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HALL EFFECTS ON MHD FLOW PAST AN EXPONENTIALLY ACCELERATED ISOTHERMAL VERTICAL PLATE WITH VARIABLE MASS DIFFUSION IN THE PRESENCE OF ROTATING FLUID

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Abstract: The present study is performed to investigate the effects of radiation on unsteady MHD flow past an exponentially accelerated infinite vertical plate with variable temperature and variable mass diffusion. The flow is induced by a general time-dependent movement of the vertical plate, and the cases of isothermal plates are studied. The mathematical model, under the usual Boussinesqs' approximation, was reduced to a system of coupled linear partial differential equations for velocity and temperature. The dimensionless governing equations are solved by the Laplace transform method. The effect of concentration, temperature and velocity fields are studied for different parameters like Rotation parameter, Hall parameter, Hartmann number, thermal Grashof number, mass Grashof number, Schmidt number, radiation parameter, accelerated parameter and time.
Keywords: Hall Effects, mass diffusion, isothermal, exponential, vertical plate, rotating fluid

1. INTRODUCTION

The study of natural convection heat transfer from a vertical plate has received much attention in the literature due to its industrial and technological applications. Free convection flow involving coupled heat and mass transfer occurs frequently in nature and in industrial processes. Magneto hydrodynamic free convective flows along with the effects of heat and mass transfer have considerable applications in geophysics; the rotating flow of an electrically conducting fluid in the presence of magnetic field is encountered in geophysical fluid dynamics; also in solar physics, involved in the sunspot development, the solar cycle and the structure of rotating magnetic stars. Buoyancy is also of importance in an environment where differences between land and air temperatures can give rise to complicated flow patterns. The study of hydro magnetic flows and heat transfer have become more important in recent years because of its varied applications in agricultural engineering and petroleum industries. Other applications of MHD heat transfer include MHD generators, plasma propulsion in astronautics, nuclear reactor thermal dynamics and ionized-geothermal energy systems.

Flow past an exponentially accelerated infinite vertical plate and temperature with variable mass diffusion was found by Asogwa [1] and Chandrakala [2] considered the MHD Effects on flow past an exponentially accelerated vertical plate with variable temperature and uniform mass diffusion. Rajput and Surendra Kumar [8] have obtained the Rotation and Radiation Effects on MHD flow past an Impulsively Started Vertical Plate with Variable Temperature. Vijaya and Ramana Reddy [12] investigated MHD Free convection flow past an exponentially accelerated vertical plate with variable temperature and variable mass diffusion. MHD rotating heat and mass transfer free convective flow past an exponentially accelerated isothermal plate with fluctuating mass diffusion were studied by Jonah Philliph et al.[3]. On flow past a parabolic started isothermal vertical plate with variable mass diffusion in the presence of Thermal Radiation were analyzed by Muthucumaraswamy and Lakshmi[4]. Muthucumaraswamy and Visalakshi [6] presented radiative flow past an exponentially accelerated vertical plate with variable temperature and mass diffusion. Effect of internal heat generation absorption on dusty fluid flow over an exponentially stretching sheet with viscous dissipation, has been recently realized by Pavithra [7]. Rajesh and Varma [9] have considered radiation and mass transfer on MHD free convection flow past an exponentially accelerated vertical plate with variable temperature. Saraswat Amit and Srivastava [10] studied heat and mass transfer effects on flow past an oscillating infinite vertical plate with variable temperature through porous media. Muthucumaraswamy et al [5] investigated Mass transfer effects on exponentially accelerated isothermal vertical plate. Uwanta [11] discussed heat and mass transfer with variable temperature and mass diffusion. Visalakshi and Vasanthabhavam [13] investigated the skin friction analysis of exponentially accelerated vertical plate with variable mass diffusion.

The objective of this paper is to study the Magneto hydrodynamic rotating heat and mass transfer free convective flow past an exponentially accelerated isothermal vertical plate with variable mass diffusion. The dimensionless governing equations are solved using the Laplace-transform technique. The solutions are in terms of exponential and complementary error function.

2. FORMULATION OF THE PROBLEM AND ITS SOLUTION

An unsteady hydro magnetic flow of radiating fluid past an exponentially accelerated vertical infinite plate with variable temperature and concentration has been presented. A temperature dependent heat source is assumed to be present in the flow. The fluid and the plate rotate in unison with a uniform angular velocity Ω' about the z' - axis normal to the plate. Initially the fluid is assumed to be at rest and surrounds an infinite vertical plate with temperature T'_∞ and concentration C'_∞ . A magnetic field of uniform strength B_0 is transversely applied to the plate. The x' -axis is taken along the plate in the vertically upward direction and the z' - axis is taken normal to the plate. At time $\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial y^2}$, the plate and the fluid are at the same temperature T'_∞ in the stationary condition with concentration level C'_∞ at all the points. At time $t'>0$, the plate is exponentially accelerated with a velocity $u=u_0\exp(a't')$ where the constant u_0 is the amplitude of the motion, a' is the accelerating parameter in its own plane and the plate temperature and concentration are raised to and C'_w and are maintained constantly thereafter. All the physical properties of the fluid are considered to be constant except the influence of the body-force term. Then under the usual Boussinesqs' approximation the unsteady flow equations are momentum equation, energy equation, and mass equation respectively.

