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MODELLING OF ROTATIONAL FLUID WITH AN ACCELERATED VERTICAL PLATE EMBEDDED IN A DARCIAN POROUS REGIME

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ABSTRACT: A mathematical study is conducted for the unsteady hydromagnetic flow of a viscous, incompressible, electrically conducting, and Newtonian rotating fluid past a uniformly accelerated infinite vertical plate immersed in a Darcian porous regime, under the action of transversely applied magnetic field. The coupled non-linear partial differential equations for the primary and secondary flow are solved using Laplace transform technique. An increase in Darcian number (K_r), the primary velocity is decelerated, while the secondary velocity accelerated. It is observed that an increase in the rotation parameter (Ω leads to decrease both the primary and secondary velocity profiles in the Darcian porous regime. Applications of the study arise in the field of stellar and planetary magnetospheres, aeronautics, chemical engineering and electronics.
KEYWORDS: Darcian porous regime, Rotational fluid, Isothermal vertical plate, Magnetic field, Chemical Engineering

INTRODUCTION

The hydrodynamic rotating flow of electrically conducting viscous incompressible fluids has gained considerable attention because of its numerous applications in physics and engineering. In geophysics it is applied to measure and study the positions and velocities with respect to a fixed frame of reference on the surface of earth which rotate with respect to an inertial frame in the presence of its magnetic field. The subject of geophysical dynamics 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. In engineering it finds its application in MHD generators, ion propulsion, MHD bearings, MHD pumps, MHD boundary layer control of reentry vehicles etc.

Present research field has attracted many researchers in recent years due to its astounding applications. Free convection effects on flow past an accelerated vertical plate with variable suction and uniform heat flux in the presence of magnetic field was studied by Raptis al (1981). Mass transfer effects on flow past a uniformly accelerated vertical plate was studied by Soundalgekar (1982). Singh (1984) studied MHD flow past an impulsively started vertical plate in a rotating fluid. MHD effects on flow past an infinite vertical plate for both the classes of impulse as well as accelerated motion of the plate was studied by Raptis and Singh (1985).

Ahmed (2008) 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. Ahmed (2010) 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. The transient natural convection-radiation flow of viscous dissipation fluid along an infinite vertical surface embedded in a porous medium, by means of network simulation method, investigated by Zueco (2008).

Ahmed (2010) investigated the effect of periodic heat transfer on unsteady MHD mixed convection flow past a vertical porous flat plate with constant suction and heat sink when the free stream velocity oscillates in about a non-zero constant mean. The steady magnetohydrodynamic (MHD) mixed convection stagnation point flow over a vertical flat plate is investigated by Ali et. al. (2011). Sahin et. al. (2012) investigated the effect of the transverse magnetic field on a transient free and forced convective flow over an infinite vertical plate impulsively held fixed in free stream taking into account the induced magnetic field. Steven et. al. (2012) studied the magnetic hydrodynamic free convective flow past an infinite vertical porous plate with the effect of viscous dissipation subject to *a constant suction velocity. The problem of a steady magnetohydrodynamic free convective boundary layer flow over a porous vertical isothermal flat plate with constant suction where the effects of the induced magnetic field as well as viscous and magnetic dissipations of energy studied by Ahmed and Batin (2013).*

Harouna (2010) presented a numerical simulation on unsteady hydromagnetic free convection near a moving infinite flat plate in a rotating medium. Muthucumaraswamy et. al. (2011) studied the effects of rotation on the hydromagnetic free convection flow of an incompressible viscous and electrically conducting fluid past a uniformly accelerated infinite vertical plate in the presence of variable temperature and uniform mass diffusion. Ahmed and Kalita (2013) presented the magnetohydrodynamic transient convective radiative heat transfer one-dimensional flow in an isotropic, homogenous porous regime adjacent to a hot vertical plate. Ahmed and Kalita (2013) investigated the effects of chemical reaction as well as magnetic field on the heat and mass transfer of Newtonian two-dimensional flow over an infinite vertical oscillating plate with variable mass diffusion. Ahmed and Batin (2013) studied the effects of thermal radiation and porosity of the medium on flow past an impulsively started infinite isothermal vertical plate in the presence of magnetic field.

