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Analytical study of Unsteady Magnetohydrodynamic Chemically reacting fluid over a vertical porous plate in a Darcian Porous Regime: A rotating system

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Abstract: *Analytical solution for unsteady Magnetohydrodynamic (MHD) flow for a rotating vertical porous plate immersed in a Darcian porous Regime in presence of first order homogeneous chemical reaction is presented. A uniform magnetic field is applied transversely to the porous plate. In this investigation, the fluid is considered to be of viscous, incompressible, electrically conducting, laminar and Newtonian with periodic heat and mass flux. The Non-dimensional governing equations have been solved by the Classical Perturbation Technique and their analytical solutions are presented through graphs. It has been observed that the primary velocity (u) decelerated with the increase of chemical reaction parameter (C_r). The skin-friction of the primary velocity is raised by the effects of M or K_0. Practical interest of such study includes applications in liquid metal cooling in Nuclear Reactor, Magnetic suppression of molten semi-conducting materials and in many branches of Engineering and Sciences.*

Keywords: *Rotational fluid, Unsteady flow, MHD, Vertical Porous Plate, Darcian Porous Regime, Laminar flow, Perturbation Technique, Nuclear Reactor, Chemical reaction.*

I. Introduction:

The hydrodynamic rotating flow of electrically conducting viscous incompressible fluids has gained considerable attention because of its numerous applications in physics and engineering which are directly governed by the action of Coriolis and magnetic forces. In geophysics it is applied to measure and study the positions and velocities with respect to a fixed frame of reference on the surface of earth which rotate with respect to an inertial frame in the presence of its magnetic field. The subject of geophysical dynamics now a day has become an important branch of fluid dynamics due to the increasing interest to study environment. In astrophysics it is applied to study the steller and solar structure, inter planetary and inter steller matter, solar storms and flares etc. In engineering it finds its application in MHD generators, ion propulsion, MHD bearings, MHD pumps, MHD boundary layer control of reentry vehicles etc. Several scholars viz. Crammer and Pai (1973), Ferraro and Plumpton (1966), Shercliff (1965) have studied such flows on account of their varied importance.

Several investigations are carried out on the problem of hydrodynamic flow of a viscous incompressible fluid in rotating medium considering various variations in the problem. Mention may be made of the studies Greenspan and Howard (1963), Holton (1965), Walin (1969), Siegmann (1971), Hayat and Hutter (2004), Singh *et al*. (2005). The problem of Magnetohydrodynamic flow of a viscous incompressible electrically conducting fluid in a rotating medium is studied by many researchers, namely, Ghosh (2001), Singh (2000), Hossain *et al*. (2001), Ghosh and Pop (2002), Hayat *et al.* (2008), Hayat and Abelman (2007), Abelman *et al.* (2009), Wang and Hayat (2004) under different conditions and configurations to analyze various aspects of the problem and to find its application in Science and Engineering. Seth *et al*. (2011) studied the unsteady hydromagnetic Couette flow of a viscous incompressible electrically conducting fluid in a rotating system in the presence of a uniform transverse magnetic field.

Greenspan (1990) carried out a pioneer work on the theory of rotating fluid, and Thronley (1968) gave theoretical presentation of Stokes and Rayleigh layers in rotating systems. A rich variety of important analytical, numerical and experimental investigations concerning the rotating system of fluid are available in the literatures based on the basic work of Greenspan, Batchelor (1967) and Cowling (1957), for example, Gupta (1972), Pop and Soundalgekar (1973), Puri (1975), El-Kabeir *et al*. (2007) and Gebhart *et al*. (1988). Vidyanidhi and Nigam (1967) considered viscous flow between rotating parallel plates under constant pressure gradient. Free convection effects on flow past an accelerated vertical plate with variable suction and uniform heat flux in presents of magnetic field was studied by Rapties *et al*. (1981). Mass transfer effects on flow past a uniformly accelerated vertical plate was studied by Soundalgekar (1982). Singh presented the MHD flow past an impulsively started vertical plate in a rotating fluid. MHD effects on flow past an infinite vertical plate for both the classes of impulse as well as accelerated motion of the plate was studied by Raptis and Singh (1985). Singh (2012) investigated the oscillatory mixed convection flow of an electrically conducting viscous incompressible flow in a vertical channel.

