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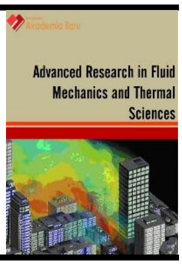

MHD Rotating Flow Through a Porous Medium with Heat and Mass Transfer

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ABSTRACT

In this paper, we have considered heat and mass transfer on the unsteady two dimensional MHD flow through porous medium under the influence of uniform transverse magnetic field in a rotating parallel plate channel. A mathematical model is developed for unsteady state situations using slip conditions. Analytical expressions for the velocity, temperature and concentration profiles, wall shear stress, rates of heat and mass transfer and volumetric flow rate have been obtained and computationally discussed with respect to the non-dimensional parameters. We concluded that the velocity reduces with increasing Hartmann number *M* and enhances with permeability parameter *K*. Blood visco-elasticity lesser flow velocity significantly. The resultant velocity enhance with increasing Gr, Gc and slip parameter. At any particular location as the thermal radiation increases, both heat transfer rate and temperature are reduced to an appreciable extent. However, the velocity is not significantly affected by thermal radiation.

1. Introduction

Flow of a viscous fluid in rotating channels is of considerable importance due to the occurrence of various natural phenomena and for its application in various technological situations which are governed by the action of Coriolis force gave a rigorous theoretical proof for the existence of the slip at the nominal surface postulated. Magnetohydrodynamics is currently undergoing a period of great enlargement and differentiation of subject matter. In light of these applications, steady MHD free convective flow past a heated vertical flat plate has been studied by many researchers such as Gupta [1], Lykoudis [2] and Nanda and Mohanty [3]. Later, Chennabasappa and Ramanna [4] discussed the effect of the thickness of the porous material on the parallel plate channel. Lavanya [5] studied Unsteady MHD Convective laminar flow between two Vertical Porous plates with mass transfer. Debnath [6] gave the exact solutions of the unsteady hydrodynamic and hydro magnetic boundary layer equations in a rotating fluid system. Blood flow through narrow tube with periodic body

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acceleration in the presence of magnetic field and its applications to cardiovascular diseases was discussed by Rani. Sasthry *et al.,* [7] also discussed blood flow through stenosed inclined tubes with periodic body acceleration in the presence of magnetic field and its applications to cardiovascular diseases. Lavanya *et al.,* [8] studied Effects of Dissipation and Radiation on Heat Transfer Flow of a Convective Rotating Cuo-Water Nano-fluid in a Vertical Channel. Veera Krishna *et al.,* [9]. "Steady Hydro Magnetic Flow of a Couple Stress Fluid through a Composite Medium in a Rotating Parallel Plate Channel with Porous Bed on the Lower Half. Veera Krishna, M., and S. G. Malashetty [10] "Unsteady Flow of an Incompressible Electrically Conducting Second Grade Fluid through a Porous Medium in a Rotating Parallel Plate Channel Bounded by a Porous Bed. Lavanya [11] discussed Effect Of Radiation On Free Convection Heat And Mass Transfer Flow Through Porous Medium In A Vertical Channel With Heat Absorption/Generation And Chemical Reaction. Hall effects on unsteady flow of an incompressible electrically conducting second grade fluid through a porous medium in a rotating parallel plate channel bounded by a porous bed studied by M.VeeraKrishna and S.G.Malashetty [12].

The Newtonian approach may be sufficient to understand the flow of classical fluids through microchannel under various assumptions Motivated in view of the above discussions, in this paper, we have considered the unsteady MHD oscillatory flow through porous medium under the influence of uniform transverse magnetic field in a rotating parallel plate channel.

2. Mathematical Formulation and Solution of the Problem

We consider the MHD flow of an incompressible viscous fluid through porous medium under the influence of uniform transverse magnetic field in rotating parallel plate channel. The formulation analysis that follows, we use Cartesian coordinates. The flow is considered symmetric about the axis of the channel and driven by the stretching of the channel wall, such that the velocity of each wall is proportional to the axial coordinate.

The physical sketch of the problem is as shown in Figure 1. A magnetic field of constant intensity B_0 is considered to be applied in the *y*-direction.

