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Hall Effect on MHD Mixed Convection Flow of Viscous-Elastic Incompressible Fluid Past of an Infinite Porous Medium

T. K. Das, N. Senapatil, R. K. Dhal

***Abstract*—**An unsteady mixed free convection MHD flow of elastic-viscous incompressible fluid past an infinite vertical porous flat plate is investigated when the presence of heat Source/sink, temperature and concentration are assumed to be oscillating with time and hall effect. The governing equations are solved by complex variable technique. The expressions for the velocity field, temperature field and species concentration are demonstrated in graphs. The effects of the Prandtl number, the Grashof number, modified Grashof number, the Schimidt number, the Hall parameter, Elastic parameter & Magnetic parameter are discussed.

***Keyword*—**MHD, Mixed convective, Elastic-viscous incompressible, rotational, heat transfer, mass transfer, suction and injection.

I. Introduction

THE convection problem in a porous medium has important application in geothermal reservoirs and geothermal energy extractions. MHD has attracted the attention of many scholars due to its diverse application in geophysics and astrophysics. It is applied to study the stellar and solar structure, interstellar matter, radio propagation through the ionosphere, design of MHD generators and accelerators in geophysics, in design of underground water energy storage system, soil-sciences, astrophysics, nuclear power reactors and so on. The phenomena of mass transfer is very common in theory of stellar structure, burning a pool of oil, spray drying, adsorption, leaching and mass transport process in animal and plant life. The effect of Hall current on the fluid flow with variable concentration has many applications in MHD power generation, in several astrophysical and meteorological studies as well as in plasma flow through MHD power generators.

The studies in convection flows of a viscous electrically conducting fluid in rotating channels partially filled with porous substrates in the presence of a magnetic field have a wide range of scientific and engineering applications. During alloy solidification convection effects are important because they affect the solid fluid content within a porous layer known as mushy layer. Further, these rotating flows are electromagnetically braked by a force (Lorentz force) and therefore have applications. Datta and Jana [1] have investigated the problem of flow and heat transfer in an elastic-viscous liquid over an oscillating plate in a rotating flame. Biswal and Sahoo [2] have studied the Hall effect on oscillatory hydromagnetic free convective flow of a viscous-elastic fluid past an infinite vertical porous flat plate with mass transfer. Acharya et al. [3] have studied the Hall Effect with simultaneous thermal and mass diffusion on unsteady hydromagnetic flow near an accelerated vertical plate. Aboeldahab et al. [4] have analyzed Hall current effect on magnetohydrodynamics free convection flow past a semi-infinite vertical plate with mass transfer. Senapati et al. [5] have discussed the Effect of heat and mass transfer on MHD free convection flow past an oscillating vertical plate with variable temperature embedded in porous medium. Abel et al. [6], [8], [9] & [11] have studied the viscoelasticity on the flow and heat transfer in a porous medium over a stretching sheet. Andersson [7] have investigated the flow problem of electrically conducting viscous-elastic fluid past a flat and impermeable elastic. Sheddeek [10] have studied Heat & Mass transfer on a stretching sheet with a magnetic field in a viscous-elastic fluid flow through a porous medium. Prasad et al. [12] have investigated the effect of variable viscosity on viscous-elastic fluid flow and Heat transfer over a stretching sheet. Rajgopal et al. [13] have examined for a special class of visco-elastic fluids known as second order fluids.

In the present analysis, it is proposed to study the effect of simultaneous heat and mass transfer on the flow of viscous-elastic fluid past an impulsively started infinite vertical plate with mass transfer and taking Hall Effect into account. Closed form analytical solutions have been obtained for the velocity, temperature and concentration distributions and are shown graphically.

II. Problem Formulation

Consider the unsteady flow of an electrically conducting fluid past an infinite vertical porous flat plate coinciding with the plane y=0 such that the x-axis is along the plate and y-axis is normal to it. A uniform magnetic field B0 is applied in the direction y-axis and the plate is taken as electrically non-conducting. Taking Z-axis normal to xy-plane and assuming that the velocity V and the magnetic H have components (u, v, w) and (Hx, Hy, Hy) respectively, the equation of continuity $\nabla . v$=0 and solenoidal relation $\nabla . H = 0$ give v=-v0 constant,

T. K. Das is with the Gurukula institute of technology, BBSR, Orissa, India (e-mail: tusharkant.dash078@gmail.com).
N. Senapati is with the Department of Mathematics, Ravenshaw University, Cuttack, Orissa-753003, India (e-mail: nityananda.senapati@gmail.com).
R. K. Dhal is with the J.N.V. Paralakhemundi, Gajapati, Orissa-761201, India (e-mail: dhal.rajendra@gmail.com).

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$$v_0 > 0 \tag{1}$$

from Maxwell's electromagnetic field equation

$$\frac{dHy}{dy}=0 \tag{2}$$

If the magnetic Reynold number is small, induced magnetic field is negligible in comparison with the applied magnetic field, so that Hx=Hz=0 and Hy=B0(constant). If (Jx, Jy, Jz) are the components of electric current density $\vec{J}$, the equation of Conservation of electric charge $\nabla.\vec{J}=0$ gives

$$\text{Jy} = \text{constant} \tag{3}$$

Since the plate is non-conducting, Jy = 0 at the plate and hence zero everywhere in the flow.

