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Heat and mass transfer on Unsteady MHD flow of a second grade fluid through porous medium between two vertical plates

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Abstract

In this Paper, an investigation of the heat and mass transfer on the flow of an oscillatory convective MHD viscous incompressible, radiating and electrically conducting second grade fluid in a vertical porous rotating channel in slip flow regime and taking Hall current into account is carried out. The fluid is assumed to be gray, absorbing and emitting radiation out in non scattering medium. The MHD flow is assumed to be laminar and fully developed. A closed form solutions of the equations governing the flow are obtained for the velocity and temperature distributions making use of regular perturbation technique. The velocity, temperature and concentration profiles are discussed through graphically as well as skin friction coefficient, Nusselt number and Sherwood number are evaluated numerically and presented in the form of tables and discussed for different values of governing flow parameters.

Key words: Hall Effect, radiating fluid, MHD oscillatory flow, rotating channel, slip flow regime.

2. Introduction

The study of flow in rotating porous channel is motivated by its practical applications in geophysics and engineering. Among the applications of rotating flow in a porous media to engineering disciplines, one can find the food processing industry, chemical processing industry, centrifugation filtration processes and rotating machinery. In engineering, it finds its application in MHD generator ion propulsion, MHD bearing, MHD pumps, MHD boundary layer control of re-entry vehicles etc. Several scholars *viz.* Hall effect on unsteady MHD free and forced convection flow in a porous rotating channel has been investigated by several researchers

Sivaprasad *et al.*[1], Singh and Kumar[2], Singh and Pathak[3], and Ghosh *et al.*[4]. Raptis[5] studied the radiation free convective flow through a porous medium. Alagoa *et al.*[6] has analysed the effect of radiation on MHD flow through the porous medium between infinite parallel plates in the presence of time dependent suction. Zhu and Granick[7]. Recently, the slip condition has become much more compelling and it is now reasonably certain that viscous fluid can slip against solid surfaces if the surface is very smooth Navier[8]. Recently, Krishna and Swarnalathamma[9] 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. Raghunath and Siva Prasad[10] discussed heat and mass transfer on unsteady MHD flow of a visco elastic fluid past an infinite vertical oscillating porous plate. Farhad Ali(2017) Unstead MHD flow of Second grade fluid over an oscillating vertical plate with isothermal temperature in a porous medium with Heat and Mass Transfer by Using the Laplace Transform technique.

3. Formulation and Solution of the Problem :

Consider the flow of a viscous, incompressible and electrically conducting second grade fluid through a porous medium bounded by two infinite vertical insulated plates at d distance apart under the influence of uniform transverse magnetic field with magnetic flux density vector B_0 normal to the channel and taking Hall current into account. We introduce a Cartesian co-ordinate system with x-axis oriented vertically upward along the centreline of this channel and z-axis taken perpendicular to the planes of the plates which is the axis of the rotation and the entire system comprising of the channel and the fluid are rotating as a solid body about this axis with constant angular velocity Ω. A constant injection velocity w_0 is applied at the plate $z=-d/2$ and the same constant suction velocity, w_0, is applied at the plate $z=d/2$. The schematic diagram of the physical problem is shown in the Fig. 1.

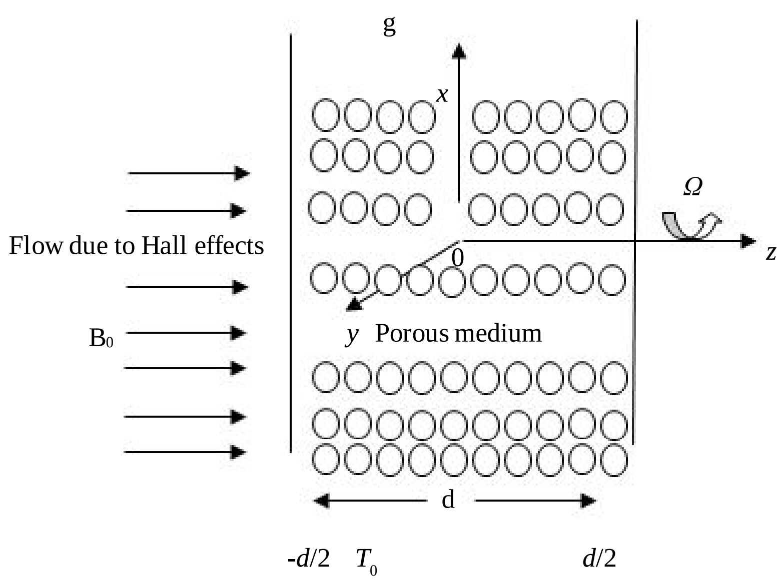


Fig. 1 Physical Configuration of the Problem

Since the plates of the channel occupying the planes $z=\pm d/2$ are of infinite extent, all the physical quantities depend upon only on z and t only. Under the Boussinesq approximation the flow of the fluid through the porous medium in a rotating channel is governed by the following equation:

