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Exact Solutions of MHD, Radiation and Rotation Effects on Impulsively Started Vertical Plate with Variable Mass Diffusion

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Abstract- An exact solution of radiation rotation effects on vertical plate with variable mass diffusion in the presences of MHD is obtained for the axial and transverse components of the velocity by defining a complex velocity. The effects of velocity, temperature and concentration for different parameters like radiation parameter, rotation parameter, magnetic field parameter, Schmidt number, thermal Grashof number, mass Grashof number, Prandtl number and time are discussed.

Keywords- Magnetic field, Radiation, gray, rotation, vertical plate, heat and mass transfer.

1. Introduction

The study of hydromagnetic flow is called hydromagnetics or magneto hydrodynamics (MHD), which studies the dynamics of electrically conducting fluids. The set of equations which describe MHD are a combination of the Navier-Stokes equation of fluid dynamics and Maxwell's equations of electromagnetism.

Many research works have been done based on the action of an uniform transverse magnetic field either fixed to the fluid or to the plate. Heat and mass transfer on MHD flows have applications in Meteorology, solar physics, cosmic fluid dynamics, astrophysics and geophysics. Magneto convection plays an important role in various industrial applications such as magnetic control of molten iron flow in the steel industry, liquid metal cooling in nuclear reactors, electromagnetic pumps, controlled fusion research, crystal growing, MHD couples and bearings, plasma jets, chemical synthesis and underground nuclear waste storage sites.

Radiative heat and mass transfer play an important role in manufacturing industries for the design of reliable equipment, Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles. The effect of Coriolis force has wide applications in science and technology.

Arpaci [2] studied the interaction between thermal radiation and laminar convection of heated Vertical plate in a stagnant radiating gas. Bestman and Adjepong [3] studied the magnetohydrodynamic free convection flow, with radiative heat transfer, past an infinite moving plate in rotating incompressible, viscous and optically transparent medium. Das *et al.* [4] have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate. England and Emery [6] have studied the thermal radiation effects of an optically thin gray gas bounded by a stationary vertical plate. Greenspan, H.P [7] Discussed the theory of rotating fluids owing to its numerous applications in cosmical and geophysical fluid dynamics, meterology and engineering, Muthucumaraswamy R.and Ganesan P [8] have considered radiation effects on flow past an impulsively started infinite vertical plate with variable temperature. Naroua et al.[9] considered the radiative free convictive flow of an optically thin gray gas past a semi-infinite vertical plate. Raptis and Perdikis [10] considered the effects of thermal radiation and free convection flow past a moving vertical plate. Again, Raptis and Perdikis [11] investigationted free convection and mass transfer effects on optically thin gray gas past an infinite moving vertical plate. Singh [12] studied the effects of coriolis as well as magnetic force on the flow field of an electrically conducting fluid past an impulsively started infinite vertical plate. Saravanan and Kandaswamy [13] have analysed the effect of temperature dependent thermal conductivity on duoyancy induced convection in the presence of a uniform magnetic field. It was inferred that it is advantageous to use Prandtl number liquid metals or alloys as coolants in fast reactors whose thermalconductivity doesnot depend much on the temperature. Soundalgekar et al [14] studied Stoke's problem for an infinite vertical plate whose temperature varies with time in the presence of transverse magnetic field for an incompressible fluid.Again Soundalgakar and Takhar [15] considered the radiative free convective flow of an optically thin gray gas past a semi-infinite vertical plate. Cavus and Karafistan [16] studied the effects of differential rotation in the lower convective region of the sun. The governing equations were solved analytically.

However, MHD effects on a moving infinite vertical plate with in a rotating fluid in the presence of thermal radiation are not studied in the literature. It is proposed to study MHD effects on flow past an impulsively started infinite isothermal vertical plate with variable mass diffusion in a rotating fluid in the presence of thermal radiation. The dimensionless governing equations are solved by Laplace transform technique.