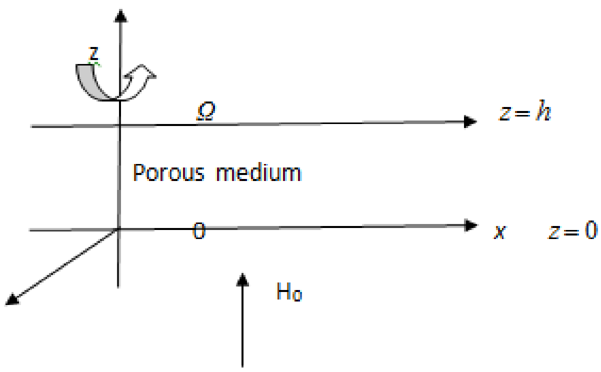

Fig. 1. Physical configuration of the problem

The unsteady hydromagnetic equations of the momentum, heat transfer and mass transfer for the MHD oscillatory flow through a porous medium in the rotating parallel plate

$$\frac{\partial u}{\partial t} - 2\Omega v = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial z^2} - \frac{\sigma B_0^2}{\rho}u - \frac{\nu}{k}u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \tag{1}$$

$$\frac{\partial v}{\partial t}+2\Omega u=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0^2}{\rho}v-\frac{\nu}{k}v \tag{2}$$

$$\frac{\partial T}{\partial t}=\frac{K_1}{\rho C_p}\frac{\partial^2 T}{\partial z^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial z} \tag{3}$$

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}-K_c(C-C_0) \tag{4}$$

where, the meanings of all the symbols appearing in the equations are their usual meaning. The boundary conditions for the problem under consideration are given by

$$u=\lambda\frac{\partial u}{\partial z}, v=\lambda\frac{\partial v}{\partial z},\ T=T_0+(T_w-T_0)e^{i\omega t}, C=C_0+(C_w-C_0)e^{i\omega t} \quad \text{at} \quad z=h \tag{5}$$

$$u=\lambda\frac{\partial u}{\partial z}, v=\lambda\frac{\partial u}{\partial z}, T=T_0, C=C_0 \qquad \text{at} \quad z=0 \tag{6}$$

Using Rosseland approximation, the radiative transfer term q_r in Eq. (3) may be expressed as

$$q_r=-\frac{4\sigma^*}{3\alpha_r}\frac{\partial T^4}{\partial z} \tag{7}$$

We assume that the temperature differences within the flow are such that T^4 can be expressed as a linear function of the temperature *T*. This is accomplished by expanding T^4 in a Taylor series about T_0 (which is assumed to be independent of *z*) and neglecting powers of *T* higher than the first. Thus we have

$$T^4=4T_0^3T-3T_0^4 \tag{8}$$

Then the heat transfer equation becomes

$$\frac{\partial T}{\partial t}=\frac{K_1}{\rho C_p}\frac{\partial^2 T}{\partial z^2}-\frac{16\sigma^* T_0^3}{3\rho C_p\alpha_r}\frac{\partial^2 T}{\partial z^2} \tag{9}$$

Combining the equations (1) and (2), $q=u+iv$ and we obtain

$$\frac{\partial q}{\partial t}+2i\Omega q=-\frac{1}{\rho}\frac{\partial p}{\partial \xi}+\nu\frac{\partial^2 q}{\partial z^2}-\frac{\sigma B_0^2}{\rho}q-\frac{\nu}{k}q+g\beta(T-T_\infty)+g\beta^*(C-C_\infty) \tag{10}$$

We now introduce the following non-dimensional variables:

$$x^*=\frac{x}{h}, y^*=\frac{y}{h}, z^*=\frac{z}{h}, q^*=\frac{q}{U_0}, t^*=\frac{tU_0}{h}, \theta=\frac{T-T_0}{T_w-T_0},$$

$$\phi = \frac{C - C_0}{C_w - C_0},\ \omega^* = \frac{\omega h}{U_0},\ t^* = \frac{t w_0^2}{\nu}, \xi^* = \frac{\xi}{h},\ p^* = \frac{p}{\rho U_0^2}$$

