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Hall current effects on Unsteady MHD Convective flow of heat generating/absorbing fluid through porous medium in a rotating parallel plate channel

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Abstract.* In this paper, we discussed the heat and mass transfer on the unsteady hydro magnetic convective flow of an incompressible viscous electrically conducting heat generating/absorbing fluid through porous medium in a rotating parallel plate channel under the influence of uniform transfer magnetic field normal to the channel taking Hall current effects into account. The momentum equation for the flow is governed by the Brinkman's model. The analytical solutions for the velocity, temperature and concentration distributions are obtained by making use of regular perturbation technique. The variations of said quantities with different flow parameters are computed by using Mathematical Software and discussed with the help of plots. The skin friction, Nusselt number, and Sherwood number are also evaluated analytically and computationally discussed with reference to pertinent parameters in detail.

Keywords: Hall effects, heat and mass transfer, viscous fluid, MHD flows, porous medium.

I. Introduction

In the recent past a considerable attention has been gained by the magneto hydrodynamic (MHD) rotating flows of electrically conducting, viscoelastic incompressible fluids due to its numerous applications in the cosmic and geophysical fluid dynamics. The subject of geophysical dynamics nowadays has become an important branch of fluid dynamics due to the increasing interest to study environment. In astrophysics it is applied to study the stellar and solar structure, inter planetary and inter stellar matter, solar storms and flares etc. During the last few decades it also finds its application in engineering. Among the applications of rotating flow in porous media to engineering disciplines, one can find the food processing industry, chemical process industry, centrifugation and filtration processes and rotating machinery. In recent years a number of studies have also appeared in the literature on the fluid phenomena on earth involving rotation to a greater or lesser extent viz. Vidyanidhu and Nigam [1],Gupta [2],Jana and Datta [3]. Mazumder[4] obtained an exact solution of an oscillatory Couette flow in a rotating system. There after Ganapathy[5] presented the solution for rotating Couette flow. Singh [6] analyzed the oscillatory MHD Couette flow in a rotating system in the presence of transverse magnetic field. Singh [7] also obtained an exact solution of MHD mixed convection flow in a rotating vertical channel with heat radiation. Hossanien and Mansour [8] investigated unsteady magnetic flow through a porous medium between two infinite parallel plates. The study of the flows of visco-elastic fluids is important in the fields of petroleum technology and in the purification of crude oils. In recent years, flows of visco-elastic fluids attracted the attention of several scholars in view of their practical and fundamental importance associated with many industrial applications. Literature is replete with the various flow problems considering variety of geometries such as Rajgopal[9], Rargopal and Gupta[10], Ariel[11], Pop and Gorla[12]. Hayat et al [13] discussed periodic unsteady flow of a non-Newtonian fluid. Choudhury and Das [14] studied the oscillatory viscelastic flow in a channel filled with porous medium in the presence of radiative heat transfer. Singh [15] analyzed viscoelastic mixed convection MHD oscillatory flow through a porous medium filled in a vertical channel. Taking the rotating frame of reference into account Puri[16] investigated rotating flow of an elastic-viscous fluid on an oscillating plate. Puri and Kulshrestha [17] analyzed rotating flow of non-Newtonian fluids. Hayat et al[18] studied hydromagnetic Couette flow of an Oldroyd-B fluid in a rotating system. Hayat et al [19] investigated the unsteady hydromagnetic rotating flow of a conducting second grade fluid. Many common liquids such as oils, certain paints, polymer solution, some organic liquids and many new material of industrial importance exhibit both viscous and elastic properties. Therefore, the above fluid, called visco elastic fluids, is being studied extensively. Many researchers have shown their interest in the fluctuating flow of a viscous incompressible fluid past an infinite or semi-infinite flat plate. Visco elastic fluid flow through porous media has attracted the attention of scientists and engineers because of its importance notably in the flow of the oil through porous rocks, the extraction of energy from geothermal region, the filtration of solids from liquids and drug permeation through human skin. The knowledge of flow through porous media is useful in there covery of crude oil efficiently from the pores of reservoir rocks by displacement with immiscible water. The flow through porous media occurs in the ground water hydrology, irrigation, and drainage problems and also in absorption and filtration processes in chemical engineering, the scientific treatment of the problem of irrigation, soil erosion and tile drainage are the present developments of porous media. Rahmann and Sarkar [20] investigated the unsteady MHD flow of a visco elastic Oldroyd fluid under time varying body forces through a rectangular channel. Singh and Singh[21] analyzed MHD flow of a dusty visco elastic (Oldroyd B-liquid) through a porous medium between two parallel plates inclined to the horizon. Oscillatory motion of an electrically conducting visco-elastic fluid over a stretching sheet in a saturated porous medium was studied by Rajagopal et al[22]. Prasuna et al[23] examined an unsteady flow of a visco elastic fluid through a porous media between two impermeable parallel plates. Very recently, Sahoo [24] studied the heat and mass transfer effect on MHD flow of a visco elastic fluid through a porous medium bounded by an oscillating porous plate in slip flow regime. When the strength of the magnetic field is strong enough then one cannot neglect the effects of Hall currents. Even though it is of considerable importance to study how the results of the hydro dynamical problems get modified by the effects of Hall currents. A comprehensive discussion of Hall currents is given by Cowling [25]. Soundalgekar [26] studied the Hall and Ion-slip effects in MHD Couette flow with heat transfer. Soundalgekar and Uplekar [27] also analyzed Hall effects in MHD Couette flow with heat transfer. Hossain and Rashid [28] investigate Hall effect on hydromagnetic free convection flow along a porous flat plate with mass transfer. Attia[29] studied Hall current effects on the velocity and temperature fields on an unsteady Hartmann flow. Effects of Hall currents on free convective flow past an accelerated vertical porous plate in a rotating system with heat source /sink is analyzed by Singh and Garg [30]. The wall slip flow is another very important phenomenon that is widely encountered in this era of industrialization. It has numerous applications, for example in lubrication of mechanical devices where a thin film of lubricant is attached to the surface slipping over one another or when the surfaces are coated with special coatings to minimize the friction between them. Marques et al[31] have considered the effect of the fluid slippage at the plate for Couette flow. Rhodes and Rouleau [32] studied the hydrodynamic lubrication of partial porous metal bearings. The problem of the slip-flow regime is very important in this era of modern science, technology and vast ranging industrialization. Hayat et al[33] analyzed slip flow and heat transfer of a second grade fluid past a stretching sheet through a porous space. Mehmood and Ali [34] extended the problem of oscillatory MHD flow in a channel filled with porous medium studied by Makinde and Mhone[35] to slip-flow regime. Further by applying the perturbation technique Kumar et al [36] investigated the same problem of slip flow regime for the unsteady MHD periodic flow of viscous fluid through a planer channel. In this paper, we discussed the heat and mass transfer on the unsteady hydromagnetic convective flow of an incompressible viscous electrically conducting heat generating/absorbing fluid through porous medium in a rotating parallel plate channel under the influence of uniform transfer magnetic field normal to the channel taking Hall current effects into account.