2. Basic Equations

Three dimensional flow of a viscous, incompressible, electrically conducting fluid past an impulsively started infinite vertical isothermal plate with variable mass diffusion in a rotating fluid [3, 12] is considered. On this plate, the x'-axis is taken along the plate in the vertically upward direction and the y'-axis is taken normal to x'-axis in the plane of the plate and z'-axis is normal to it. Both the fluid and the plate are in a state of rigid rotation with uniform angular velocity Ω' about the z'-axis. The fluid considered here is a gray, absorbing-emitting radiation but a non-scattering medium. A transverse magnetic field B_0 of uniform strength is applied normal to the plate in the z' direction. The induced magnetic field and viscous dissipation is assumed to be negligible. The set of equations which describe MHD are a combination of the Navier-Stokes equation of fluid dynamics and Maxwell's and the complex velocity $q = u + iv$, $i = \sqrt{-1}$ in equations (1) to (5), the equations relevant to the problem reduces to equations of electromagnetism. Initially, the plate and fluid are at rest with the temperature T'_∞ and concentration C'_∞ everywhere. At time $t' > 0,$ the plate is given an impulsive motion in the vertical direction against gravitational field with constant velocity u_0 in a fluid, in the presence of thermal radiation. At the same time the plate temperature is raised to T'_w and the concentration to C'_w, which are there after maintained constant. Since the plate occupying the plane $z' = 0$ is of infinite extent, all the physical quantities depend only on z' and t'. Then by usual Boussinesq's approximation, the unsteady flow is governed by the following equations:

$$\frac{\partial \boldsymbol{u'}}{\partial \boldsymbol{t'}} - 2\Omega' \boldsymbol{v'} = \boldsymbol{g}\beta(\boldsymbol{T'} - \boldsymbol{T'_\infty}) + \boldsymbol{g}\beta^*(\boldsymbol{C'} - \boldsymbol{C'_\infty}) + \nu \frac{\partial^2 \boldsymbol{u'}}{\partial \boldsymbol{z'}^2} - \sigma \frac{\boldsymbol{B_0}^2}{\rho} \boldsymbol{u'} \quad (1)$$

$$\frac{\partial \boldsymbol{v'}}{\partial \boldsymbol{t'}} + 2\Omega' \boldsymbol{u'} = \nu \frac{\partial^2 \boldsymbol{v'}}{\partial \boldsymbol{z'}^2} - \frac{\sigma \boldsymbol{B_0}^2}{\rho} \boldsymbol{v'} \quad (2)$$

$$\rho \boldsymbol{C_p} \frac{\partial \boldsymbol{T'}}{\partial \boldsymbol{t'}} = \boldsymbol{k} \frac{\partial^2 \boldsymbol{T'}}{\partial \boldsymbol{z'}^2} - \frac{\partial \boldsymbol{q_r}}{\partial \boldsymbol{z'}} \quad (3)$$

$$\frac{\partial \boldsymbol{C'}}{\partial \boldsymbol{t'}} = \boldsymbol{D} \frac{\partial^2 \boldsymbol{C'}}{\partial \boldsymbol{z'}^2} \quad (4)$$

The term $\frac{\partial q_r}{\partial z'}$ represents the change in the radiative flux with distance normal to the plate with the following initial and boundary conditions:

$$\begin{aligned} t' \le 0: &\quad u' = 0, \quad T' = T'_\infty, \quad C' = C'_\infty \quad \text{for all } z' \\ t' > 0: &\quad u' = u_0, \quad T' = T'_w, \quad C' = C'_w + (C'_w - C'_\infty) \quad \text{at} \quad z' = 0 \\ &\quad u = 0, \quad T \to T_\infty, \quad C' \to C'_\infty \quad \text{as} \quad z' \to \infty. \end{aligned} \quad (5)$$

By Rosseland approximation [10], radiative heat flux of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial z'} = -4a^* \sigma (T'^4_\infty - T'^4) \quad (6)$$

It is assume that the temperature differences within the flow are sufficiently small such that T'^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T'^4 in a Taylor series about T'_∞ and neglecting higher-order terms, thus

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \quad (7)$$

By using equations (6) and (7), equation (3) reduces to

$$\rho C_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} + 16a^* \sigma T'^3_\infty (T'_\infty - T') \quad (8)$$

