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EFFECTS OF ROTATION AND MAGNETIC FIELD ON THE FLOW PAST AN EXPONENTIALLY ACCELERATED VERTICAL PLATE WITH CONSTANT TEMPERATURE

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ABSTRACT

In the present paper, we study the effects of rotation on unsteady flow of a viscous, incompressible and electrically conducting fluid past an exponentially accelerated vertical plate with constant temperature in the presence of a uniform transverse magnetic field. Let the fluid motion is induced due to the movement of the plate. The problem is solved analytically in closed forms by Laplace transform technique and the expressions for velocity, temperature and skin-friction have been obtained. The numerical results for velocity and temperature are presented graphically for different values of the parameters like magnetic parameter, thermal Grashof number, Prandtl number, rotation parameter, accelerating parameter and time. The numerical values of the skin-friction have been tabulated.

Keywords: *MHD, Rotation effects, Heat transfer, Accelerated vertical plate.*

Mathematics Subject Classification: *76W05, 78A40, 80A20.*

INTRODUCTION:

The study of flow for an electrically conducting fluid has many applications in engineering problems such as magmetohydrodynamics generators, plasma studies, nuclear reactors, geothermal energy extraction, and the boundary layer control in the field of aerodynamics. On the other hand, the rotating flow of an electrically conducting fluid in the presence of a magnetic field is encountered in Geographical fluid dynamics. It is also important in the solar physics dealing with the sunspot development, the solar cycle and the structure of rotating magnetic stars. It is well known that a number of astronomical bodies possess fluid interiors and magnetic fields. Debnath (1975) examined exact solutions of the unsteady hydrodynamic and hydro magnetic boundary layer equations in a rotating fluid system. Mass transfer effects on the flow past an exponentially accelerated vertical plate with constant heat flux was studied by Jha et al. (1991). Singh (2000) has studied an oscillatory hydromagnetic Couette flow in a rotating system. Takhar et al. (2002) have presented the effects of magnetic field, Hall currents and free stream velocity on MHD flow over a moving plate in a rotating fluid. Muthucumaraswamy et al. (2008) studied the effects of Mass transfer on exponentially accelerated isothermal vertical plate. Prasad and Reddy (2008) have studied radiation effects on an unsteady MHD convective heat and mass transfer flow past a semi infinite vertical permeable moving plate embedded in a porous medium. Singh and Rakesh (2009) have studied an oscillatory free convective MHD flow of a viscous, incompressible and electrically conducting fluid in a vertical porous channel in the presence of Hall current.

Chauhan and Rastogi (2010) investigated the unsteady natural convection MHD flow of a rotating viscous electrically conducting fluid in a vertical channel partially filled by a porous medium with high porosity in the presence of radiation effects. Das and Jana (2010) presented the effect of heat and mass transfer on free convection flow near an infinite plate embedded in porous medium. Rajesh (2010) has presented the effect of a uniform transverse magnetic field on the free convection and mass transfer flow of an electrically conducting fluid past an exponentially accelerated infinite vertical plate through porous medium with variable temperature. Seth et al. (2010) considered unsteady hydromagnetic convective flow of a viscous incompressible electrically conducting heat generating/absorbing fluid within a parallel plate rotating channel in a uniform porous medium under slip boundary conditions. Muthucumarswamy et al. (2010) investigated rotation effects on unsteady flow of an incompressible and electrically conducting fluid past a uniformly accelerated infinite isothermal vertical plate, under the action of transversely applied magnetic field. Ahmed and Sarmah (2011) have presented exact solution of transient three dimensional MHD flow of an electrically conducting, viscous, incompressible fluid past an impulsively started infinite horizontal porous plate relative to a rotating system taking into account the effect of Hall current. Rajput and Surendra (2011) have studied rotation and radiation effects on