Equation of Momentum:

$$\frac{\partial u}{\partial t'}-2\Omega' v=\vartheta\frac{\partial^2 u}{\partial z^2}-\frac{1}{\rho}\frac{\partial p}{\partial x}+g+\frac{B_0}{\rho}j_y \tag{1}$$

$$\frac{\partial v}{\partial t'}+2\Omega' u=\vartheta\frac{\partial^2 v}{\partial z^2}-\frac{B_0}{\rho}j_x \tag{2}$$

Equation of Energy:

$$\rho C_p\frac{\partial T'}{\partial t'}=k\frac{\partial^2 T'}{\partial z^2}-\frac{\partial q_r}{\partial z} \tag{3}$$

Equation of diffusion:

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial z^2} \tag{4}$$

Since there is no large velocity gradient here, the viscous term in Equation (1) vanishes for small and hence for the outer flow, beside there is no magnetic field along x-direction gradient, so we have

$$0=-\frac{\partial p}{\partial x}-\rho_\infty g \tag{5}$$

By eliminating the pressure term from Equations (1) and (5), we obtain

$$\frac{\partial u}{\partial t'}-2\Omega' v=\vartheta\frac{\partial^2 u}{\partial z^2}+(\rho_\infty-\rho)g+\frac{B_0}{\rho}j_y \tag{6}$$

The Boussinesq approximation gives

$$\rho_\infty-\rho=\rho_\infty\beta(T'-T'_\infty)+\rho_\infty\beta^*(C'-C'_\infty) \tag{7}$$

On using (7) in the equation (6) and noting that ρ_∞ is approximately equal to 1, the momentum equation reduces to

$$\frac{\partial u}{\partial t'}-2\Omega' v=\vartheta\frac{\partial^2 u}{\partial z^2}+\frac{B_0}{\rho}j_y+g\beta(T'-T'_\infty)+g\beta^*(C'-C'_\infty) \tag{8}$$

The generalized Ohm's law, on taking Hall currents into account and neglecting ion-slip and thermo-electric effect, is

$$\vec{j}+\frac{\omega_e\tau_e}{B_0}(\vec{j}\times\vec{B})=\sigma(\vec{E}+\vec{q}\times\vec{B}) \tag{9}$$

The equation (9) gives

$$j_x-mj_y=\sigma vB_0 \tag{10}$$

$$j_y+mj_x=-\sigma uB_0 \tag{11}$$

where $m=\omega_e\tau_e$ is the Hall parameter. Solving (10) and (11) for j_x and j_y, we have

$$j_x=\frac{\sigma B_0}{1+m^2}(v-mu) \tag{12}$$

$$j_y=\frac{\sigma B_0}{1+m^2}(u+mv) \tag{13}$$

On the use of (12) and (13), the momentum equations (8) and (2) become

$$\frac{\partial u}{\partial t'}=\vartheta\frac{\partial^2 u}{\partial z^2}+2\Omega' v-\frac{\sigma B_0^2(u+mv)}{\rho(1+m^2)}+g\beta(T'-T'_\infty)+g\beta^*(C'-C'_\infty) \tag{14}$$

$$\frac{\partial v}{\partial t'}=\vartheta\frac{\partial^2 v}{\partial z^2}-2\Omega' u+\frac{\sigma B_0^2(mu-v)}{\rho(1+m^2)} \tag{15}$$

The initial and boundary conditions are given by

$$\left.\begin{array}{ll} & u=0,\ v=0,\ T'=T'_\infty,\ C'=C'_\infty,\ \dfrac{\partial C'}{\partial t'}=D\dfrac{\partial^2 C'}{\partial y^2}\quad \forall z \\ t'>0 & u=u_0\exp(a't'),\ \ v=0,\ T'=T'_w,\ C'=C'_\infty+(C'_w-C'_\infty)At' \ \text{ at } z=0 \\ & u\to 0,\ v\to 0,\ T'\to T'_\infty,\ C'\to C'_\infty \ \text{ as } \ z\to\infty \end{array}\right\} \tag{16}$$

where, $A=\dfrac{u_0^2}{\gamma}$

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial z}=-4a^*\sigma(T'^4_\infty-T'^4) \tag{17}$$

It is assumed 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

$$T'^4\cong 4T'^3_\infty T'-3T'^4_\infty \tag{18}$$

By using equations (17) and (18), equation (3) reduces to

$$\rho C_p\frac{\partial T'}{\partial t'}=k\frac{\partial^2 T'}{\partial z^2}+16a^*\sigma T'^3_\infty(T'_\infty-T') \tag{19}$$