The purpose of the present analysis is to study an unsteady hydromagnetic free convection flow of an electrically conducting viscous incompressible fluid past a uniformly accelerated infinite vertical plate embedded in a Darcian porous regime in the presence of variable temperature and uniform mass diffusion. The dimensionless governing equations are solved using the Laplace transform technique. The solutions are in terms of exponential and complementary error function. Such a study is found useful in magnetic control of molten iron flow in the steel industry, liquid metal cooling in nuclear reactors, magnetic suppression of molten semi-conducting materials and meteorology.

MATHEMATICAL ANALYSIS

Consider the unsteady hydromagnetic flow of an electrically conducting fluid induced by viscous incompressible fluid past a uniformly accelerated motion of an isothermal vertical infinite plate in a Darcian porous regime when the fluid and the plate rotate as a rigid body with a uniform angular velocity $\overline{\Omega}$ about $\overline{z}$-axis in the presence of an imposed uniform magnetic field B_0 normal to the plate. Initially, the temperature of the plate and concentration near the plate are assumed to be $\overline{T_\infty}$ and $\overline{C_\infty}$. At time $\overline{t}$ > 0, the plate starts moving with a velocity u = $u_0\,\overline{t}$ in its own plane and the temperature from the plate is raised linearly with time and the concentration level near the plate are also raised to $\overline{C_w}$. Since the plate occupying the plane $\overline{z}=0$ is of infinite extent, all the physical quantities depend only on $\overline{t}$ and $\overline{t}$. It is assumed that the induced magnetic field is negligible so that $\vec{B}=(0,0,B_0)$.

For unsteady motion of a hydromagnetic Newtonian fluid occupying Darcian porous space in a rotating system, given by Sherman and Sutton (1965), and Maxwell's equations, the fundamental equations are in vector form:

$$\nabla\cdot\vec{q}=0 \tag{1}$$

$$\frac{\partial\vec{q}}{\partial\overline{t}}+(\vec{q}\cdot\nabla)\vec{q}+2\overline{\Omega}\hat{k}\times\vec{q}=-\frac{1}{\rho}\nabla\overline{p}+\vec{g}+\nu\nabla^2\vec{q}-\frac{\nu}{\overline{K}}\vec{q}+\frac{1}{\rho}\vec{J}\times\vec{B} \tag{2}$$

$$\frac{\partial\overline{T}}{\partial\overline{t}}+(\vec{q}\cdot\nabla)\overline{T}=\frac{\kappa}{\rho C_P}\nabla^2\overline{T} \tag{3}$$

$$\frac{\partial\overline{C}}{\partial\overline{t}}+(\vec{q}\cdot\nabla)\overline{C}=D\nabla^2\overline{C} \tag{4}$$

$$\nabla\times\vec{B}=\mu_e\vec{J}\ \text{(Ampere's Law)} \tag{5}$$

$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}\ \text{(Faraday's Law)} \tag{6}$$

$$\nabla\cdot\vec{B}=0\ \text{(Solenoidal relation i.e. magnetic field continuity)} \tag{7}$$

$$\vec{J}=\sigma\left(\vec{E}+\vec{q}\times\vec{B}\right)\ \text{(Ohm's Law for a moving conductor)} \tag{8}$$

where $\vec{q}$, $\vec{B}$, $\vec{E}$, $\vec{J}$ and μ_e are, respectively, the velocity vector, magnetic field vector, electric field vector and current density vector, the magnetic permeability of the fluid.