Making use of non-dimensional quantities (dropping asterisks), the governing equation (10), (2) and (3) can be written as

$$\mathrm{Re}\frac{\partial q}{\partial t} = -\frac{\partial p}{\partial \xi} + \frac{\partial^2 q}{\partial z^2} - \left(M^2 + 2iE^{-1} + \frac{1}{K}\right)q + \mathrm{Gr}\,\theta + \mathrm{Gc}\,\phi \quad (11)$$

$$\mathrm{Pr}\frac{\partial \theta}{\partial t} = (1+R)\frac{\partial^2 \theta}{\partial z^2} \quad (12)$$

$$\mathrm{Sc}\frac{\partial \phi}{\partial t} = \frac{\partial^2 \phi}{\partial z^2} - \mathrm{Kc}\,\phi \quad (13)$$

The corresponding non-dimensional boundary conditions assume the form

$$q = \lambda\frac{\partial q}{\partial z},\ \theta = e^{i\omega t}, \phi = e^{i\omega t} \quad \text{at} \quad z = 1 \quad (14)$$

$$q = \lambda\frac{\partial q}{\partial z},\ \theta = 0,\ \phi = 0 \quad \text{at} \quad z = 0 \quad (15)$$

where

$M^2 = \frac{\sigma B_0^2 h^2}{\rho \nu}$ is the Hartmann number (Magnetic field parameter)

$K = \frac{k}{h^2 \rho}$ is the Permeability parameter

$E = \frac{\nu}{\Omega h^2}$ is the Ekman number

$\mathrm{Gr} = \frac{g\beta(T_w - T_0)h^2}{\nu U_0}$ is the thermal Grashof number

$\mathrm{Gc} = \frac{g\beta^*(C_w - C_0)h^2}{\nu U_0}$ is the mass Grashof number

$Pr = \frac{\rho C_p}{K_1}$ is Prandtl parameter

$R = \frac{16\sigma^* T_0^3}{3\alpha_r K_1}$ is the Radiation parameter

$\mathrm{Kc} = DK_c(C_w - C_0)$ chemical reaction parameter

$\mathrm{Sc} = \frac{\nu}{D}$ is the Schmidt number.

From Eq. (11), it follows that, $\partial p / \partial \xi$ is a function of *t* only. We consider it to be of the form,

$$\frac{\partial p}{\partial \xi} = Pe^{i\omega t} \tag{16}$$

To solve Eq. (11), (12) and (13) subject to the boundary conditions (14) and (15), we further write the velocity, temperature and concentration as

$$q(z,t) = q_1 e^{i\omega t} \tag{17}$$

$$\theta(z,t) = \theta_1 e^{i\omega t} \tag{18}$$

$$\phi(z,t) = \phi_1 e^{i\omega t} \tag{19}$$

Substituting these expressions (17), (18) and (19) in (11), (12) and (13) respectively and comparing the co-efficients of like terms we have the equations.

$$\frac{\partial^2 q_1}{\partial z^2} - \left(\mathrm{Re} i\omega + M^2 + 2iE^{-1} + \frac{1}{K}\right) q_1 = -P - \mathrm{Gr}\,\theta_1 - \mathrm{Gc}\,\phi_1 \tag{20}$$

$$(1+R)\frac{\partial^2 \theta_1}{\partial z^2} - \mathrm{Pr} i\omega \theta_1 = 0 \tag{21}$$

$$\frac{\partial^2 \phi_1}{\partial z^2} - (\mathrm{Sc} i\omega + \mathrm{Kc})\phi_1 = 0 \tag{22}$$

with corresponding boundary conditions

$$q = \lambda \frac{\partial q_1}{\partial z},\ \theta_1 = 1,\ \phi_1 = 1 \quad \text{at} \quad z = 1 \tag{23}$$

$$q = \lambda \frac{\partial q_1}{\partial z},\ \theta_1 = 0,\ \phi_1 = 0 \quad \text{at} \quad z = 0 \tag{24}$$

Solving (20) – (22) subject to the conditions (23) and (24), we have velocity field, temperature, concentration respectively,

$$q(z,t) = \left(a_1 e^{m_1 z} + a_2 e^{m_2 z} - \frac{P}{\mathrm{Re} i\omega + M^2 + 2iE^{-1} + (1/K)} - \frac{\mathrm{Gr}}{e^{m_3} - e^{m_4}}\left[\frac{e^{m_3 z}}{a_3} - \frac{e^{m_4 z}}{a_4}\right] - \right.$$

$$-\frac{\mathrm{Gc}}{e^{m_5}-e^{m_6}}\left[\frac{e^{m_5 z}}{a_5}-\frac{e^{m_6 z}}{a_6}\right]\Bigg)e^{i\omega t} \tag{25}$$

$$\theta(z,t)=\frac{1}{e^{m_3}-e^{m_4}}\left(e^{m_3 z}-e^{m_4 z}\right)e^{i\omega t} \tag{26}$$

$$\phi(z,t)=\frac{1}{e^{m_5}-e^{m_6}}\left(e^{m_5 z}-e^{m_6 z}\right)e^{i\omega t} \tag{27}$$