Neglecting polarization effect, we get

$$\vec{E}=0 \tag{4}$$

Hence $\vec{j}=(Jx,0,Jz)$, $\vec{H}=(0,B_0,0)$

$$\vec{V}=(u,V_0,w) \tag{5}$$

The generalized Ohm's law, taking Hall Effect into account is given by

$$\vec{j}+\frac{w_e\tau_e}{B_0}\left(\vec{J}\times\vec{H}\right)=\sigma(\vec{E}+\vec{V}\times\vec{B}+\frac{1}{e\eta_e}\nabla p_e) \tag{6}$$

where $\vec{V}$ is the velocity vector, w_e is the electron frequency, τ_e is the electron collision time, e is the electron charge, η_e is the number density of electron, p_e is the electron pressure, σ is the electric conductivity and $\vec{E}$ is the electric field. In writing (6) ion slip, thermoelectric effects and polarization effects are neglected. Further it is also assumed that $w_e\tau_e \approx 0$ and $w_i\tau_i \le 1$, where w_e, w_i are cyclone frequency of electrons and ions and τ_e, τ_i are collision times of electrons and ions (5) & (6) yield

$$J_X=\frac{\sigma B_0(mu-w)}{1+m^2}$$

$$J_y=\frac{\sigma B_0(u+mw)}{1+m^2}$$

where u & w are the x-component and z-component of $\vec{V}$ and $m=w_e\tau_e$ is the hall parameter. The equation of motion, energy and concentration governing the flow under the usual Boussinesq approximation are

Equation of continuity

$$\frac{\partial v}{\partial y}=0$$

Since $v=-v_0$ where v_0 is constant suction velocity

Momentum equation

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^{\,2}(u+mw)}{\rho(1+m^2)}+g\beta(T-T_\infty)+g\beta^*(C-C_\infty)-\frac{\upsilon u}{k}-k_0\frac{\partial^3 u}{\partial y^2\partial t} \tag{7}$$

$$\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial y}=v\frac{\partial^2 w}{\partial y^2}-\frac{\sigma B_0^{\,2}(w-mu)}{\rho(1+m^2)}-\frac{\upsilon w}{k}-k_0\frac{\partial^3 w}{\partial y^2\partial t} \tag{8}$$

$$\frac{\partial(T-T_\infty)}{\partial t}+v\frac{\partial(T-T_\infty)}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2(T-T_\infty)}{\partial y^2} \tag{9}$$

$$\frac{\partial(C-C_\infty)}{\partial t}+v\frac{\partial(C-C_\infty)}{\partial y}=D\frac{\partial^2(C-C_\infty)}{\partial y^2} \tag{10}$$

Now using $v=-v_0$, $T(y,t)-T_\infty=\theta(y,t)$ and $C(y,t)-C_\infty=C^*(y,t)$

Initial boundary conditions are

t≤ 0 : u(y ,t) = w(y, t) = 0, $\theta=0, C^*=0$ for all y

u(0 ,t)=w(0 ,t)=0, $\theta(0,t)=ae^{iwt}$, $C^*(0,t)=be^{iwt}$ at y = 0 (11)

u(∞,t)=w(∞,t)=0, $\theta(\infty,t)=0$, $C^*(\infty,t)=0$ at y→∞ (t>0)

Introducing the following non-dimensional quantities

$$\eta=\frac{v_0 y}{v}, t'=\frac{v_0^{\,2}t}{4v}, u'=\frac{u}{v_0}, w'=\frac{w}{v_0}, \theta'=\frac{\theta}{a},$$

$$C'=\frac{C^*}{b}, G=\frac{4g\beta\upsilon_a}{v_0^{\,3}}, G_c=\frac{4g\beta^*\upsilon_b}{v_0^{\,3}}, M=\frac{4B_0^{\,2}\sigma v}{\rho v_0^{\,3}}$$

$$P_r=\frac{v\rho C_P}{k}, Sc=\frac{v}{D}, k'=\frac{v_0^{\,2}k}{4v^2}, S'=\frac{4Sv}{v_0^{\,2}}, \alpha=\frac{k_0 v_0^{\,2}}{v^2}, \Omega=\frac{4vw}{v_0^{\,2}} \tag{12}$$

In (7) and to (10), with the boundary condition are transformed to their corresponding non dimensional forms by dropping dashes as

$$\frac{\partial u}{\partial t}-4\frac{\partial u}{\partial \eta}=4\frac{\partial^2 u}{\partial \eta^2}-\frac{M}{(1+m^2)}(mw+u)+Gr\theta'+GmC'-\frac{u}{k}-4\alpha\frac{\partial^3 u}{\partial \eta^2 \partial t} \quad (13)$$

$$\frac{\partial w}{\partial t}-4\frac{\partial w}{\partial \eta}=4\frac{\partial^2 w}{\partial \eta^2}-\frac{M}{(1+m^2)}(w-mu)-\frac{w}{k}-4\alpha\frac{\partial^3 w}{\partial \eta^2 \partial t} \quad (14)$$

$$\frac{\partial \theta}{\partial t}-4\frac{\partial \theta}{\partial \eta}=\frac{4}{\Pr}\frac{\partial^2 \theta}{\partial \eta^2} \quad (15)$$

$$\frac{\partial c}{\partial t}-4\frac{\partial c}{\partial \eta}=\frac{4}{Sc}\frac{\partial^2 c}{\partial \eta^2} \quad (16)$$

where v_0 is some reference velocity,Gr is the Grashof number for heat transfer ,Gm is the Modified Grashof number for mass transfer, Pr is the Prandtl number, Sc is the Schmidt number, M is the magnetic field parameter and α is Elastic parameter.