II. Formulation and Solution of the Problem:

We consider the unsteady flow of an incompressible viscous fluid through a porous medium bounded by two parallel non conducting plates under a uniform transverse magnetic field H_o and taking hall current into account. In undisturbed state both the plates and the fluid rotate with the same angular velocity Ω

$$\frac{\partial u}{\partial t}-2\Omega v=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial z^2}+B_0J_y-\frac{\nu}{k}u+g\beta(T-T_0)+g\beta^*(C-C_0) \quad (1)$$

$$\frac{\partial v}{\partial t}+2\Omega u=\nu\frac{\partial^2 v}{\partial z^2}-B_0J_x-\frac{\nu}{k}v \quad (2)$$

$$0=-\frac{1}{\rho}\frac{\partial p}{\partial z} \quad (3)$$

$$\frac{\partial T}{\partial t}=\frac{K_1}{\rho C_p}\frac{\partial^2 T}{\partial z^2}-\frac{Q_0}{\rho C_p}(T-T_0) \quad (4)$$

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}-K_c(C-C_0) \quad (5)$$

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

$$J+\frac{\omega_e\tau_e}{B_O}\left(J\times B\right)=\sigma\left[E+V\times B+\frac{1}{e\eta_e}\nabla P_e\right] \quad (6)$$

Where ω_e the cyclotron frequency of the electrons is, 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 (6). Further it is assumed that $\omega_e\tau_e$ ~ O (1) and $\omega_i\tau_i \ll 1$, where ω_i and τ_i are the cyclotron frequency and collision time for ions respectively. In equation (6) 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

$$J_x+m\,J_y=\sigma B_0 v \quad (7)$$

$$J_y-m\,J_x=-\sigma B_0 u \quad (8)$$

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

On solving equations (7) and (8) we obtain

$$J_x=\frac{\sigma B_0}{1+m^2}(v+mu) \quad (9)$$

$$J_y=\frac{\sigma B_0}{1+m^2}(mv-u) \quad (10)$$

Substituting the equations (9) and (10) in (3) and (2) respectively, we obtain

$$\frac{\partial u}{\partial t}-2\Omega v=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial z^2}-\left(\frac{\sigma B_0^2}{\rho(1+m^2)}+\frac{\nu}{k}\right)u+g\beta(T-T_0)+g\beta^*(C-C_0) \quad (11)$$

$$\frac{\partial v}{\partial t}+2\Omega u=\nu\frac{\partial^2 v}{\partial z^2}-\left(\frac{\sigma B_0^2}{\rho(1+m^2)}+\frac{\nu}{k}\right)v \quad (12)$$

