The magnetic field is applied transversely to the direction of the flow. The resulting problem has been solved and the graphs for velocity profile, temperature profile, concentration profile and shear stress are plotted and discussed. The analysis of the obtained results showed that the flow field is appreciably influenced by the material parameter of the second-order fluid and the flow parameters involved in the problems.**

Keywords— **Visco-elastic, Second-order, Magnetic field, First-order chemical reaction, Heat transfer, Mass transfer.**

I. INTRODUCTION

The phenomenon of heat and mass transfer problems with chemical reaction has been the object of extensive research due to its application in many industrial processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower, and the flow in a desert cooler, heat and mass transfer occurs simultaneously. Many practical diffusive operations involve the molecular diffusion of a species in the presence of chemical reaction within or at the boundary. Therefore, the study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists. One of the simplest chemical reactions is the first-order reaction in which the rate of the reaction is directly proportional to the species concentration. The chemical reactions can be codified as either heterogeneous or homogeneous processes. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of the first order if the rate of the reaction is directly proportional to the concentration. Soundalgekar and Warve (1977) have analyzed two dimensional unsteady free convection flows, past an infinite vertical plate with oscillating wall temperature and constant suction. The effects of suction, which oscillates in time about a constant mean, have also been studied by them. Lin and Wu (1995) have analyzed the problem of simultaneous heat and mass transfer with entire range of buoyancy ratio for most practical chemical species in dilute and aqueous solutions.

Singh and Kumar (2010) investigated the effects of chemical reaction and heat generation/absorption on unsteady MHD free convection heat and mass transfer flow of an electrically conducting, viscous, incompressible fluid past an infinite hot vertical porous plate through porous medium when the plate temperature is span wise co- sinusoidally fluctuating with time. Abo-Eldahab *et al*. (2005) studied MHD mixed free-forced heat and mass convective steady incompressible laminar boundary layer flow of a gray optically thick electrically conducting viscous fluid past a semi-infinite inclined plate for high temperature and concentration differences. Pal and Talukdar (2010) presented an analysis for the problem of unsteady mixed convection with thermal radiation and first-order chemical reaction on magnetohydrodynamics boundary layer flow of viscous, electrically conducting fluid past a vertical permeable plate has been presented. The combined effects of Joule heating and chemical reaction on unsteady magnetohydrodynamic mixed convection with viscous dissipation over a vertical plate in the presence of porous media and thermal radiation.

Oscillatory flows are associated with higher rates of heat and mass transfer. Many studies have been done to understand its characteristics in different systems such as reciprocating engines, pulse combustors and chemical reactors etc. A detailed study on fluid mechanics of oscillatory and modulated flows and associated applications in heat and mass transfer have been made by Cooper *et al.* (1993). Choudhury and Das (2012) studied the problem of heat transfer to MHD oscillatory visco-elastic flow in a channel filled with porous medium. Fusegi (1997) has numerically studied the influence of convective heat transfer from periodic open cavities in a channel with oscillatory flow. Modather *et al.* (2009) presented an analysis for the problem of heat and mass transfer of an oscillatory two- dimensional viscous, electrically conducting micropolar fluid over an infinite moving permeable plate in a saturated porous medium in the presence of a transverse magnetic field. Bhargava *et al*. (2009) analyzed the problem of unsteady incompressible magneto-hydrodynamic (MHD) free convection flow with mass transfer past a semi-infinite vertical plate in a Darcian porous medium in the presence of significant thermal radiation, first order homogenous chemical reaction and viscous heating. Bakr (2011) studied the steady and unsteady MHD micropolar flow and mass transfers flow with constant heat source in a rotating frame of reference in the presence of chemical reaction of the first-order, taking an oscillatory plate velocity and a constant suction velocity at the plate. The effects of chemical reaction on MHD free convective oscillatory flow past a porous plate with viscous dissipation and heat sink has been studied by Sekhar and Reddy (2012). Das (2012) studied the visco-elastic effects on MHD oscillatory flow in a channel filled with porous medium in the presence of first-order chemical reaction and radiative heat transfer. Devika *et al*. (2013) presented an analysis of MHD oscillatory flow of a visco elastic fluid in a porous channel with chemical reaction. Several investigators (Mahanta and Choudhury, 2013; Singh *et al*., 2014; Prakash and Makinde, 2015; Misra and Adhikary, 2016) studied MHD oscillatory flow problems in different situations.

