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Effects of Hall current on MHD Free Convective rotating flow through a porous medium

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Abstract

In this paper, we have considered heat and mass transfer on the MHD free convection flow of second grade fluid through porous medium bounded by an infinite vertical porous rotating plate taking hall current into account. The vertical plate is subjected to the uniform constant suction perpendicular to it and the temperature on the plate varies with time about a non-zero constant mean while the temperature of free stream taken to be constant. The precise solutions for the velocity, temperature and concentration are obtained making use of perturbation technique. The velocity, temperature and concentration is analysed graphically, and computational results for the skin friction, Nusselt number and Sherwood number are also obtained.

Key words: Hall effects, Heat and mass transfer, MHD flows, porous medium, rotating channels, second grade fluids.

1. Introduction

The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. In particular, the study of chemical reaction, heat and mass transfer with heat radiation is of considerable importance in chemical and hydrometallurgical industries. A reaction is said to be first-order if the rate of reaction is directly proportional to the concentration itself. In many chemical processes, a chemical reaction occurs between a foreign mass and a fluid in which a plate is moving. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware, and food processing Cussler[16]. Chambre and Young[11] analyzed the diffusion of chemically reactive species in a laminar boundary layer flow. Vajravelu[34] studied the exact solution for hydrodynamic boundary layer flow and heat transfer over a continuous, moving horizontal flat surface with uniform suction and internal heat generation/absorption. Chamkha[15] presented an analytical solution for heat and mass transfer by laminar flow of a Newtonian, viscous, electrically conducting fluid and heat generation/absorption.

On the other hand, flow through a porous medium have numerous engineering and geophysical applications, for example, in chemical engineering for filtration and purification process; in agriculture engineering to study the underground water resources; in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. In view of these applications, many researchers have studied MHD free convective heat and mass transfer flow in a porous medium; some of them are Raptis and Kafoussias[27], Sattar[29] and Kim[21]. Jaiswal and Soundalgekar[20] obtained an approximate solution to the problem of an unsteady flow past an infinite vertical plate with constant suction and embedded in a porous medium with oscillating plate temperature. The unsteady flow through a highly porous medium in the presence of radiation was studied by Raptis and Perdikis[15]. Sahin investigated the effect of transverse periodic permeability oscillating with time on the 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. Sahin[2,3] studied the effect of transverse periodic permeability oscillating with time on the free convective heat transfer flow of a viscous incompressible fluid through a highly porous medium bounded by an infinite vertical porous plate subjected to a periodic suction velocity. If the temperature of surrounding fluid is rather high, radiation effects play an important role and this situation does not exist in space technology. In such cases one has to take into account the effect of thermal radiation and mass diffusion. Boundary layer flow on moving horizontal surfaces was studied by Sakiadis[28]. The effects of transversely applied magnetic field on the flow of an electrically conducting fluid past an impulsively started isothermal vertical plate was studied by Soundalgekar *et al.*[33]. MHD effects on impulsively started vertical infinite plate with variable temperature in the presence of transverse magnetic field were studied by Soundalgekar *et al*.[32]. The dimensionless governing equations were solved using Laplace transform technique. Soundalgekar and Takhar[31] have considered the radiation free convection flow of an optically thin gray- gas past a semi- infinite vertical plate. Radiation effects on mixed convection along isothermal vertical plate were studied by Hossain and Takhar[19]. In all above studies, the stationary vertical plate is considered. Raptis and Perdikis[26] studied the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Also, Sahin and Liu[4] analyzed the effects of mixed convection and mass transfer of three-dimensional oscillatory flow of a viscous incompressible fluid past an infinite vertical porous plate in presence of transverse sinusoidal suction velocity oscillating with time and a constant free stream velocity. Singh[30] investigated the flow of fluid through porous medium bounded by vertical channel with slip-flow condition and in the presence of thermal radiation and the fluid is of optically thin with relatively low-density. Recently, Sahin[5] investigated the effects of radiation and chemical reaction on a steady mixed convective heat and mass transfer past an infinite vertical permeable plate with constant suction taking into account the induced magnetic field. A study of unsteady laminar hydro magnetic flow and heat transfer in a porous channel with temperature-dependent properties was presented by Chamkha[12]. Sahin and Kalita[6] investigated the effects of porosity and magneto hydrodynamic on a horizontal channel flow of a viscous incompressible electrically conducting, Newtonian and radiating fluid through a porous medium in the presence of thermal radiation and transverse magnetic field. Jaiswal and Soundalgekar[20] obtained an approximate solution to the problem of an unsteady flow past an infinite vertical plate with constant suction and embedded in a porous medium with oscillating plate temperature. Kumar and Verma[22] studied the problem of an unsteady flow past an infinite vertical permeable plate with constant suction and transverse magnetic field with oscillating plate temperature.

Magneto hydrodynamic 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 vertical plate for high temperature and concentration differences have studied by Emad and Gamal[1]. Orhan and Kaya[8] investigated the mixed convection heat transfer about a permeable vertical plate in the presence of magneto and thermal radiation effects using the Keller box scheme, an efficient and accurate finite-difference scheme. Ghosh *et al.*[17] considered an exact solution for the hydro magnetic natural convection boundary layer flow past an infinite vertical flat plate under the influence of a transverse magnetic field with magnetic induction effects and the transformed ordinary differential equations are solved exactly. On the other hand, Ghosh and Bég[18] for unsteady convection in porous media, Bég *et al.*[9] for coupled species and heat diffusion in nonlinear porous media (using a network electrical simulator), Zueco and Bég[35] for hydro magnetic gas flow from a two-dimensional wedge in porous media. Muthucumaraswamy and Janakiraman[23] studied the thermal radiation effects on flow past an impulsively started infinite vertical plate with uniform temperature and variable mass diffusion in the presence of transverse applied magnetic field. The governing equations are solved by the Laplace-transform technique. Rajput and Kumar[24] considering the radiation effects on MHD flow past an impulsively started vertical plate with variable heat and mass transfer by Laplace transform technique. Ahmed and Kalita[7] presented the magneto hydrodynamic transient convective radiative heat transfer in an isotropic, homogenous porous regime adjacent to a hot vertical plate using the Laplace transform technique. Such a study has not appeared in the literature and constitutes an important addition to the area of porous media convection studies in presence of transverse magnetic field. Chamkha *et al*.[13] considered the natural convection flow from an inclined, semi-infinite, impermeable flat plate embedded in a variable porosity porous medium due to solar radiation and in the presence of an externally applied magnetic field. Chamkha[14] presented the model for Darcian and non-Darcian effects of the porous medium and the Hall effects of magneto hydrodynamics. It is assumed that the magnetic Reynolds number is small so that the induced magnetic field is neglected. The flow is assumed unsteady, laminar, and incompressible.

Recently, Krishna and Swarnalathamma[38] discussed the peristaltic MHD flow of an incompressible and electrically conducting Williamson fluid in a symmetric planar channel with heat and mass transfer under the effect of inclined magnetic field. Swarnalathamma and Krishna (2016) discussed the theoretical and computational study of peristaltic hemodynamic flow of couple stress fluids through a porous medium under the influence of magnetic field with wall slip condition. Veera Krishna and M.G. Reddy[36-38] discussed MHD free convective rotating flow of visco-elastic fluid past an infinite vertical oscillating plate. Veera Krishna and G.S.Reddy[36-38] discussed unsteady MHD convective flow of second grade fluid through a porous medium in a Rotating parallel plate channel with temperature dependent source.