$t\leq 0$:u(η ,t) = w(η , t) = 0, $\theta = 0, C = 0$ for all η

u(0,t)=w(0,t)=0, $\theta(0,t)=e^{iwt}$, $C(0,t)=e^{iwt}$ at η =0 (17)

u(∞,t)=w(∞,t)=0, $\theta(\infty,t)=0$, $C(\infty,t)=0$ at $\eta \to \infty$ (t>0)

III. Method of Solution

Equations (13) & (14) can be combined using the complex variable

$$\psi = u + iw \quad (18)$$

Giving

$$\Rightarrow \frac{\partial^2 \psi}{\partial \eta^2}-\alpha\frac{\partial^3 \psi}{\partial \eta^2 \partial t}-\frac{1}{4}\frac{\partial \psi}{\partial t}+\frac{\partial \psi}{\partial \eta}-\frac{1}{4}[\frac{M(1-im)}{1+m^2}+\frac{1}{k}]\psi=-\frac{Gr\theta}{4}-\frac{GmC}{4} \quad (19)$$

Introducing the non-dimensional parameter $\Omega=\frac{4vw}{v_0^2}$ and using (18), the boundary condition in (17) are transferred to

$$\psi(0,t)=\psi(\infty,t)=0, C(0,t)=e^{i\Omega t}$$
$$\theta(0,t)=e^{i\Omega t}, \theta(\infty,t)=0, C(\infty,t)=0 \quad (20)$$

Putting $\theta(\eta,t)=e^{i\Omega t}f(\eta)$ in (15), we get

$$\frac{\partial \theta}{\partial t'}-4\frac{\partial \theta}{\partial \eta}=\frac{4}{\Pr}\frac{\partial^2 \theta}{\partial \eta^2}$$

$$\Rightarrow e^{i\Omega t}.i\Omega f(\eta)-4e^{i\Omega t}f'(\eta)=\frac{4}{\Pr}e^{i\Omega t}f''(\eta)$$

$$\Rightarrow f''(\eta)+\Pr f'(\eta)-\frac{i\Omega f(\eta)\Pr}{4}=0 \quad (21)$$

which has to be solved under the boundary condition:

$$f(0)=1, f(\infty)=0 \quad (22)$$

Hence

$$f(\eta)=e^{\frac{1}{2}[-\Pr-\sqrt{\Pr(\Pr+i\Omega)}]\eta}$$

$$\theta(\eta,t)=e^{i\Omega t-[\Pr+\sqrt{\Pr(\Pr+i\Omega)}]\frac{\eta}{2}}$$

Separating real and imaginary part, the real part is given by

$$\theta_r(\eta,t)=Cos(\Omega t-\frac{\eta}{2}R_1 Sin\frac{\beta_1}{2})e^{-\frac{\eta}{2}(\Pr+R_1 Cos\frac{\beta_1}{2})} \quad (23)$$

where

$$R_1=\Pr^{\frac{1}{2}}(\Pr^2+\Omega^2)^{\frac{1}{4}}, \beta_1=\tan^{-1}(\frac{\Omega}{\Pr}) \quad (24)$$

Putting $C(\eta,t)=e^{i\Omega t}g(\eta)$ in (10)

$$g''(\eta)+Scg'(\eta)-\frac{i\Omega g(\eta)Sc}{4}=0 \quad (25)$$

which can be solved under boundary conditions:

$$g(0)=1, g(\infty)=0$$

Hence

$$g(\eta)=e^{\frac{1}{2}[-Sc-\sqrt{Sc(Sc+i\Omega)}]\eta}$$

$$C(\eta,t)=e^{i\Omega t-\frac{\eta}{2}[Sc+\sqrt{Sc(Sc+i\Omega)}]} \quad (26)$$

Separating real and imaginary part, the real part is given by

$$C_r(\eta,t)=Cos(\Omega t-\frac{\eta}{2}R_2 Sin\frac{\beta_2}{2})e^{-\frac{\eta}{2}(Sc+R_2 Cos\frac{\beta_2}{2})}$$

where

$$R_2=Sc^{\frac{1}{2}}(Sc^2+\Omega^2)^{\frac{1}{4}}, \beta_2=\tan^{-1}(\frac{\Omega}{Sc}) \quad (27)$$

In order to solve

$$\frac{\partial^2 \psi}{\partial \eta^2}-\alpha\frac{\partial^3 \psi}{\partial \eta^2 \partial t}-\frac{1}{4}\frac{\partial \psi}{\partial t}+\frac{\partial \psi}{\partial \eta}-\frac{1}{4}[\frac{M(1-im)}{1+m^2}+\frac{1}{k'}]\psi=-\frac{Gr\theta}{4}-\frac{GmC}{4}$$

Substituting $\psi=e^{i\Omega t}F(\eta)$

Using the boundary conditions

$$F(0) = 0, \ F(\infty) = 0 \tag{28}$$

Separating real and imaginary part, we get

Real part

$$u = Fr = \begin{bmatrix} -e^{-\frac{\eta}{2}} e^{-\frac{\eta}{2}A10} [A_{15} Cos(-\frac{\eta}{2} A_9) + A_{18} Sin(-\frac{\eta}{2} A_9)] + A_{13} e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{B1}{2})} Cos(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) \\ - A_{16} Sin(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{\beta 1}{2})} + A_{14} Cos(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} \\ - A_{17} Sin(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} \end{bmatrix} \tag{A}$$