In this paper, an attempt has been made to study the problem of unsteady hydromagnetic oscillatory flow of a visco-elastic fluid through an inclined channel between two parallel flat plates under the influence of a uniform transverse magnetic field with heat generating sources or heat absorbing sinks. A first-order homogeneous chemical reaction is assumed between the fluid and species concentration. A closed form analytical solutions have been obtained for the velocity, temperature and concentration distributions and are shown graphically.

II. FORMULATION OF THE PROBLEM

Consider the unsteady MHD oscillatory flow of a visco-elastic, incompressible, electrically conducting fluid through an inclined channel between two parallel flat plates which are at a distance $2h$ apart under the influence of a uniform transverse magnetic field. The $\bar{x}$-axis is taken along a straight line mid-way between the two plates and the $\bar{y}$–axis perpendicular to it. The Physical model is shown in Fig. 1.

The following assumptions are made:

(i) All the fluid properties except the density in the buoyancy force are constant.

(ii) The plates are infinitely long, so that the fluid velocity $\bar{u}$ along $\bar{x}$-axis is function of $\bar{y}$ and time $\bar{t}$ only.

(iii) The flow is slow and slowly moving. The flow between the plates is fully developed.

(iv) A uniform magnetic field of strength B_0 is applied along $\bar{y}$-direction.

(v) The magnetic Reynolds number is small so that the induced magnetic field can be neglected.

(vi) The Hall Effect and viscous dissipation are assumed to be neglected. Only electro-magnetic body force (Lorentz force) is considered.

(vii) There exists a first-order homogeneous chemical reaction between the fluid and species concentration with rate constant K_R between the diffusing species and the fluid.

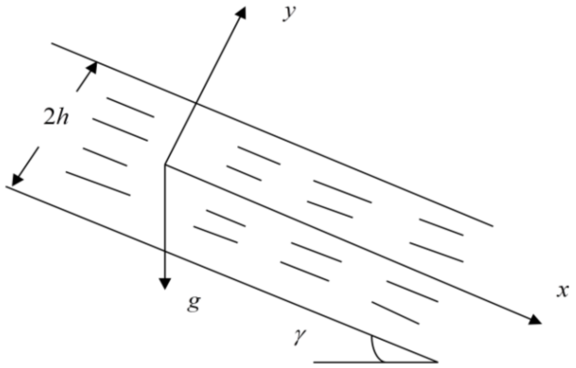

Fig. 1. Schematic representation of the flow geometry.

(viii) At time $\bar{t}$>0 the temperature and concentration at the plate $\bar{y}$=-h changes to $\bar{T} = T_0 + (T_w - T_0)e^{i\bar{\varpi}\bar{t}}$ and $\bar{C} = C_0 + (C_w - C_0)e^{i\bar{\varpi}\bar{t}}$ respectively. The temperature and concentration at the plate $\bar{y}$ =h changes accordingly to $\partial\bar{T}/\partial\bar{y} = 0$ and $\partial\bar{C}/\partial\bar{y} = 0$ respectively, where T_w and T_0 are temperature of the plates, C_w and C_0 are the concentration at the walls, and $\bar{\varpi} \geq 0$ is a real number, denoting the decay factor.

The constitutive equation for the incompressible second-order fluid given by Coleman and Noll (1960) is

$$S = -pI + \mu_1 A_1 + \mu_2 A_2 + \mu_3 (A_1)^2,$$

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 (Markovitz and Coleman, 1964).

The expressions for A_1 and A_2 are given by

$$A_{(1)ij} = v_{i,j} + v_{j,i},$$

$$A_{(2)ij} = a_{i,j} + a_{j,i} + 2v_{m},_{i} v_{m,j},,$$

where v_i and a_i are the i th component of the velocity and acceleration vectors respectively and a comma denotes co-variant differentiation with respect to the symbol following it.

Under the above assumptions, the governing equations of continuity, momentum, energy and concentration equations for the unsteady flow and heat transfer problem of incompressible second-order fluid are

$$\frac{\partial\bar{u}}{\partial\bar{x}} = 0, \tag{1}$$

$$\frac{\partial\bar{u}}{\partial\bar{t}} = -\frac{\partial\bar{p}}{\partial\bar{x}} + \nu_1\frac{\partial^2\bar{u}}{\partial\bar{y}^2} + \nu_2\frac{\partial^3\bar{u}}{\partial\bar{y}^2\bar{t}} + g\sin\gamma + g\beta_T(\bar{T} - T_0)\sin\gamma + g\beta_c(\bar{T} - T_0)\sin\gamma - \sigma B_0^2\bar{u}, \tag{2}$$