We have considered oscillatory Hartmann convective flow so pressure p is assumed in the following form

$$p=2Rx\cos(\omega t)+F(y)+G(z) \quad (13)$$

It is noticed from equations (1), (2), (3), (4) and (5) that pressure p is constant along the axis of rotation i.e., $\frac{\partial p}{\partial z}=G^{'}(z)=0$. The absence of pressure gradient term $\frac{\partial p}{\partial y}=F^{'}(y)$ in equation (2) implies that there is a net cross flow in *y*-

direction. Buoyacy term $g\beta(T - T_0)$ is considered in equation (1) only because free-convection in this problem takes place under gravitational force. Boundary conditions for the fluid velocity are hydrodynamic slip boundary conditions which are given by

$$\mu \frac{du}{dz} = -\beta u \text{ and } \mu \frac{dv}{dz} = -\beta v \text{ at z=0} \qquad (14)$$

$$\mu \frac{du}{dz} = -\beta u \text{ and } \mu \frac{dv}{dz} = \beta v \text{ at z=L} \qquad (15)$$

Boundary conditions (7-8) for the fluid velocity are well known hydrodynamic slip boundary conditions derived by Beavers and Joseph (1967). Here μ and β are, respectively, coefficient of dynamic viscosity and coefficient of sliding friction.

Boundary conditions for the fluid temperature and concentration are

$T = T_0$, $C = C_0$ at z=0, (16)

$T = T_0 + (T_w - T_0)\cos\omega t$, $C = C_0 + (C_w - C_0)$ at z = L, (17)

Where, $T0 < T < T_w$, $C_0 < C < C_w$.

Equation (1), (2) and (4),in non-dimensional form, because

$$\frac{\partial u}{\partial t} - 2K^2 v = -\frac{\partial p}{\partial \varsigma} + \frac{\partial^2 u}{\partial \eta^2} - \left(\frac{M^2}{1+m^2} + \frac{1}{K}\right)u + G_r T + G_m C \qquad (18)$$

$$\frac{\partial v}{\partial t} + 2K^2 u = \frac{\partial^2 v}{\partial \eta^2} - \left(\frac{M^2}{1+m^2} + \frac{1}{K}\right)v \qquad (19)$$

$$\frac{\partial T}{\partial t} = \frac{1}{P_r}\frac{\partial^2 T}{\partial \eta^2} - \phi T, \qquad (20)$$

$$\frac{\partial C}{\partial t} = \frac{1}{SC}\frac{\partial^2 C}{\partial z^2} - K_c C \qquad (21)$$

Where

$$\zeta = \frac{x}{L}, z^* = \frac{z}{L}, u^* = \frac{uL}{\upsilon}, v^* = \frac{vL}{\upsilon}, t^* = \frac{t\upsilon}{L^2}, p^* = \frac{L^2 p}{\rho\upsilon^2}, T^* = \frac{(T - T_0)}{(T_w - T_0)}, C^* = \frac{(C - C_0)}{(C_w - C_0)}, Sc = \frac{\nu}{D}$$

$$E^2 = \frac{\Omega l^2}{\nu}, K = \frac{k}{l^2}, M^2 = \frac{\sigma B_0^2 l^2}{\rho\nu}, \mathrm{Pr} = \frac{\nu\rho C_p}{K_1}, \mathrm{Gr} = g\beta\frac{(T_w - T_0)l^3}{\nu^2}, Kc = \frac{k_c l^2}{2R}(C_w - C_0), \phi = \frac{Q_0 l^2}{\rho\nu c_p}$$

$K^2, M^2, G_r, P_r, K_1, \phi$, Sc and Kc are rotation parameter which is reciprocal of Ekman number, magnetic parameter which is square of Hartmann number, Grashof number, Prandtl number, Permeablitity parameter and heat generation/absorption coefficient, Schmidt number, Chemical reaction parameter respectively.