Moreover, natural convection in a fluid-saturated porous medium is of fundamental importance in many industrial and environmental problems. On the other hand, heat and mass transfer from a vertical flat plate is encountered in various applications such as heat exchangers, cooling systems and electronic equipment. In addition, Non-Newtonian fluids such as molten plastics, polymers, glues, ink, pulps, foodstuffs or slurries are increasingly used in various manufacturing, industrial and engineering applications especially in the chemical engineering processes. Singh (2011) obtained an exact solution of an oscillatory MHD flow in a channel filled with porous medium. Ahmed (2008) investigated the effect of transverse periodic permeability oscillating with time on heat transfer flow of a viscous incompressible fluid through a highly porous medium bounded by an infinite vertical porous plate, by means of series solution method. The effect of transverse periodic permeability oscillating with time on the free convective heat transfer flow of a viscous incompressible fluid through highly porous medium bounded by an infinite vertical porous plate subjected to a periodic suction velocity is presented by Ahmed (2010). The transient natural convection-radiation flow of viscous dissipation fluid along an infinite vertical surface embedded in a porous medium, by means of network simulation method, investigated by Zueco (2008). The study of vertical channel flow bounded by a wavy wall and a vertical flat plate filled with porous medium was presented by Ahmed (2008). Later on Ahmed (2009) also investigated the effects of free convection heat transfer on the three-dimensional channel flow through a porous medium with periodic injection velocity. Recently, Fasogbon (2010) studied the simultaneous buoyancy force effects of thermal and species diffusion through a vertical irregular channel by using parameter perturbation technique. Very recently, Ahmed and Zueco (2011) investigate the effects Hall current, magnetic field, rotation of channel and suction-injection on the oscillatory free convective MHD flow in a rotating vertical porous channel when the entire system rotates about an axis normal to the channel plates and a strong magnetic field of uniform strength is applied along the axis of rotation. Magnetohydrodynamic oscillatory convective flow of a viscous, incompressible and electrically conducting fluid in a rotating vertical porous channel is analytically presented by Singh (2012).

Also, Ahmed (2010) investigated the effects of periodic heat transfer on unsteady MHD mixed convection flow past a vertical porous flat plate with constant suction and heat sink when the free stream velocity oscillates in about a non-zero constant mean. The steady Magnetohydrodynamic (MHD) mixed convection stagnation point flow over a vertical flat plate is investigated by Ali *et al*. (2011).

The present work is focuses on the rotating system in a Darcian porous regime of unsteady hydromagnetic chemically reacting fluid in presence of variable heat and mass transport. The boundary layer equations are solved analytically and the numerical results are presented graphically.

II. Mathematical Formulation:

An infinite vertical porous plate rotates in unison with a viscous fluid occupying the porous region with the constant angular velocity Ω about an axis which is perpendicular to the vertical plane surface. The Cartesian Co-ordinate system is chosen such that x*, y* axes respectively are in the vertical upward and perpendicular directions on the plane of the vertical porous surface z*=0 while z*-axis is normal to it. With the above frame of reference and assumptions, and physical variables, except the pressure p*, are functions of z* and time t* only. The boundary layer equations expressing the conservation of mass, momentum and energy and the equation of mass transfer, neglecting the heat due to viscous dissipation which is valid for small velocities are

$$\frac{\partial w^*}{\partial z^*} = 0\ , \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + w^*\frac{\partial u^*}{\partial z^*} - 2\Omega v^* = \begin{Bmatrix} g\beta(T^* - T^*_\infty) + g\beta^*(C^* - C^*_\infty) \\ + \nu\dfrac{\partial^2 u^*}{\partial z^{*2}} - \dfrac{\nu}{K^*}u^* - \dfrac{\sigma B_0^2\, u^*}{\rho} \end{Bmatrix}, \tag{2}$$

$$\frac{\partial v^*}{\partial t^*} + w^*\frac{\partial v^*}{\partial z^*} + 2\Omega u^* = \nu\frac{\partial^2 v^*}{\partial z^{*2}} - \frac{\nu}{K^*}v^* - \frac{\sigma B_0^2\, v^*}{\rho}\ , \tag{3}$$

$$0 = -\frac{1}{\rho}\frac{\partial p^*}{\partial z^*} - \frac{\nu}{K^*}w^*\ , \tag{4}$$