Let us introducing the following non-dimensional quantities

$$U=\frac{u}{u_0},\ V=\frac{v}{u_0},\ Z=\frac{zu_0}{\gamma},\ t=\frac{t'u_0{}^2}{\gamma},\ \Omega=\frac{\Omega'\gamma}{u_0{}^2},\ M^2=\frac{\Omega\sigma B_0{}^2\gamma}{2\rho u_0{}^2},\ \theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},$$

$$C=\frac{C'-C'_\infty}{C'_w-C'_\infty},\ Pr=\frac{\rho C_p}{k},\ Sc=\frac{\nu}{D},\ Gr=\frac{g\beta\gamma(T'_w-T'_\infty)}{u_0{}^3},\ R=\frac{16a^*\sigma\gamma^2T'^3_\infty}{ku_0{}^2},\ Gc=\frac{g\beta^*\gamma(C'_w-C'_\infty)}{u_0{}^3},\quad a=\frac{a'\gamma}{u_0{}^2}$$

Using these boundary conditions in above equations, we obtain the following dimensionless form of the governing equations:

$$\frac{\partial U}{\partial t}=\frac{\partial^2 U}{\partial Z^2}+2\Omega V-\frac{2M^2(U+mV)}{1+m^2}+Gr\theta+GcC \tag{20}$$

$$\frac{\partial V}{\partial t}=\frac{\partial^2 V}{\partial Z^2}-2\Omega U+\frac{2M^2(mU-V)}{1+m^2} \tag{21}$$

$$\frac{\partial\theta}{\partial t}=\frac{1}{Pr}\frac{\partial^2\theta}{\partial Z^2}-\frac{R}{Pr}\theta \tag{22}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial Z^2} \tag{23}$$

The boundary conditions for corresponding order are

$$\left.\begin{array}{c} U=0\,,V=0\,,\ \theta=0,\ C=0\ \text{ at } t\le 0 \ \text{ for all } Z \\ t>0\,,U=\exp(at)\,,V=0,\ \theta=1,\ C=t\ \text{ at } Z=0 \\ U\to 0\,,V\to 0\,,\theta\to 0\ C\to 0\ \text{ as } Z\to\infty \end{array}\right\} \tag{24}$$

Now equations (20) & (21) and boundary conditions (24) can be combined to give

$$\frac{\partial F}{\partial t} = \frac{\partial^2 F}{\partial Z^2} - wF + Gr\theta + GcC \tag{25}$$

where $w=\dfrac{2M^2}{1+m^2}+2i(\Omega-\dfrac{M^2 m}{1+m^2})$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2\theta}{\partial Z^2} - \frac{R}{Pr}\theta \tag{26}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial Z^2} \tag{27}$$

The initial and boundary conditions in non-dimensional quantities are

$$\left.\begin{array}{c} F=0\,,\theta=0,\ C=0\ \text{ for all } Z,\ t\le 0 \\ t>0\,,F=\exp(at)\,,\theta=1\,,C=t\ \text{ at } Z=0 \\ F\to 0\,,\theta\to 0\ C\to 0\ \text{ as } Z\to\infty \end{array}\right\} \tag{28}$$

Exact solution for the fluid temperature and concentration of (26), (27) is expressed in the following form by taking inverse Laplace transform of solution as

$$C(Z,t)=\operatorname{erfc}(\eta\sqrt{Sc}) \tag{29}$$

$$\theta(Z,t)=\frac{1}{2}\left[\exp(2\eta\sqrt{bPrt})\operatorname{erfc}(\eta\sqrt{Pr}+\sqrt{bt})+\exp(-2\eta\sqrt{bPrt})\operatorname{erfc}(\eta\sqrt{Pr}-\sqrt{bt})\right] \tag{30}$$

The equations (25), (26), (27), subject to the boundary conditions (28), are solved by the usual Laplace-transform technique and the solutions are derived as follows:

$$\begin{aligned} F(Z,t)=\; & g_1(\exp(2\eta\sqrt{(w+a)t})\operatorname{erfc}(\eta+\sqrt{(w+a)t})+\exp(-2\eta\sqrt{(w+a)t})\operatorname{erfc}(\eta-\sqrt{(w+a)t}))+ \\ & (A-B)(\frac{1}{2})(\exp(2\eta\sqrt{wt})\operatorname{erfc}(\eta+\sqrt{wt})+\exp(-2\eta\sqrt{wt})\operatorname{erfc}(\eta-\sqrt{wt}))- \\ & Be(\frac{t}{2})(\exp(2\eta\sqrt{wt})\operatorname{erfc}(\eta+\sqrt{wt})+\exp(-2\eta\sqrt{wt})\operatorname{erfc}(\eta-\sqrt{wt}))- \\ & Ag_2(\exp(2\eta\sqrt{(w+d)t})\operatorname{erfc}(\eta+\sqrt{(w+d)t})+\exp(-2\eta\sqrt{(w+d)t})\operatorname{erfc}(\eta-\sqrt{(w+d)t}))+ \\ & Bh(\exp(2\eta\sqrt{(w+e)t})\operatorname{erfc}(\eta+\sqrt{(w+e)t})+\exp(-2\eta\sqrt{(w+e)t})\operatorname{erfc}(\eta-\sqrt{(w+e)t}))+ \\ & Ag_2(\exp(2\eta\sqrt{Pr(b+d)t})\operatorname{erfc}(\eta\sqrt{Pr}+\sqrt{(b+d)t})+\exp(-2\eta\sqrt{Pr(b+d)t})\operatorname{erfc}(\eta\sqrt{Pr}-\sqrt{(b+d)t}))- \\ & \frac{A}{2}(\exp(2\eta\sqrt{Pr\,bt})\operatorname{erfc}(\eta\sqrt{Pr}+\sqrt{bt})+\exp(-2\eta\sqrt{Pr\,bt})\operatorname{erfc}(\eta\sqrt{Pr}-\sqrt{bt}))- \\ & Bh(\exp(2\eta\sqrt{(Sc)et})\operatorname{erfc}(\eta\sqrt{Sc}+\sqrt{et})+\exp(-2\eta\sqrt{(Sc)et})\operatorname{erfc}(\eta\sqrt{Sc}-\sqrt{et}))+ \\ & Bet((1+2\eta^2 Sc)\operatorname{erfc}(\eta\sqrt{Sc})-\frac{2\eta\sqrt{Sc}}{\sqrt{\pi}}\exp(-2\eta\sqrt{(Sc)et}))-\ B(\operatorname{erfc}(\eta\sqrt{Sc})) \end{aligned}$$

where $\eta=\dfrac{z}{2\sqrt{t}}$ $\quad A=\dfrac{Gr}{(1-Pr)d}$; $B=\dfrac{Gc}{(Sc-1)e^2}$; $b=\dfrac{R}{Pr}$; $d=\dfrac{bPr-w}{1-Pr}$; $e=\dfrac{w}{Sc-1}$; $g_1=\dfrac{\exp(at)}{2}$; $g_2=\dfrac{\exp(dt)}{2}$; $h=\dfrac{\exp(et)}{2}$

3. RESULTS AND DISCUSSION

The problem of an exponentially accelerated infinite vertical plate and temperature with variable mass diffusion has been formulated, analyzed and solved analytically. The effects of parameters on the velocity, temperature as well as on the concentration profiles are studied though graphs. The numerical values of the primary velocity, secondary velocity are computed and are shown graphically for different parameters like rotation parameter Ω, Hartmann number M, Hall parameter m, radiation parameter R, thermal Grashof number Gr , mass Grashof number Gc, Schmidt number Sc, accelerating parameter *a* and time t. The value of Sc

(Schmidt number) is taken to be 0.6 which corresponds to the water vapour. Also, the value of Pr (Prandtl number) are chosen such that they represent air (Pr=0.71) at 20^0 C at 1 atmosphere.

Figure 1 represents the effect of the concentration profiles for different values of Schmidt number. It is observed that at time t=0.2 decreases with increase in the values of Sc. Figure 2 shows the temperature profile for different values of thermal radiation parameter(R=0.2, 0.2, 2.0, 5.0) and time (t=0.2, 0.6, 0.2, 0.2).It is observed that the temperature increases with decreasing radiation parameter and the temperature increases with increase of time t.