$$\frac{\partial w}{\partial z}=0 \tag{2.1}$$

$$\frac{\partial u}{\partial t}-2i\Omega v+w_0\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\frac{\partial^2 u}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2\partial t}+\frac{B_0J_y}{\rho}-\frac{v}{k}u+g\beta T+g\beta_c C \tag{2.2}$$

$$\frac{\partial v}{\partial t}+2i\Omega u+w_0\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\frac{\partial^2 v}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 z}{\partial z^2\partial t}-\frac{B_0J_x}{\rho}-\frac{v}{\kappa}v \tag{2.3}$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+w_0\frac{\partial T}{\partial z}\right)=K_1\frac{\partial^2 T}{\partial z^2}-Q_0T+Q_1C-\frac{\partial q_1}{\partial z} \tag{2.4}$$

$$\frac{\partial C}{\partial t}+w_0\frac{\partial C}{\partial z}=D\frac{\partial^2 T}{\partial z^2}-K_cC \tag{2.5}$$

The boundary conditions are

$$u=\frac{2-f_1L}{f_1}\frac{\partial u}{\partial z}=L\frac{\partial u}{\partial z},v=\frac{2-f_1L}{f_1}\frac{\partial v}{\partial z}=L\frac{\partial v}{\partial z},\ T=0,C=0, \quad \text{at} \quad z=-\frac{d}{2} \tag{2.6}$$

$$u=v=0,\ T=T_0\cos\omega t,C=C_0\cos\omega t \quad \text{at} \quad z=\frac{d}{2} \tag{2.7}$$

Where, $L=\mu\left(\frac{\pi}{2p\rho}\right)^{1/2}$ is the mean free path which is constant for an incompressible fluid.

When the strength of the magnetic field is very large, the generalized Ohm's law is modified to include the hall current so that,

$$J+\frac{w_e\tau_e}{B_0}(J\times B)=\sigma(E+V\times B+\frac{1}{\rho\eta_e}\nabla p_e) \tag{2.8}$$

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 assumption reduces to,

$$J_x+mJ_y=\sigma B_0^2 v \tag{2.9}$$

$$J_y-mJ_x=-\sigma B_0^2 u \tag{2.10}$$

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

On solving the equations (2.9) and (2.10),
We obtain,

$$J_x=\frac{\sigma B_0}{1+m^2}(v+mu) \quad \text{and} \quad J_y=\frac{\sigma B_0}{1+m^2}(mv-u) \qquad (2.11) \text{ and } (2.12)$$

Using the equations (2.11) and (2.12), the equations (2.2) and (2.3) reduces,

$$\frac{\partial u}{\partial t}-2i\Omega v+w_0\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2\partial t}+\frac{\sigma B_0^2}{\rho(1+m^2)}(mv-u)\ -\frac{\nu}{k}u+g\beta T+g\beta_c C \quad (2.13)$$

$$\frac{\partial v}{\partial t}+2i\Omega u+w_0\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\frac{\partial^2 v}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2\partial t}+\frac{\sigma B_0^2}{\rho(1+m^2)}(v+mu)-\frac{\nu}{k}v \quad (2.14)$$

Following[22] the last term in the energy equation stand for heat flux which is given by

$$\frac{\partial q_1}{\partial z}=4\alpha^2 T \quad (2.15)$$

Where α is the mean variation absorption coefficient.
Introducing non-dimensional variables,

$$z^*=\frac{z}{d},x^*=\frac{x}{d},y^*=\frac{y}{d},u^*=\frac{u}{d},v^*=\frac{v}{d},\theta=\frac{T}{T_0},\ \phi=\frac{C}{C_0},\ t^*=\frac{t\,w_0}{d},\ p^*=\frac{p}{\rho\, w_0^2},\omega^*=\frac{\omega d}{w_0}$$