Boundary conditions (14) and (15), in dimensionless from, are

$$u = -\alpha\frac{\partial u}{\partial z} \text{ and } v = -\alpha\frac{\partial v}{\partial z} \quad \text{at} \quad z = 0 \qquad (22)$$

$$u = \alpha\frac{\partial u}{\partial z} \text{ and } v = \alpha\frac{\partial v}{\partial z} \quad \text{at} \quad z = 1 \qquad (23)$$

T = 0 at z = 0 and T = $\cos\omega t$ at z = 1, (24)

C = 0 at z=0 and C = $\cos\omega t$ at z = 1, (25)

Where is $\alpha = \mu / \beta L$ is slip parameter and $\omega = \omega^1 L^2 / \nu$ is frequency parameter

Equations (18)and (19), in compact form , become

$$\frac{\partial F}{\partial t} + 2iK^2 F = -\frac{\partial p}{\partial \varsigma} + \nu\frac{\partial^2 F}{\partial z^2} - \left(\frac{M^2}{1+m^2} + \frac{1}{K}\right)F + G_r T + G_m C \qquad (26)$$

Where F = *u* + i*v*.

Boundary conditions (15) and (16), in dimensionless from, are

$$F+\alpha\frac{\partial F}{\partial \eta}=0 \text{ at z = 0 and } F-\alpha\frac{\partial F}{\partial \eta}=0 \text{ at z = 1} \quad (27)$$

It may be noted that the fluid flow past a plate may be induced due to either by motion of the plate or free stream or by heating of the fluid or by both. We have considered oscillatory Hartmann convective flow so fluid flow, in our case, is induced due to applied and oscillatory pressure gradient and by heating of the fluid because lower and upper plates. Therefore, pressure gradient $\frac{\partial p}{\partial \varsigma}$, fluid velocity F($\eta$, t) and fluid temperature T(η, t) are assumed, in non-dimensional form, as

$$\frac{\partial p}{\partial \varsigma}=R(e^{i\omega t}+e^{-i\omega t}), \quad (28)$$

$$F(\eta,t)=F_1(z)\, e^{i\omega t} + F_2(z)\, e^{-i\omega t} \quad (29)$$

$$\theta\,(\eta,t)=T_1(z)\, e^{i\omega t} + T_2(z)\, e^{-i\omega t} \quad (30)$$

$$C(\eta,t)=C_1(z)\, e^{i\omega t} + C_2(z)\, e^{-i\omega t} \quad (31)$$

Where R < 0 for favourable pressure

Equations (25) and (28) with the use of (30) and (31) reduce to

$$\frac{d^2T_1}{dz^2} - P_r(\phi+i\omega)T_1=0 \quad (32)$$

$$\frac{d^2T_2}{dz^2} - P_r(\phi+i\omega)T_2=0 \quad (33)$$

$$\frac{d^2C_1}{dz^2} - S_c(k_c+i\omega)C_1=0 \quad (34)$$

$$\frac{d^2C_2}{dz^2} - S_c(k_c+i\omega)C_2=0 \quad (35)$$

$$\frac{d^2F_1}{dz^2}-\left\{\frac{1}{K_1}+M^2+i(2K^2+\omega)\right\}F_1=R-G_rT_1-G_mC_1, \quad (36)$$

$$\frac{d^2F_2}{dz^2}-\left\{\frac{1}{K_1}+M^2+i(2K^2-\omega)\right\}F_2=R-G_rT_2-G_mC_2, \quad (37)$$

Boundary conditions (27) and (29) becomes

$T_1 = 0$ and $T_2 = 0$ at z = 0 (38)

$T_1 = 1/2$ and $T_2 = 1/2$ at z =1 (39)

$C_1 = 0$ and $C_2 = 0$ at z = 0 (40)

$C_1 = 1/2$ and $C_2 = 1/2$ at z =1 (41)

$$F_1+\alpha\frac{\partial F_1}{\partial z}=0 \text{ and and } F_2+\alpha\frac{\partial F_2}{\partial z}=0 \quad \text{at z = 0} \quad (42)$$

$$F_1-\alpha\frac{\partial F_1}{\partial z}=0 \text{ and } F_2-\alpha\frac{\partial F_2}{\partial \eta}=0 \text{ at z = 0} \quad (43)$$