On introducing the following dimensionless quantities:

$$\begin{aligned} &(\boldsymbol{u}, \boldsymbol{v}) = \frac{(\boldsymbol{u'}, \boldsymbol{v'})}{\boldsymbol{u_0}}, \quad \boldsymbol{t} = \frac{\boldsymbol{t'} \boldsymbol{u'^2_0}}{\nu}, \quad \boldsymbol{z} = \frac{\boldsymbol{z'} \boldsymbol{u_0}}{\nu}, \quad \theta = \frac{\boldsymbol{T'} - \boldsymbol{T'_\infty}}{\boldsymbol{T'_w} - \boldsymbol{T'_\infty}}, \\ &Gr = \frac{g\beta\nu(T'_w - T'_\infty)}{u'^3_0}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Gc = \frac{\nu g \beta^* (C'_w - C'_\infty)}{u_0^3}, \\ &M = \frac{\sigma B_0^2 u'}{\rho}, \quad Pr = \frac{\mu C_p}{k}, \quad \Omega = \frac{\Omega' \nu}{u'^2_0}, \quad R = \frac{16 a^* \nu^2 \sigma T'^3_\infty}{k u'^2_0} \end{aligned} \quad (9)$$

and the complex velocity $q = u + iv$, $i = \sqrt{-1}$ in equations (1) to (5), the equations relevant to the problem reduces to

$$\frac{\partial q}{\partial t} + 2i\Omega q = Gr\theta + GcC + \frac{\partial^2 q}{\partial z^2} - Mq,$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial z^2} - \frac{R}{Pr} \theta$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C}{\partial z^2} \quad (12)$$

The initial and boundary conditions in non-dimensional form are

$$\begin{aligned} &q = 0, \quad \theta = 0, \quad C = 0, \quad \text{for all} \quad z \le 0 \,\&\, t \le 0 \\ t > 0: \; &q = 1, \quad \theta = 1, \quad C = t, \quad at \quad z = 0 \\ &q = 0, \quad \theta \to 0, \quad C \to 0, \quad as \quad z \to \infty. \end{aligned} \quad (13)$$

All the physical variables are defined in the nomenclature. The solutions are obtained for the equations (10) to (12), subject to the boundary conditions (13), by Laplace-transform technique and the solutions are derived as follows:

$$\theta = \frac{1}{2}[\exp(z\sqrt{R}) erfc(\eta\sqrt{\Pr} + \sqrt{at}) + \exp(-z\sqrt{R}) erfc(\eta\sqrt{\Pr} - \sqrt{at})] \quad (14)$$

$$C = t[(1 + 2\eta^2 Sc) erfc(\eta\sqrt{Sc}) - \frac{2}{\sqrt{\pi}} \eta\sqrt{Sc} \exp(-\eta^2 Sc)] \quad (15)$$

$$\begin{aligned} q = &\frac{1}{2}\left(1 + \frac{Gr}{b(1-Pr)} + \frac{Gc}{c^2(1-Sc)} + \frac{Gct}{c(1-Sc)}\right)[\exp(2\eta\sqrt{mt}) erfc(d1) + \exp(-2\eta\sqrt{mt}) erfc(d2)] \\ &- \frac{Gr \exp(bt)}{2b(1-Pr)}[\exp(2\eta\sqrt{(b+m)t}) erfc(d3) + \exp(-2\eta\sqrt{(b+m)t}) erfc(d4)] \\ &- \frac{Gc\eta}{2c(1-Sc)}\sqrt{\frac{t}{m}}[\exp(-2\eta\sqrt{mt}) erfc(d2) - \exp(2\eta\sqrt{mt}) erfc(d1)] \\ &- \frac{Gc \exp(ct)}{2c^2(1-Sc)}[\exp(2\eta\sqrt{(c+m)t}) \; erfc(d5) + \exp(-2\eta\sqrt{(c+m)t}) \; erfc(d6)] \\ &+ \frac{Gr \exp(bt)}{2b(1-Pr)}[\exp(2\eta\sqrt{Pr(b+a)t}) \; erfc(d9) + \exp(-2\eta\sqrt{Pr(b+a)t}) \; erfc(d10)] \\ &- \frac{Gr}{2b(1-Pr)}[\exp(2\eta\sqrt{Rt}) erfc(d7) + \exp(-2\eta\sqrt{Rt}) erfc(d8)] - \frac{Gc}{c^2(1-Sc)} erfc(\eta\sqrt{Sc}) \\ &- \frac{Gc}{c(1-Sc)}[t(1 + 2\eta^2 Sc) erfc(\eta\sqrt{Sc}) - \frac{2}{\sqrt{\pi}}\eta\sqrt{Sc}\exp(-\eta^2 Sc)] \\ &+ \frac{Gc \exp(ct)}{2c^2(1-Sc)}[\exp(2\eta\sqrt{Sc\, ct}) erfc(d11) + \exp(-2\eta\sqrt{Sc\, ct}) erfc(d12)] \end{aligned} \quad (16)$$