Making use of non-dimensional variables, the equations (2.12), (2.13) and (2.4) reduces to (dropped asterisks)

$$\mathrm{Re}\left(\frac{\partial u}{\partial t}+\frac{\partial u}{\partial z}\right)-2iRv=-\mathrm{Re}\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial z^2}+S\frac{\partial^3 u}{\partial z^2\partial t}+\frac{M^2}{1+m^2}(mv-u)-\frac{1}{K}u+\mathrm{Gr}\,\theta+\mathrm{Gc}\,\phi \quad (2.16)$$

$$\mathrm{Re}\left(\frac{\partial v}{\partial t}+\frac{\partial v}{\partial z}\right)+2iRu=-\mathrm{Re}\frac{\partial p}{\partial y}+\frac{\partial^2 v}{\partial z^2}+S\frac{\partial^3 v}{\partial z^2\partial t}+\frac{M^2}{1+m^2}(mu+v)-\frac{1}{K}v \quad (2.17)$$

$$\mathrm{Re}\,\mathrm{Pr}\left(\frac{\partial\theta}{\partial t}+\frac{\partial\theta}{\partial z}\right)=\frac{\partial^2\theta}{\partial z^2}-\mathrm{Pr}\,\phi_1\theta+\mathrm{Re}^2\,\mathrm{Pr}\,Q\phi-\mathrm{Pr}\,N^2\theta \quad (2.18)$$

$$\mathrm{Sc}\,\mathrm{Re}\left(\frac{\partial\phi}{\partial t}+\frac{\partial\phi}{\partial z}\right)=\frac{\partial^2\phi}{\partial z^2}-\mathrm{Sc}\,\mathrm{Re}\,\mathrm{Kc}\,\phi \quad (2.19)$$

The corresponding boundary conditions in non dimensional form are

$$u=h\frac{\partial u}{\partial z},\ v=h\frac{\partial v}{\partial z},\ T=0 \qquad \text{at} \qquad z=-\frac{1}{2} \quad (2.20)$$

$$u=v=0,\ T=T_0\cos\omega t \qquad \text{at} \qquad z=\frac{1}{2} \quad (2.21)$$

Where, $\mathrm{Re}=\frac{w_0 d}{\nu}$ is Reynolds number, $R=\frac{\Omega d^2}{\nu}$ is the rotation parameter, $K=\frac{k}{d^2}$ is the permeability parameter, $\mathrm{Gr}=\frac{g\beta d^2 T_0}{\nu w_0}$ is the thermal Grashof number, $\mathrm{Gc}=\frac{g\beta_c d^2 C_0}{\nu w_0}$ is the mass Grashof number,

$\Pr = \dfrac{\mu C_p}{K_1}$ is the Prandtl number, $\mathrm{Sc} = \dfrac{\nu}{D}$ is the Schmidt number, $\mathrm{Kc} = \dfrac{K_c d}{w_0}$ is the chemical reaction parameter, $N = \dfrac{2\alpha d}{\sqrt{K_1}}$ is the Radiation parameter, $\phi_1 = \dfrac{Q_0\, d^2}{\mu\, C_p}$ is the Heat absorption parameter, $Q = \dfrac{Q_1 \nu C_0}{\rho\, C_p w_0^2 T_0}$ is the Radiation absorption number, $M^2 = \dfrac{\sigma B_0^2\, d^2}{\mu}$ is the Hartmann number and $S = \dfrac{\alpha_1}{\rho d^2}$ is the second grade fluid parameter.

Combining equations (2.12) and (2.13), let $q = u + iv$ and $\xi = x - iy$, we obtain

$$\mathrm{Re}\left(\frac{\partial q}{\partial t}+\frac{\partial q}{\partial z}\right) = -\mathrm{Re}\frac{\partial p}{\partial \xi}+\frac{\partial^2 q}{\partial z^2}+S\frac{\partial^3 q}{\partial z^2 \partial t}-\left(\frac{M^2}{1-im}+2iR+\frac{1}{K}\right)q+\mathrm{Gr}\,\theta+\mathrm{Gc}\phi \tag{2.22}$$

We assume the flow under the influence of pressure gradient varying periodically with time,

$$-\frac{\partial p}{\partial \xi} = A\cos\omega t \tag{2.23}$$

The equation (2.23) is substituting in the equation (2.22) we obtain

$$\mathrm{Re}\left(\frac{\partial q}{\partial t}+\frac{\partial q}{\partial z}\right) = \mathrm{Re}\,A\cos\omega t+\frac{\partial^2 q}{\partial z^2}+S\frac{\partial^3 q}{\partial z^2 \partial t}-\left(\frac{M^2}{1-im}+2iR+\frac{1}{K}\right)q+\mathrm{Gr}\,\theta+\mathrm{Gc}\phi \tag{2.24}$$