$$\frac{\partial T^*}{\partial t^*} + w^*\frac{\partial T^*}{\partial z^*} = \frac{k}{\rho\, C_p}\frac{\partial^2 T^*}{\partial z^{*2}}\ , \tag{5}$$

$$\frac{\partial C^*}{\partial t^*} + w^*\frac{\partial C^*}{\partial z^*} = D\frac{\partial^2 C^*}{\partial z^{*2}} - C_r^*(C^* - C^*_\infty)\ , \tag{6}$$

with the boundary conditions

$$\begin{bmatrix} \begin{Bmatrix} u^* = 0\,, v^* = 0\,,\ T^* = T_w^* + \varepsilon\,(T_w^* - T_\infty^*)\,e^{iwt}, \\ C^* = C_w^* + \varepsilon\,(C_w^* - C_\infty^*)\,e^{iwt}\,, \end{Bmatrix} \text{at } z^* = 0 \\ u^*, v^* \to 0\,, T^* \to T_\infty^*\,, C^* \to C_\infty^* \qquad as \quad z^* \to \infty \end{bmatrix} \tag{7}$$

In physically realistic situation, we cannot ensure perfect insulation in any experimental setup. There will always be some fluctuations in the temperature. The plate temperature is assumed to vary harmonically with time. It varies from $T_w^* \pm \varepsilon\,(T_w^* - T_\infty^*)$ as t varies from 0 to 2π/ω. Since ε is small, the plate temperature varies only slightly from the mean value T_w^* .

For constant suction, we have from eq. (1) in view of eq. (7)

$$w^* = -w_0$$

Considering $u^* + iv^* = U^*$ and taking into account eq. (8) then eq. (2) and eq. (3) can written as

$$\frac{\partial U^*}{\partial t^*} - w_0\,\frac{\partial U^*}{\partial z^*} + 2\Omega i U^* = \begin{Bmatrix} g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) \\ +\nu\,\dfrac{\partial^2 U^*}{\partial z^{*2}} - \dfrac{\nu}{K^*}U^* - \dfrac{\sigma B_0^2\,U^*}{\rho} \end{Bmatrix} \tag{9}$$

We introduce the following non-dimensional quantities:

$$\begin{Bmatrix} Z = \dfrac{w_0\,Z^*}{\nu}\,,\ U = \dfrac{U^*}{w_0}\,,\ t = \dfrac{t^*\,w_0^2}{\nu}\,,\ w = \dfrac{\nu\,w^*}{w_0^2}\,,\ T = \dfrac{T^* - T_\infty^*}{T_w^* - T_\infty^*} \\ C = \dfrac{C^* - C_\infty^*}{C_w^* - C_\infty^*}\,,\ Sc = \dfrac{\nu}{D}\,,\ Pr = \dfrac{\rho\,\nu C_p}{K}\,,\ K_0 = \dfrac{w_0^2\,K^*}{\nu^2}\,, \\ Gr = \dfrac{\nu g\beta(T_w^* - T_\infty^*)}{w_0^3}\,,\ Gm = \dfrac{\nu g\beta^*(C_w^* - C_\infty^*)}{w_0^3}\,,\ R = \dfrac{\Omega\nu}{w_0^2}\,, \\ Cr = \dfrac{\nu C_r^*}{w_0^2}\,,\ M^2 = \dfrac{\sigma B_0^2}{\rho}.\dfrac{\nu}{w_0^2} \end{Bmatrix} \tag{10}$$

In view of the non-dimensional quantities (10), Eq. (9), (5), and (6) reduce respectively to,

$$\frac{\partial U}{\partial t} - \frac{\partial U}{\partial z} + 2RiU = GrT + GmC + \frac{\partial^2 U}{\partial z^2} - \left(\frac{1}{K_0} + M^2\right)U \tag{11}$$

$$\frac{\partial T}{\partial t} - \frac{\partial T}{\partial z} = \frac{1}{Pr}\frac{\partial^2 T}{\partial z^2} \tag{12}$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial z} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} - CrC \tag{13}$$

and boundary condition (7) becomes

$$\begin{Bmatrix} U = 0\,,\ T = 1 + \varepsilon e^{i\omega t}\,,\ C = 1 + \varepsilon e^{i\omega t} \quad \text{at} \quad z = 0 \\ U \to 0\,,\ T \to 0,\ C \to 0 \quad \text{as} \quad z \to \infty \end{Bmatrix} \tag{14}$$