Motivated the above studies, the aim of the present study was to analyze the effects on the unsteady MHD free convection flow of an incompressible electrically conducting second grade fluid through porous medium bounded by an infinite vertical porous surface in the presence of heat source and chemical reaction in a rotating system taking hall current into account.

2. Mathematical Formulation and Solution of the Problem:

We consider the unsteady MHD free convection flow of an electrically conducting viscous incompressible second grade fluid bounded by a vertical porous surface in a rotating system in the presence of heat source and chemical reaction subjected to a uniform transverse magnetic field of strength B_0 normal to plate and taking hall current into account. The temperature on the surface varies with the time about a non-zero constant mean while the temperature of free stream is taken to be constant. We consider that the vertical infinite porous plate rotates with the constant angular velocity about an axis is perpendicular to the vertical plane surface. The physical configuration of the problem is as shown in Fig. 1.

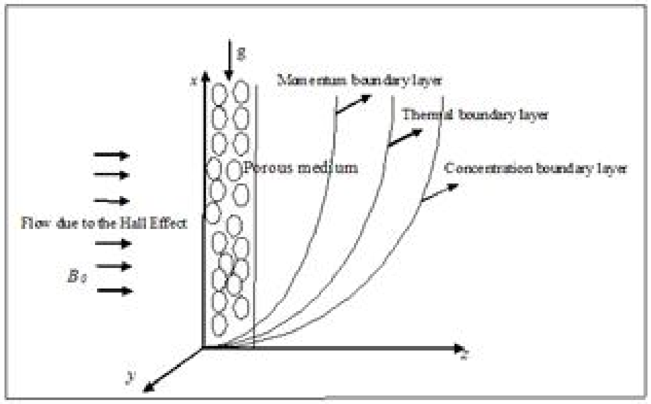

Figure 1: Physical configuration of the problem

We choose a Cartesian co-ordinate system $O(x, y, z)$ 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 normal to it. The interaction of Coriolis force with the free convection sets up a secondary flow in addition to primary flow and hence the flow becomes three dimensional. With the above frame of reference and assumptions, all the physical variables are functions of *z* and *t* alone. In the equation of motion, along x-direction the x-component current density $B_0 J_y$ and the x-component current density $-B_0 J_x$.

The constitutive equation for the stress T in an incompressible fluid of second grade is given by

$$T(t) = -pI + \mu A_1 + \alpha_1 A_2 + \alpha_2 A_1 \quad (2.1)$$

Where, μ is the dynamic viscosity α_1, α_2 are the normal stress moduli and the kinematical tensors A_1 and A_2 are defined through [Rivlin *et.al.* (29)].

$$A_1 = (gradV) + (gradV)^T,\ A_2 = \frac{DA_1}{Dt} + A_1(gradV) + (gradV)^T A_1 \quad (2.2)$$

Where, *V* is the velocity, *grad* the gradient operator and *D/Dt* the material time derivative.

The unsteady hydro magnetic flow in a rotating co-ordinate system is governed by the equation of motion, continuity equation and the Maxwell equations in the form.

$$\rho\left(\frac{\partial V}{\partial t} + (V.\nabla)V + 2\Omega \times V + \Omega \times (\Omega \times r)\right) = \nabla.T + J \times B \quad (2.3)$$

$$\nabla.V = 0 \quad (2.4)$$

$$\nabla.B = 0 \quad (2.5)$$

$$\nabla \times B = \mu_m J \quad (2.6)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (2.7)$$

Where, J is the current density, B is the total magnetic field, E is the total electric field, μ_m is the magnetic permeability and r is radial co-ordinate given by $r^2 = x^2 + y^2$. When the strength of the magnetic field is very large, the generalized ohm's law is modified to include the hall current so that

$$J + \frac{\omega_e \tau_e}{B_O}(J \times B) = \sigma\left[E + V \times B + \frac{1}{e\eta_e}\nabla P_e\right] \tag{2.8}$$

Where ω_e is the cyclotron frequency of the electrons, τ_e is the electron collision time, σ is the electrical conductivity, e is the electron charge and P_e is the electron pressure. The ion-slip and thermo electric effects are not included in equation (2.8). Further it is assumed that $\omega_e\tau_e$ ~ 0 (1) and $\omega_i\tau_i << 1$, where ω_i and τ_i are the cyclotron frequency and collision time for ions respectively. The unsteady hydro magnetic flow in a rotating system is governed by the equation of motion for momentum, the conservation of mass, energy and the equation of mass transfer, under usual Boussinesq approximation, are given by

$$\frac{\partial w}{\partial z} = 0 \tag{2.9}$$

$$\frac{\partial u}{\partial t} + w\frac{\partial u}{\partial z} - 2\Omega v = \nu\frac{\partial^2 u}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2 \partial t} + B_0 J_y - \frac{\nu}{K_1}u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \tag{2.10}$$

$$\frac{\partial v}{\partial t} + w\frac{\partial v}{\partial z} + 2\Omega u = \nu\frac{\partial^2 v}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2 \partial t} - B_0 J_x - \frac{\nu}{K_1}v \tag{2.11}$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{\nu}{k}w \tag{2.12}$$

$$\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial z^2} + S_1(T - T_\infty) \tag{2.13}$$

$$\frac{\partial C}{\partial t} + w\frac{\partial C}{\partial z} = D\frac{\partial^2 C}{\partial z^2} - K_C(C - C_\infty) \tag{2.14}$$

where, (u, v) is the velocity components along *x* and *y* directions, T is the temperature of the fluid, C is the species concentration, α_1 is the normal stress modulus, ρ is the density of the fluid, σ is the electrical conductivity of the fluid, K_1 is the permeability of the porous medium, B_0 is the uniform magnetic field of strength, ν is the coefficient of kinematic viscosity, k is the thermal conductivity of the fluid, C_p is the specific heat of the fluid at constant pressure, β is the volumetric coefficient of the thermal expansion, β^* is the volumetric coefficient of the thermal expansion with concentration, g is the acceleration due to gravity, D is the thermal diffusivity of the fluid, S_1 is the heat source/sink parameter and K_C is the chemical reaction parameter.

In equation (2.8) the electron pressure gradient, the ion-slip and thermo-electric effects are neglected. We also assume that the electric field $E=0$ under assumptions reduces to

$$J_x + m\ J_y = \sigma B_0 v \tag{2.15}$$

$$J_y - m\ J_x = -\sigma B_0 u \tag{2.16}$$

Where $m = \tau_e \omega_e$ is the hall parameter.