Then the unsteady flow is governed by free-convective flow of an electrically conducting fluid in a rotating system filled with porous medium under the usual Boussinesq's approximation in dimensionless form are as follows:

$$\frac{\partial \bar{u}}{\partial \bar{t}} - 2\bar{\Omega}\bar{v} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{x}} + g + \nu\frac{\partial^2 \bar{u}}{\partial \bar{z}^2} - \frac{\nu}{\bar{K}}\bar{u} - \frac{\sigma B_0^2 \bar{u}}{\rho} \tag{9}$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} - 2\bar{\Omega}\bar{u} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{y}} + \nu\frac{\partial^2 \bar{v}}{\partial \bar{z}^2} - \frac{\nu}{\bar{K}}\bar{u} - \frac{\sigma B_0^2 \bar{v}}{\rho} \tag{10}$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\kappa}{\rho C_P}\frac{\partial^2 \bar{T}}{\partial \bar{z}^2} \tag{12}$$

$$\frac{\partial \bar{C}}{\partial \bar{t}} = D\frac{\partial^2 \bar{C}}{\partial \bar{z}^2} \tag{13}$$

$$0 = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{z}} \tag{14}$$

Since there is no large velocity gradient here, the viscous term in Equation (9) vanishes for small ▫ and hence for the outer flow, beside there is no magnetic field along x-direction gradient, so we have

$$0 = -\frac{\partial \bar{p}}{\partial \bar{x}} - \rho_\infty g$$

By eliminating the pressure term from Equations (9) and (14), we obtain

$$\frac{\partial \bar{u}}{\partial \bar{t}} - 2\bar{\Omega}\bar{v} = (\rho_\infty - \rho)g + \nu\frac{\partial^2 \bar{u}}{\partial \bar{z}^2} - \frac{\nu}{\bar{K}}\bar{u} - \frac{\sigma B_0^2 \bar{u}}{\rho} \tag{15}$$

The Boussinesq approximation gives

$$\rho_\infty - \rho = \rho_\infty \beta(\bar{T} - \bar{T}_\infty) + \rho_\infty \bar{\beta}(\bar{C} - \bar{C}_\infty) \tag{16}$$

On using (16) in the equation (15) and noting that ρ_∞ is approximately equal to 1, the momentum equation reduces to

$$\frac{\partial \bar{u}}{\partial \bar{t}} - 2\bar{\Omega}\bar{v} = g\beta(\bar{T} - \bar{T}_\infty) + g\bar{\beta}(\bar{C} - \bar{C}_\infty) + \nu\frac{\partial^2 \bar{u}}{\partial \bar{z}^2} - \frac{\nu}{\bar{K}}\bar{u} - \frac{\sigma B_0^2 \bar{u}}{\rho} \tag{17}$$

The initial and boundary conditions are:

$$\begin{aligned} &\bar{u} = 0, \bar{T} = \bar{T}_\infty, \bar{C} = \bar{C}_\infty \quad \text{for all } \bar{z}, \bar{t} \le 0 \\ &\left.\begin{aligned} &\bar{u} = u_0 \bar{t}, \bar{T} = \bar{T}_\infty + (\bar{T}_w - \bar{T}_\infty)A\bar{t}, \bar{C} = \bar{C}_w \quad \text{at } \bar{z} = 0 \\ &\bar{u} \to 0, \bar{T} \to \bar{T}_\infty, \bar{C} \to \bar{C}_\infty \quad \text{as } \bar{z} \to \infty \end{aligned}\right\} \bar{t} > 0 \end{aligned} \tag{18}$$

On introducing the following non-dimensional quantities:

$$z = \bar{z}\left(\frac{u_0}{\nu^2}\right)^{1/3}, u = \frac{\bar{u}}{(\nu u_0)^{1/3}}, \ v = \frac{\bar{v}}{(\nu u_0)^{1/3}}, \ t = \bar{t}\left(\frac{u_0^2}{\nu^2}\right)^{1/3}, \ \Omega = \bar{\Omega}\left(\frac{\nu}{u_0^2}\right)^{1/3},$$

$$\theta = \frac{\bar{T} - \bar{T}_\infty}{\bar{T}_w - \bar{T}_\infty}, \ \phi = \frac{\bar{C} - \bar{C}_\infty}{\bar{C}_w - \bar{C}_\infty}, \ Sc = \frac{\nu}{D}, \ \Pr = \frac{\rho \nu C_P}{\kappa}, \ K_r = \bar{K}\left(\frac{u_0^2}{\nu^4}\right)^{1/3},$$

$$Gr = \frac{g\beta(\bar{T}_w - \bar{T}_\infty)}{u_0}, \ Gr_m = \frac{g\bar{\beta}(\bar{C}_w - \bar{C}_\infty)}{u_0}, \ M = \frac{\sigma B_0^2}{\rho}\left(\frac{\nu}{u_0^2}\right)^{1/3}, \ A = \left(\frac{u_0^2}{\nu}\right)^{1/3},$$