$$\frac{\partial\bar{T}}{\partial\bar{t}} = \frac{k}{\rho C_p}\frac{\partial^2\bar{T}}{\partial\bar{y}^2} + \frac{\bar{S}}{\rho C_p}(\bar{T} - T_0), \tag{3}$$

$$\frac{\partial\bar{C}}{\partial\bar{t}} = D\frac{\partial^2\bar{T}}{\partial y^2} + K_R(\bar{C} - C_0)\cdot \tag{4}$$

with boundary conditions

$$\bar{t} > 0, \bar{u} = -u_0, \bar{T} = T_0 + (T_w - T_0)e^{-i\bar{\omega}\bar{t}},$$
$$\bar{C} = C_0 + (C_w - C_0)e^{-i\bar{\omega}\bar{t}} \quad \text{at} \quad y = -h; \tag{5}$$
$$\bar{u} = u_0, \partial\bar{T}/\partial y = 0, \partial\bar{C}/\partial y = 0 \quad \text{at} \quad y = h,$$

where ρ is the density of the fluid, $\bar{p}$ is the pressure, g is the acceleration due to gravity, γ is the angle of the flow channel to the horizontal, σ is the electrical conductivity of the fluid, k is the thermal conductivity, $\bar{S}$ is the source or sink parameter, β_T is the coefficient of volume expansion due to temperature, β_C is the coefficient of volume expansion due to mass transfer, c_p is the specific heat at constant pressure, D is the mass diffusion coefficient, $v_i=\mu_i/\rho$ (i=1,2).

Introducing non-dimensional parameters

$$x = \frac{\bar{x}}{h},\ y = \frac{\bar{y}}{h},\ u = \frac{\bar{u}}{h},\ t = \frac{\bar{t}v_1}{h},\ p = \frac{\bar{p}}{\rho u_0^2},\ S = \frac{h^2\bar{S}}{v_1\rho C_p},$$
$$\omega = \frac{\bar{\omega}h^2}{v_1},\ K_r = \frac{K_R}{v_1},\ Sc = \frac{v_1}{D},\ R = \frac{hu_0}{v_1},\ F_r = \frac{u_0^2}{gh},$$
$$M^2 = \frac{\sigma B_0^2 h^2}{\rho v_1},\ \Pr = \frac{\mu_1 C_p}{k},\ Gr = \frac{g\beta_T(T_w - T_0)h^2}{v_1 u_0},$$
$$Gc = \frac{g\beta_c(C_w - C_0)h^2}{v_1 u_0}. \tag{6}$$

Equations (1)-(4) become

$$\frac{\partial u}{\partial x} = 0, \tag{7}$$

$$\frac{\partial u}{\partial t} = -R\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} + \alpha\frac{\partial^3 u}{\partial y^2 t} + \frac{R}{F_r}\sin\gamma + Gr\theta\sin\gamma + Gc\phi\sin\gamma - M^2 u, \tag{8}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2} + S\theta, \tag{9}$$

$$\frac{\partial\phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2} + K_r\phi. \tag{10}$$

where K_r is the chemical reaction parameter, Sc is the Schimdt number, R is the Reynolds number, F_r is the Froude number, Pr is the Prandtl number, Gr is the Grashof number for heat transfer, Gc is the Grashof number for mass transfer, $\alpha=v_2/h^2$ is the visco-elastic parameter.

The dimensionless form of the boundary conditions (5) become

$$t > 0, u = -1, \theta = e^{-i\omega t}, \phi = e^{-i\omega t} \quad \text{at} \quad y = -1; \tag{11}$$
$$u = 1, \partial\theta/\partial y = 0, \partial\phi/\partial y = 0 \quad \text{at} \quad y = 1,$$

III. METHOD OF SOLUTION

The Eq. (7) shows that u is a function of y and t only or a constant. Thus, the term $\partial p/\partial x$ must be a constant or the function of t only.