Imaginary

$$w = Fi = \begin{bmatrix} -e^{-\frac{\eta}{2}} e^{-\frac{\eta}{2}A10} [A_{15} Sin(-\frac{\eta}{2} A_9) + A_{18} Cos(-\frac{\eta}{2} A_9)] + A_{13} e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{B1}{2})} Sin(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) \\ + A_{16} Cos(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{\beta 1}{2})} + A_{14} Sin(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} \\ + A_{17} Cos(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} \end{bmatrix} \tag{B}$$

From (A)

u = Fr

$$\begin{bmatrix} -e^{-\frac{\eta}{2}(1+A10)} [A_{15} Cos(-\frac{\eta}{2} A_9) + A_{18} Sin(-\frac{\eta}{2} A_9)] + e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{B1}{2})} [A_{13} Cos(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) - A_{16} Sin(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2})] \\ + e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} [A_{14} Cos(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) - A_{17} Sin(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2})] \end{bmatrix}$$

From (B)

w =Fi =

$$\begin{bmatrix} -e^{-\frac{\eta}{2}(1+A10)} [A_{15} Sin(-\frac{\eta}{2} A_9) + A_{18} Cos(-\frac{\eta}{2} A_9)] + e^{-\frac{\eta}{2}(\Pr + R1 Cos\frac{B1}{2})} [A_{13} Sin(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2}) + A_{16} Cos(-\frac{\eta}{2} R_1 Sin\frac{\beta_1}{2})] \\ + e^{-\frac{\eta}{2}(Sc + R2 Cos\frac{\beta 2}{2})} [A_{14} Sin(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2}) + A_{17} Cos(-\frac{\eta}{2} R_2 Sin\frac{\beta_2}{2})] \end{bmatrix}$$

Here we take

$$a_1 = \frac{1}{2}(1 + \frac{1}{k'}), a_2 = \frac{M}{2(1+m^2)}, a_3 = \frac{1}{2}(\frac{Mm}{1+m^2}), a_4 = \frac{\alpha\Omega}{2}[\Omega - \frac{Mm}{1+m^2}] = \frac{\alpha\Omega}{2}[\Omega - 2a_3]$$

$$a_5 = \frac{\Omega}{2}[\frac{\alpha M}{1+m^2} + \frac{\alpha}{k'} - 1], a_6 = R_1 Sin\frac{\beta_1}{2}, a_7 = R_1 Cos\frac{\beta_1}{2}, a_8 = R_2 Sin\frac{\beta_2}{2}, a_9 = R_2 Cos\frac{\beta_2}{2}$$

Now

$$A_1 = a_1 + a_2 + a_4, A_2 = a_3 + a_5, A_3 = \sqrt{A_1^2 + A_2^2}, A_4 = \sqrt{A_3 + A_1},$$

$$A_5 = \alpha\Omega, A_6 = \sqrt{A_3 - A_1}, A_7 = A_5(1 + A_4), A_8 = A_5 * A_6, A_9 = \frac{A_7 + A_6}{1 + A_5^2}$$

$$A_{10} = \frac{A_4 - A_8}{1 + A_5^2}, A_{11} = \frac{M}{1 + m^2} + \frac{1}{k'}, A_{12} = 2a_3 - \Omega$$

$$A_{13} = \frac{Gr \times A_{11}}{A_{11}^2 + A_{12}^2}, A_{14} = \frac{Gm \times A_{11}}{A_{11}^2 + A_{12}^2}, A_{15} = (A_{13} + A_{14})$$

$$A_{16} = \frac{Gr \times A_{12}}{A_{11}^2 + A_{12}^2}, A_{17} = \frac{Gm \times A_{12}}{A_{11}^2 + A_{12}^2}, A_{18} = (A_{16} + A_{17})$$

$$R_1 = \Pr^{\frac{1}{2}}(\Pr^2 + \Omega^2)^{\frac{1}{4}}, \beta_1 = \tan^{-1}(\frac{\Omega}{\Pr})$$

$$R_2 = Sc^{\frac{1}{2}}(Sc^2 + \Omega^2)^{\frac{1}{4}}, \beta_2 = \tan^{-1}(\frac{\Omega}{Sc})$$

IV. Discussion and Results

In this paper we have studied the Hall Effect on MHD mixed convection flow of viscous-elastic incompressible fluid past of an infinite porous medium. The effect of Gr, Gm, M, K, Sc, Pr, Ω, α, ω and t on flow characteristics have been studied and shown by means of graphs and tables. In the time of drawing the graphs, the real and imaginary parts of velocity and real part of temperature and mass concentration are taken as one axis.

Fig. 1 illustrates the effect of the parameters α,Pr and Sc on velocity profile (u) at any point of the fluid, when M=1, K=1, Gr=1, Gm=1, Ω=1, t=1, m=1 and ω=1. It is noticed that the velocity decreases with the increase of Prandtl number (Pr), Schmidt number (Sc) and Elastic parameter (α).

Fig. 2 illustrates the effect of the parameters Gr, Gm and m on velocity profile (u) at any point of the fluid, when M=1, K=1, Pr=1, Sc=1, Ω=1, t=1 and ω=1. It is noticed that the velocity increases with the increase of modified Grashof number (Gm) and decreases with the increase of Hall parameter (m). Again the velocity initially increases and then decreases with the increase of Grashof number (Gr).

Fig. 3 illustrates the effect of the parameters M, K and Ω on velocity profile (u) at any point of the fluid, when Gr=1, Gm=1, Pr=1, Sc=1, m=1, t=1 and ω=1. It is noticed that the velocity decreases with the increase of porous parameter (K) and frequency parameter (Ω) and increases with the increase of magnetic parameter (M).