III. Method of Solution:

In order to solve the system of partial differential eqs. (11) to (13) under the boundary conditions (14), to a system of ordinary differential equations in the non-dimensional form, we assume the following for velocities, temperature and concentration of the flow field as the amplitude ε<<1 of the permeability variations is very small.

$$\begin{Bmatrix} U(z,t) = U_0(z) + \varepsilon e^{i\omega t}\,U_1(z) \\ T(z,t) = T_0(z) + \varepsilon e^{i\omega t}\,T_1(z) \\ C(z,t) = C_0(z) + \varepsilon e^{i\omega t}\,C_1(z) \end{Bmatrix} \tag{15}$$

Substituting (15) into the system (11) to (13) and equating harmonic and non- harmonic terms, we get

$$U_0'' + U_0' - 2iRU_0 - (K_0^{-1} + M^2)U_0 = -(GrT_0 + GmC_0) \qquad (16)$$

$$U_1'' + U_1' - U_1\left(K_0^{-1} + M^2 + i(\omega + 2R)\right) = -(GrT_1 + GmC_1) \qquad (17)$$

$$T_0'' + PrT_0' = 0 \qquad (18)$$

$$T_1'' + PrT_1' - i\omega PrT_1 = 0 \qquad (19)$$

$$C_0'' + ScC_0' - ScCrC_0 = 0 \qquad (20)$$

$$C_1'' + ScC_1' - (i\omega + Cr)\,ScC_1 = 0 \qquad (21)$$

The appropriate boundary conditions reduce to

$$\left\{\begin{matrix} U_0(0) = 0, T_0(0) = 1, C_0(0) = 1 \\ U_1(0) = 0, T_1(0) = 1, C_1(0) = 1 \\ U_0(\infty) \to 0, T_0(\infty) \to 0\ \ C_0(\infty) \to 0 \\ U_1(\infty) \to 0, T_1(\infty) \to 0, C_1(\infty) \to 0 \end{matrix}\right\} \qquad (22)$$

The solutions of eqs. (16) to (21) subject to eqs. (22) can be shown as

$$U_0(z) = -L_1e^{-Prz} - L_1e^{-\eta_1 z} + L_3e^{-\lambda_1 z}, \qquad (23)$$

$$U_1(z) = -L_4e^{-\xi z} - L_5e^{-\eta_2 z} + L_6e^{-\lambda_2 z}, \qquad (24)$$

$$T_0(z) = e^{-Prz}, \qquad (25)$$

$$T_1(z) = e^{-\xi z}, \qquad (26)$$

$$C_0(z) = e^{-\eta_1 z}, \qquad (27)$$

$$C_1(z) = e^{-\eta_2 z}, \qquad (28)$$

where

$$\xi = \frac{Pr + \sqrt{Pr^2 + 4i\omega Pr}}{2}, \eta_1 = \frac{Sc + \sqrt{Sc^2 + 4ScCr}}{2},$$

$$\eta_2 = \frac{Sc + \sqrt{Sc^2 + 4(i\omega + Cr)Sc}}{2}, \quad \lambda_1 = \frac{1 + \sqrt{1 + 4(2iR + K_0^{-1} + M^2)}}{2}$$

$$\lambda_2 = \frac{1 + \sqrt{1 + 4\left(K_0^{-1} + M^2 + i(\omega + 2R)\right)}}{2}, \quad L_1 = \frac{Gr}{Pr^2 - Pr - (2iR + K_0^{-1} + M^2)},$$

$$L_2 = \frac{Gm}{\eta_1^2 - \eta_1 - (2iR + K_0^{-1} + M^2)}, \quad L_3 = L_1 + L_2, L_6 = L_4 + L_5$$

$$L_4 = \frac{Gr}{\xi^2 - \xi - \left(\frac{1}{K_0} + M^2 + i(\omega + 2R)\right)}, \quad L_5 = \frac{Gm}{\eta_2^2 - \eta_2 - \left(\frac{1}{K_0} + M^2 + i(\omega + 2R)\right)}.$$