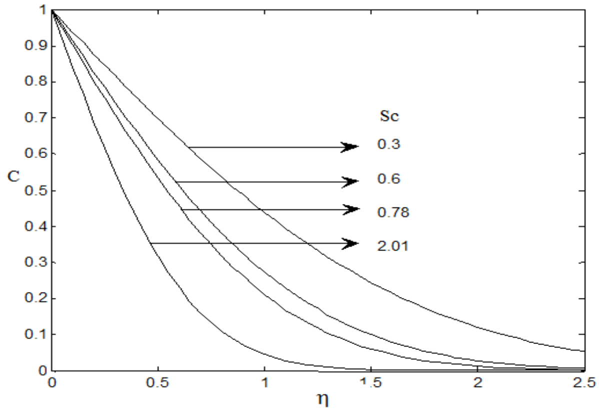

Figure1. Concentration profiles for different values of Sc

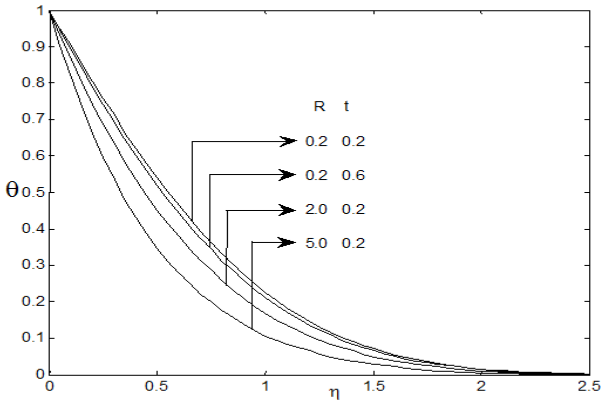

Figure 2. Temperature profiles for different values of R and t

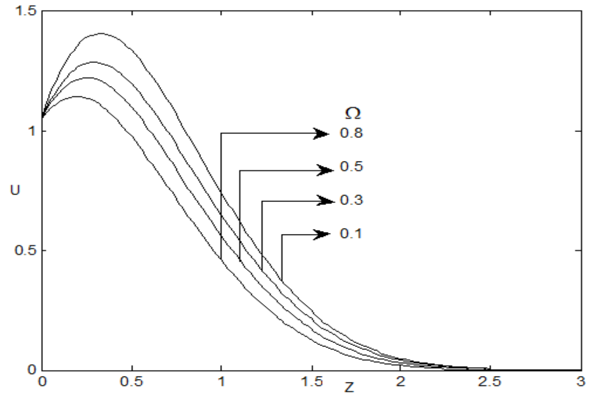

Figure 3. Primary velocity profiles for several values of Ω

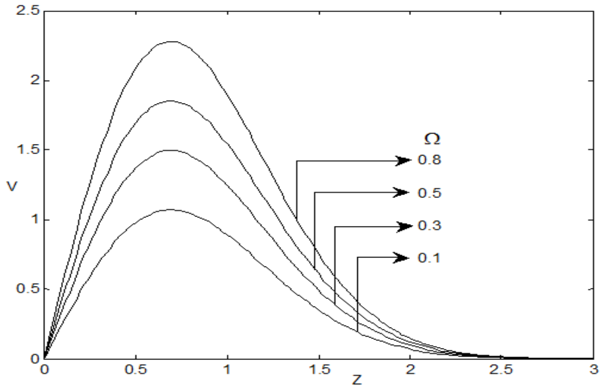

Figure 4. Secondary velocity profiles for several values of Ω

In figure 3 the primary velocity profile for different Ω when Sc=0.6, Pr=0.71, a=0.1, t=0.2,M=0.5, m=0.5, Gr=5, Gc=5, R=5 has been presented and it is observed that the primary velocity U falls when Ω are increased. In figure 4 the secondary velocity profile for different Ω when Sc=0.6, Pr=0.71, a=0.1, t=0.2,M=0.5, m=0.5, Gr=5, Gc=5, R=5 has been presented It is observed from figure 4 secondary velocity increases as Ω increases.

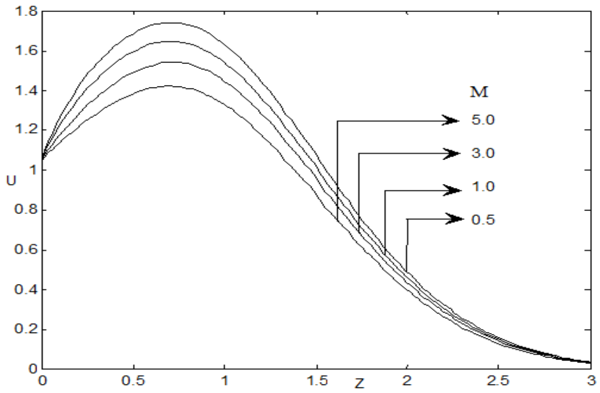

Figure 5: Primary velocity profiles for several values of M

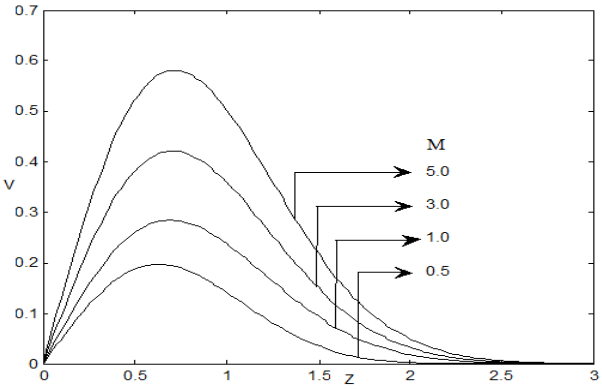

Figure 6: Secondary velocity profiles for several values of M

From figure 5 it is clear that the primary velocity increases with decreasing values of the Hartmann number (M). Figure 6 show that due to an increase in the Hartmann number M, the secondary velocity increases when Sc=0.6, Pr=0.71, a=0.1,t=0.2, Ω=0.1, m=0.5, Gr=5, Gc=5, R=5. Figure 7 and 8 represents the velocity profiles for various values of m when Sc=0.6, Pr=0.71, a=0.1, t=0.2, Ω=0.1, M=0.5, Gr=5, Gc=5, R=5. It is observed from figure 7 that the primary velocity rises due to increasing value of the Hall parameter m. It is found that from figure 8 due to an increase in the Hall parameter, m, there is rise in the secondary velocity components.