Where

$$d1, d2 = \left[\eta \pm \sqrt{mt}\right], \qquad d3, d4 = \left[\eta \pm \sqrt{(b+m)t}\right],$$
$$d5, d6 = \left[\eta \pm \sqrt{(c+m)t}\right], \qquad d7, d8 = \left[\eta\sqrt{Pr} \pm \sqrt{at}\right],$$
$$d9, d10 = \left[\eta\sqrt{Pr} \pm \sqrt{(a+b)t}\right], \qquad d11, d12 = \left[\eta\sqrt{Sc} \pm \sqrt{ct}\right],$$

$$\boldsymbol{a} = \frac{\boldsymbol{R}}{\boldsymbol{Pr}}, \quad \boldsymbol{b} = \frac{\boldsymbol{R}-\boldsymbol{m}}{1-\boldsymbol{Pr}}, \quad \eta = \frac{\boldsymbol{z}}{2\sqrt{\boldsymbol{t}}} \quad \text{and} \quad \boldsymbol{m} = \boldsymbol{M} + 2\boldsymbol{i}\Omega.$$

In equation (16), the argument of the complementary error function and error function is complex. Hence in order to obtain the u and v components of the velocity and skin-friction, we have used the following formula due to Abramowitz and stegun [1]:

$$erf(a+ib) = erf(a) + \frac{\exp(-a^2)}{2a\pi}\left[1-\cos(2ab) + i\sin(2ab)\right] + \frac{2\exp(-a^2)}{\pi}\sum \frac{\exp(-n^2/4)}{n^2+4a^2}\left[f_n(a,b) + i g_n(a,b)\right] + \varepsilon(a,b)$$

Where

$$f_n = 2a - 2a\cosh(nb)\cos(2ab) + n\sinh(nb)\sin(2ab)$$
$$g_n = 2a\cosh(nb)\sin(2ab) + n\sinh(nb)\cos(2ab)$$
$$|\varepsilon(a,b)| \approx 10^{-16}|erf(a+ib)|.$$

Using the above formula, expressions for u, v are obtained but they are omitted here to save the space. In order to get a physical view of the problem, these expressions are used to obtain the numerical values of u, v, for different values of the various parameter like magnetic field, rotation, radiation, Schmidt number, thermal Grashof number and mass Grashof number.

Fig. 1, depicts the concentration profiles for different values of the Schmidt number (Sc = 0.16, 0.24, 0.6, 0.78) at time t = 0.2. It is observed that there is a fall in concentration due to increasing the values of the Schmidt number.