In the view of the above solutions, the velocity, temperature and concentration of the boundary layer become

$$U(z,t) = \left\{\begin{matrix} -L_1e^{-Prz} - L_1e^{-\eta_1 z} + L_3e^{-\lambda_1 z} \\ +\varepsilon e^{i\omega t}\left(-L_4e^{-\xi z} - L_5e^{-\eta_2 z} + L_6e^{-\lambda_2 z}\right) \end{matrix}\right\} \qquad (29)$$

$$T(z,t) = e^{-Prz} + \varepsilon e^{i\omega t}e^{-\xi z} \qquad (30)$$

$$C(z,t) = e^{-\eta_1 z} + \varepsilon e^{i\omega t}e^{-\eta_2 z} \qquad (31)$$

IV. Skin-Friction

The shear stress (τ) of the viscous fluid is given by

$$\tau = \left.\frac{\partial U}{\partial z}\right|_{z=0} = \left.\frac{\partial U_0}{\partial z}\right|_{z=0} + \varepsilon e^{i\omega t}\left.\frac{\partial U_1}{\partial z}\right|_{z=0}$$

$$= (PrL_1 + \eta_1 L_2 - \lambda_1 L_3) + \varepsilon e^{i\omega t}(\xi L_4 + \eta_2 L_5 - \lambda_2 L_6)$$

$$= \tau_0 + \varepsilon(\cos\omega t + \sin\omega t)\tau_1$$

V. Rate of mass transfer

The rate of mass transfer in terms of Sherwood number (***Sh***) is given by

$$Sh = \frac{\partial c}{\partial z}\Big|_{z=0} = \frac{\partial c_0}{\partial z}\Big|_{z=0} + \varepsilon e^{i\omega t}\frac{\partial c_1}{\partial z}\Big|_{z=0}$$

$$= -\eta_1 - \varepsilon e^{i\omega t}\eta_2$$

VI. Results and Discussion:

The effects of flow parameters such as the magnetic parameter (M), rotation parameter (R), porosity parameter (K_0), chemical reaction (Cr), Prandtl number (Pr), Schmidt number(Sc) on primary, secondary velocity field, concentration, skin-friction and Sherwood number have been studied analytically and presented with the help of Figs. 1 to 12. The dimensionless primary and secondary velocity components for different values of Gr=5=Gm, K_0=0.1, R=5, M=5, ε= 0.02, Sc=0.78 (Ammonia), Pr=0.71(air), t=0.2 are shown in Figs. 1 to 8.

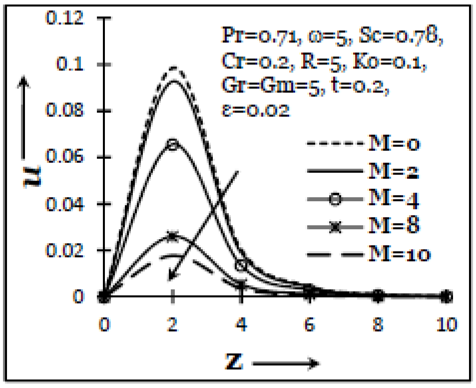

Fig.1: Primary velocity distribution for magnetic field

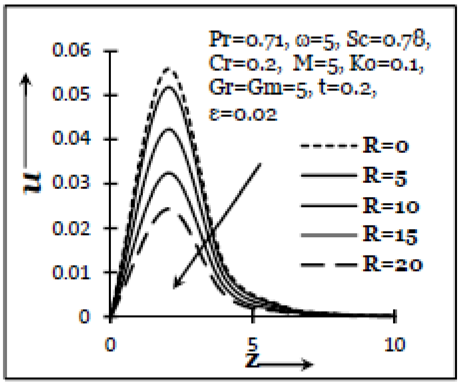

Fig.2: Primary velocity distribution for rotation parameter

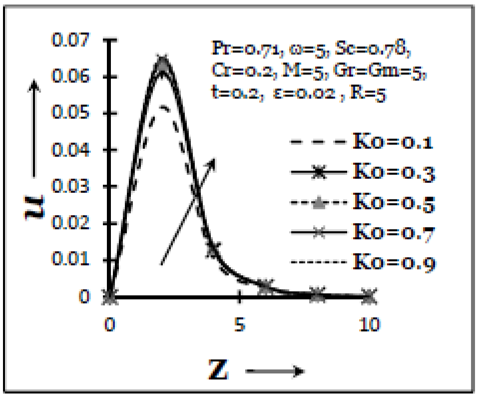

Fig. 3: Primary velocity distribution for Porosity.