In view of the non-dimensional quantities, the equations (10), (11) to (16) become:

$$\frac{\partial u}{\partial t} - 2\Omega v = Gr\theta + Gr_m\phi + \frac{\partial^2 u}{\partial z^2} - \left(M + K_r^{-1}\right)u \tag{17}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\partial^2 v}{\partial z^2} - \left(M + K_r^{-1}\right)v \tag{18}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial z^2} \tag{19}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial z^2} \tag{20}$$

With the following initial and boundary conditions:

$$u = 0, \theta = 0, \phi = 0 \quad \text{for all} \quad z, t \le 0$$
$$t > 0 \begin{cases} u = t, \; \theta = t, \; \phi = 1 & \text{at} \quad z = 0 \\ u \to 0, \; \theta \to 0, \; \phi \to 0 & \text{as} \quad z \to \infty \end{cases} \tag{21}$$

The hydromagnetic rotating free-convection flow past an accelerated vertical plate embedded in a Darcian porous medium is described by coupled partial differential equations (17) to (20) with the prescribed boundary conditions (21). To solve the equations (1) and (2), we introduce a complex velocity $f = u + i v$ equations (17) and (18) can be combined into a single equation:

$$\frac{\partial f}{\partial t} = Gr\theta + Gr_m\phi + \frac{\partial^2 f}{\partial z^2} - m f \tag{22}$$

The following initial and boundary conditions:

$$u = 0, \theta = 0, \phi = 0 \quad \text{for all} \quad z, t \le 0$$
$$t > 0 \begin{cases} f = t, \; \theta = t, \; \phi = 1 & \text{at} \quad z = 0 \\ f \to 0, \; \theta \to 0, \; \phi \to 0 & \text{as} \quad z \to \infty \end{cases} \tag{23}$$
$$m = \left(M + K_r^{-1}\right) + 2i\Omega$$

METHOD OF SOLUTION

The dimensionless governing equations (19), (20) and (22), subject to the initial and boundary conditions (8), are solved by the usual Laplace-transform technique and the solutions are derived as follows:

$$\begin{aligned} f = &\left(\frac{t}{2} + c + cat + d\right)\left[\exp(2\eta\sqrt{mt})\, erfc(\eta + \sqrt{mt}) + \exp(-2\eta\sqrt{mt})\, erfc(\eta - \sqrt{mt})\right] \\ &- \eta\sqrt{\frac{t}{m}}\left[\frac{1}{2} + ac\right]\left[\exp(-2\eta\sqrt{mt})\, erfc(\eta - \sqrt{mt}) - \exp(2\eta\sqrt{mt})\, erfc(\eta + \sqrt{mt})\right] \\ &- 2c\, erfc\left(\eta\sqrt{\Pr}\right) - c\exp(at)\left[\exp(2\eta\sqrt{(m+a)t})\, erfc\left\{\eta + \sqrt{(m+a)t}\right\}\right. \\ &\left. + \exp(-2\eta\sqrt{(m+a)t})\, erfc\left\{\eta - \sqrt{(m+a)t}\right\}\right] - 2d\, erfc\left(\eta\sqrt{Sc}\right) \\ &+ c\exp(at)\left[\exp(2\eta\sqrt{at\Pr})\, erfc(\eta\sqrt{\Pr} + \sqrt{at}) + \exp(-2\eta\sqrt{at\Pr})\, erfc(\eta\sqrt{\Pr} - \sqrt{at})\right] \\ &- d\exp(bt)\left[\exp\left\{2\eta\sqrt{(m+b)t}\right\} erfc(\eta + \sqrt{(m+b)t})\right. \\ &\left. + \exp\left\{-2\eta\sqrt{(m+b)t}\right\} erfc(\eta - \sqrt{(m+b)t})\right] \\ &+ d\exp(bt)\left[\exp(2\eta\sqrt{bt\,Sc})\, erfc(\eta\sqrt{Sc} + \sqrt{bt}) + \exp(-2\eta\sqrt{bt\,Sc})\, erfc(\eta\sqrt{Sc} - \sqrt{bt})\right] \\ &- 2act\left[(1 + 2\eta^2\Pr)\, erfc(\eta\sqrt{\Pr}) - \frac{2\eta\sqrt{\Pr}}{\sqrt{\pi}}\exp(-\eta^2\Pr)\right] \end{aligned} \tag{24}$$