On solving equations (2.15) and (2.16) we obtain

$$J_x = \frac{\sigma B_0}{1+m^2}(v + mu) \tag{2.17}$$

$$J_y = \frac{\sigma B_0}{1+m^2}(mv - u) \tag{2.18}$$

Using the equations (2.17) and (2.18), the equations of motion with reference to a rotating frame are given by

$$\frac{\partial u}{\partial t} + w\frac{\partial u}{\partial z} - 2\Omega v = \nu\frac{\partial^2 u}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2 \partial t} + \frac{\sigma B_0^2}{1+m^2}(mv - u) - \frac{\nu}{K_1}u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \tag{2.19}$$

$$\frac{\partial v}{\partial t} + w\frac{\partial v}{\partial z} + 2\Omega u = \nu\frac{\partial^2 v}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2 \partial t} - \frac{\sigma B_0^2}{1+m^2}(v + mu) - \frac{\nu}{K_1}v \tag{2.20}$$

The corresponding boundary conditions are

$$u = v = 0,\ T = T_w + \varepsilon(T_w - T_\infty)e^{i\omega t}, C = C_w + \varepsilon(C_w - C_\infty)e^{i\omega t} \quad \text{at} \quad z = 0 \tag{2.21}$$

$$u = v = 0, T = T_\infty, C = C_\infty \quad \text{at} \quad z = \infty \tag{2.22}$$

Where $\varepsilon << 1$ and ω is the frequency of oscillation. There will be always some fluctuation 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 $\pi / 2\omega$. Now there may also occur some variation in suction at the plate due to the variation of the temperature, here we assume that, the frequency of suction and temperature variation are same.

Integrating the equation (2.9), we get

$$w(t) = -w_0(1 + \varepsilon A e^{i\omega t}) \tag{2.13}$$

Where A is the suction parameter, w_0 is the constant suction velocity and ε is the small positive number such that $\varepsilon A \leq 1.$ The equation (2.12) determines the pressure distribution along the axis of rotation and the absence of $\frac{\partial p}{\partial y}$ in the equation (2.11) implies that there is a net cross flow in the $y-$ direction. We choose, $q = u + iv$ and taking into consideration (2.23), the momentum equation (2.19) and (2.20) can be written as

$$\frac{\partial q}{\partial t} - w_0(1+\varepsilon A e^{i\omega t})\frac{\partial q}{\partial z} + 2i\Omega q = \nu\frac{\partial^2 q}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 q}{\partial z^2 \partial t} - \frac{\sigma B_0^2}{\rho(1-im)}q - \frac{\nu}{K_1}q$$

$$+ g\beta(T-T_\infty) + g\beta^*(C-C_\infty) \quad (2.24)$$

Introducing the following non-dimensional quantities:

$$z^* = \frac{w_0 z}{\nu},\ q^* = \frac{q}{w_0},\ T^* = \frac{T-T_\infty}{T_w - T_\infty},\ C^* = \frac{C-C_\infty}{C_w - C_\infty},\ \omega^* = \frac{\nu\omega}{w_0^2},\ t^* = \frac{t w_0^2}{\nu}$$

Making use of non-dimensional quantities (dropping asterisks), the equation (2.24), (2.13) and (2.14) can be written as

$$\frac{\partial q}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial q}{\partial z} + 2iRq = \frac{\partial^2 q}{\partial z^2} + \alpha\frac{\partial^3 q}{\partial z^2 \partial t} - \left(\frac{M^2}{1-im} + \frac{1}{K}\right)q + G_r T + G_m C \quad (2.25)$$

$$\frac{\partial T}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial T}{\partial z} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial z^2} + ST \quad (2.26)$$

$$\frac{\partial C}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial C}{\partial z} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} - K_C C \quad (2.27)$$

Where,

$M^2 = \frac{\sigma B_0^2 \nu}{\rho w_0^2}$ is the Hartmann number (Magnetic field parameter), $K = \frac{K_1 w_0^2}{\nu^2}$ is the Porosity parameter, $R = \frac{\Omega\nu}{w_0^2}$ is the Rotation parameter, $\alpha = \frac{\alpha_1 w_0^2}{\rho\nu^2}$ is the second grade fluid parameter, $G_r = \frac{g\beta\nu(T_w - T_\infty)}{w_0^3}$ is the thermal Grashof number, $G_m = \frac{g\beta^*\nu(C_w - C_\infty)}{w_0^3}$ is the mass Grashof number, $\Pr = \frac{\rho\nu C_p}{k}$ is Prandtl parameter, $S = \frac{S_1\nu}{w_0}$ is the Source parameter, $K_C = \frac{K_C\nu}{w_0^2}$ chemical reaction parameter, $m = \tau_e\omega_e$ is the hall parameter and $Sc = \frac{\nu}{D}$ is the Schmidt number.

The corresponding non-dimensional boundary conditions

$$q = 0, T = 1 + \varepsilon e^{i\omega t}, C = 1 + \varepsilon e^{i\omega t} \quad \text{at} \quad z = 0 \tag{2.28}$$

at (2.29)

In order to reduce the system of partial differential equations (2.25) – (2.27) under their boundary conditions (2.28) and (2.29), to a system of ordinary differential equations in the non-dimensional form, In view of the equation (2.23) and oscillating plate temperature T, The solution form of the equations (2.25), (2.26) and (2.27) are,

$$q(z,t) = q_0(z) + \varepsilon q_1(z) e^{i\omega t} \tag{2.30}$$

$$T(z,t) = T_0(z) + \varepsilon T_1(z) e^{i\omega t} \tag{2.31}$$

$$C(z,t) = C_0(z) + \varepsilon C_1(z) e^{i\omega t} \tag{2.32}$$

These equations (2.30) – (2.32) are valid for small amplitude of oscillation. Substituting from (2.30) to (2.32) into the system of equations (2.25) – (2.27) respectively, and equating the harmonic and non-harmonic terms, we get

$$\frac{d^2 q_0}{dz^2} + \frac{dq_0}{dz} - \left(2iR + \frac{M^2}{1-im} + \frac{1}{K}\right) q_0 = -G_r T_0 - G_m C_0 \tag{2.33}$$

$$(1+\alpha i\omega)\frac{d^2 q_1}{dz^2} + \frac{dq_1}{dz} - \left((2R+\omega)i + \frac{M^2}{1-im} + \frac{1}{K}\right) q_1 = -G_r T_1 - G_m C_1 - A\frac{dq_0}{dz} \tag{2.34}$$

$$\frac{d^2 T_0}{dz^2} + \Pr\frac{dT_0}{dz} + S \Pr T_0 = 0 \tag{2.35}$$

$$\frac{d^2 T_1}{dz^2} + \Pr\frac{dT_1}{dz} - (i\omega - S)\Pr T_1 = -A\Pr\frac{dT_0}{dz} \tag{2.36}$$

$$\frac{d^2 C_0}{dz^2} + Sc\frac{dC_0}{dz} - Sc\, K_C\, C_0 = 0 \tag{2.37}$$

$$\frac{d^2 C_1}{dz^2} + Sc\frac{dC_1}{dz} - (i\omega + K_C) ScC_1 = -A\, Sc\frac{dC_0}{dz} \tag{2.38}$$

The corresponding boundary conditions

$$\left.\begin{array}{l} q_0 = 0, T_0 = 1, C_0 = 1 \\ q_1 = 0, T_1 = 1, C_1 = 1 \end{array}\right\} \text{at} \quad z = 0 \tag{2.39}$$

$$\left.\begin{array}{l} q_0 = T_0 = C_0 = 0 \\ q_1 = T_1 = C_1 = 0 \end{array}\right\} \text{at} \quad z = \infty \tag{2.40}$$