Fig. 4 illustrates the effect of the parameters α, Pr and Sc on velocity profile (w) at any point of the fluid, when M=1, K=1, Gr=1, Gm=1, Ω=1, m=1, t=1 and ω=1. It is noticed that the velocity increases with the increase of Prandtl number (Pr), Schmidt number (Sc) and Elastic parameter (α).

Fig. 5 illustrates the effect of the parameters Gr, Gm and m on velocity profile (w) at any point of the fluid, when M=1, K=1, Pr=1, Sc=1, Ω=1, t=1 and ω=1. It is noticed that the velocity decreases with the increase of Hall parameter (m). Again the velocity initially increases and then decreases with the increase of Grashof number (Gr) and modified Grashof number (Gm).

Fig. 6 illustrates the effect of the parameters M, K and Ω on velocity profile (w) at any point of the fluid, when Gr=1, Gm=1, Pr=1, Sc=1, m=1, t=1 and ω=1. It is noticed that the velocity decreases with the increase of porous parameter (K) and increases with the increase of magnetic parameter (M) and frequency parameter (Ω).

Fig. 7 illustrates the effect of the parameters Pr, t and Ω on temperature profile. It is noticed that the temperature falls with increases of frequency parameter (Ω), Prandtl number (Pr) and time (t).

Fig. 8 illustrates the effect of the parameters Sc, t and Ω on the mass concentration profile. It is noticed that the mass concentration decreases with increases of frequency parameter (Ω), Schmidt number (Sc) and time (t).

V. Conclusion

Results are presented graphically to shows the variation of velocity, temperature, mass concentration with various parameters. In this study, the following conclusions are set out:

i. The velocity (u) decreases with the increase in Pr, Sc, m, k, α, Ω and fluctuate then decreases for the increase of Gr, whereas increases with the increase in Gm, M.
ii. The velocity (w) decreases with the increase in m, k and fluctuate then decreases for the increase of Gr and Gm, whereas increases with the increase in Pr, Sc, α, Ω, M.
iii. The temperature falls for the increasing of Pr, t and Ω.
iv. The mass profile decreases for the increasing of Sc, t and Ω.

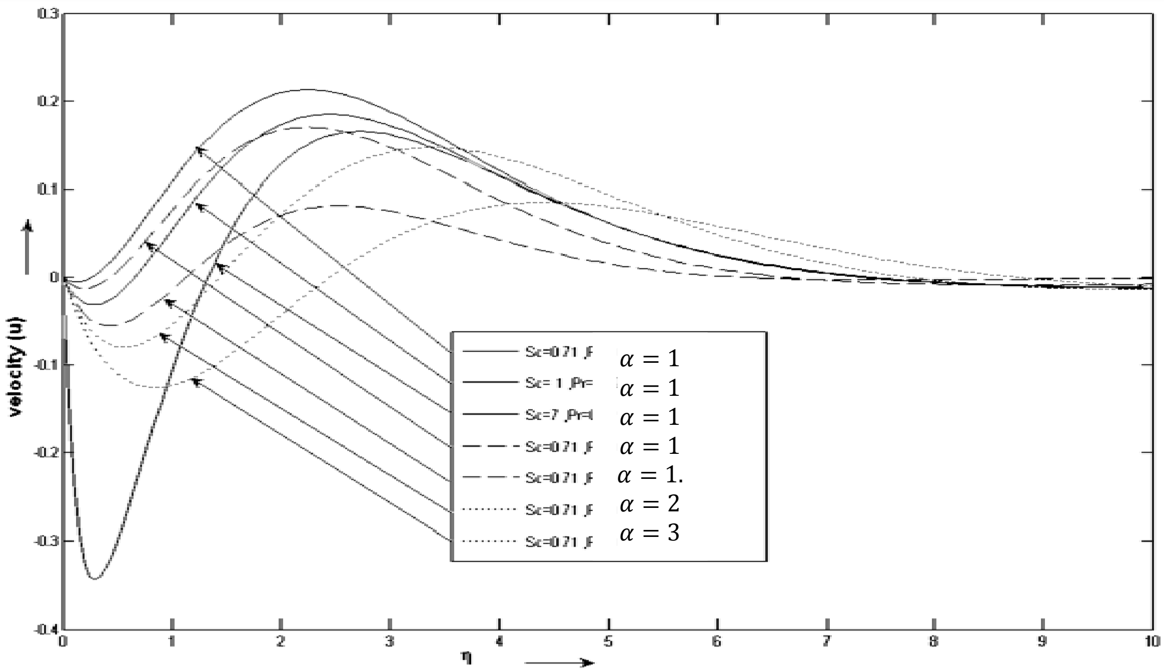

Fig. 1 Effect of α, Pr and Sc on velocity profile(u), when M=1, K=1, Gr=1, Gm=1, Ω=1, t=1, m=1 and ω=1