$$\theta = t\left[(1 + 2\eta^2\Pr)\, erfc(\eta\sqrt{\Pr}) - \frac{2\eta\sqrt{\Pr}}{\sqrt{\pi}}\exp(-\eta^2\Pr)\right] \tag{25}$$

$$\phi = erfc(\eta\sqrt{Sc}) \tag{26}$$

In order to get the physical insight into the problem, the numerical values of f have been computed from (24). While evaluating this expression, it is observed that the argument of the error function is complex and, hence, we have separated it into real and imaginary parts by using the following formula:

$$erf(a + ib) = erf(a) + \frac{\exp(-a^2)}{2a\pi}\left[1 - \cos(2ab) + i\sin(2ab)\right]$$

$$+\frac{\exp(-a^2)}{\pi}\sum_{n=1}^{\infty}\frac{\exp(-n^2/4)}{n^2+4a^2}\left[h_n(a,b)+i\,g_n(a,b)+\varepsilon(a,b)\right]$$

where $h_n(a,b)=2a-2a\cosh(nb)\,\cos(2ab)+n\sinh(nb)\,\sin(2ab)$

$$g_n(a,b)=2a\cosh(nb)\,\sin(2ab)+n\sinh(nb)\,\cos(2ab)$$

$$\left|\varepsilon(a,b)\right|\approx 10^{-6}\left|erf(a+ib)\right|$$

RESULTS AND DISCUSSION

To describe the flow behavior, the system of non-linear differential equations (17)-(20) together with the boundary conditions (21) has been solved analytically by using Laplace Transform technique. The numerical results are displayed in the form of non-dimensional primary and secondary velocity profiles for various values of the parameters that represent the flow. Here we consider Gr = Gr_m = 5 > 0 (cooling of the plate) i.e. free convection currents convey heat away from the plate in to the boundary layer, t =1, Sc = 0.60 throughout the discussion. The Prandtl number Pr is taken for air at 20°C (Pr = 0.71), electrolytic solution (Pr = 1.0) and water (Pr = 7.0).

To judge the accuracy of the present numerical data, a comparison of the temperature distribution with the previously published paper of Muthucumaraswamy et. al. [14] for K_r = 0 different values of the Prandtl number, the results are observed to be in good agreement.

Table 1: Comparison of values of the temperature distribution (θ) for the present results with [14] when Gr = Gr_m = 5 , K_r = 0, Sc = 0.6, M = 5, t = 0.5:

	Present work			Previous work [14]		
	Pr			Pr		
y	0.71	1.0	7.0	0.71	1.0	7.0
0.0	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
2.0	0.42061	0.36192	0.30730	0.42058	0.36188	0.30722
4.0	0.09819	0.06160	0.02737	0.09817	0.06153	0.02731
6.0	0.01730	0.01510	0.00363	0.01725	0.01508	0.00357
8.0	0.01358	0.00375	0.00045	0.01350	0.00370	0.00041
10.0	0.00532	0.00000	0.00000	0.00527	0.00000	0.00000

In Table 1 it is seen that, as Pr the increases the thickness of the thermal boundary layer decreases. It is inferred that the thickness of thermal boundary layer is greater for air (Pr = 0.71) and there is more uniform temperature profile across the thermal boundary layer as compared to water (Pr = 7.0) and steam (Pr = 1.0). The reason is that smaller values of Prandtl number are equivalent to increasing thermal conductivity and therefore heat is able to diffuse away from the heated surface more rapidly than for higher values of Prandtl number. Thus temperature falls more rapidly for water than air and steam.