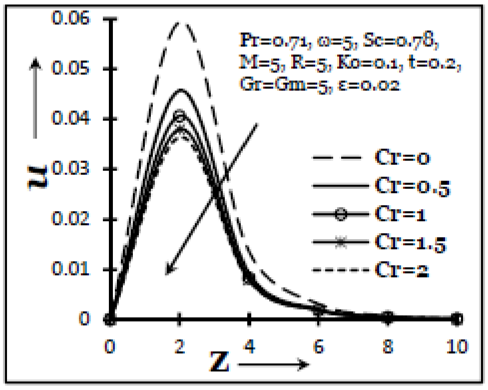

Fig.4: Primary velocity distribution for chemical Reaction.

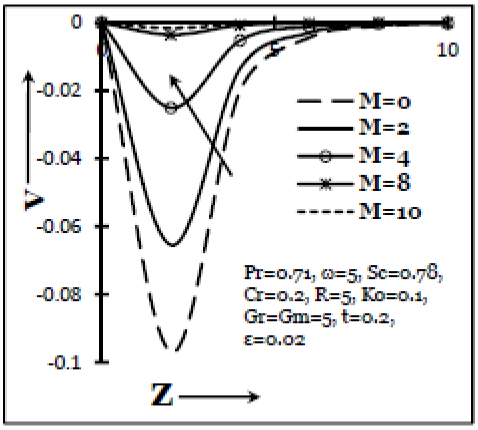

Fig. 5: Secondary velocity distribution for magnetic Field.

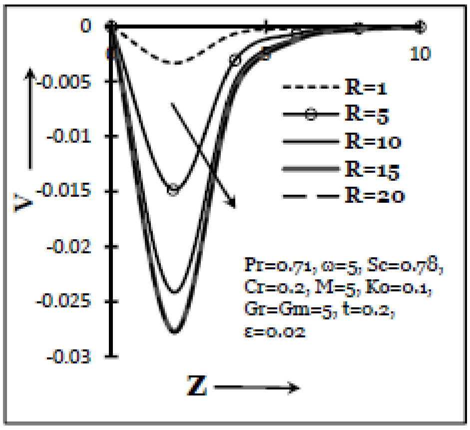

Fig. 6: Secondary velocity distribution for rotation parameter.

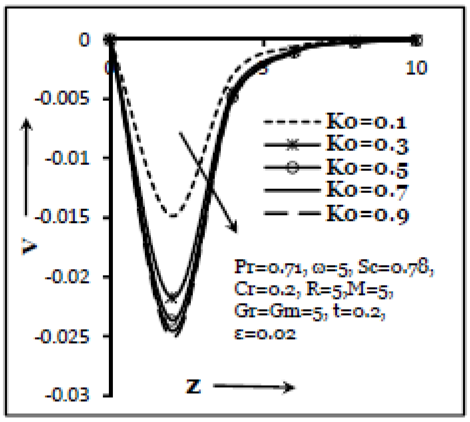

Fig. 7: Secondary velocity distribution for porosity.

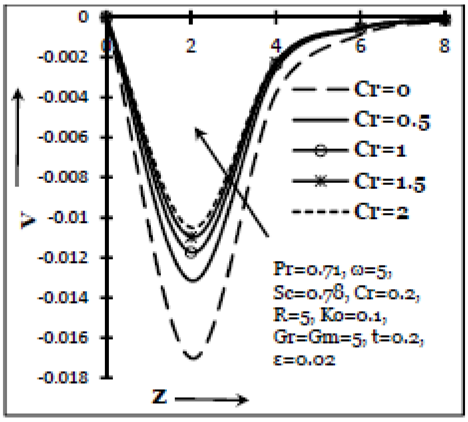

Fig. 8: Secondary velocity distribution for chemical reaction

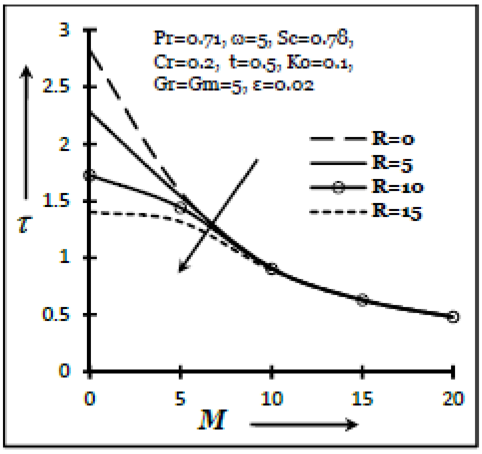

Fig. 9: Skin friction for rotation parameter.