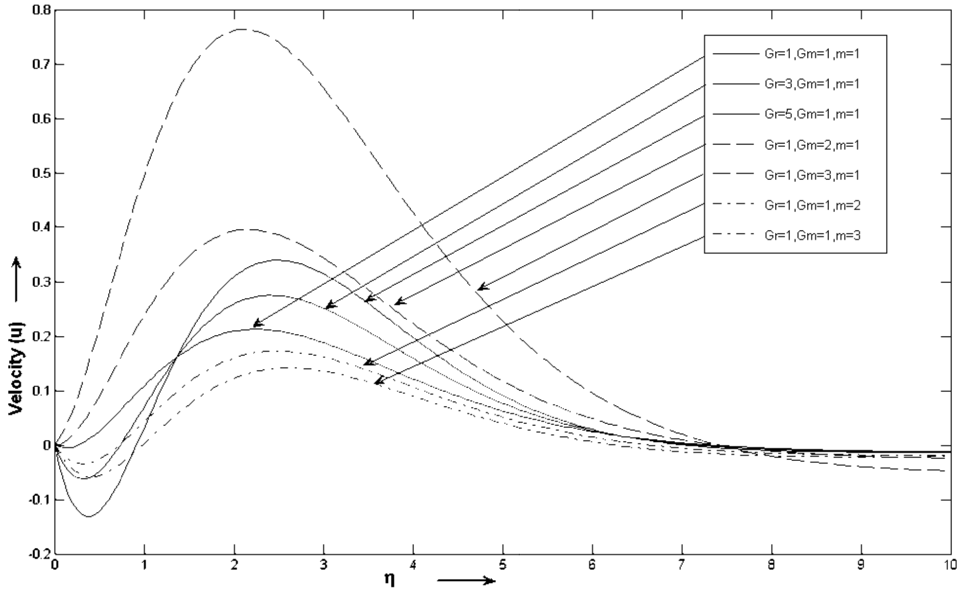

Fig. 2 Effect of Gr, Gm and m on velocity profile (u), when M=1, K=1, Pr=1, Sc=1, Ω=1, t=1 and ω=1

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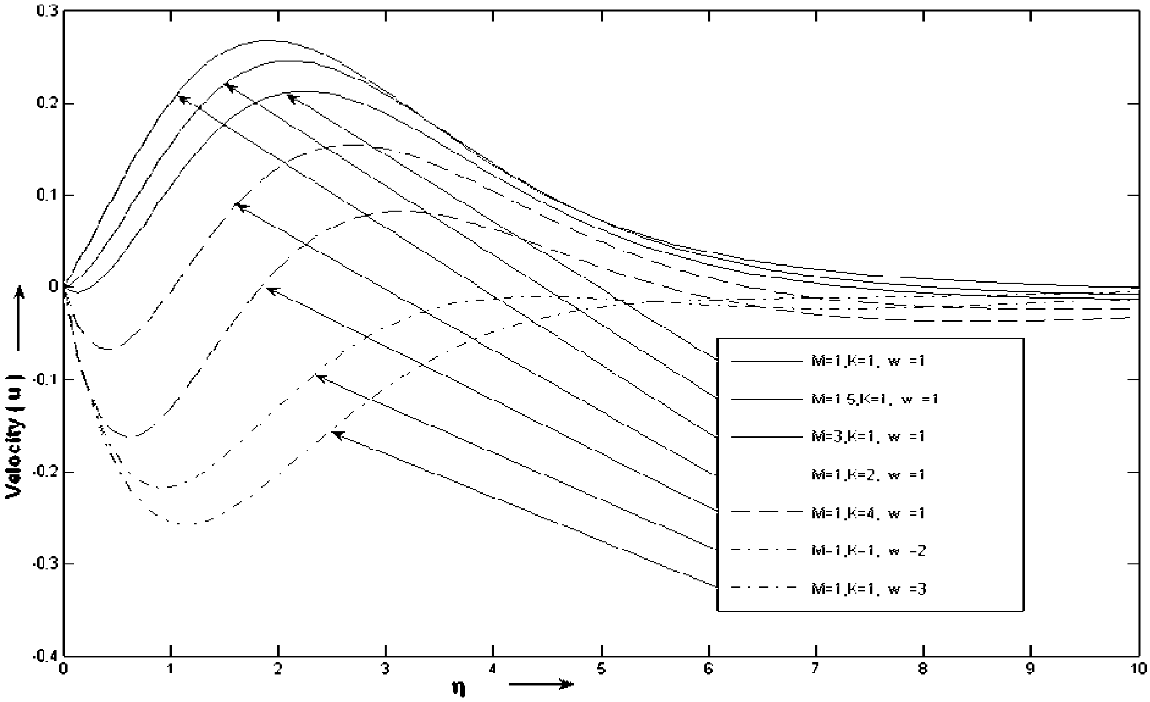

Fig. 3 Effect of M, K and Ω on velocity profile (u), when Gr=1, Gm=1, Pr=1, Sc=1, m=1, t=1 and ω=1