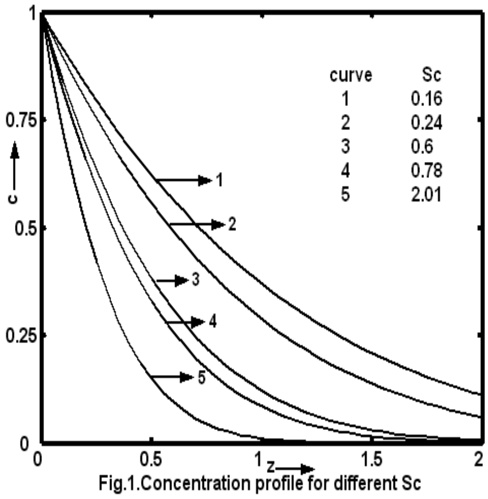

Fig.1.Concentration profile for different Sc

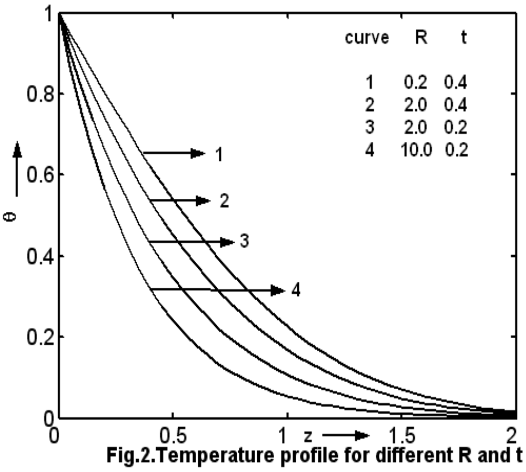

Fig.2.Temperature profile for different R and t

The temperature profiles for air (Pr = 0.71) are calculated for different values of thermal radiation parameter(R=0.2, 2, 10) and time (t=0.2, 0.4) from (14) and these are shown in Fig. 2. The effect of thermal radiation parameter is important in temperature profiles. It is observed that the temperature increases with decreasing radiation parameter as well as increasing time.

The primary velocity profiles of air for different values of the radiation parameter (R = 2, 25), Gr = 20, Gc = 5, Sc = 0.6, t = 0.2, Pr = 0.71, M=0.2 and rotation parameter (Ω = 2, 3) are shown in Fig. 3. It is observed that the primary velocity increases with decreasing radiation parameter R as well as the rotation parameter Ω in cooling of the plate. This shows that primary velocity decreases in the presence of high thermal radiation and rotation.

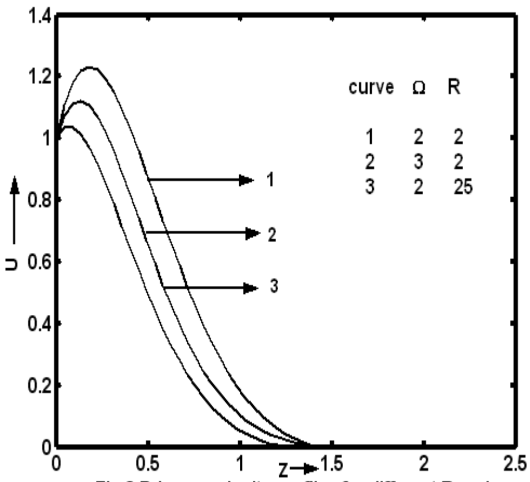

Fig.3.Primary velocity profiles for different R and Ω

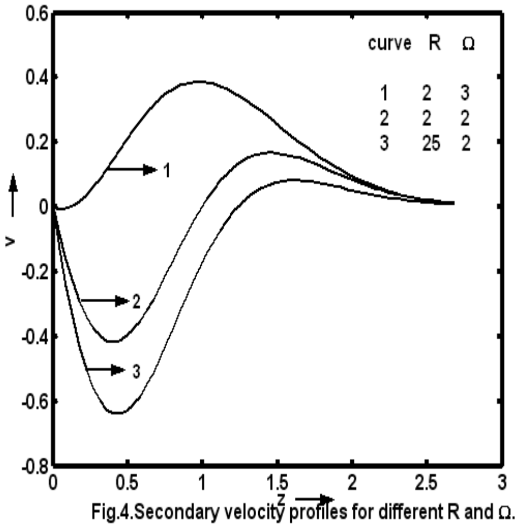

Fig.4.Secondary velocity profiles for different R and Ω.

The secondary velocity profiles of air for different values of the radiation parameter (R = 2, 25), Gr = 20, Gc = 5, Sc = 0.6, t = 0.2, Pr = 0.71, M=0.2 and rotation parameter (Ω =3, 2) are shown in Fig. 4, the effect of radiation has a retarding effect on the secondary velocity v. But the effect of rotation on v is just reverse to that of radiation parameter.