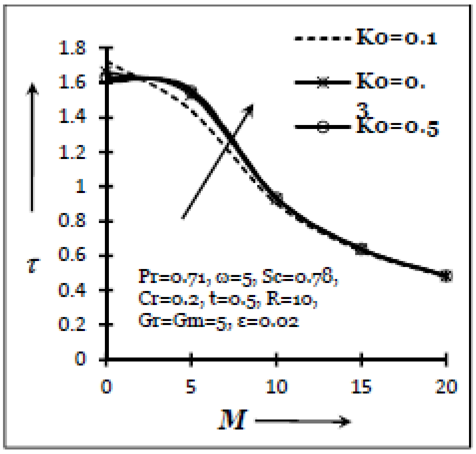

Fig. 10: Skin friction distribution for porosity and magnetic body force

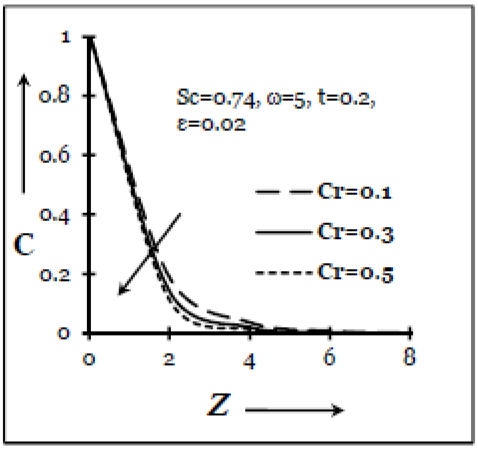

Fig.11: Concentration distribution for Chemical Reaction.

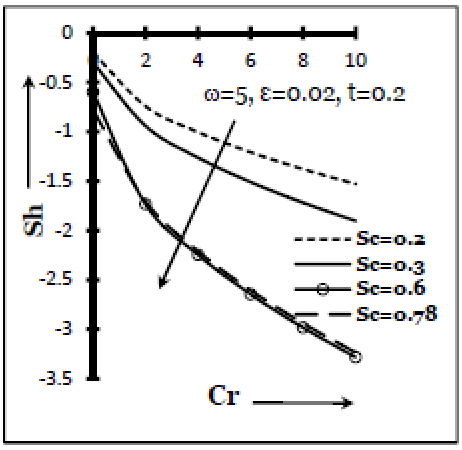

Fig. 12: Sherwood distribution for Chemical Reaction and Schmidt number.

The primary velocity profiles (u) are plotted in figure 1 for various values of Magnetic body force (M). It is obvious that the existence of the magnetic field is to decrease the velocity in the momentum boundary layer because the application of the transverse magnetic field results in a resisting type of force called Lorentz force, similar to drag force that resists the fluid flow which results in reducing the velocity of the fluid in the boundary layer. In figure 2 it has also been observed that, the Primary velocity decelerated with the increase of Rotation parameter (R). The velocity profiles across the boundary layer are shown in figure 3 for various values of the porosity parameter (K_0). It is clearly seen that as K_0 increases the velocity profiles across the boundary layer increases since the resistance offered by the porous medium decreases as the permeability of the porous medium increases. But with the existence of porosity the Primary Velocity gradually increases near the plate and then decreases to zero at the free stream. Inspection of figure 4 shows that an increase in the chemical reaction (Cr) induces a significant deceleration in the flow velocity (u).