Figures 1(a)-1(b) indicate the behaviour of Primary and Secondary velocities with the variations in Darcy number (K_r). The Primary velocity shows a decrement with the increases in Darcy number for K_r = 0.01, 0.2, 0.5. It is because that the presence of a porous medium increases the resistance to flow and thus reduces the fluid velocity. Further, the secondary velocity increases with the increase in Darcy number K_r.

Effects of M are plotted in Fig. 2(a) and Fig. 2(b). As M increases from 0.0 through 3.0 to 10.0, a considerable reduction in the primary velocity occurs. As a matter of fact, the presence of a transverse magnetic field will result in a resistant type of force known as Lorentz force which increases the resistance to the flow, leading to decrease in the fluid velocity. As the magnetic parameter increases the thickness of the momentum boundary layer increases for secondary velocity. Also observe that strength of magnetic field is much higher in secondary velocity profiles.

Fig. 3(a) and Fig. 3(b) give the dimensionless velocity profiles (primary and secondary velocity), for various values of rotation parameter □, it is observed that an increase in the rotation parameter □ leads to decrease both the primary velocity and secondary velocity profiles in the porous regime. But the primary velocity profile shows a minor decreasing effect while the secondary velocity profile has quite larger decreasing effect.

Fig. 4(a) and Fig. 4(b) represent the variation of Prandtl number (Pr) in the primary and secondary velocity profiles. It is observed that with the increase of Prandtl number decreases the primary velocity, while the secondary velocity increases. It is mentioned that for water (=7.0), the velocity profiles is much higher in both cases than that of other. It also shows the larger decreasing effect on the primary velocity and minor increasing effect on the secondary velocity.