MHD flow of a viscous, incompressible and electrically conducting fluid past an impulsively started vertical plate with variable temperature. We have already studied two MHD models, namely (i) the effect of a uniform transverse magnetic field on unsteady transient free convection flow of an incompressible viscous electrically conducting fluid between two infinite vertical parallel plates with constant temperature and Variable mass diffusion (2011) and (ii) the influence of first order homogeneous chemical reactions on unsteady transient free convection flow of a viscous, incompressible, electrically conducting fluid between two long vertical parallel plates through a porous medium with heat generation/absorption in the presence of transverse magnetic field (2011). Muthucumarswamy et al. (2011) have studied rotation effects on unsteady flow of a viscous, incompressible and electrically conducting fluid past a uniformly accelerated infinite vertical plate in the presence of transversely applied magnetic field with variable temperature and uniform mass diffusion. Kumar and Verma (2011) investigated the effects of radiation on unsteady MHD flow of an electrically conducting radiating, viscous, incompressible fluid past an impulsively started moving exponentially accelerated vertical plate with variable temperature in the presence of heat generation and applied transverse magnetic field.

The aim of the present investigation is to analyze the effects of rotation and magnetic field on unsteady flow of a viscous, electrically conducting incompressible fluid past an exponentially accelerated vertical plate with constant temperature.

FORMULATION OF THE PROBLEM:

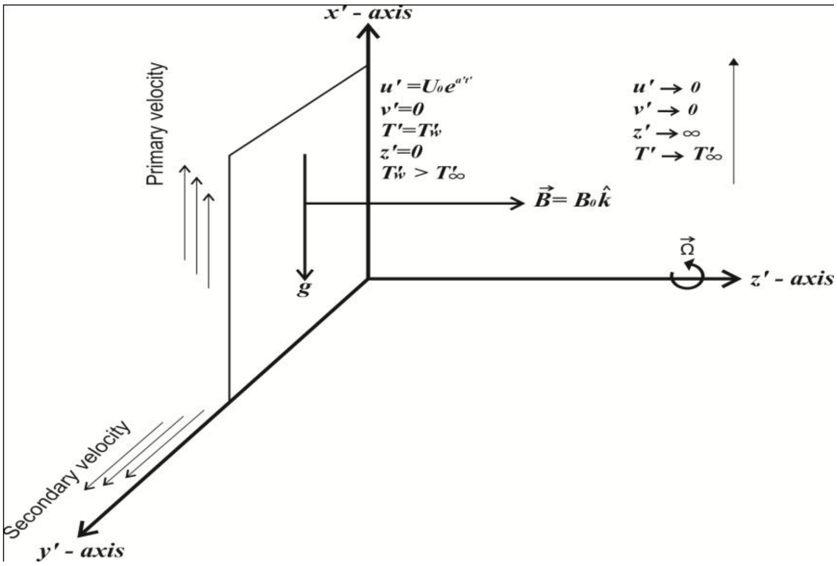

Figure 1: Physical Model of the problem

In this problem we consider the unsteady flow of a viscous, incompressible and electrically conducting fluid past an exponentially accelerated infinite vertical plate occupying the plane $z' = 0$ with constant temperature in the presence of a uniform transverse magnetic field B_0 applied parallel to z' - axis which is normal to the plane of the plate. Let the fluid and the plate rotate as a rigid body with a uniform angular velocity Ω' about the z' - axis perpendicular to the plane of the flow (x'-y' plane). Initially, at time $t' \le 0$, the fluid and the plate are assumed to be at rest and at same temperature T'_∞. When time $t' > 0$, the plate is exponentially accelerated with a velocity $u' = U_0 \exp(a't')$ in its own plane and at the same time the plate temperature is raised to T'_w. Since the plate occupying the plane $z' = 0$ is of infinite extent, therefore, all physical quantities are independent of x' and y'. Thus, $\vec{q} = (u', v', 0), \vec{B} = (0, 0, B_0)$ and $\vec{\Omega} = (0, 0, \Omega')$.