Equations (32) to (35) subject to boundary conditions (36) and (37) are solved and the solution for fluid temperature and fluid velocity is presented in the following form

$$\theta(z,t)=\frac{1}{2}\left[\frac{\sinh m_1 z}{\sinh m_1}e^{i\omega t}+\frac{\sinh m_3 z}{\sinh m_3}e^{-i\omega t}\right], \quad (44)$$

$$C(z,t)=\frac{1}{2}\left[\frac{\sinh m_7 z}{\sinh m_7}e^{i\omega t}+\frac{\sinh m_8 z}{\sinh m_8}e^{-i\omega t}\right], \quad (45)$$

$$F(z,t)=\left\{C_1\cosh m_2 z + C_2\sinh m_2 z - \frac{R}{m_2^2} - \frac{G_r \sinh m_1 z}{2(m_1^2-m_2^2)\sinh m_1}\right\}e^{i\omega t},$$

$$+\left\{C_3\cosh m_4 z + C_4\sinh m_4 z - \frac{R}{m_4^2} - \frac{G_r \sinh m_3 z}{2(m_3^2-m_4^2)\sinh m_3}\right\}e^{i\omega t} \qquad (46)$$

III. Results and Discussions

We discussed the heat and mass transfer on the unsteady hydromagnetic convective flow of an incompressible viscous electrically conducting heat generating/absorbing fluid through porous medium in a rotating parallel plate channel under the influence of uniform transfer magnetic field normal to the channel and taking hall current into account. The momentum equation for the flow is governed by the Brinkman's model. The analytical solutions for the velocity, temperature and concentration distributions are obtained by making use of regular perturbation technique. 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 (1-6) shows the effects of non-dimensional parameters *M* the Hartmann number, K_1 permeability parameter, Gr Grashof number, Gm mass Grashof number, m hall parameter and K rotation parameter; the Figure (7) exhibit the temperature distribution with different variations in the governing parameters Pr, and the Figures (8) depicts the concentration profiles with variations in Schmidt number Sc and chemical reaction parameter Kc.

It is noticed that, from the Figures 1 the magnitude of the velocity *u* reduces with increasing the intensity of the magnetic field (Hartmann number M) throughout the fluid region. The magnitude of the velocity component *v* enhances with increasing *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 reversal behaviour is observed for increasing the permeability parameter K_1 (Figure 2). The resultant velocity q enhances with increasing *K*; 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 depicts the velocity component *u* enhances with increasing Grashof number Gr and mass Grashof number Gm. The profiles show the magnitude of the velocity component *v* reverse trend whenever there is increasing Gr or Gm. The resultant velocity q increases with increasing Gr or Gm. We noticed that, from the figure (5) the magnitude of the velocity components *u* and *v* increase with increasing hall parameter *m*. similar behaviour is observed for the resultant velocity with increasing hall parameter *m*. The magnitude of the velocity component *u* decreases and *v* increases with increasing rotation parameter K. The resultant velocity with increasing rotation parameter K. This has been shown in the figure (6).

The temperature profiles exhibit in the Figure 7 for different variations in Prandtl number Pr. 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. It is concluded that Prandtl number Pr reduces the temperature in all layers. The concentration profiles are shown in the Figures 8 for different variations in Schmidt number Sc, the chemical reaction parameter Kc. 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.

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, thermal Grashof number Gr and mass Grashof number Gm, Schmidt number *Sc*, chemical reaction parameter *Kc* and Prandtl number Pr where as it reduces with increase in Hartmann number *M*.

From the table 2 that the magnitude of the Nusselt number Nu increases for the parameters 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.

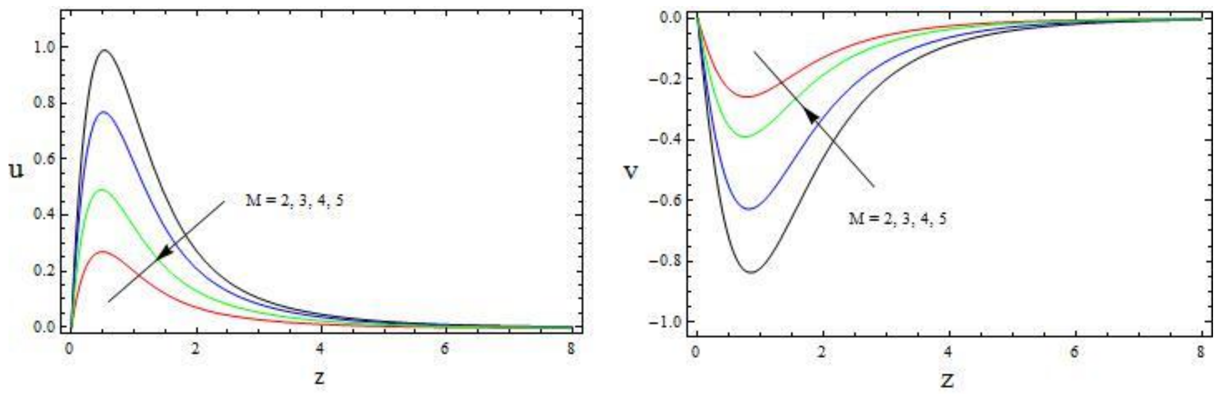

Fig. 1. The velocity profiles for the components *u* and *v* for M with $t = 0.2$