The corresponding boundary conditions are

$$q = h\frac{\partial q}{\partial z},\ \theta = 0,\ \phi = 0 \qquad \text{at} \quad z = -\frac{1}{2} \tag{2.25}$$

$$q = 0, \theta = \cos\omega t,\ \phi = \cos\omega t \qquad \text{at} \quad z = \frac{1}{2} \tag{2.26}$$

In order to solve the equations (2.24), (2.18) and (2.19) with the boundary conditions (2.25) & (2.26) following Choudary *et al.*[23] we assume the solution of the form

$$q(z,t) = q_0(z)e^{i\omega t} \tag{2.27}$$

$$\theta(z,t) = \theta_0(z)e^{i\omega t} \tag{2.28}$$

$$\phi(z,t) = \phi_0(z)e^{i\omega t} \tag{2.29}$$

Substituting the equations (2.27), (2.28) and (2.29) in (2.24), (2.18) and (2.19) respectively, the resulting equations are,

$$(1+Si\omega)\frac{d^2 q_0}{dz^2}-\mathrm{Re}\frac{dq_0}{dz}-\left(\frac{M^2}{1-im}+\frac{1}{K}+i(2R+\omega\,\mathrm{Re})\right)q_0 = -\mathrm{Re}\,A-\mathrm{Gr}\,\theta_0-\mathrm{Gr}\,\phi_0 \tag{2.30}$$

$$\frac{d^2\theta_0}{dz^2}-\mathrm{Re}\Pr\frac{d\theta_0}{dz}-\left(\Pr\phi+\Pr N^2+i\omega\,\mathrm{Re}\Pr\right)\theta_0+\mathrm{Re}^2\Pr Q\phi_0 = 0 \tag{2.31}$$

$$\frac{d^2\phi_0}{dz^2} - \operatorname{Re}\operatorname{Sc}\frac{d\phi_0}{dz} - (i\omega + \mathrm{Kc})\operatorname{Re}\operatorname{Sc}\phi_0 = 0 \tag{2.32}$$

The corresponding boundary conditions are

$$q_0 = h\frac{\partial q}{\partial z},\ \ \theta_0 = 0,\ \phi_0 = 0 \qquad \text{at} \quad z = -\frac{1}{2} \tag{2.33}$$

$$q_0 = 0,\ \ \theta_0 = 1,\ \phi_0 = 1 \qquad \text{at} \quad z = \frac{1}{2} \tag{2.34}$$

Solving the equations (2.30), (2.31) and (2.32) with respect to the boundary conditions (2.33) and (2.34), we obtained the following expressions for the velocity and temperature.

$$q(z,t) = \Big\{ B_3\cosh m_1 z + B_4 \sinh m_2 z + \frac{\operatorname{Re} A}{a_1} - \frac{\mathrm{Gr}B_1}{2}\left(\frac{e^{m_3 z}}{a_2} + \frac{e^{-m_3 z}}{a_3}\right) - -\frac{\mathrm{Gr}B_2}{2}8\left(\frac{e^{m_4 z}}{a_4} + \frac{e^{-m_4 z}}{a_5}\right) - A_8 e^{\left(\frac{1}{2}+z\right)m_5} + A_9 e^{\left(\frac{1}{2}+z\right)m_6}\Big\} e^{i\omega t} \tag{2.35}$$

$$\theta = \left\{ B_1\cosh m_3 z + B_2\sinh m_4 z + \frac{\Pr \operatorname{Re}^2 Q}{e^{m_5} - e^{m_6}}\left(\frac{e^{\left(\frac{1}{2}+z\right)m_5}}{m_5^2 - \operatorname{Re}\Pr m_5 - b_1^2} - \frac{e^{\left(\frac{1}{2}+z\right)m_6}}{m_6^2 - \operatorname{Re}\Pr m_6 - b_1^2}\right)\right\} e^{i\omega t} \tag{2.36}$$

$$\phi = \frac{1}{e^{m_5} - e^{m_6}}\left\{ e^{\left(\frac{1}{2}+z\right)m_5} - e^{\left(\frac{1}{2}+z\right)m_6}\right\} e^{i\omega t} \tag{2.37}$$