The flow model of an incompressible, viscous and electrically conducting fluid in a rotating system in the presence of a magnetic field is governed by the following equations.

Equation of continuity:

$$\nabla.\vec{q} = 0, \tag{1}$$

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Equation of motion:

$$\frac{\partial \vec{q}}{\partial t'}+(\vec{q}.\nabla)\vec{q}+2\vec{\Omega}\times\vec{q}=-\frac{1}{\rho}\nabla p'+\nu\nabla^2\vec{q}+\frac{1}{\rho}(\vec{J}\times\vec{B})+g\beta(T'-T'_\infty)\hat{i}, \tag{2}$$

Ohm's law for a moving conductor:

$$\vec{J}=\sigma(\vec{E}+\vec{q}\times\vec{B}), \tag{3}$$

Maxwell's equations:

$$\left.\begin{aligned}\nabla\times\vec{E}&=-\frac{\partial\vec{B}}{\partial t'},\\ \nabla\times\vec{B}&=\mu_e\vec{J},\\ \nabla.\vec{B}&=0,\\ \nabla.\vec{J}&=0,\end{aligned}\right\} \tag{4}$$

Energy equation:

$$\frac{\partial T'}{\partial t'}+(\vec{q}.\nabla)T'=\frac{k}{\rho C_p}\nabla^2T'. \tag{5}$$

Here $\vec{q}$ is the fluid velocity, $\vec{B}$ - magnetic field, $\vec{J}$ - current density, $\vec{E}$ - electric field, $\vec{\Omega}$ - angular velocity, $\hat{i}$ - unit vector along x' - axis, $\hat{k}$ - unit vector along z' - axis, ρ - fluid density, σ - electrical conductivity, g - acceleration due to gravity, k - thermal conductivity of the fluid, β - volumetric co-efficient of thermal expansion, t' - time, T' - temperature of the fluid, T'_∞ - temperature of the mainstream fluid, p' - pressure, ν - kinematic viscosity and C_p - Specific heat at constant pressure.

It is assumed that the magnetic Reynolds number is so small that the induced magnetic field can be neglected in comparison to the transverse magnetic field. Also, no external electric field is applied; therefore, the effect of polarization of fluid is neglected. Further, it is assumed that the plate is electrically non-conducting. Therefore, we take:

$\vec{J}=(J_x, J_y, 0)$ and $\vec{E}=(0,0,0)$.

Under above assumptions, equation of motion and energy equation reduce to:

$$\frac{\partial u'}{\partial t'}-2\Omega'v'=\nu\frac{\partial^2u'}{\partial z'^2}+g\beta(T'-T'_\infty)-\frac{\sigma B_0^2}{\rho}u', \tag{6}$$

$$\frac{\partial v'}{\partial t'}+2\Omega'u'=\nu\frac{\partial^2v'}{\partial z'^2}-\frac{\sigma B_0^2}{\rho}v, \tag{7}$$

with $\frac{\partial p'}{\partial z'}=0,$

$$\rho C_p\frac{\partial T'}{\partial t'}=k\frac{\partial^2T'}{\partial z'^2}. \tag{8}$$

The term $\frac{\partial p'}{\partial z'}=0$ shows that pressure p' is constant along the axis of rotation. The absence of pressure gradient term $\frac{\partial p'}{\partial y'}=P_1(y')$ in Eq^n (7) implies that there is a net cross flow in y' – direction (Prasad Rao et al, 1982). Since the fluid motion is induced due to the movement of the plate in x' – direction, so the pressure gradient term is not taken in account in Eq^n (6).