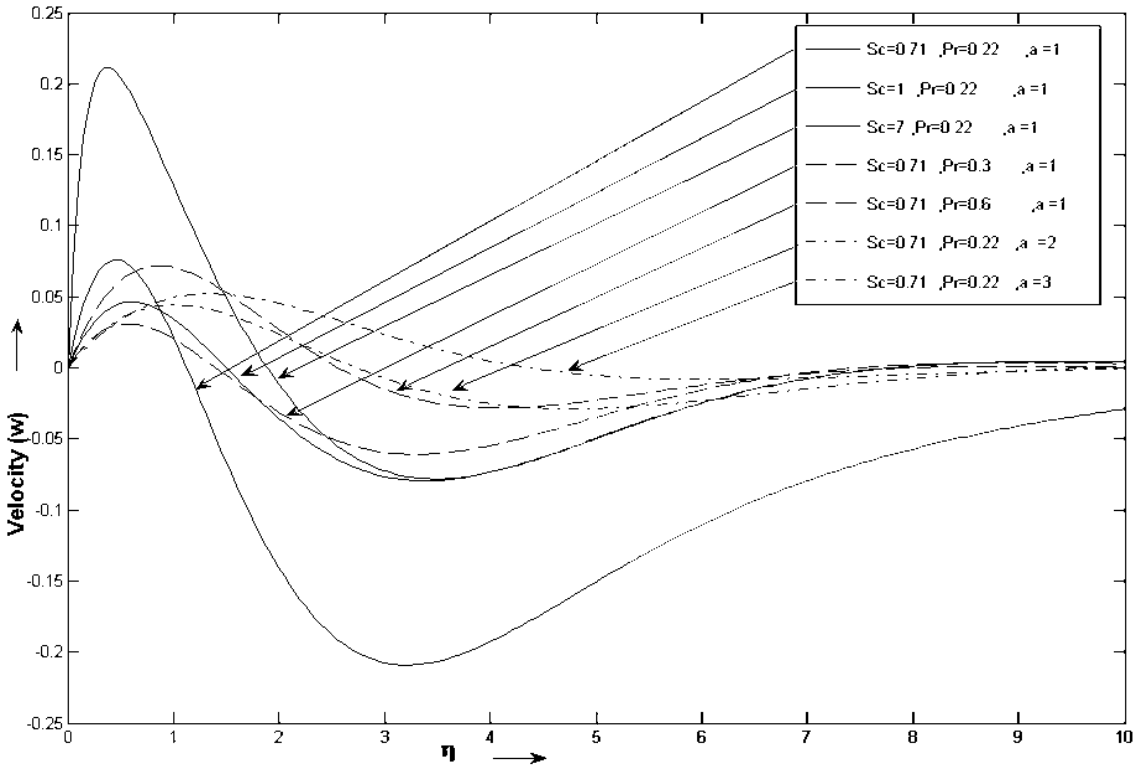

Fig. 4 Effect of α, Pr and Sc on velocity profile (w), when M=1, K=1, Gr=1, Gm=1, Ω=1, m=1, t=1 and ω=1

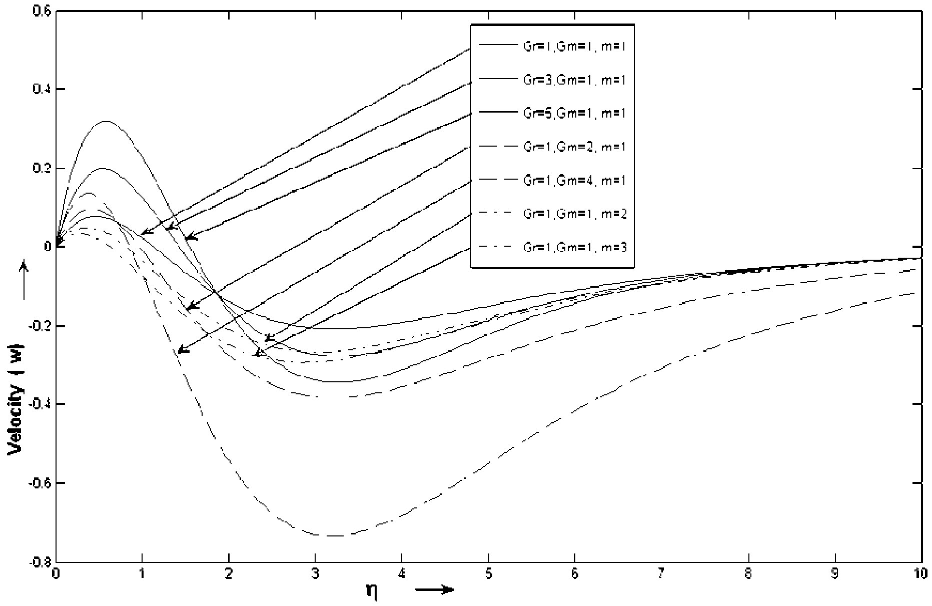

Fig. 5 Effect of Gr, Gm and m on velocity profile (w), when M=1, K=1, Sc=1, Pr=1, Ω=1, t=1 and ω=1

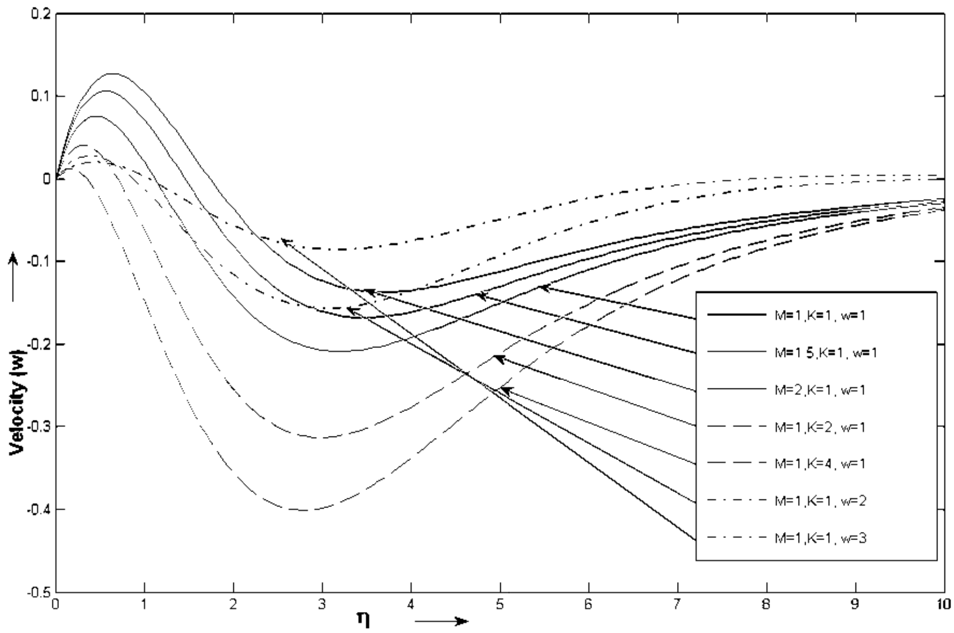

Fig. 6 Effect of M, K and Ω on velocity profile (w), when Gr=1, Gm=1, Sc=1, Pr=1, m=1, t=1 and ω=1