The validity and the correctness of the present solution are verified by taking $S = \mathrm{Gr} = M = R = h = 0$ and $K \to \infty$.
i.e., for the horizontal channel in the absence of rotation, slip flow and the condition of the ordinary medium so that

$$q(z,t) = \frac{A}{i\omega}\left\{ 1 - \frac{\cosh\left(\frac{\operatorname{Re} + \sqrt{\operatorname{Re}^2 + 4i\omega \operatorname{Re}}}{2}\right)z}{\cosh\left(\frac{\operatorname{Re} + \sqrt{\operatorname{Re}^2 + 4i\omega\operatorname{Re}}}{2}\right)}\right\} e^{i\omega t} \tag{2.38}$$

This solution reported by Schlichting and Gersten[24] for periodic variation of the pressure gradient along axis of the channel.

3.1 Skin Fraction :
We find the Skin Fraction τ_L at the left plate in terms of its amplitude and the phase angle as

$$\tau_L = \left(\frac{\partial q}{\partial z}\right)_{z=-\frac{1}{2}} = |q| \cos(\omega t + \gamma)$$

3.2 Nusselt number:

The rate of heat transfer (N_U) in terms of amplitude and the phase angle can be obtained as

$$Nu = \left(\frac{\partial T}{\partial z}\right)_{z=-\frac{1}{2}} = |r| \cos(\omega t + \psi)$$

3.3 Sherwood number:

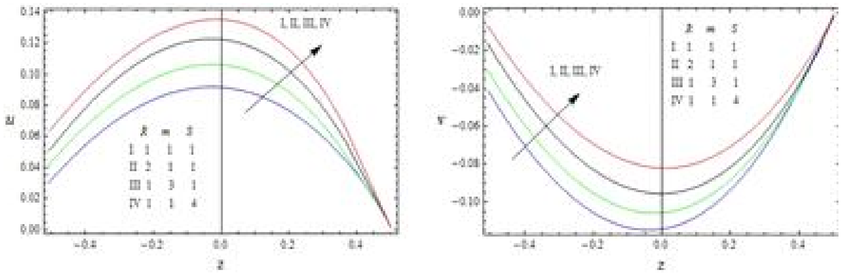
The rate of mass transfer (Sh) in terms of amplitude and the phase angle can be obtained as

$$Sh = \left(\frac{\partial \phi}{\partial z}\right)_{z=-\frac{1}{2}} = |s| \cos(\omega t + \eta)$$

4. Results and Discussions

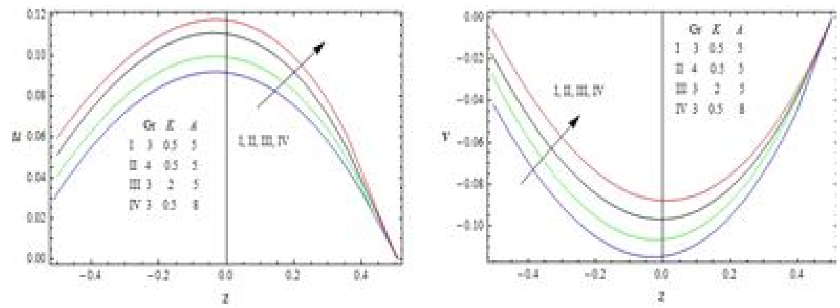
The heat and mass transfer on the flow of an oscillatory convective MHD viscous incompressible, radiating and electrically conducting second grade fluid in a vertical porous rotating channel in slip flow regime and taking Hall current into account have been discussed. The flow is governed by the non-dimensional parameters namely, Re Reynolds number, A amplitude of pressure gradient, h slip parameter, m hall parameter, R the rotation parameter, K the permeability parameter, Gr the thermal Grashof number, Gc is the mass Grashof number, Pr the Prandtl number, Sc the Schmidt number, Kc the chemical reaction parameter, N the Radiation parameter, ϕ_1 the Heat absorption parameter, Q the Radiation absorption number, M the Hartmann number, S is the second grade fluid parameter and the frequency of oscillation ω. The velocity profiles depict from the figures (2-6) while the temperature and concentration profiles from the figures (7-10) and figures (11-12). The effect of the Rotation number R, the hall parameter m, second grade fluid parameter S on the velocity profile shown by the Figs. 2. We noticed that the magnitude of velocity components u and v enhance with increasing R, m and S throughout the fluid region. Similar behaviour is observed for increasing thermal Grashof number Gr, permeability of the porous medium K and the amplitude of the pressure gradient A (Figs. 3). It is observed from these figures (4-5) that the velocity profile is diminished with the increase of all these parameters heat absorption parameter ϕ_1, slip parameter h, the frequency of oscillation ω, Hartmann number M, Prandtl number Pr and radiation parameter N. That is it starts decreasing near the left plate of the channel. Finally from the figs. 6, the velocity components u and v enhances with increasing mass Grashof number Gc and continuously reduces with increasing chemical reaction parameter Kc and Radiation absorption number Q in the entire fluid region.