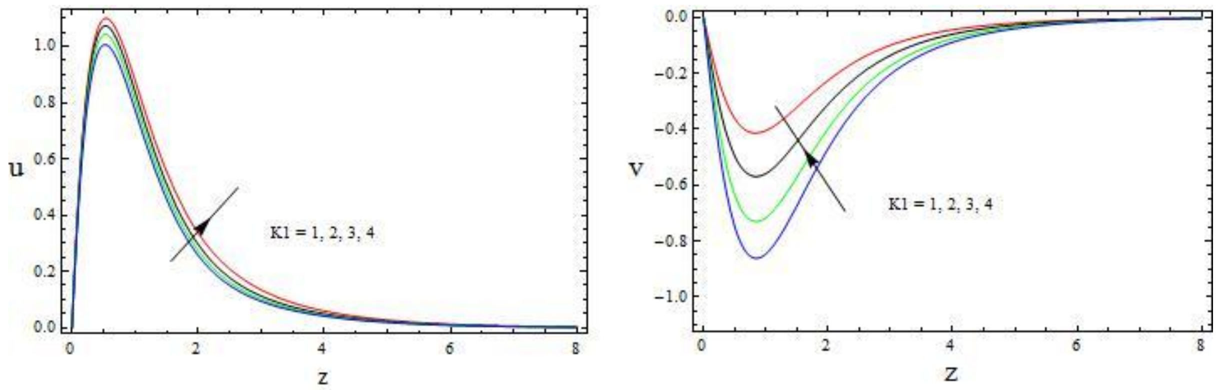

Fig. 2. The velocity profiles for the components *u* and *v* for K with $t = 0.2$

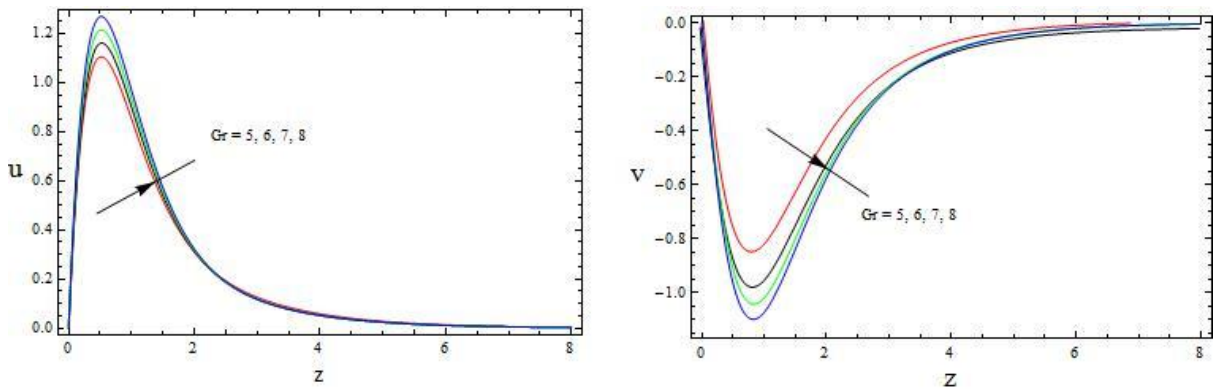

Fig. 3. The velocity profiles for the components *u* and *v* for Gr with $t = 0.2$

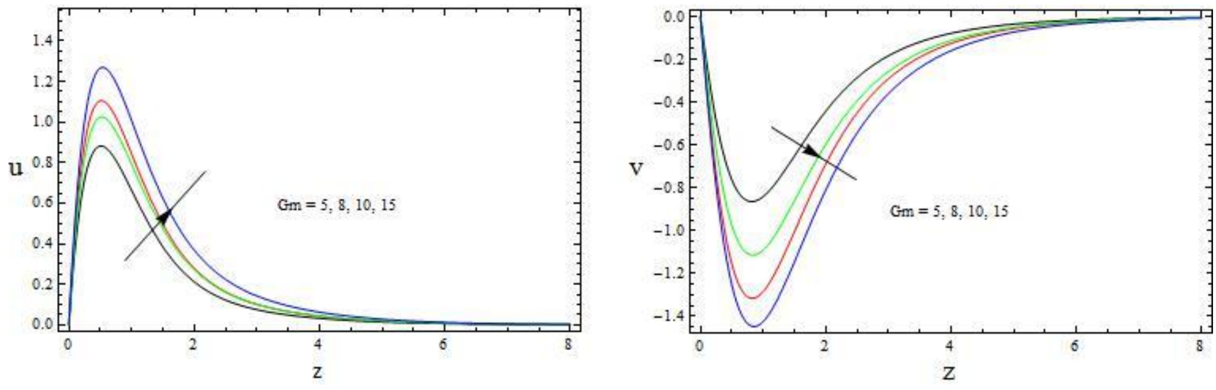

Fig. 4. The velocity profiles for the components *u* and *v* for Gm with $t = 0.2$