The solutions of the equations (2.35) and (2.36) using the boundary conditions (2.39) and (2.40), we obtain T_0 and T_1, the equation (2.31) becomes,

$$T(z,t)=e^{C_5 z}+\varepsilon\left(e^{a_2 z}+\frac{A\Pr C_5}{C_6}(e^{a_2 z}-e^{C_5 z})\right)e^{i\omega t} \tag{2.41}$$

The solutions of the equations (2.37) and (2.38) using the boundary conditions (2.39) and (2.40), we obtain C_0 and C_1, the equation (2.32) becomes,

$$C(z,t)=e^{C_2 z}+\varepsilon\left(e^{a_4 z}+\frac{AScC_2}{C_3}(e^{a_4 z}-e^{C_2 z})\right)e^{i\omega t} \tag{2.42}$$

The solutions of the equations (2.33) and (2.34) using the boundary conditions (2.39) and (2.40), we obtain q_0 and q_1, the equation (2.30) becomes,

$$q(z,t)=b_1 e^{C_5 z}+b_2 e^{C_2 z}+b_3 e^{a_6 z}+$$

$$\varepsilon\left(C_{17}e^{a_8 z}+C_{12}e^{a_2 z}+C_{13}e^{C_5 z}+C_{14}e^{a_4 z}+C_{15}e^{C_2 z}+C_{16}e^{a_6 z}\right)e^{i\omega t} \tag{2.43}$$

The equation (2.43) reveals that the steady part of the velocity field has three layer character while the oscillatory part of the fluid field exhibits a multilayer character. From equations (2.41) and (2.42), we observe that in case of considerably slow motion of the fluid. i.e., when the viscous dissipation term is neglected, the temperature profiles are mainly affected by Prandtl number (Pr) and Source parameter (*S*): and the concentration profiles are affected by Schimdt number (*Sc*) and chemical reaction parameter (K_C) of the fluid respectively. Considering

$$q_0=u_0+iv_0 \text{ and } q_1=u_1+iv_1$$

Now it is convenient to write the primary and secondary velocity fields in terms of the fluctuating parts, separating the real and imaginary parts from the equation (2.43) and taking only the real parts as they have physical significance. The velocity distribution of the flow field can be expressed as in fluctuating parts,

$$q(z,t)=q_0(z)+\varepsilon\, q_1(z)\,e^{i\omega t}$$

$$u+iv=u_0+iv_0+\varepsilon\,u_1\cos\omega t+i\,\varepsilon\,u_1\sin\omega t+i\,\varepsilon\,v_1\cos\omega t-\varepsilon\,v_1\sin\omega t$$

Comparing real and imaginary parts,

$$u(z,t)=w_0(u_0(z)+\varepsilon\,(u_1\cos\omega t-v_1\sin\omega t)) \tag{2.44}$$

$$v(z,t)=w_0(v_0(z)+\varepsilon\,(u_1\sin\omega t+v_1\cos\omega t)) \tag{2.45}$$

Hence the expression for the transient velocity profiles for

$\omega t=\pi/2$ are given by

$$u\left(z,\frac{\pi}{2\omega}\right)=w_0\,(u_0(z)-\varepsilon\,v_1(z)) \tag{2.46}$$

$$v\left(z,\frac{\pi}{2\omega}\right)=w_0\,(v_0(z)+\varepsilon\,u_1(z)) \tag{2.47}$$

Skin friction:

The non-dimensional skin friction at the plate $z=0$ in term of amplitude and phase angle is given by

$$\tau = \left(\frac{dq}{dz}\right)_{z=0} = \left(\frac{dq_0}{dz}\right)_{z=0} + \varepsilon\left(\frac{dq_1}{dz}\right)_{z=0} e^{i\omega t}$$

$$= C_5 b_1 + C_2 b_2 + C_3 a_6 + \varepsilon\,(a_8 C_{17} + a_2 C_{12} + C_5 C_{13} + a_4 C_{14} + C_2 C_{15} + a_6 C_{16})\, e^{i\omega t} \qquad (2.48)$$

The τ_{xz} and τ_{yz} components of skin friction at the plate are given by

$$\tau_{xz} = \left(\frac{du_0}{dz}\right)_{z=0} - \varepsilon\left(\frac{dv_1}{dz}\right)_{z=0} \quad \text{and} \quad \tau_{yz} = \left(\frac{dv_0}{dz}\right)_{z=0} + \varepsilon\left(\frac{du_1}{dz}\right)_{z=0}$$

Rate of heat transfer (Nusselt number):

The rate of heat transfer co-efficient at the plate $z = 0$ in term of amplitude and phase angle is given by

$$Nu = \left(\frac{dT}{dz}\right)_{z=0} = \left(\frac{dT_0}{dz}\right)_{z=0} + \varepsilon\left(\frac{dT_1}{dz}\right)_{z=0} e^{i\omega t} = C_5 + \varepsilon\left(a_2 + \frac{A\Pr C_5}{C_6}(a_2 - C_5)\right) e^{i\omega t} \qquad (2.49)$$

Rate of mass transfer (Sherwood number):

The rate of mass transfer co-efficient at the plate $z = 0$ in term of amplitude and phase angle is given by

$$Sh = \left(\frac{dC}{dz}\right)_{z=0} = \left(\frac{dC_0}{dz}\right)_{z=0} + \varepsilon\left(\frac{dC_1}{dz}\right)_{z=0} e^{i\omega t} = C_2 + \varepsilon\left(a_4 + \frac{A\,Sc\,C_2}{C_3}(a_4 - C_2)\right) e^{i\omega t} \qquad (2.50)$$

Where,

$$a_1 = \frac{-\Pr + \sqrt{\Pr^2 + 4\Pr(i\omega - S)}}{2}, \quad a_2 = \frac{-\Pr - \sqrt{\Pr^2 + 4\Pr(i\omega - S)}}{2},$$

$$a_3 = \frac{-Sc + \sqrt{Sc^2 + 4Sc(i\omega - K_C)}}{2}, \quad a_4 = \frac{-Sc - \sqrt{Sc^2 + 4Sc(i\omega - K_C)}}{2}$$

$$a_5 = \frac{-1 + \sqrt{1 + 4\left(2iR + \frac{M^2}{1-im} + \frac{1}{K}\right)}}{2}, \quad a_6 = \frac{-1 - \sqrt{1 + 4\left(2iR + \frac{M^2}{1-im} + \frac{1}{K}\right)}}{2},$$

$$a_7 = \frac{-1 + \sqrt{1 + 4(1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)}}{2}, \quad a_8 = \frac{-1 - \sqrt{1 + 4(1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)}}{2},$$

$$b_1 = \frac{-G_r}{C_5^2 + C_5 - \left(2iR + \frac{M^2}{1-im} + \frac{1}{K}\right)}, \quad b_2 = \frac{-G_m}{C_2^2 + C_2 - \left(2iR + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$b_3 = -(b_1 + b_2),\quad C_1 = \frac{-Sc + \sqrt{Sc^2 + 4ScK_C}}{2},\quad C_2 = \frac{-Sc - \sqrt{Sc^2 + 4ScK_C}}{2},$$

$$C_3 = C_2^2 + Sc\,C_2 - Sc\,(i\omega + K_C),\quad C_4 = \frac{-\Pr + \sqrt{\Pr^2 - 4S\Pr}}{2},\quad C_5 = \frac{-\Pr - \sqrt{\Pr^2 - 4S\Pr}}{2}$$