The volumetric flow rate is calculated as

$$Q=\int_0^1 q\,dz \tag{28}$$

The wall shear stress at the wall of the upper plate representing the upper wall of the blood vessel is found as

$$\tau_w =_{z=1}\left(\frac{\partial q}{\partial z}\right) \tag{29}$$

The rates of heat and mass transfer across the upper plate (upper wall) are calculated as

$$Nu = -\left(\frac{\partial \theta}{\partial z}\right)_{z=1} \tag{30}$$

$$Sh=\left[-\frac{\partial \phi}{\partial z}\right]_{z=1}=-\frac{1}{e^{m_5}-e^{m_6}}\left(m_5\,e^{m_5}-m_6\,e^{m_6}\right)e^{i\omega t} \tag{31}$$

3. Results and Discussion

The flow governed by the non-dimensional parameters M Hartmann number, permeability parameter K, Re the Reynolds number, E Eckman number, R radiation parameter, Gr thermal Grashof number, Gc mass Grashof number, Sc Schmidt number, ω the frequency of oscillation, λ slip velocity parameter, Kc the chemical reaction parameter. The velocity, temperature, concentration, the shear stresses at the boundaries, Nusselt number (Nu), Sherwood number (Sh) and the volumetric flow rate (discharge) between the plates are evaluated analytically and computationally discussed for different variations in the governing parameters. The Figures. 2-6 represent the velocity profiles for u and v; the Figure 7 represent the temperature profiles for θ; the Figure. 8 represent the concentration profiles for $\emptyset$.

From the Figure. 2, we noticed that, both the velocity components u and v reduces with increasing the intensity of the magnetic field or Hartmann number M. Also we have been seen that the resultant velocity is experiences retardation throughout the fluid region. The similar behaviour is observed with increasing Pr, Kc and Sc. The velocity component u increases and v reduces with increasing permeability parameter K. The resultant velocity enhances with increasing K in the flow field. We also noticed that lower the permeability lesser the fluid speed is observed the entire fluid region (Figure.

3). The similar behaviour is observed for the velocity components with radiation parameter R. This gives an idea of the influence of chemical reaction on the velocity distribution under identical condition of heat radiation. From the Figures 4 and 6 the velocity components *u* and *v* as well as resultant velocity increase with increasing thermal Grashof number Gr. The same nature is observed for increasing the parameters Gc or λ or *E*. We also find that the magnitude of the velocity component *u* reduces and *v* enhances with increasing the frequency of oscillation ω. The resultant velocity reduces throughout the fluid region with increasing the frequency of oscillation (Figure 5).