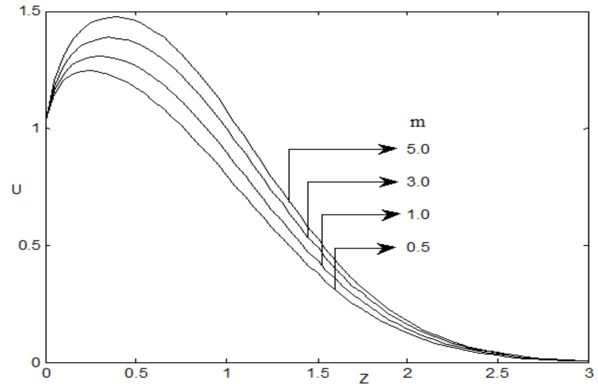

Figure 7. Primary velocity profiles for several values of m

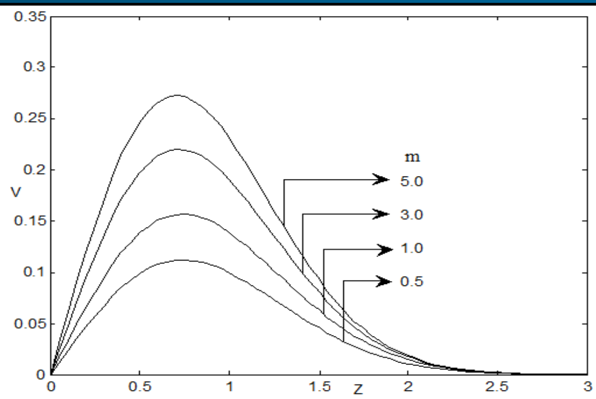

Figure 8. Secondary velocity profiles for several values of m

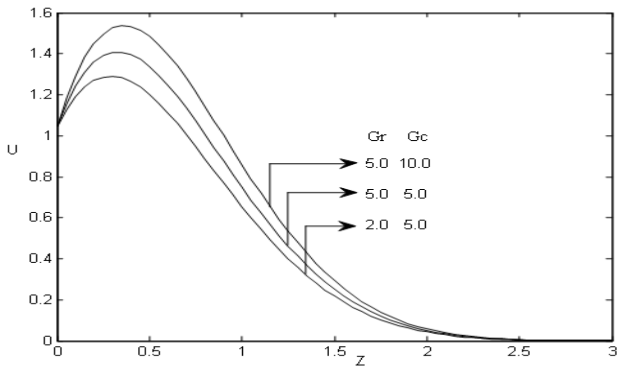

Figure 9. Primary velocity profiles for several values of Gr and Gc

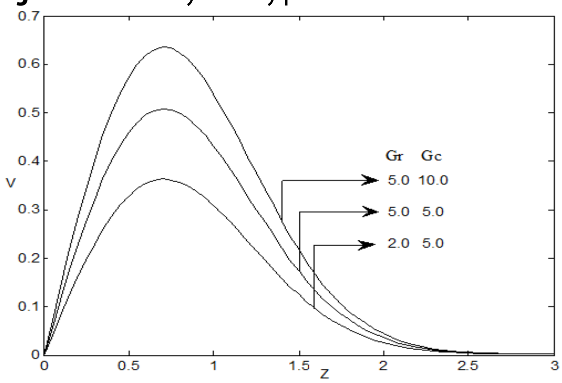

Figure10. Secondary velocity profiles for several values of Gr and Gc

In the figure 9 and 10 it is observed that the primary and secondary velocity increases with increasing values of the thermal Grashof number or mass Grashof number when Sc=0.6, Pr=0.71, a=0.1, t=0.2, Ω=0.1, M=0.5, m=0.5, R=5. From figure 11 it is clear that the primary velocity increases with decreasing values of radiation parameter. Figure12 show that due to an increase in the radiation parameter, the secondary velocity increases when Sc=0.6, a=0.1, t=0.2, Pr=0.71, Ω=0.1, M=0.5, m=0.5, Gr=5, Gc=5.