In figure 5 the influence of Magnetic body force (M) on secondary velocity evolution through the boundary layer is plotted. With an increase in M, there is a strong deceleration in the flow in magnitude. Figure 6 illustrates the influence of the Rotation Parameter (R) on the secondary velocity profiles. It is seen that the secondary velocity is accelerated in magnitude with the increase of Rotation Parameter (R). In figure 7 we observe that with an increase in porosity parameter (K_0) (over 0.1 through 0.3, 0.5, 0.7 to 0.9) there is a considerable increase in magnitude of the velocity, v. The effects of chemical Reaction (Cr) on secondary velocity profiles are presented in figure 8. From this figure we observe that, as the value of Cr increases, the flow velocity decelerated in the momentum boundary layer due to the fact that the momentum boundary layer thickness decreases with increase in the radiation parameter Cr. Moreover, all the profiles of secondary flow velocities for the influence of M, R, K_0 and Cr are highly negative from the plate, and hence there is significant flow reversal.

The skin –Friction (τ) for primary velocity profiles have been plotted for rotation (R) and magnetic body force (M) in figure 9. It is seen that the skin-friction reduces with the increase of M or R near the plate Z=0, but away the plate the profiles approaches to a converging point 0.48375.

The skin friction distribution for the effect of porosity (K_0) and magnetic body force (M) is presented in figure 10. Near the plate z = 0, it is seen that the porosity suppressed the skin friction, while this trend is reversed away the plate. Moreover, the values of skin friction reduce for the bigger values of Hartmann number and all the profiles reduce to a converging point.

The effect of generative chemical reaction parameter (Cr) on the species concentration profiles is illustrated in figure 11. It is noticed from this graph that there is marked effect of increasing the value of the chemical reaction rate parameter (Cr) on concentration distribution in the solutal boundary layer. It is observed that increasing the value of the chemical reaction rate parameter decreases the concentration of species in the boundary layer this is due to the fact that solutal boundary layer decreases with (Cr).

Figure 12 depicts the graph of the Sherwood number for various values of Chemical reaction (Cr) and Schmidt number (Sc) in the boundary layer. It is seen that the effect of Cr or Sc is to increase the Sherwood number in the boundary layer. All the profiles of Sherwood number are negative due to foreign species of concentration in presence of generative chemical reaction.

VII. Conclusion:

The problem of unsteady MHD free convective flow with heat and mass transfer effects in a rotating porous medium in presence of first order Chemical reaction has been considered. The solutions for Primary and Secondary velocity field, and Concentration profiles are obtained using the perturbation technique. All numerical calculation has been done through **Mathematica Code 8.0**.The above analysis brings out the following results.

- It is observed that existence of magnetic body force, rotation parameter and chemical reaction decreases the primary velocity.
- It is observed that in the presence of magnetic body force and chemical reaction, the secondary velocity decreases but in the existence of rotation parameter and porosity, the secondary velocity increases. For all the values of V are negative, so back flow has been observed.
- The permeability parameter (Ko) and magnetic body force (M) have the influence of increasing the Primary Skin-friction.
- The concentration boundary layer decreases with increasing values of the Chemical reaction parameter (Cr).
- The chemical reaction (Cr) and Schmidt number (Sc) have the influence of decreasing the Rate of Shear Stress.

Nomenclature:

B_o	Magnetic Induction.
C	Dimensionless Concentration.
C^*	Concentration.
C_∞^*	Concentration at free stream.
C_p	Specific heat at constant pressure.
C_r^*	Chemical Reaction.
C_w^*	Concentration at the surface.
D	Mass diffusion Co-efficient.
g	Acceleration due to gravity.
G_r	Thermal Grashof number.
G_m	Mass Grashof number.
K^*	Permeability of Porous medium.
Ko	Porosity Parameter.
M	Magnetic Body force.
P	Pressure.
Pr	Prandtl number.
R	Rotational parameter.
Sc	Schmidt number.
t^*	Time
T^*	Temperature.
T_∞^*	Temperature at free stream.
u^*	Components of velocity along x^* direction.
v^*	Components of velocity along y^* direction.
w^*	Components of velocity along z^* direction.
z^*	Dimensional distances normal to the plate.

Greek Alphabet:

Ω	Angular velocity.
β	Co-efficient of volume expansion for heat transfer.
β^*	Co-efficient of volume expansion for mass transfer.
κ	Thermal conductivity.
ν	Fluid kinematic viscosity.
σ	Fluid electrically conductivity.
ρ	Fluid density.
ε	Scalar constant (<< 1).

Subscript:

W	Conditions on the wall.
∞	Free stream conditions.

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