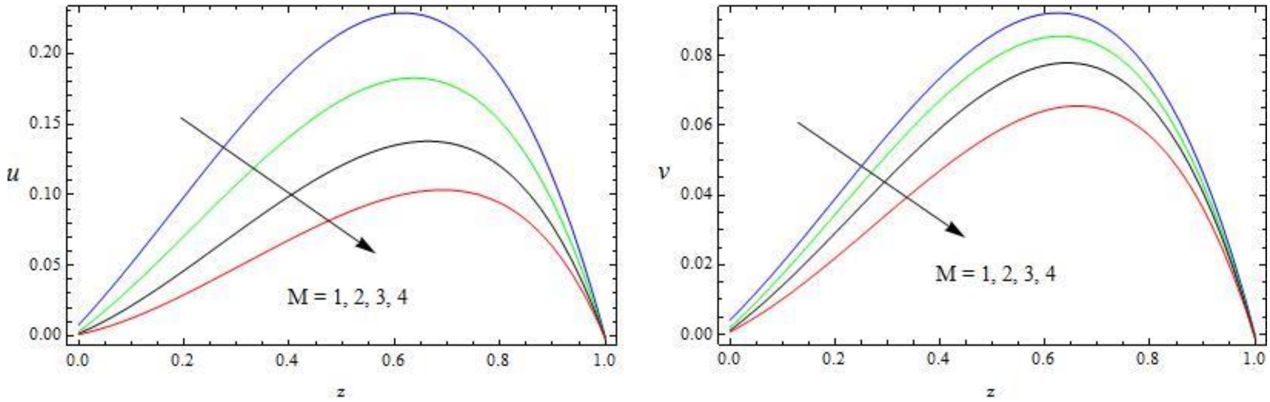

Fig. 2. The velocity Profiles for *u* and *v* against M with *t* = 1, Re=1, K=1, α=0.5, Pr=0.71, Gr=5, R=0.5, Sc= 0.22, $\omega=\pi/4$, λ=0.002, Kc=0.5

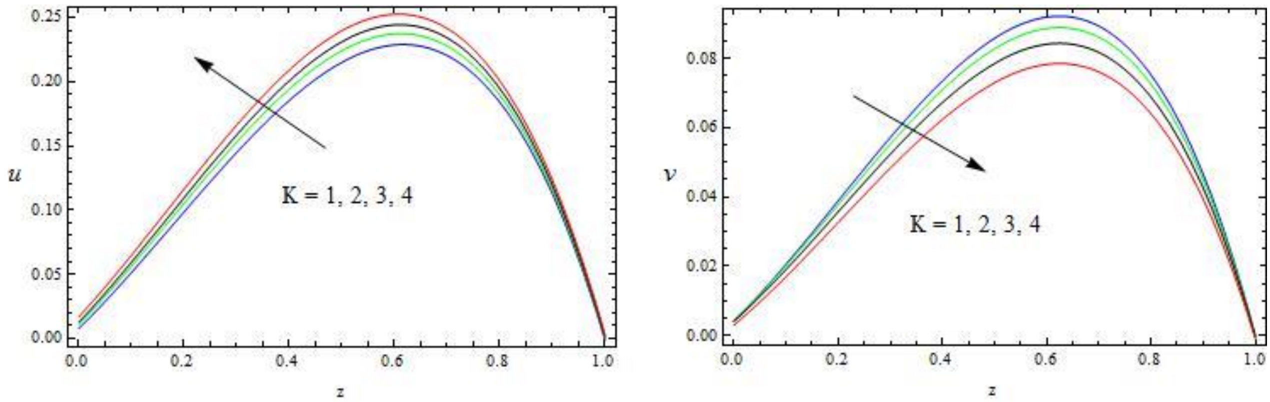

Fig. 3. The velocity Profiles for *u* and *v* against K with *t* = 1, Re=1, M=1, α=0.5, Pr=0.71, Gr=2, Gc=5, R=0.5, Sc=0.22, $\omega=\pi/4$, λ=0.002, Kc=0.5

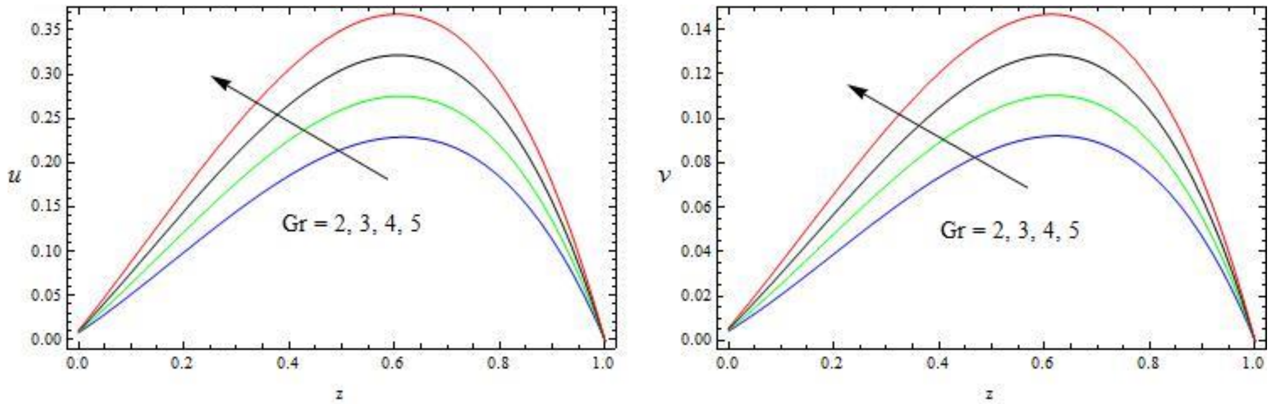

Fig. 4. The velocity Profiles for *u* and *v* against Gr with *t* = 1, Re=1, K=1, α=0.5, Pr=0.71, M=1, Gc=5, R=0.5, Sc= 0.22, $\omega=\pi/4$, λ=0.002, Kc=0.5