The primary velocity profiles of air for different values of the magnetic parameter (M = 0.2, 2,), Gr = 20, Gc = 5, Sc = 0.6, t = 0.2, Pr = 0.71, R=2 and rotation parameter (Ω = 2, 3) are shown in Fig. 5. It is observed that the primary velocity increases with decreasing magnetic parameter M as well as the rotation parameter Ω in cooling of the plate. This shows that primary velocity decreases in the presence of high magnetic field and rotation. In fact rotation has more influence than magnetic field on primary velocity.

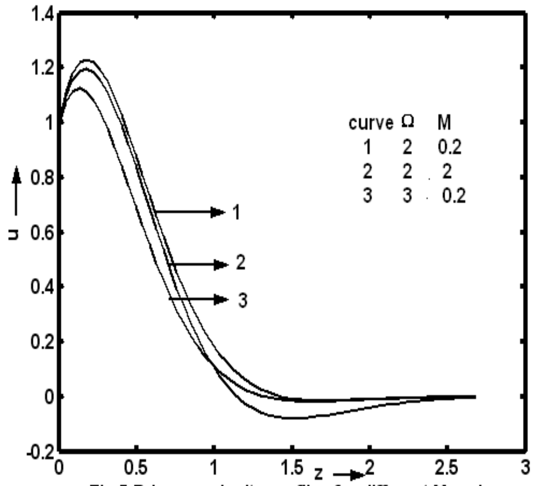

Fig.5,Primary velocity profiles for different M and Ω

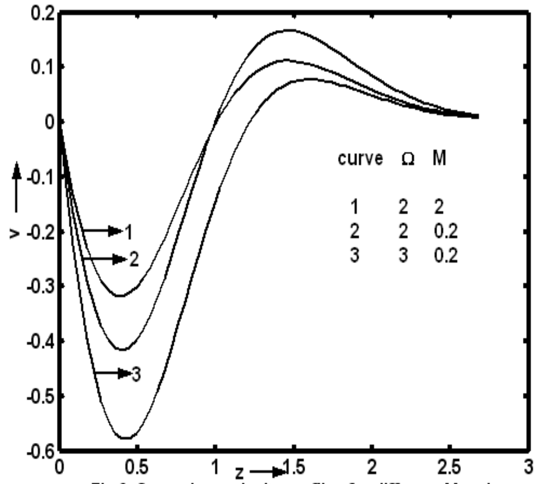

Fig.6. Secondary velocity profiles for different M and Ω

The secondary velocity profiles of air for different values of the magnetic parameter (M = , 0.2,2,), Gr = 5, Gc = 5, Sc = 0.6, t = 0.2, Pr = 0.71 , R=2 and rotation parameter (Ω = 2,3) are shown in Fig.6, the effect of magnetic field increases the secondary velocity v. But the effect of rotation on v is just reverse to that of magnetic parameter. The influence of rotation has a significant effect on secondary velocity.

The primary velocity profiles for different thermal Grashof number (Gr = 5, 5, 2), mass Grashof number (Gc = 2, 10, 2), Sc = 0.6 and time t = 0.2 are shown in Fig. 7. It is clear that the primary velocity increases with increasing thermal Grashof number and decreases with mass Grashof number.