The variations in the temperature profile are presented in the figs (7-10). It is observed from this Fig. 7 that the temperature profiles decrease with the increasing Reynolds number Re and the Prandtl number Pr. The similar behaviour is observed with increasing the radiation parameter N and Schmidt number Sc. The temperature profile is diminished with increasing chemical reaction parameter Kc, the radiation absorption parameter Q, the frequency of oscillation ω and it increases with the heat absorption parameter for $0 \le \phi_1 \le 1$ and decreases for $\phi_1 \ge 1$ (Figs. 8-10). A variation in the concentration profile is plotted in the Fig (11-12) and it is evident from the study of this figure that the amplitude of the concentration profile decreases with all the parameters Reynolds number Re, chemical reaction parameter Kc, Schmidt number Sc and the frequency of oscillation ω effecting the concentration equation.



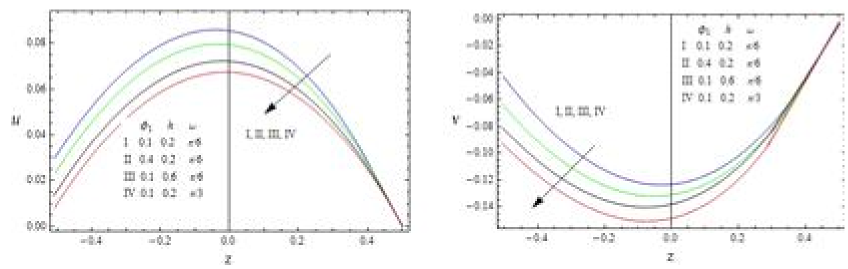
Figs. 2 The velocity profiles for u and v against R, m and S with

$\mathrm{Gr} = 3, M = 0.5, \mathrm{Pr} = 0.71, K = 0.5, A = 5, h = 0.2, \phi_1 = 0.1, N = 1, \omega = \pi/6, \mathrm{Gc} = 5, \mathrm{Kc} = 1, Q = 1$



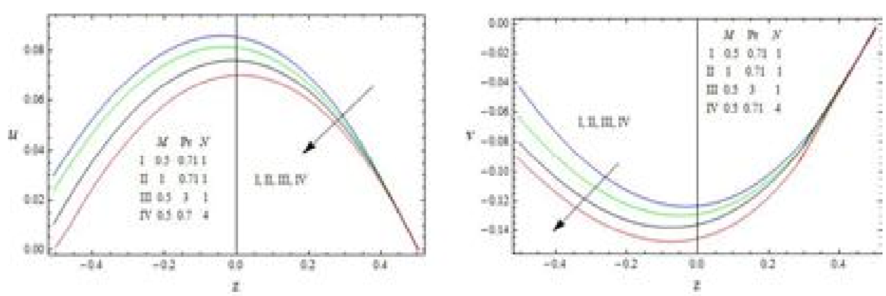
Figs. 3 The velocity profiles for u and v against Gr, K and A with

$R = 1, M = 0.5, \mathrm{Pr} = 0.71, m = 1, S = 1, h = 0.2, \phi_1 = 0.1, N = 1, \omega = \pi/6, \mathrm{Gc} = 5, \mathrm{Kc} = 1, Q = 1$



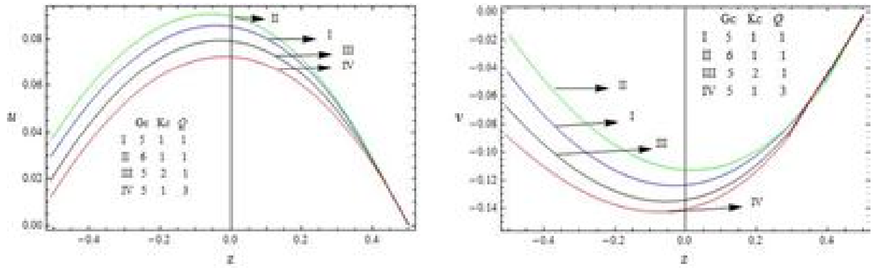
Figs. 4 The velocity profiles for u and v against ϕ_1, h and ω with