Let $\partial p/\partial x=h(t)$, then the Eq. (8) become

$$\frac{\partial u}{\partial t} = -Rh(t) + \frac{\partial^2 u}{\partial y^2} + \alpha\frac{\partial^3 u}{\partial y^2 t} + \frac{R}{F_r}\sin\gamma + Gr\theta\sin\gamma + Gc\phi\sin\gamma - M^2 u, \tag{12}$$

In order to solve the Eqs. (9), (10), and (12) for oscillatory flow, let

$$u = F(y)e^{-i\omega t},\quad \theta = G(y)e^{-i\omega t},$$
$$\phi = H(y)e^{-i\omega t},\quad h = h_0 e^{-i\omega t}. \tag{13}$$

Substituting the above expressions on (12), (9), and (10), we get

$$(1 - i\omega\alpha)F'' + i\omega F - Rh_0 - M^2 F = -GrG\sin\gamma - GcH\sin\gamma - \frac{R}{F_r}e^{i\omega t}\sin\gamma, \tag{14}$$

$$G'' + (\Pr S + i\omega)G = 0, \tag{15}$$

$$H'' + Sc(K_r - i\omega)H = 0. \tag{16}$$

The boundary conditions become

$$F(-1) = -e^{i\omega t}, G(-1) = 1, H(-1) = 1 \quad \text{at} \quad y = -1; \tag{17}$$
$$F(1) = e^{i\omega t}, G(1) = 0, H(1) = 0 \quad \text{at} \quad y = 1,$$

The solutions of the Eqs. (15) and (16) under boundary conditions (17) are

$$G(y) = e^{-A_2 y}\{C_1\cos(A_3 y) + C_2\sin(A_3 y)\},$$
$$H(y) = e^{-A_5 y}\{C_3\cos(A_6 y) + C_4\sin(A_6 y)\},$$

where

$$A_1 = \sqrt{\Pr^2 s^2 + \omega^2},\ A_2 = \sqrt{A_1(A_1 - s\Pr)/2},$$
$$A_3 = \sqrt{A_1 + s\Pr},\ A_4 = \sqrt{Kr^2 + \omega^2},$$
$$A_5 = \sqrt{A_4(A_4 - Kr)/2},\ A_6 = \sqrt{A_4 - Kr},$$
$$C_1 = \frac{e^{-A_3}\cos A_3}{2\cos(2A_3)},\ C_2 = \frac{C_1\sin A_3}{\cos A_3},\ C_3 = \frac{e^{-A_5}\cos A_6}{2\cos(2A_6)},$$
$$C_4 = \frac{C_3\sin A_6}{\cos A_6}.$$

The solution of the Eq. (14) under boundary conditions (17) is obtained, but not presented here for the sake of brevity.

The shear stress distribution is given by

$$\tau = \frac{\bar{\tau}}{\frac{\mu_1 u_0}{h}} = \left[\frac{\partial u}{\partial y} + \alpha\frac{\partial^2 y}{\partial y\partial t}\right].$$

IV. RESULT AND DISCUSSION

In this paper, the unsteady MHD oscillatory flow of a slow and slowly moving visco-elastic incompressible electrically conducting fluid through an inclined channel between two parallel flat plates under the influence of a uniform transverse magnetic field and chemical reaction is studied. Numerical evaluation for the analytical solution of this problem is performed and the results are illustrated by means of graphs. We have considered the real parts of the results throughout for numerical validation. Throughout the numerical computations, the following numerical values are assigned Pr=5, γ=45°, S=-1, K_r=0.1, α=-0.1, Sc=0.1, Gc=1, Gr=5, M=0.2, R=1, h_0=1, t=1 unless otherwise stated.

Figures 2-8 illustrates the effect on velocity profile due to magnetic field parameter (M), Schmidt number (Sc), Prandtl number (Pr), solutal Grashof number (Gc), thermal Grashof number (Gr), heat suction parameter (-S), visco-elastic parameter $|\alpha|$, respectively.

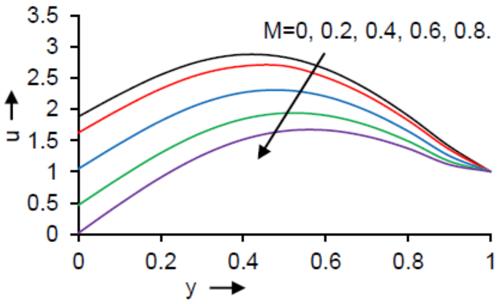

Fig. 2. Velocity profile for different values of *M*.

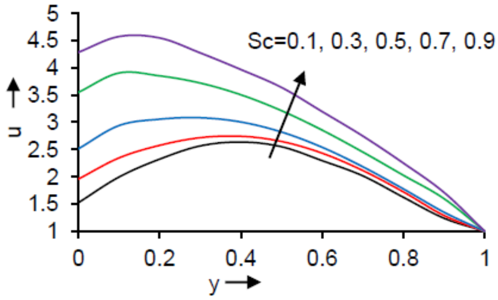

Fig. 3. Velocity profile for different values of *Sc*.