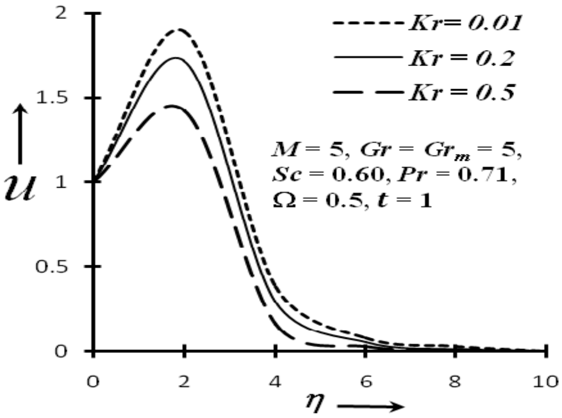

Fig. 1(a): Primary velocity profile for different values of K_r

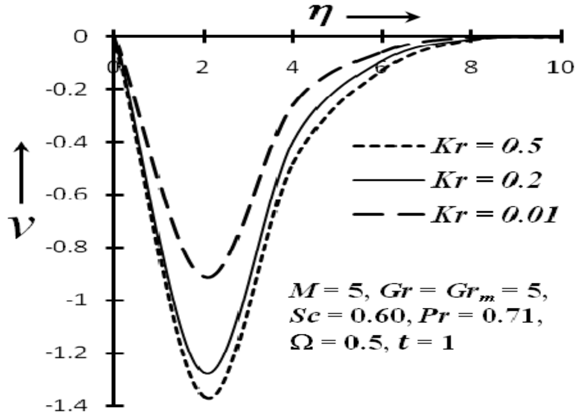

Fig. 1(b): Secondary velocity profile for different values of K_r

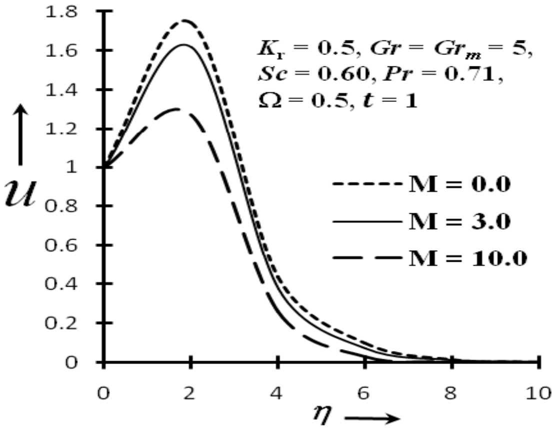

Fig. 2(a): Primary velocity profile for different values of M

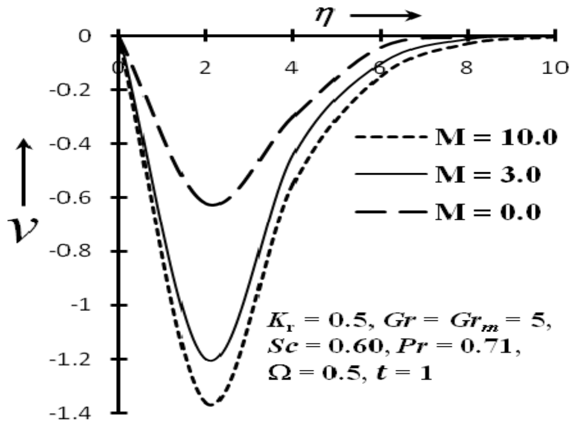

Fig. 2(b): Secondary velocity profile for different values of M

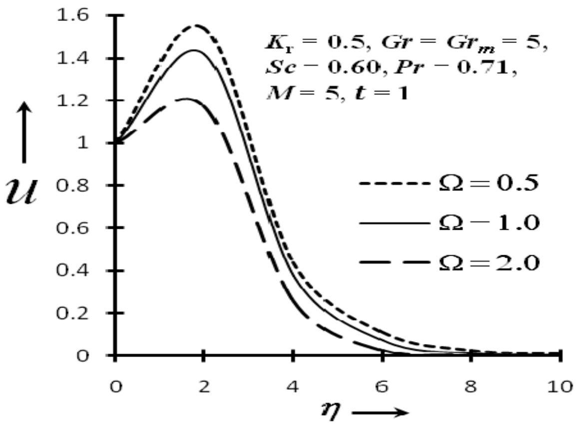

Fig. 3(a): Primary velocity profile for different values of Ω

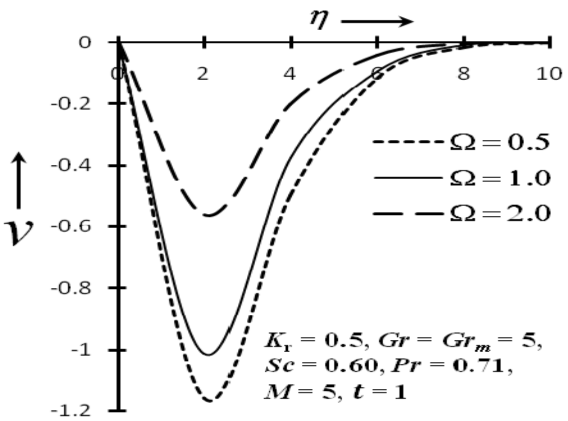

Fig. 3(b): Secondary velocity profile for different values of Ω

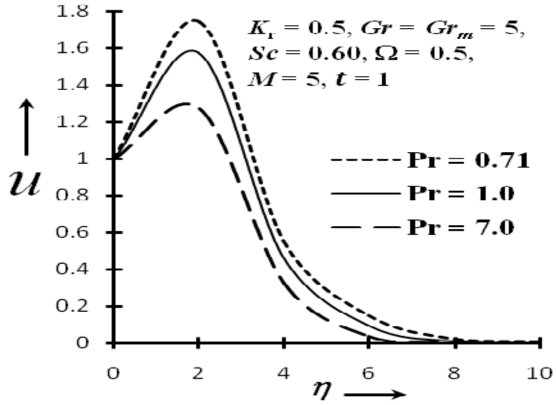

Fig. 4(a): Primary velocity profile for different values of Pr

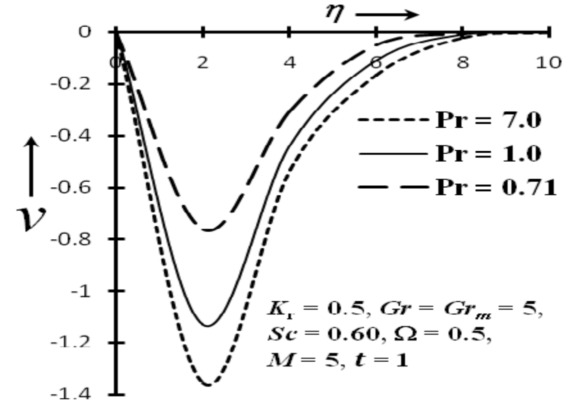

Fig. 4(b): Secondary velocity profile for different values of Pr

CONCLUSIONS

The above analysis brings out the following results of physical interest on the primary and secondary velocity profiles of the flow field.