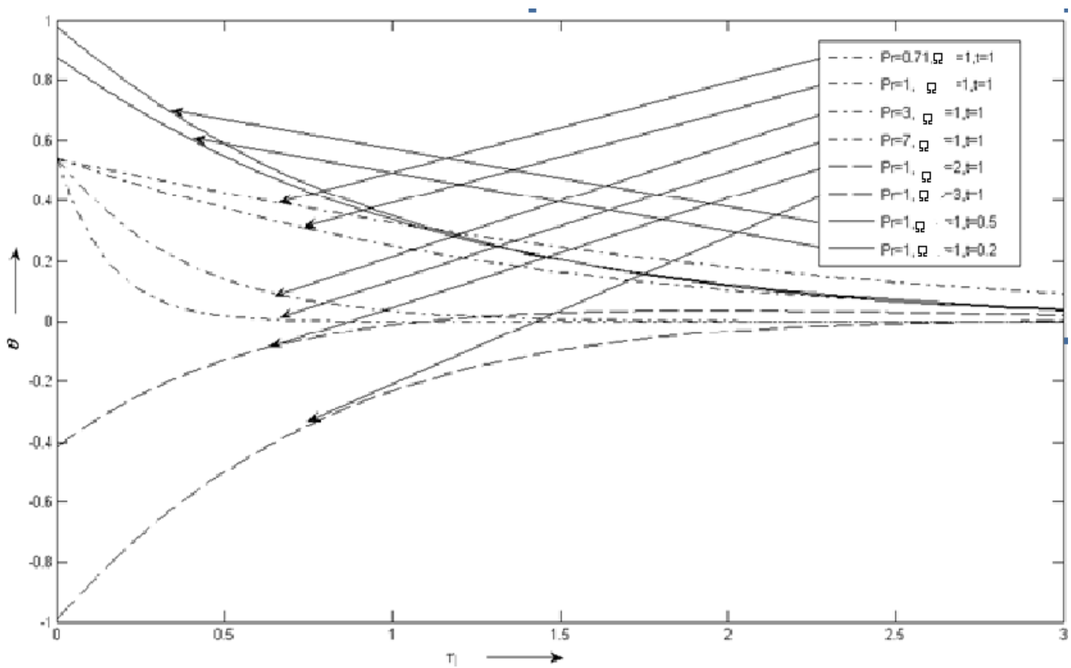

Fig. 7 Effect of Pr, t and Ω on temperature profile (Θr) in the absence of other parameters

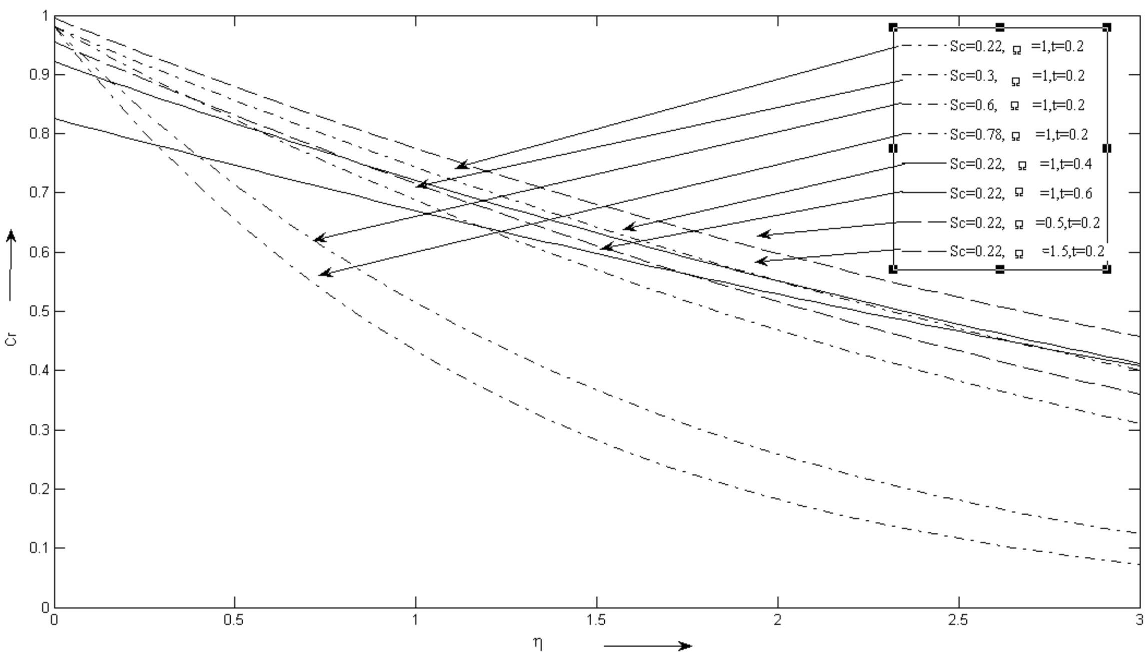

Fig. 8 Effect of Sc, t and Ω on mass concentration profile (Cr) in the absence of other parameters

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