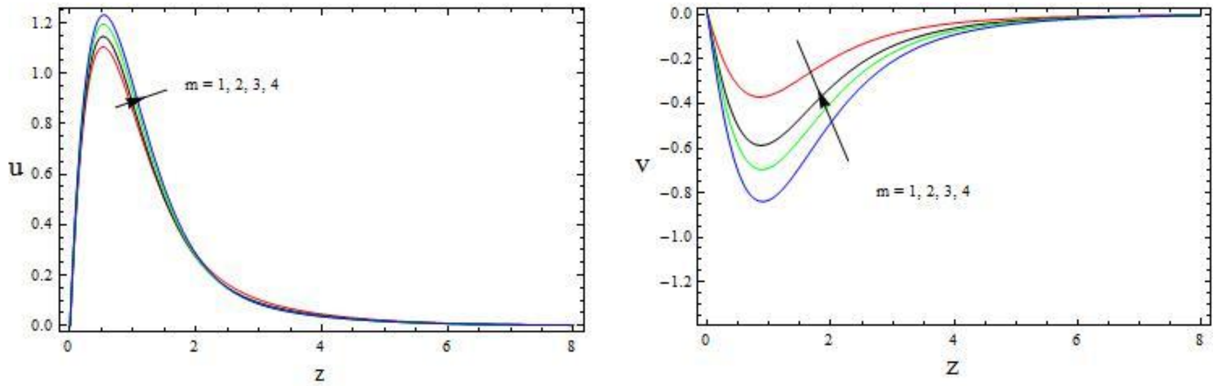

Fig. 5. The velocity profiles for the components *u* and *v* for m with $t = 0.2$

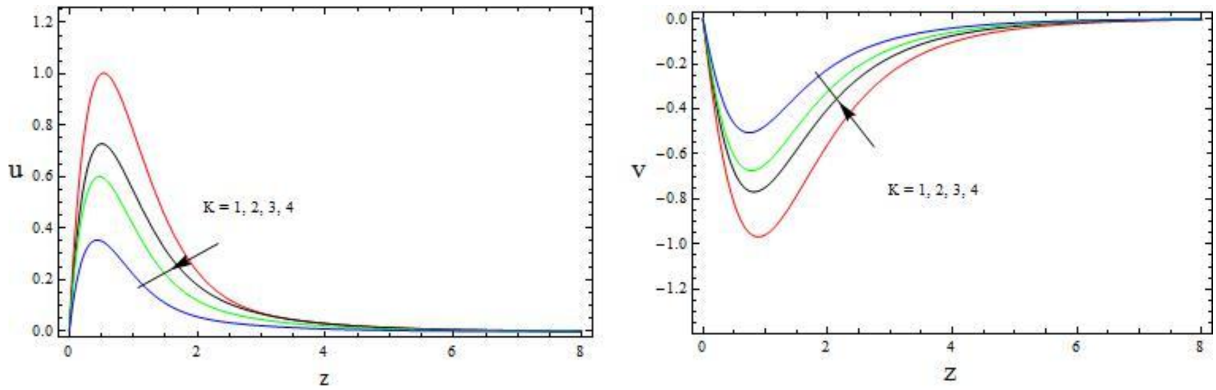

Fig. 6. The velocity profiles for the components *u* and *v* for K with $t = 0.2$