- *The Darcian parameter has the influence of decreasing the primary velocity and it has the influence of increasing the magnitude of the secondary velocity profiles.*
- *The rotation parameter has the effect of decreasing the primary velocity profiles as well as the magnitude of the secondary velocity profiles.*
- *The rotation parameter has large effect on velocity profiles, and hence can effectively be used to control the fluid motion.*
- *We have found satisfactory agreement of our present results with those of [14].*
- *The Hartmann number has the effect of decreasing the flow field (Primary velocity) at all the points due to the magnetic pull of the Lorentz force acting on the flow field. So magnetic field can effectively be used to control the flow*
- *A comparison of temperature profiles shows that the temperature decreases throughout the Darcian regime.*

NOMENCLATURE

x - Spatial coordinate along the plate
y - Coordinate axis normal to the plate
z - Dimensionless coordinate axis normal to the plate
$\bar{t}$ - Time
t - Dimensionless time
A - Constant
$\bar{C}$ - Species concentration (Kg. m^{-3})
C_p - Specific heat at constant pressure (J. kg^{-1}. K)
$\bar{C}_\infty$ - Species concentration in the free stream (Kg. m^{-3})
$\bar{C}_\infty$ - Species concentration at the surface (Kg. m^{-3})
D - Chemical molecular diffusivity ($m^2.s^{-1}$)
g - Acceleration due to gravity ($m.s^{-2}$)
Gr - Thermal Grashof number
Gr_m - Mass Grashof number
M - Hartmann number/Magnetic parameter
B_0 - Uniform magnetic field
$\bar{p}$ - Pressure (Pa)
Kr - Darcy number or porosity parameter
Pr - Prandtl number
Sc - Schmidt number
$\bar{T}$ - Dimensional Temperature
$\bar{T}_w$ - Dimensional Fluid temperature at the surface
$\bar{T}_\infty$ - Dimensional Fluid temperature in the free stream
u - Dimensionless velocity component in x-direction (m. s^{-1})
u_0 - Velocity of the plate (m. s^{-1})
erfc-Complementary error function
erf-Error function
exp-Exponential function

Greek symbols

β - Coefficient of volume expansion for heat transfer (K^{-1}),
$\bar{\beta}$ - Coefficient of volume expansion for mass transfer (K^{-1})
η - Similarity parameter
θ - Dimensionless fluid temperature (K),
k - Thermal conductivity (W. m^{-1}. K^{-1}),
μ - Coefficient of viscosity (kg. m^{-31})
ν - Kinematic viscosity ($m^2.s^{-1}$),
ρ - Density (kg. m^{-3}),
σ - Electrical conductivity
Φ - Dimensionless species concentration (Kg. m^{-3})

Subscripts

w - Conditions on the wall
∞ - Free stream conditions

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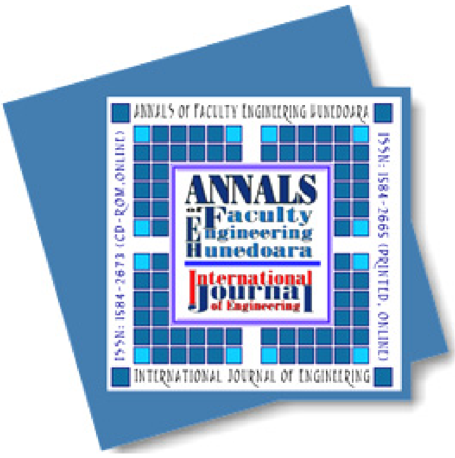

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