$\mathrm{Gr} = 3, M = 0.5, \mathrm{Pr} = 0.71, K = 0.5, S = 1, m = 1, R = 1, N = 1, A = 5, \mathrm{Gc} = 5, \mathrm{Kc} = 1, Q = 1$



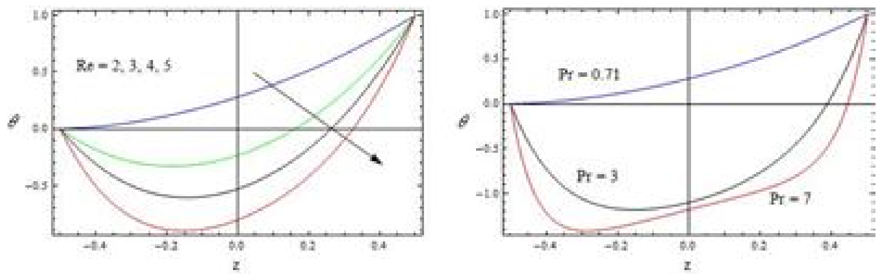
Figs. 5 The velocity profiles for u and v against M, Pr and N with

$\mathrm{Gr} = 3, S = 1, m = 1, R = 1, K = 0.5, A = 5, h = 0.2, \phi_1 = 0.1, \omega = \pi/6, \mathrm{Gc} = 5, \mathrm{Kc} = 1, Q = 1$



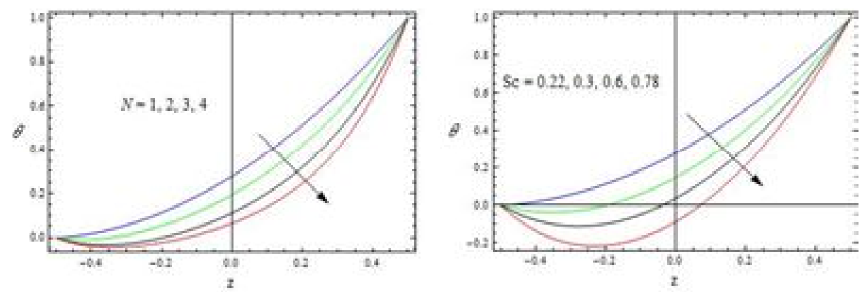
Figs. 6 The velocity profiles for u and v against Gc, Kc and Q with

$\mathrm{Gr} = 3, S = 1, m = 1, R = 1, K = 0.5, A = 5, h = 0.2, \phi_1 = 0.1, \omega = \pi/6, M = 0.5, \mathrm{Pr} = 0.71, N = 1$



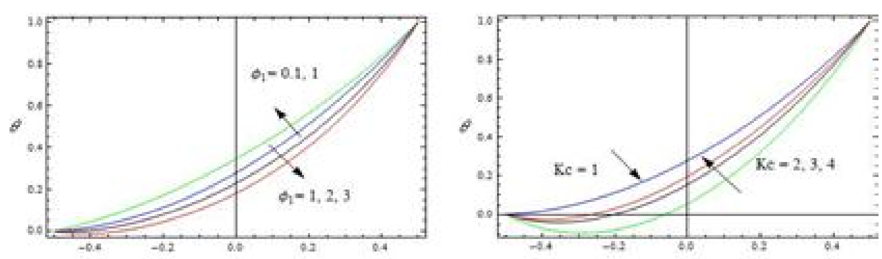
Figs. 7 The Temperature profiles for θ against Re and Pr

$Q = 0.5, \mathrm{Sc} = 0.22, \mathrm{Kc} = 1, \phi_1 = 0.1, \omega = \pi/6, N = 1$