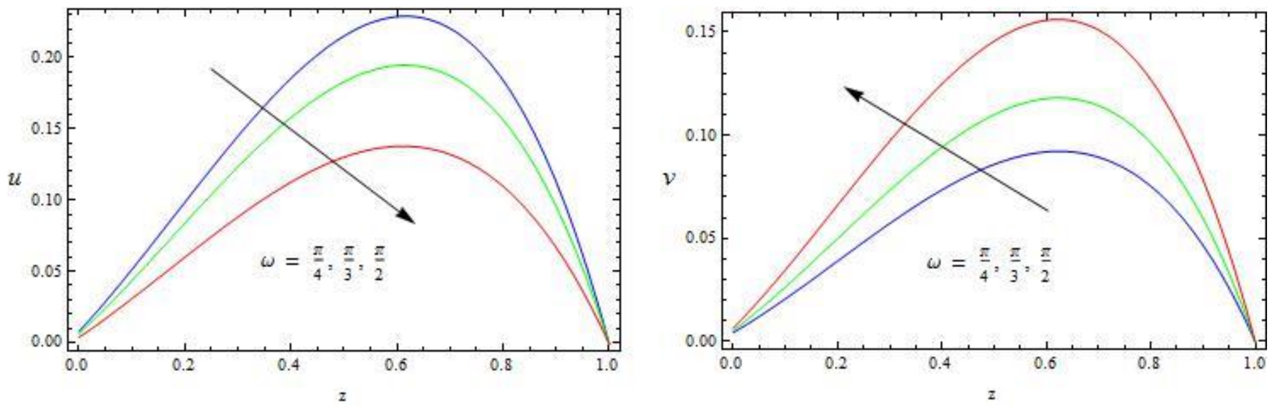

Fig. 5. The velocity Profiles for *u* and *v* against ω with *t* = 1, Re=1, K=1, α=0.5, Pr=0.71, Gr=2, Gc=5, R=0.5, Sc= 0.22, M=1, λ=0.002, Kc=0.5

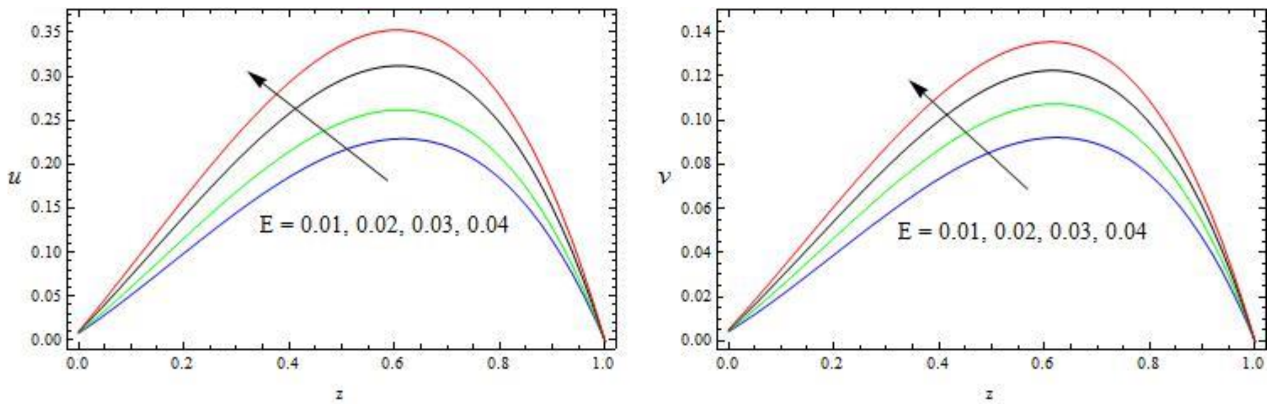

Fig. 6. The velocity Profiles for *u* and *v* against E with *t* = 1, Re=1, K=1, α=0.5, Pr=0.71, Gr=2, R=0.5, Sc= 0.22, $\omega=\pi/4$, λ=0.002, M=1

We noticed that from the Figure 7, the magnitude of the temperature reduces with increasing radiation parameter R, whereas the reversal behaviour is observed throughout the fluid region with increasing Prandtl number Pr.