The initial and boundary conditions are:

$$\left.\begin{array}{lll} t' \le 0: \; u'(z',0)=0,\; v'(z',0)=0, & T'(z',0)=T'_\infty & \text{for all } z', \\ t'>0: \; u'(0,t')=U_0 e^{a't'},\; v'(0,t')=0, & T'(0,t')=T'_w & \text{at } z'=0, \\ \quad u'(\infty,t')\to 0,\; v'(\infty,t')\to 0, & T'(\infty,t')\to T'_\infty & \text{as } z'\to\infty\,. \end{array}\right\} \tag{9}$$

We introduce the following non-dimensional variables and parameters:

$$\left.\begin{array}{l} u=\dfrac{u'}{U_0}, v=\dfrac{v'}{U_0}, t=\dfrac{t'U_0^2}{\nu}, z=\dfrac{z'U_0}{\nu}, Gr=\dfrac{g\beta\nu(T'_w-T'_\infty)}{U_0^3}, \\ \Pr=\dfrac{\mu C_p}{k}, \Omega=\dfrac{\Omega'\nu}{U_0^2}, \theta=\dfrac{(T'-T'_\infty)}{(T'_w-T'_\infty)}, M=\dfrac{\sigma B_0^2\nu}{\rho U_0^2}, a=\dfrac{\nu a'}{U_0^2}, \end{array}\right\} \tag{10}$$

where x' is the co-ordinate axis vertically in the direction of the plate velocity, z' - co-ordinate axis normal to the plane of plate, y' - co-ordinate axis perpendicular to both x' - axis and z' - axis, u' - velocity of fluid in the x' - direction, v' - velocity of fluid in the y' - direction, u - Dimensionless velocity along x - axis, v - dimensionless velocity along y - axis, t - dimensionless time, U_0 - velocity of the plate, Ω - dimensionless rotation parameter, θ - dimensionless temperature, T'_w - the temperature of the plate, Ω' - rotation parameter, B_0 - External magnetic field along z' - axis, $\Pr$ - Prandtl number, Gr - thermal Grashof number, M - magnetic field parameter, a - Accelerating parameter, μ - co-efficient of viscosity, z is the dimensionless co-ordinate axis normal to the plate.

The equations (6), (7) and (8) are reduced to the following non-dimensional form of equations:

$$\frac{\partial u}{\partial t}-2\Omega v=Gr\theta+\frac{\partial^2 u}{\partial z^2}-Mu, \tag{11}$$

$$\frac{\partial v}{\partial t}+2\Omega u=\frac{\partial^2 v}{\partial z^2}-Mv, \tag{12}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial z^2}. \tag{13}$$

The initial and boundary conditions become:

$$\left.\begin{array}{lll} t\le 0: \; u(z,0)=0,\; v(z,0)=0, & \theta(z,0)=0 & for\ all\ z, \\ t>0: \; u(0,t)=e^{at},\; v(0,t)=0, & \theta(0,t)=1 & at\ z=0, \\ \quad u(\infty,t)\to 0,\; v(\infty,t)\to 0, & \theta(\infty,t)\to 0 & as\ z\to\infty. \end{array}\right\} \tag{14}$$

Let $q=u+iv$, then equations (11) and (12) become:

$$\frac{\partial q}{\partial t}=Gr\theta+\frac{\partial^2 q}{\partial z^2}-mq, \qquad \text{where } m=M+2i\Omega\,. \tag{15}$$

The initial and boundary conditions become:

$$\left.\begin{array}{lll} t\le 0: \; q(z,0)=0, & \theta(z,0)=0 & \text{for all } z, \\ t>0: \; q(0,t)=e^{at}, & \theta(0,t)=1 & \text{at } \; z=0, \\ \quad q(\infty,t)\to 0, & \theta(\infty,t)\to 0 & \text{as } \; z\to\infty. \end{array}\right\} \tag{16}$$

Applying the Laplace transform in equations (13) and (15), we have:

$$\frac{d^2\bar{q}}{dz^2}-(s+m)\bar{q}=-Gr\bar{\theta}, \tag{17}$$

$$\frac{d^2\bar{\theta}}{dz^2}-s\Pr\bar{\theta}=0, \tag{18}$$

with, the boundary conditions:

$$\left.\begin{aligned} t>0:\ \ \bar{q}&=\frac{1}{s-a}, & \bar{\theta}&=\frac{1}{s} & &\text{at } z=0,\\ \bar{q}&=0, & \bar{\theta}&=0 & &\text{as } z\to\infty. \end{aligned}\right\} \tag{19}$$

where $\bar{q}(z,s)=\int_0^\infty e^{-st}q(z,t)dt;(s>0)$, s being Laplace transform parameter.