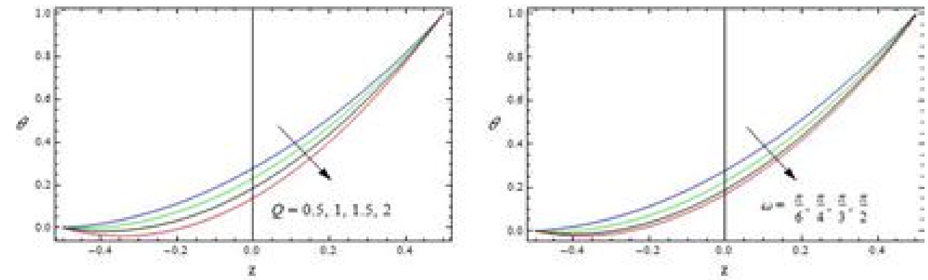
Figs. 8 The Temperature profiles for θ against Re and Pr

$\mathrm{Re} = 2, Q = 0.5, \mathrm{Kc} = 1, \phi_1 = 0.1, \omega = \pi/6, \mathrm{Pr} = 0.71$



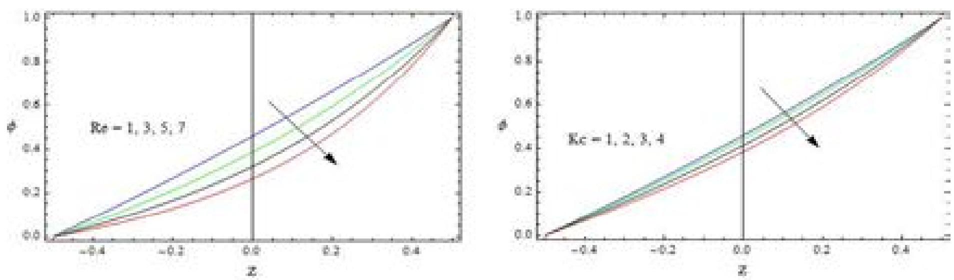
Figs. 9 The Temperature profiles for θ against ϕ_1 and Kc

$\mathrm{Re} = 2, Q = 0.5, \mathrm{Sc} = 0.22, \omega = \pi/6, \mathrm{Pr} = 0.71, N = 1$



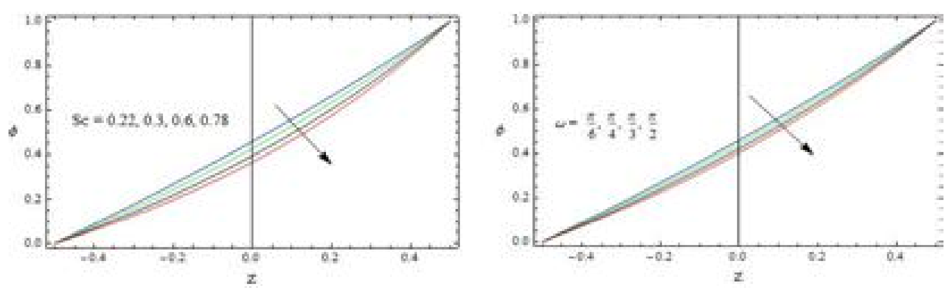
Figs. 10 The Temperature profiles for ϕ against Q and ω

$\mathrm{Re} = 2, \mathrm{Sc} = 0.22, \mathrm{Kc} = 1, \phi_1 = 0.1, \mathrm{Pr} = 0.71, N = 1$



Figs. 11 The Concentration profiles for ϕ against Re and Kc with

$\mathrm{Sc} = 0.22, \omega = \pi / 6$



Figs. 12 The Concentration profiles for ϕ against Sc and ω with

$\mathrm{Sc} = 0.22, \omega = \pi / 6$

5. Conclusions

The resultant velocity enhance with increasing *R*, *m*, *S*, Gr, *K* and *A* throughout the fluid region. The velocity profile is diminished with the increasing ϕ_1, *h*, ω, *M*, Pr and *N*. The resultant velocity enhances with increasing Gc and continuously reduces with increasing Kc and *Q* in the entire fluid region.The temperature profiles decrease with the increasing Re, Pr, *N* and Sc. The temperature profile is diminished with increasing Kc, and ω. The concentration profile decreases with all Re, Kc, Sc and ω.

The amplitude and phase angle of frictional force are enhanced with increasing the parameters *K*, *R*, *S*, Gr and Kc. The amplitude of the stress and the magnitude of the phase angle increases with Gc, Pr, *N*, *A*, *Q* and ϕ_1. The amplitude of stress reduces and phase angle increases with increasing *M*, *h* and ω. The reversal behaviour is observed with increasing *m* and Sc.

6. References

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