$$C_6 = C_5^2 + \Pr C_5 - \Pr(i\omega - S),\quad C_7 = -G_r\left(1 + \frac{A\Pr C_5}{C_6}\right),\quad C_8 = G_r\frac{A\Pr C_5}{C_6} - AC_5 b_1,$$

$$C_9 = -G_m\left(1 + \frac{AScC_2}{C_3}\right),\quad C_{10} = G_m\frac{AScC_2}{C_3} - AC_2 b_2,\quad C_{11} = Aa_6 b_3,$$

$$C_{12} = \frac{C_7}{(1+\alpha i\omega)a_2^2 + a_2 - (1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$C_{13} = \frac{C_8}{(1+\alpha i\omega)C_5^2 + C_5 - (1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$C_{14} = \frac{C_9}{(1+\alpha i\omega)a_4^2 + a_4 - (1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$C_{15} = \frac{C_{10}}{(1+\alpha i\omega)C_2^2 + C_2 - (1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$C_{16} = \frac{C_{11}}{(1+\alpha i\omega)a_6^2 + a_6 - (1+\alpha i\omega)\left(i(2R+\omega) + \frac{M^2}{1-im} + \frac{1}{K}\right)},$$

$$C_{17} = -(C_{12} + C_{13} + C_{14} + C_{15} + C_{16})$$

3. Results and Discussion

The unsteady magneto hydrodynamic free convection flow of an incompressible electrically conducting second grade fluid bounded by an infinite vertical porous surface in a rotating system taking hall current into account under the presence of heat source and chemical reaction. The closed form solutions for the velocity $q = u + iv$, temperature θ and concentration *C* are obtained making use of perturbation technique. The velocity expression consists of steady state and oscillatory state. It reveals that, the steady part of the velocity field has three layer characters while the oscillatory part of the fluid field exhibits a multi layer character. The Figures (2-4) shows the effects of non-dimensional parameters *M* the Hartmann number, α the second grade fluid parameter, *K* permeability parameter, m hall parameter, R rotation parameter, S heat source parameter, Gr Grashof number, Gm mass Grashof number, Kc chemical reaction parameter, Pr the Prandtl number and *t* time; the Figure (5) exhibit the temperature distribution with different variations in the governing parameters S, Pr, the frequency of oscillation and time *t*; and the Figure (6) depicts the concentration profiles with variations in Schmidt number Sc and chemical reaction parameter Kc, ω the frequency of oscillation and time *t*.

It is noticed that, from the Figures 2(a-h) the magnitude of the velocity *u* reduces with increasing the intensity of the magnetic field (Hartmann number M) while it enhances with increasing second grade fluid parameter α or permeability of porous medium *K* or hall parameter *m* throughout the fluid region. The magnitude of the velocity component *v* enhances with increasing *M* or second grade fluid parameter α or permeability of porous medium *K* or hall parameter *m*. The application of the transverse magnetic field plays the important role of a resistive type force (Lorentz force) similar to drag force (that acts in the opposite direction of the fluid motion) which tends to resist the flow thereby reducing its velocity. The resultant velocity *q* enhances with increasing α, *K* and *m*; and reduces with increasing *M*. We observe that lower the permeability of porous medium lesser the fluid speed in the entire fluid region. From the Figures 3 (a-h) depicts the velocity component *u* reduces with increasing the rotation parameter *R* while it enhances with increasing source parameter *S*, Grashof number Gr and mass Grashof number Gm. The profiles show the magnitude of the velocity component *v* reverse trend whenever there is increasing rotation parameter *R* or source parameter *S* or Gr or Gm. The resultant velocity *q* increases with increasing *R* or Gr or Gm; and reduces with increasing *S*. Further, it is to observed that from Figures 4 (a-h) the velocity *u* reduces and *v* enhances with increasing Schmidt number *Sc*, first the velocity *u* increases and then experiences retardation where as *v* reduces in the entire fluid region with increasing chemical reaction parameter Kc. With increasing Prandtl number Pr the velocity *u* reduces and *v* enhances in the complete flow field. This implies that an increase in Prandtl number Pr leads to fall the thermal boundary layer flow. This is because fluids with large have low thermal diffusivity which causes low heat penetration resulting in reduced thermal boundary layer. Likewise the velocity *u* enhances and *v* decreases with increasing the frequency of oscillation ω and time *t*. The resultant velocity reduces with increasing Kc or Sc and increases with increasing Pr and time *t*. The temperature profiles exhibit in the Figures 5(a-d) for different variations in source parameter *S*, Prandtl number Pr, the frequency of oscillation ω and time *t*. It is observed that Prandtl number Pr leads to decrease the temperature uniformly in all layers being the heat source parameter fixed. It is found that the temperature decreases in all layers with increase in the heat source parameter *S*. It is concluded that the heat source parameter *S* and Prandtl number Pr reduces the temperature in all layers. The temperature increases with increasing the frequency of oscillation ω and time *t*. The concentration profiles are shown in the Figures 6 (a-d) for different variations in Schmidt number Sc, the chemical reaction parameter Kc, the frequency of oscillation ω and time *t*. It is noticed that the concentration decreases at all layers of the flow for heavier species such as CO_2, H_2O and NH_3 having Schmidt number 0.3, 0.6 and 0.78 respectively. It is observed that for heavier diffusing foreign species, i.e., the velocity reduces with increasing Schmidt number Sc in both magnitude and extent and thinning of thermal boundary layer occurs. Likewise, the concentration profiles decrease with increase in chemical reaction parameter Kc. It is concluded that the Schmidt number and the chemical reaction parameter reduces the concentration in all layers. The concentration increases with increasing the frequency of oscillation ω and time *t*.

It is noted from the table 1 that the magnitudes of both the skin friction components τ_{xz} and τ_{yz} increase with increase in permeability parameter K, hall parameter *m*, thermal Grashof number Gr and mass Grashof number Gm, and where as it reduces with increase in Hartmann number *M*, second grade fluid parameter α, heat source parameter *S*, Schmidt number *Sc*, chemical reaction parameter *Kc* and Prandtl number Pr. Likewise the rotation parameter *R* enhances skin friction component τ_{xz} and reduces skin friction component τ_{yz}. From the table 2 that The magnitude of the Nusselt number Nu increases for the parameters heat source parameter *S* and Prandtl number Pr or time *t*, and it reduces with the frequency of oscillation ω. Also from the table 4, the similar behaviour is observed. The magnitude of the Sherwood number *Sh* increases for increasing the parameters Schmidt number *Sc* and chemical reaction parameter Kc or time *t* and reduce with increasing the frequency of oscillation ω.