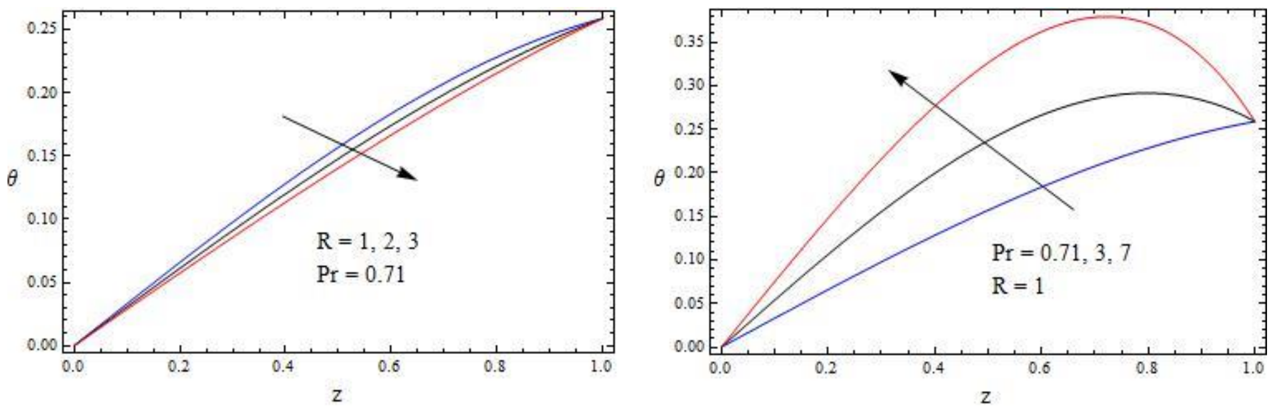

Fig. 7. The temperature Profiles for θ against R and Pr with $\omega = 5\pi/12, t = 0.1$

Also we found that from the Figure 8, the magnitude of the concentration increases with increasing Schmidt number Sc, whereas the reversal behaviour is observed throughout the fluid region with increasing chemical reaction parameter Kc. Finally, these reveal that under the purview of the present computational study, at any given distance the temperature/ concentration reduces as the thermal radiation/ chemical reaction parameter increases. Further it reveals that for any particular values of thermal radiation/chemical reaction parameter, both the temperature and the concentration increase as we move further and further from the lower wall to the upper one.

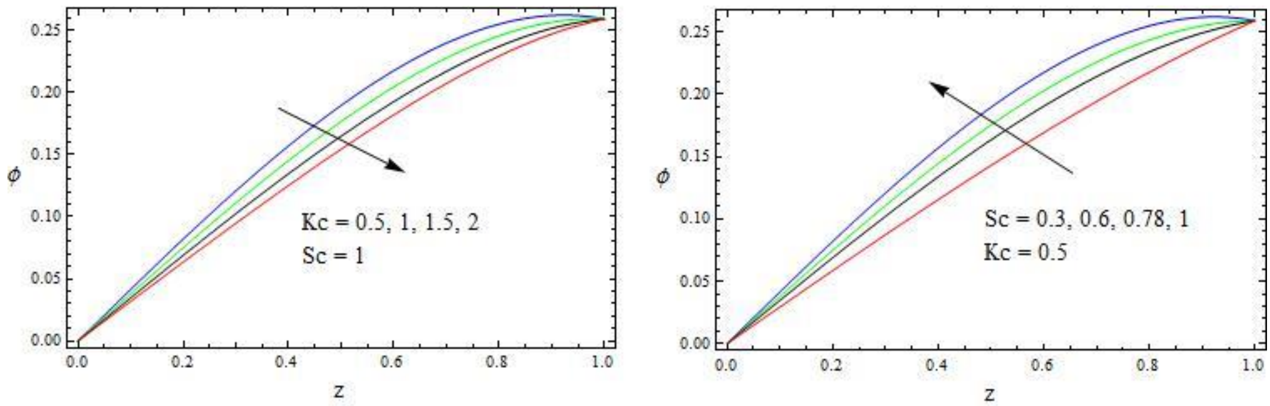

Fig. 8. The concentration Profiles for ϕ against Kc and Sc with $\omega = 5\pi/12, t = 0.1$