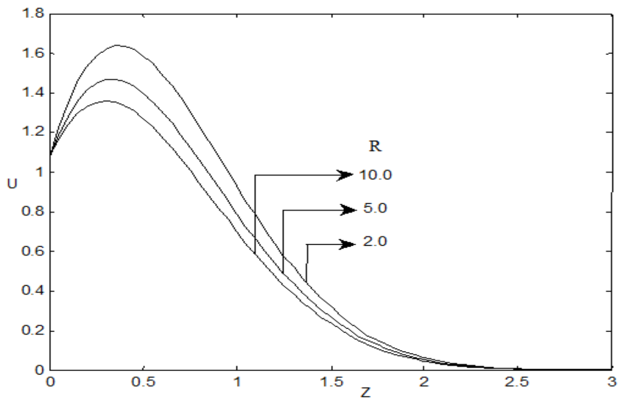

Figure 11. Primary velocity profiles for several values of R

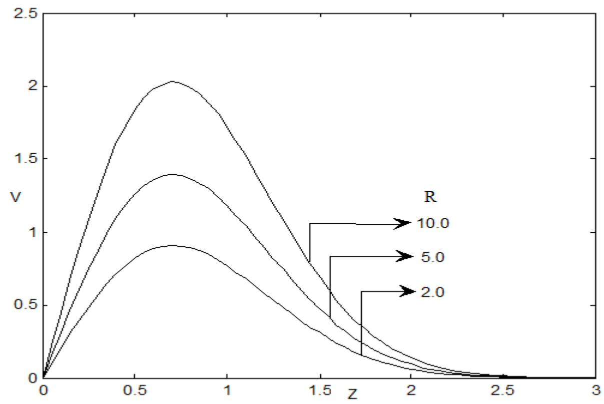

Figure12. Secondary velocity profiles for several values of R

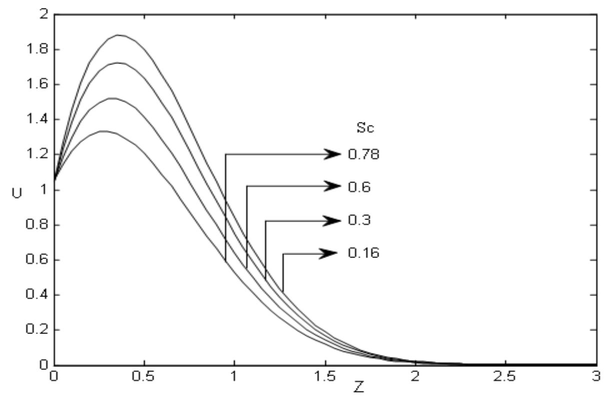

Figure 13. Primary velocity profiles for several values of Sc

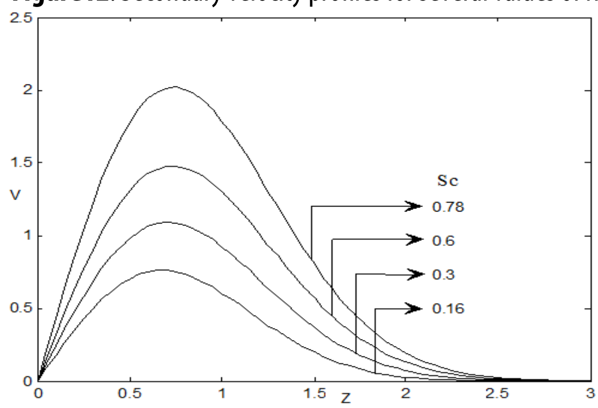

Figure14. Secondary velocity profiles for several values of Sc

In figure13 it is observed that the primary velocity increases with decreasing values of Schmidt number (Sc).In figure 14.it is observed that the secondary velocity increases with increasing values of Schmidt number Sc when Pr=0.71, a=0.1, R=5,t=0.2,Ω=0.1,M=0.5,m=0.5,Gr=5,Gc=5. The velocity profiles for different values of time t when Pr=0.71,R=5, a=0.1,Sc=0.6, Ω=0.1, M=0.5, m=0.5, Gr=5, Gc=5 are presented in figure 15, 16. It is observed that the primary velocity and secondary velocity increases with increasing values of t.

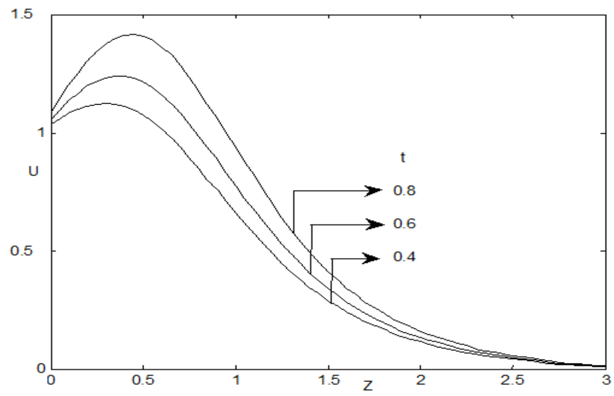

Figure15. Primary velocity profiles for several values of t

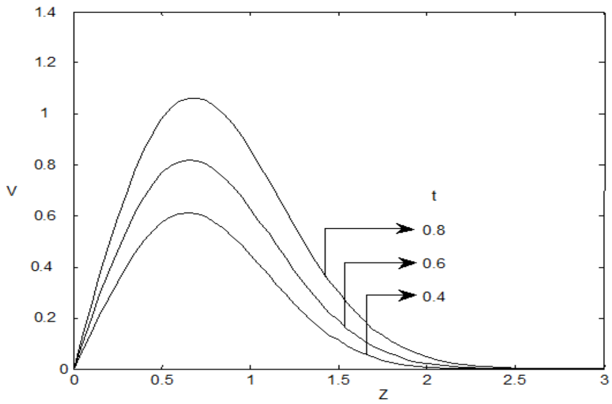

Figure16. Secondary velocity profiles for several values of t

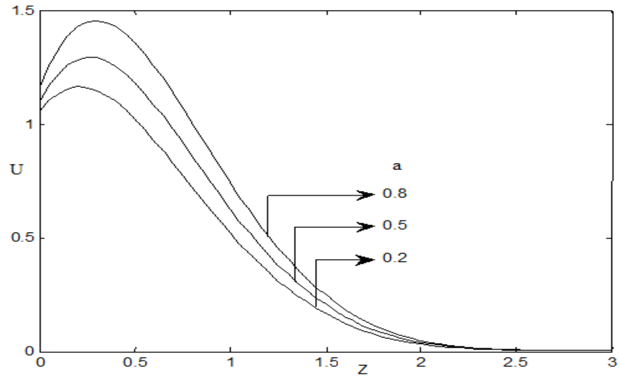

Figure17. Primary velocity profiles for several values of 'a'