Table. 1. Skin Friction

M	α	K	*m*	R	S	Gr	Gm	Sc	Kc	Pr	τ_{xz}	τ_{yz}
2	1	2	1	1.2	2	5	10	0.22	2	0.71	5.610018	-2.679655
3	1	2	1	1.2	2	5	10	0.22	2	0.71	5.280022	-2.431979
4	1	2	1	1.2	2	5	10	0.22	2	0.71	4.994062	-2.238832
2	2	2	1	1.2	2	5	10	0.22	2	0.71	5.619835	-2.675965
2	3	2	1	1.2	2	5	10	0.22	2	0.71	5.519604	-2.646093
2	1	3	1	1.2	2	5	10	0.22	2	0.71	5.630642	-2.798579
2	1	4	1	1.2	2	5	10	0.22	2	0.71	5.633692	-2.856412
2	1	2	2	1.2	2	5	10	0.22	2	0.71	5.781484	-3.117423
2	1	2	3	1.2	2	5	10	0.22	2	0.71	5.936172	-3.295582
2	1	2	1	1.4	2	5	10	0.22	2	0.71	5.368144	-2.707081
2	1	2	1	1.8	2	5	10	0.22	2	0.71	4.939473	-2.707612
2	1	2	1	1.2	3	5	10	0.22	2	0.71	5.513113	-2.599534
2	1	2	1	1.2	4	5	10	0.22	2	0.71	5.431000	-2.539932
2	1	2	1	1.2	2	6	10	0.22	2	0.71	5.938664	-2.802592
2	1	2	1	1.2	2	7	10	0.22	2	0.71	6.257066	-2.919556
2	1	2	1	1.2	2	5	5	0.22	2	0.71	3.606121	-1.635212
2	1	2	1	1.2	2	5	8	0.22	2	0.71	4.814612	-2.265465
2	1	2	1	1.2	2	5	10	0.3	2	0.71	5.438912	-2.441874
2	1	2	1	1.2	2	5	10	0.6	2	0.71	4.923213	-1.885492
2	1	2	1	1.2	2	5	10	0.22	4	0.71	5.310184	-2.286522
2	1	2	1	1.2	2	5	10	0.22	7	0.71	4.999061	-1.957933
2	1	2	1	1.2	2	5	10	0.22	2	3	4.900980	-2.261319
2	1	2	1	1.2	2	5	10	0.22	2	7	4.533414	-2.153403

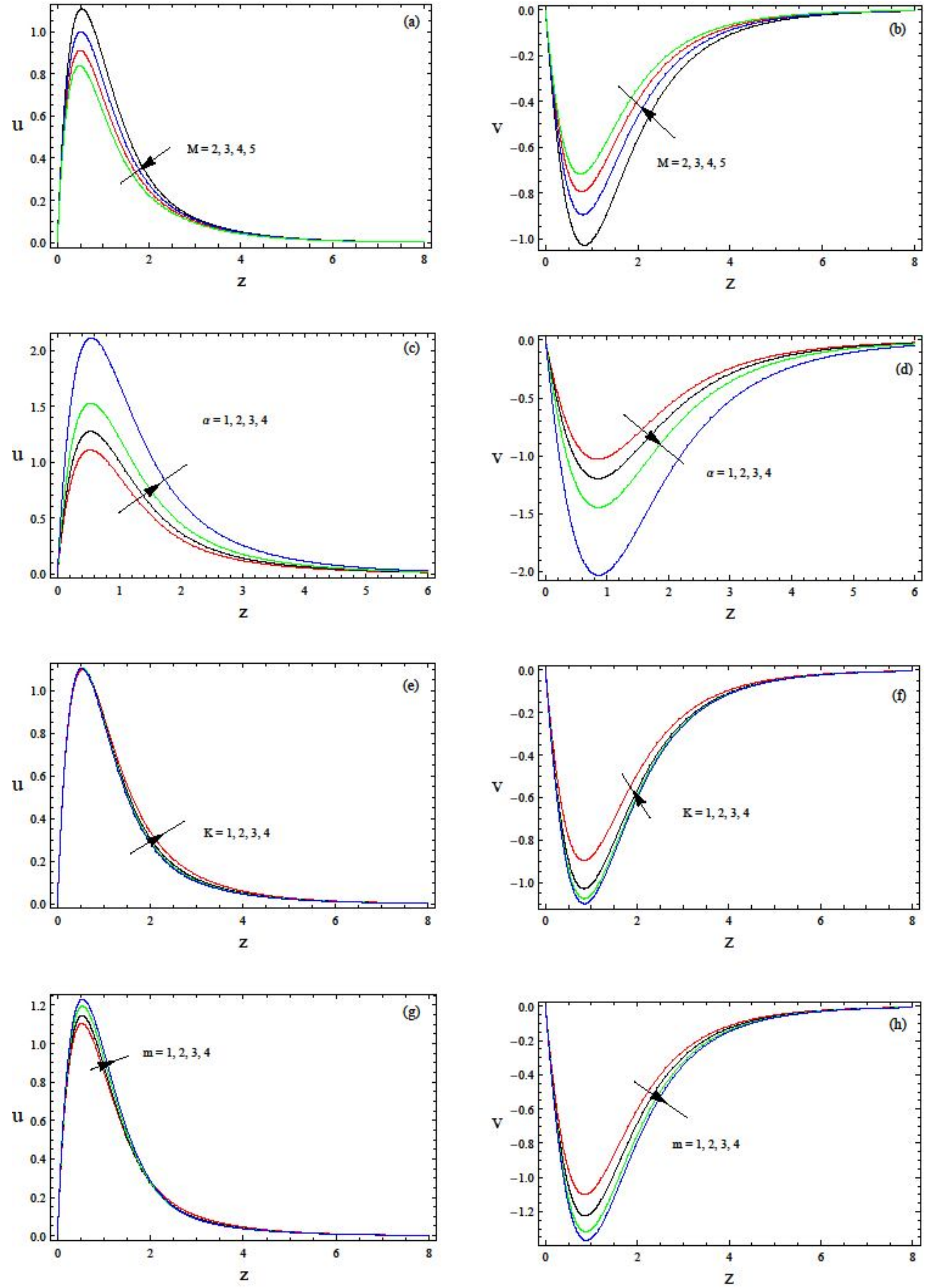

Fig. 2. The velocity profiles for the components u and v for M, α, K and m with $A = 0.05$; $\omega = 5\pi/2$; $\varepsilon = 0.001$, $t = 0.2$