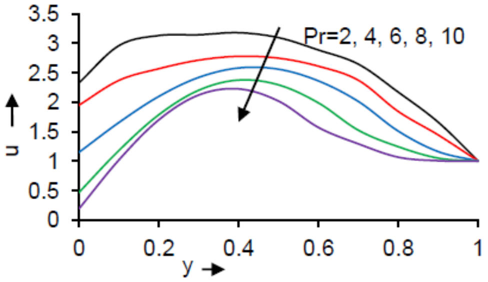

Fig. 4. Velocity profile for different values of Pr.

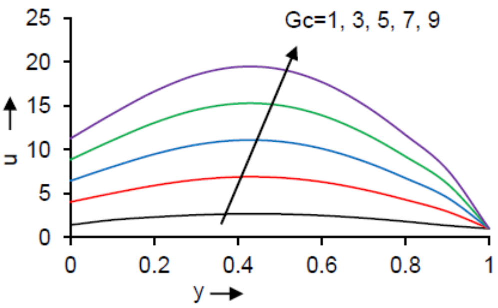

Fig. 5. Velocity profile for different values of *Gc*.

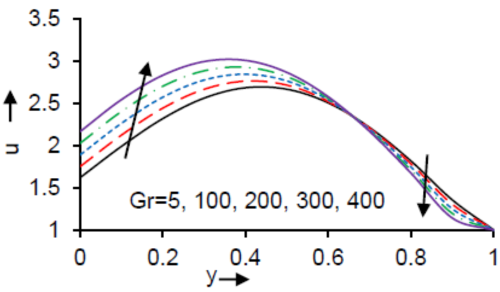

Fig. 6. Velocity profile for different values of *Gr*.

From Fig.2, it is seen that an increase in the magnetic field parameter M from M=0 (non-conducting case) to 0.8 through 0.2, 0.4, 0.6 induces a reduction in velocities. This is expected, since the presence of transverse magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts to impede the flow motion, and thus to reduce the velocity. Further, the velocity increases with the increasing values of Schimdt number (Fig. 3), solutal Grashof number (Fig. 5). But, the velocity decreases with the increasing values of Prandtl number (Fig. 4), heat suction parameter (-S) (Fig. 7) and visco-elastic parameter $|\alpha|$ (Fig. 8). The presence of heat suction parameter physically implies absorption of thermal energy which decreases the velocity. Also, from Fig. 8, it is seen that the behavior of velocity profiles remain the same for both Newtonian (α=0) and non-Newtonian cases ($\alpha \neq 0$), and the higher values of the magnitude of the visco-elastic parameter are having more stability than the lower values.

From Fig. 6 it is observed that the velocity increases initially with the increasing values of the thermal Grashof number (Gr) (for approximately $y \leq 0.65$), and then reverse effect is seen (for approximately).

Figure 9 represent the temperature profile against y for different values of the decay factor ω. From the figure, temperature increases with the increasing values of ω.

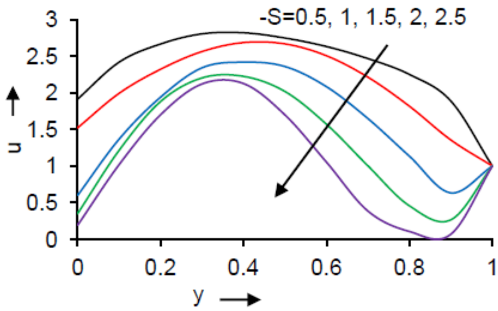

Fig. 7. Velocity profile for different values of *S*.

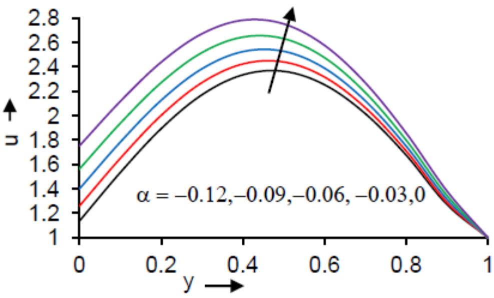

Fig. 8. Velocity profile for different values of α.

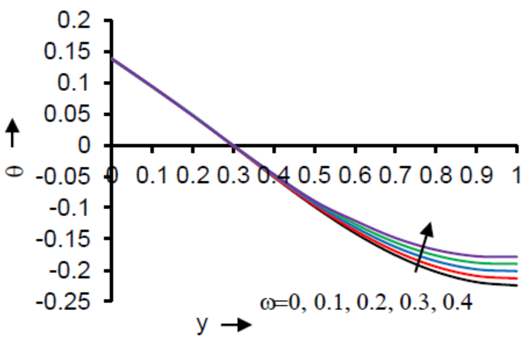

Fig. 9. Temperature profile for different values of ω.