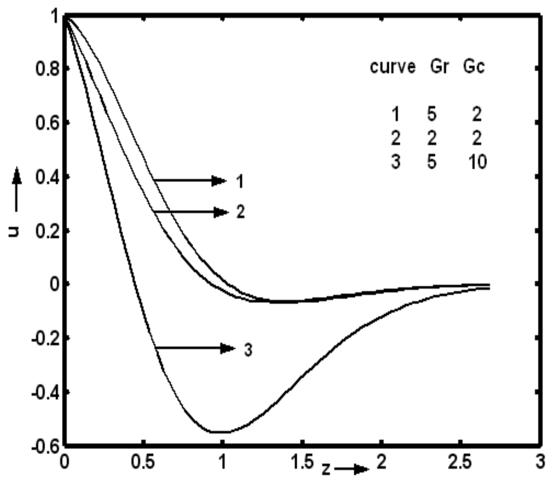

Fig.7.Primary velocity profiles for different Gr and Gc

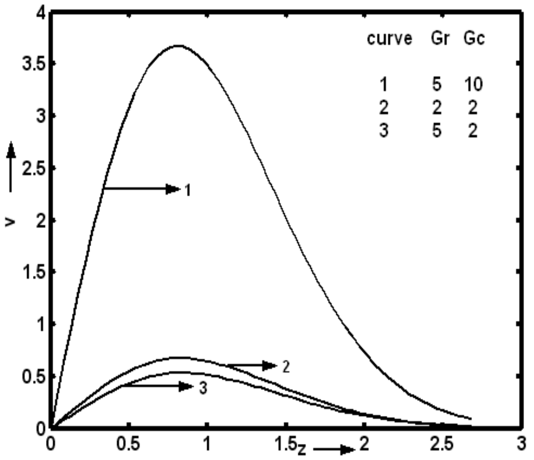

Fig.8. Secondary velocity profiles for different Gr and Gc.

The secondary velocity profiles for different thermal Grashof number (Gr = 2, 5), mass Grashof number (Gc = 2, 10), Sc = 0.6 and time t = 0.2 are shown in Fig. 8. It is clear that the secondary velocity increases with decreasing thermal Grashof number and increasing mass Grashof number.

4. Conclusions

Theoretical analysis is performed to study magneto hydrodynamic effects on flow past an impulsively started infinite isothermal vertical plate with variable mass diffusion, in the presence of thermal radiation in a rotating fluid. The dimensionless governing equations are solved by Laplace-transform technique. The conclusions of the study are as follows:

- Concentration falls with the increase in Schmidt number.
- Temperature is enhanced with the decreasing radiation parameter and increasing time.
- The thermal radiation or rotation parameter on primary flow has a retarding effect for cooling of the plate
- The influence of rotation on primary flow is significant than magnetic field, but both has a retarding effect for cooling of the plate.
- The secondary velocity is enhanced with the raise in thermal radiation or magnetic field parameter and opposite phenomenon occurs with the rotation parameter.
- The effect of thermal Grashof number or mass Grashof number enhanced the primary flow but decreased the secondary flow.

5. Appendix: Notation

a^* absorption coefficient [m^{-1}]
C' concentration [kgm^{-3}]
C dimensionless concentration
C_p specific heat at constant pressure [$Jkg^{-1}K^{-1}$]
D mass diffusion coefficient [m^2s^{-1}]
g acceleration due to gravity [ms^{-2}]
Gr thermal Grashof number
Gc mass Grashof number
k thermal conductivity of the fluid [$Wm^{-1}K^{-1}$]
Pr Prandtl number
q_r radiative heat flux in the y-direction [Wm^{-2}]
R radiation parameter
Sc Schmidt number
T'_∞ temperature of the fluid far away from the plate
T'_w temperature of the plate [K]
T' temperature of the fluid near the plate
t' time [s]
t dimensionless time
u' velocity of the fluid in the x'-direction [ms^{-1}]
u_0 velocity of the plate [ms^{-1}]
u dimensionless velocity
v' velocity of the fluid in the y'-direction [ms^{-1}]
v dimensionless velocity
y' coordinate axis normal to x'-axis
z' coordinate axis normal to the plate
z dimensionless coordinate axis normal to the plate

Greek Symbols

β volumetric coefficient of thermal expansion [K^{-1}]
β^* volumetric coefficient of expansion with concentration [K^{-1}]
μ coefficient of viscosity [$Pa.s$]
ν kinematic viscosity [$m^2.s^{-1}$]
Ω' rotation parameter [rad]
Ω dimensionless rotation parameter
ρ density [$kg.m^{-3}$]
τ dimensionless skin-friction [$kgm^{-1}s^{2}$]
σ Stefan-Boltzman constant [$Wm^{-2}K^{-4}$]
θ dimensionless temperature
$erfc$ complementary error function

Subscripts

w conditions on the wall
∞ free stream conditions

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