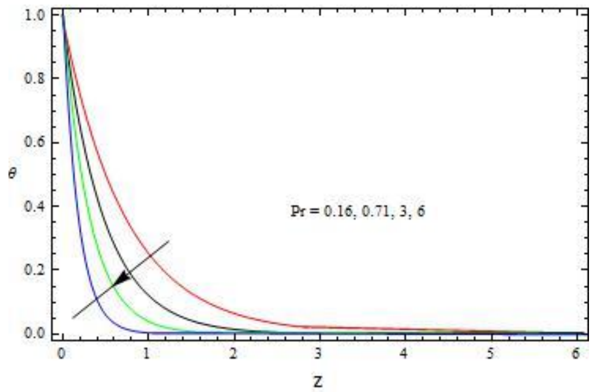

Fig. 7. The temperature profile for Pr with $t = 0.2$

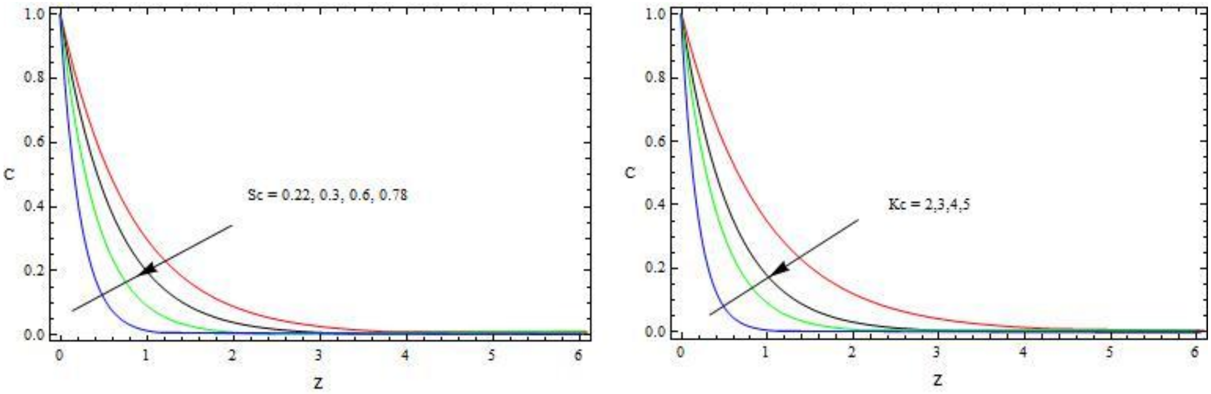

Fig. 8. The Concentration profiles for with $t = 0.2$

Table. 1. Skin Friction

M	K	Gr	Gm	Sc	Kc	m	Pr	τ_{xz}	τ_{yz}
2	**2**	**5**	**10**	**0.22**	**2**	**1**	**0.71**	6.552262	-4.285565
3	2	5	10	0.22	2	1	0.71	4.866595	-3.663289
4	2	5	10	0.22	2	1	0.71	2.336589	-2.225482
2	**3**	5	10	0.22	2	1	0.71	7.100254	-4.885462
2	**4**	5	10	0.22	2	1	0.71	8.001452	-4.966589
2	2	**6**	10	0.22	2	1	0.71	6.885965	-5.421422
2	2	**7**	10	0.22	2	1	0.71	7.225462	-6.225638
2	2	5	**5**	0.22	2	1	0.71	7.665895	-5.225621
2	2	5	**8**	0.22	2	1	0.71	8.114528	-5.833256
2	2	5	10	**0.3**	2	1	0.71	9.855479	-6.855478
2	2	5	10	**0.6**	2	1	0.71	10.85547	-8.996352
2	2	5	10	0.22	**4**	1	0.71	8.669589	-6.996589
2	2	5	10	0.22	**7**	1	0.71	9.855478	-9.225478
2	2	5	10	0.22	**7**	2	0.71	8.452145	-8.022518
2	2	5	10	0.22	**7**	3	0.71	9.114528	-10.23568
2	2	5	10	0.22	2	1	**3**	10.55625	-5.552561
2	2	5	10	0.22	2	1	7	11.25546	-6.001420

Table. 2. Nusselt Number

Pr	ω	t	Nu
0.71	$5\pi/2$	**0.2**	-1.60653
3	$5\pi/2$	0.2	-4.45861
7	$5\pi/2$	0.2	-8.61827
0.71	$7\pi/2$	0.2	-1.61538
0.71	$9\pi/2$	0.2	-1.61431
0.71	$5\pi/2$	**0.4**	-1.61854
0.71	$5\pi/2$	**0.6**	-1.60026

Table. 3. Sherwood Number

Sc	Kc	ω	t	Sh
2	**0.22**	$5\pi/2$	**0.2**	-0.791334
3	0.22	$5\pi/2$	0.2	-0.918700
4	0.22	$5\pi/2$	0.2	-1.153333
2	**0.3**	$5\pi/2$	0.2	-0.937762
2	**0.6**	$5\pi/2$	0.2	-1.434060
2	0.22	$7\pi/2$	0.2	-0.780754
2	0.22	$9\pi/2$	0.2	-0.778487
2	0.22	$5\pi/2$	**0.4**	-0.782446
2	0.22	$5\pi/2$	**0.6**	-0.794455

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