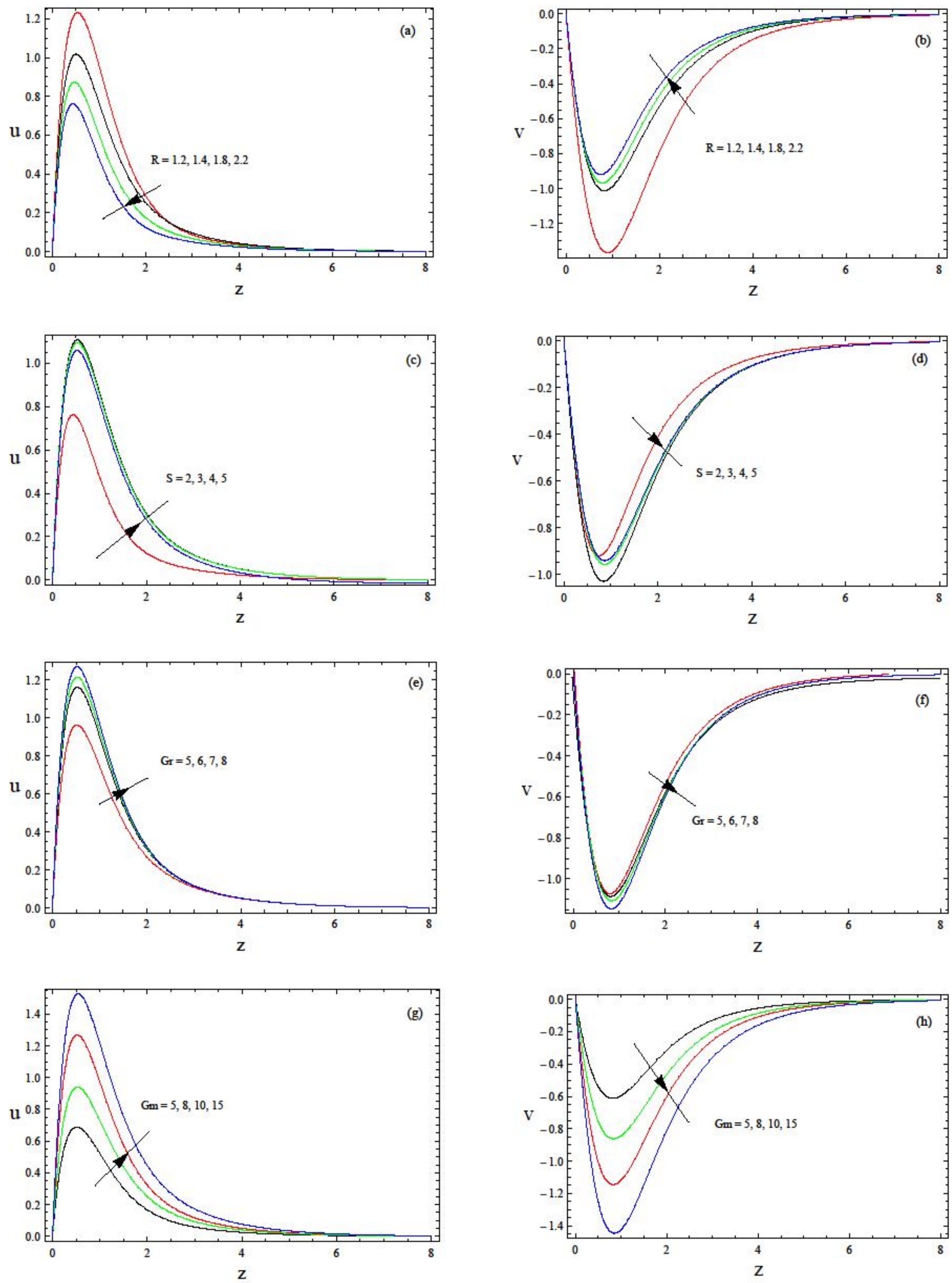

Fig. 3. The velocity profiles for the components u and v for R, S, Gr and Gm
with $A=0.05$; $\omega=5\pi/2$; $\varepsilon=0.001$, $t=0.2$

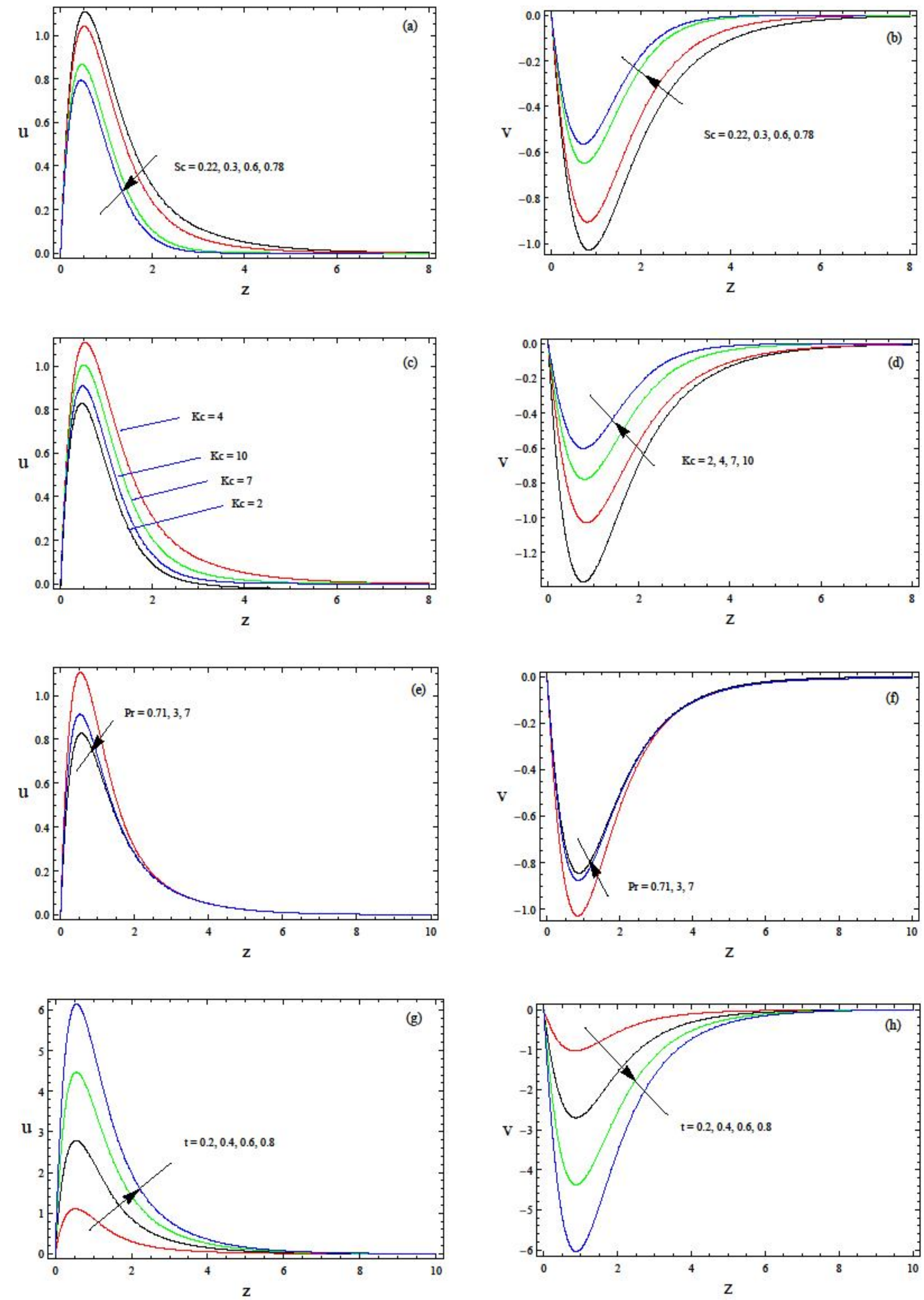

Fig. 4. The velocity profiles for the components u and v for Sc, Kc, Pr and t with $A=0.05;\ \omega=5\pi/2;\ \varepsilon=0.001;\ t=0.2$