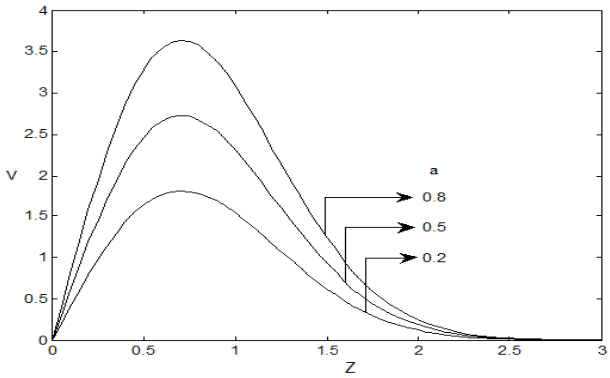

Figure18. Secondary velocity profiles for several values of 'a'

The velocity profiles for different 'a' when Pr=0.71, Sc=0.6, Ω=0.1, M=0.5, m=0.5, Gr=5,Gc=5, R=5, t=0.2 are studied and presented in figure 17, 18. It is evident from figures that the primary velocity and secondary velocity increases with increasing values of 'a'.

4. CONCLUSIONS

An analysis is performed to study the radiation effects on unsteady MHD flow past an exponentially accelerated infinite vertical plate in the presence of variable temperature and uniform mass diffusion. The effects of thermo physical parameters on velocity, temperature and concentration are analyzed and the following observations were noticed. The dimensionless governing equations are solved by the usual Laplace transform technique. The effects of different parameters such as rotation parameter Ω , Hartmann number M, Hall parameter m , radiation parameter R, thermal Grashof number Gr , mass Grashof number Gc, Schmidt number Sc, accelerating parameter *a* and time *t* have been investigated. In the analysis of the flow the following conclusions are made. The concentration increases with decreasing values of the Schmidt number.The temperature increases with decreasing radiation parameter. The axial velocity rises due to increasing value of the Hall parameter, accelerating parameter, thermal Grashof number and mass Grashof number and time. The axial velocity u falls when Ω are increased, the velocity increases with decreasing values of the Hartmann number, the radiation parameter. Transverse velocity increases as Ω increases, due to an increase in the Hartmann number M, the Hall parameter, m, accelerating parameter, the radiation parameter R, Gr, Gc, Sc and t.

NOMENCLATURE

B_0 - external magnetic field(T)

t - dimensionless time

t' - dimensional time, s

T - dimensionless temperature, K

T' -dimensional temperature of the fluid

C - dimensionless fluid concentration

C' -dimensional concentration in the fluid, kg m^{-3}

$\vec{B}$ - the magnetic field vector

$\vec{E}$ - the electric field vector

$\vec{q}$ - the velocity vector

ω_e - the cyclotron frequency

M - Hartmann number

m - Hall parameter

R - Radiation parameter

a - dimensionless accelerating parameter
a' - dimensional acceleration parameter
a^* - absorption coefficient
u - velocity of the fluid in the x - direction, m s^{-1}
v - velocity of the fluid in the z - direction
z - dimensionless co-ordinate normal to the plate.
U - dimensionless axial component of the velocity of the fluid
V - dimensionless transverse component of the velocity of the fluid
Z - dimensionless coordinate axis normal to the plate
u_0 - velocity of the plate, m s^{-1}
Ω - dimensionless angular velocity
Ω' - component of angular velocity(rad/s)
p - pressure
g - acceleration due to gravity
$\vec{j}$ - the current density vector
j_x , j_y - the components of the current density $\vec{j}$
C_p - the specific heat at constant pressure, J kg^{-1} k
q_r - the radiative heat flux in the z – direction
D - mass diffusion coefficient, m^2 s^{-1}
k - thermal conductivity, W m^{-1} k^{-1}
$\Pr$ - Prandtl number
Sc - Schmidt number
Gr - Thermal Grashof number
Gc - Mass Grashof number

Subscripts

w -conditions at the wall
∞ -free stream conditions

Greek symbols

ρ - Fluid density, kg m^{-3}
ϑ - Kinematic Viscosity, m^2 s^{-1}
τ_e - the collision time of electron
θ - Dimensionless temperature
η - Similarity parameter
σ - Electric conductivity Electric conductivity
β - Volumetric coefficient of thermal expansion, K^{-1}
β' - Volumetric coefficient of expansion with concentration, K^{-1}
γ - $\dfrac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}$
erfc - Complementary error function

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