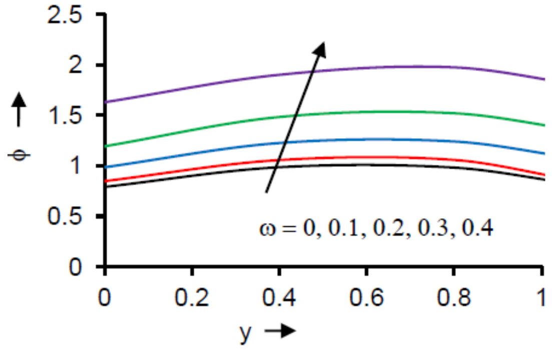

Fig. 10. Concentration profile for different values of ω.

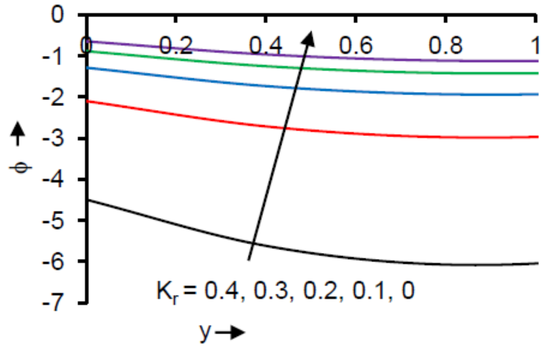

Fig. 11. Concentration profile for different values of K_r.

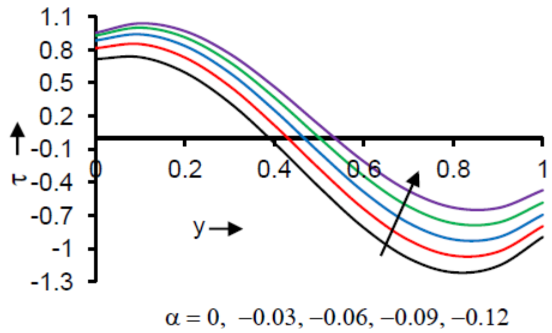

Fig. 12. Variation of shear stress for different values of α.

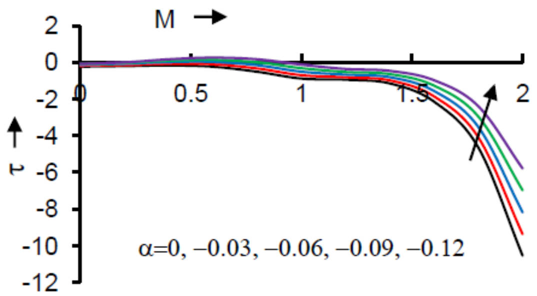

Fig. 13. Variation of shear stress against M for different values of α.

Figures 10 and 11 represents the effect on the species concentration profile for different values of ω and chemical reaction rate parameter K_r respectively, by fixing other physical parameter. It is observed that the concentration increases with the increase of ω. Further, it is observed that increasing the value of the chemical reaction parameter decreases the concentration of species.

The effect of visco-elastic parameter α on shear stress is shown in Fig. 12. From the figure, it is seen that the shear stress increases with the increasing values of the magnitude of the visco-elastic parameter $|\alpha|$. Figure 13 represent the variation of shear stress against the magnetic field parameter for various values of the visco-elastic parameter. It is observed that the shear stress decreases with the increasing values of the magnetic field parameter for both Newtonian (α=0) and non-Newtonian cases (α=-0.03, -0.06, -0.09, -0.12).

V. CONCLUSIONS

A theoretical analysis of the magnetohydrodynamic oscillatory flow of an incompressible, electrically conducting, visco-elastic fluid in an inclined channel with heat generation/suction has been conducted. Analytical solutions are obtained for velocity, temperature and concentration profiles. The above computation leads to the following conclusions

1. Velocity decreases with the increasing values of magnetic field parameter, Prandtl number, heat suction parameter and visco-elastic parameter $|\alpha|$.
2. Velocity increases with the increasing values of Schimdt number, solutal Grashof number.
3. Temperature and concentration increases with the increasing values of the decay parameter whereas chemical reaction parameter decreases the concentration profile.
4. Shear stress increases with the increasing values of the magnitude of the visco-velastic parameter whereas it decreases with the increasing values of the magnetic field parameter

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