Table 1
Skin Friction

M	K	R	Pr	Gr	Gm	Sc	ω	λ	Kc	E	τ_x	τ_y
1	1	0.5	0.71	2	5	0.3	$\pi/4$	0.002	0.5	0.01	-0.497612	0.240754
2											-0.499025	0.237324
3											-0.501214	0.231553
	2										-0.497369	0.241324
	3										-0.497287	0.241513
		1									-0.497850	0.240606
		1.5									-0.497992	0.240515
			3								-0.494421	0.242334
			7								-0.488822	0.243595
				3							-0.560383	0.272050
				4							-0.623154	0.303345
					6						-0.435064	0.210180
					7						-0.427613	0.200754
						0.6					-0.495656	0.241988
						0.78					-0.494466	0.242694
							$\pi/3$				-0.523765	0.207442
							$\pi/2$				-0.572978	0.143677
								0.008			-0.546222	0.230406
								0.01			-0.563707	0.225377
									1.0		-0.494996	0.236793
									1.5		-0.492527	0.233111
										0.02	-0.682195	0.312207
										0.03	-0.817938	0.355020

The frictional force is determined at the upper wall are presented in the Table 1. The magnitude of the stress components τ_x and τ_y enhances with increasing E and Gr. The opposite nature is observed for the same components with increasing Gc and Kc. The magnitude of the stress component τ_x reduces and τ_y increases with increasing K, Pr and Sc. The reversal behaviour is for the components τ_x and $\tau_y$with increasing M, λ, ω and R (Table 1). We also noticed that from the Table 2 the Nusselt number Nu enhances with increasing Radiation parameter R and Prandtl number Pr. Likewise the rate of mass transfer is reduces with increasing Schmidt number Sc and increases with increasing chemical reaction parameter Kc (Table 3). From Table 4 we observed that, volumetric flow rate enhances with increasing K, Gr, Gc, Sc, λ and R as well as it reduces to M, Pr, Kc and ω.

Table 2
Nusselt number

R	Pr	ω	Nu
0.5	0.71	$5\pi/12$	-0.062010
1	0.71	$5\pi/12$	-0.110643
1.5	0.71	$5\pi/12$	-0.140021
2	0.71	$5\pi/12$	-0.159684
0.5	3	$5\pi/12$	0.512785
0.5	7	$5\pi/12$	1.209667

Table 3
Sherwood number

Sc	Kc	ω	Sh
0.3	0.5	$5\pi/12$	-0.182881
0.6	0.5	$5\pi/12$	-0.067315
0.78	0.5	$5\pi/12$	0.000764
1	0.5	$5\pi/12$	0.082496
0.3	1	$5\pi/12$	-0.228894
0.3	1.5	$5\pi/12$	-0.271903

Table 4
Volumetric flow rate

M	K	R	Pr	Gr	Gm	Sc	ω	λ	Kc	E	Q
1	1	0.5	0.71	2	5	0.3	$\pi/4$	0.002	0.5	0.01	0.492651
2											0.240202
3											0.149095
	2										0.610395
	3										0.662534
		1									0.501282
		1.5									0.509929
			3								0.473134
			7								0.470046
				3							0.505164
				4							0.517717
					6						0.493948
					7						0.495450
						0.6					0.502002
						0.78					0.503443
							$\pi/3$				0.462344
							$\pi/2$				0.403587
								0.008			0.492715
								0.01			0.492741
									1.0		0.484242
									1.5		0.483650
										0.02	0.525593
										0.03	0.562935

4. Conclusions

The conclusions are made as the following.

i. The velocity reduces with increasing Hartmann number M and enhances with permeability parameter K and E.
ii. The resultant velocity enhance with increasing thermal Grashof number, mass Grashof number and slip parameter
iii. The wall shear stress is strongly pretentious by the Reynolds number.
iv. The rate of Heat transfer boosts with increasing Prandtl number.
v. Concentration and rate of mass transfer are abridged due to chemical reaction. Comparatively, the velocity distribution is less affected due to chemical reaction.
vi. The rate of mass transfer is enhanced, as the mass diffusivity reduces (i.e. as the Schmidt number increases).

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