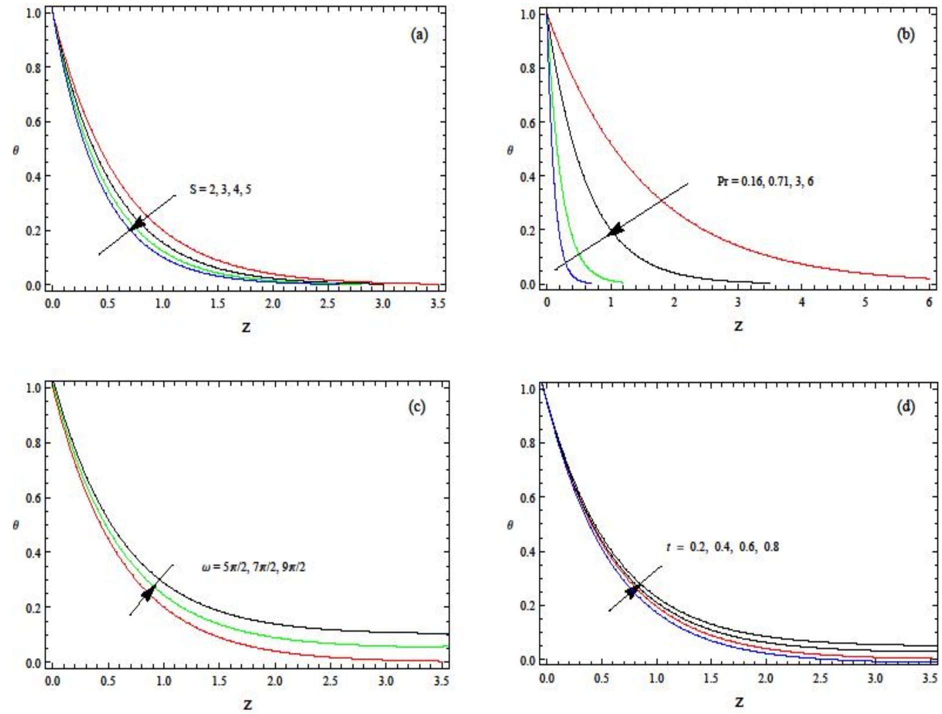

Fig. 5. The temperature profiles for θ with $A=0.05$; $\omega=5\pi/2$; $\varepsilon=0.001$; $t=0.2$

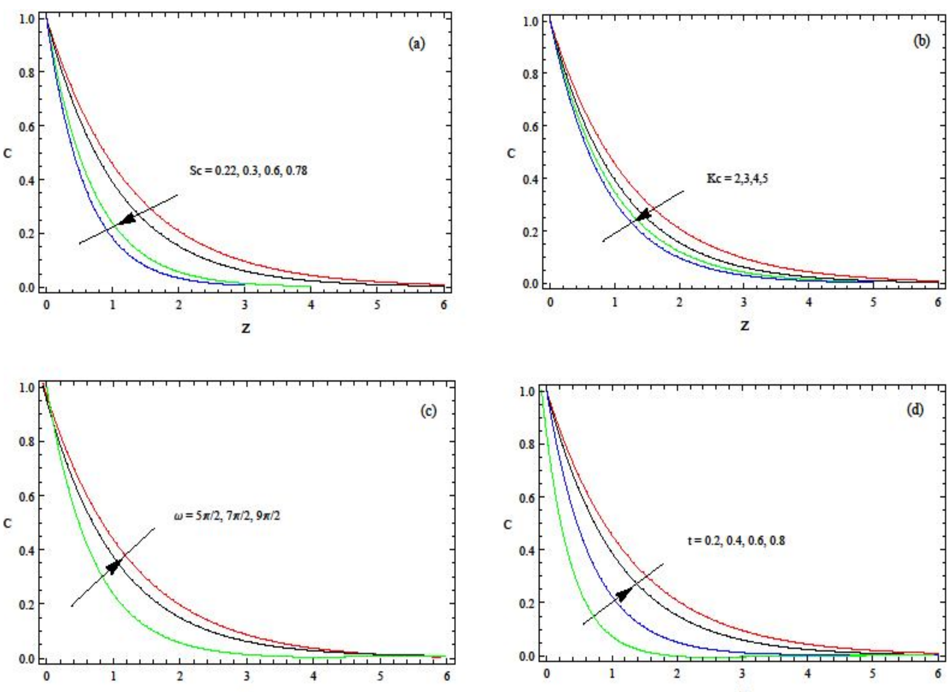

Fig. 6. The Concentration profiles for C with $A=0.05$; $\omega=5\pi/2$; $\varepsilon=0.001$; $t=0.2$

It is noted from the table 1 that the magnitudes of both the skin friction components τ_{xz} and τ_{yz} increase with increase in permeability parameter K, hall parameter *m*, thermal Grashof number Gr and mass Grashof number Gm, and where as it reduces with increase in Hartmann number *M*, second grade fluid parameter α, heat source parameter *S*, Schmidt number *Sc*, chemical reaction parameter *Kc* and Prandtl number Pr. Likewise the rotation parameter *R* enhances skin friction component τ_{xz} and reduces skin friction component τ_{yz}. From the table 2 that The magnitude of the Nusselt number Nu increases for the parameters heat source parameter *S* and Prandtl number Pr or time *t*, and it reduces with the frequency of oscillation ω. Also from the table 4, the similar behaviour is observed. The magnitude of the Sherwood number *Sh* increases for increasing the parameters Schmidt number *Sc* and chemical reaction parameter Kc or time *t* and reduce with increasing the frequency of oscillation ω.

Table. 2. Nusselt Number

S	Pr	ω	t	Nu
2	**0.71**	5π/2	**0.2**	-1.59653
3	0.71	5π/2	0.2	-1.85503
4	0.71	5π/2	0.2	-2.07512
2	**3**	5π/2	0.2	-4.36861
2	**7**	5π/2	0.2	-8.61827
2	0.71	7π/2	0.2	-1.59538
2	0.71	9π/2	0.2	-1.59431
2	0.71	5π/2	**0.4**	-1.59854
2	0.71	5π/2	**0.6**	-1.60026

Table 3. Sherwood Number

S	Pr	ω	t	Sh
2	**0.22**	5π/2	**0.2**	-0.781334
3	0.22	5π/2	0.2	-0.928700
4	0.22	5π/2	0.2	-1.053333
2	**0.3**	5π/2	0.2	-0.937762
2	**0.6**	5π/2	0.2	-1.434060
2	0.22	7π/2	0.2	-0.780754
2	0.22	9π/2	0.2	-0.778487
2	0.22	5π/2	**0.4**	-0.782446
2	0.22	5π/2	**0.6**	-0.783434

1. Conclusions

We considered the MHD free convection flow of second grade fluid through porous medium bounded by an infinite vertical porous rotating plate taking hall current into account. The conclusions are made as follows

1. The resultant velocity enhances with increasing α, K, *m*, R, Gr, Gm, Pr and time *t*; and reduces with increasing M, S, Kc and Sc.
2. Lower the permeability of porous medium lesser the fluid speed in the entire fluid region.

3. The parameters S and Pr reduce the temperature in all layers. The temperature increases with increasing ω and time.
4. The Schmidt number and Kc reduce the concentration in all layers. The concentration increases with increasing ω and time.
5. The skin friction components τ_{xz} and τ_{yz} increase with increase in K, *m*, Gr and Gm, and where as it reduces with increase in M, α, S, Sc, Kc and Pr. The rotation parameter R enhances skin friction component τ_{xz} and reduces τ_{yz}.
6. The heat transfer coefficient increases with increasing S and Pr or time span, and it reduces with ω.
7. The Sherwood number enhances for increasing the parameters Schmidt number and chemical reaction parameter or time span and reduces with increasing ω.

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