Using Laplace transform technique with the help of (Hetnarski, 1975), the solutions of equations (17) and (18) are as follow:

$$\bar{q}(z,t)=\frac{e^{-z\sqrt{s+m}}}{s-a}+\frac{Gr\ e^{-z\sqrt{s+m}}}{m(s-Q)}-\frac{Gr\ e^{-z\sqrt{s+m}}}{ms}-\frac{Gr\ e^{-z\sqrt{s\Pr}}}{m(s-Q)}+\frac{Gr\ e^{-z\sqrt{s\Pr}}}{ms}, \tag{20}$$

$$\bar{\theta}(z,t)=\frac{e^{-z\sqrt{s\Pr}}}{s}. \tag{21}$$

Taking the inverse Laplace Transform of equations (20) and (21), we have:

$$\begin{aligned} q(z,t)=&\frac{e^{at}}{2}\left[e^{-z\sqrt{m+a}}erfc\left(\frac{z}{2\sqrt{t}}-\sqrt{(m+a)t}\right)+e^{z\sqrt{m+a}}erfc\left(\frac{z}{2\sqrt{t}}+\sqrt{(m+a)t}\right)\right]\\ &+\frac{Gre^{Qt}}{2m}\left[e^{-z\sqrt{m+Q}}erfc\left(\frac{z}{2\sqrt{t}}-\sqrt{(m+Q)t}\right)+e^{z\sqrt{m+Q}}erfc\left(\frac{z}{2\sqrt{t}}+\sqrt{(m+Q)t}\right)\right]\\ &-\frac{Gr}{2m}\left[e^{-z\sqrt{m}}erfc\left(\frac{z}{2\sqrt{t}}-\sqrt{mt}\right)+e^{z\sqrt{m}}erfc\left(\frac{z}{2\sqrt{t}}+\sqrt{mt}\right)\right]\\ &-\frac{Gre^{Qt}}{2m}\left[e^{-z\sqrt{\Pr Q}}erfc\left(\frac{z\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{Qt}\right)+e^{z\sqrt{\Pr Q}}erfc\left(\frac{z\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{Qt}\right)\right]\\ &+\frac{Gr}{m}\left[erfc\left(\frac{z\sqrt{\Pr}}{2\sqrt{t}}\right)\right], \end{aligned} \tag{22}$$

$$\theta(z,t)=erfc\left(\frac{z\sqrt{\Pr}}{2\sqrt{t}}\right). \tag{23}$$

Velocity fields:

The primary and the secondary velocity fields are given by:

u = Real part of $q(z,t)$, (24)

v = Imaginary part of $q(z,t)$. (25)

Skin-friction:

The skin-friction at the plate in complex form is given by:

$$\tau = -\left(\frac{dq}{dz}\right)_{z=0} = \frac{Gr\sqrt{\Pr}}{m\sqrt{\pi t}} + \frac{Gr e^{Qt}}{2m}\left[\sqrt{\Pr Q}\left\{erfc\left(\sqrt{Qt}\right) - erfc\left(-\sqrt{Qt}\right)\right\} - \frac{2e^{-Qt}\sqrt{\Pr}}{\sqrt{\pi t}}\right]$$
$$+\frac{Gr}{2m}\left[\sqrt{m}\left\{erfc\left(\sqrt{mt}\right) - erfc\left(-\sqrt{mt}\right)\right\} - \frac{2e^{-mt}}{\sqrt{\pi t}}\right]$$
$$-\frac{e^{at}}{2}\left[\sqrt{(m+a)}\left\{erfc\left(\sqrt{(m+a)t}\right) - erfc\left(-\sqrt{(m+a)t}\right)\right\} - \frac{2e^{-(m+a)t}}{\sqrt{\pi t}}\right]$$
$$-\frac{Gre^{Qt}}{2m}\left[\sqrt{(m+Q)}\left\{erfc\left(\sqrt{(m+Q)t}\right) - erfc\left(-\sqrt{(m+Q)t}\right)\right\} - \frac{2e^{-(m+Q)t}}{\sqrt{\pi t}}\right]. \quad (26)$$

The skin-friction at the plate in the direction of the primary velocity is given by:

$$\tau_x = \text{Real part of } \tau = -\left(\frac{du}{dz}\right)_{z=0}. \quad (27)$$

The skin-friction at the plate in the direction of the secondary velocity is given by:

$$\tau_y = \text{Imaginary part of } \tau = -\left(\frac{dv}{dz}\right)_{z=0}. \quad (28)$$

RESULT AND DISCUSSION:

The numerical values of the primary velocity, secondary velocity, temperature and skin-friction are computed for different parameters like magnetic parameter M, thermal Grashof number Gr, Prandtl number $\Pr$, rotation parameter Ω, accelerating parameter a and time t. The values of the main parameters considered are: magnetic parameter M = 2.0, 4.0, 6.0; thermal Grashof number Gr = 5.0, 7.0, 10.0; Prandtl number $\Pr$ = 0.71 (for air), 3 (for the saturated liquid Freon at 372.3K), 7 (for water); rotation parameter Ω = 0.4, 2.0, 3.0; accelerating parameter a = 0.3, 0.5, 0.9, and time t = 0.2, 0.4, and 0.6.

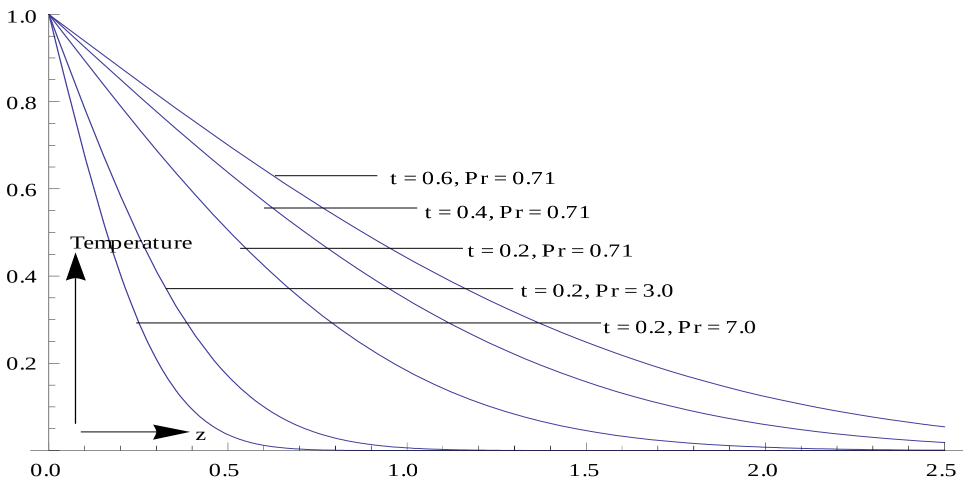

Figure 2: Temperature profiles

Figure 2 represents the temperature profile for different values of Prandtl number $\Pr$ and time t. The effect of the Prandtl number plays an important role in temperature field. It is observed that the slope of the curves shifts towards the origin as Prandtl number increases. This shows that the heat transfer is more in air than in water and liquid Freon. On the other hand, the temperature increases with increase of time t.

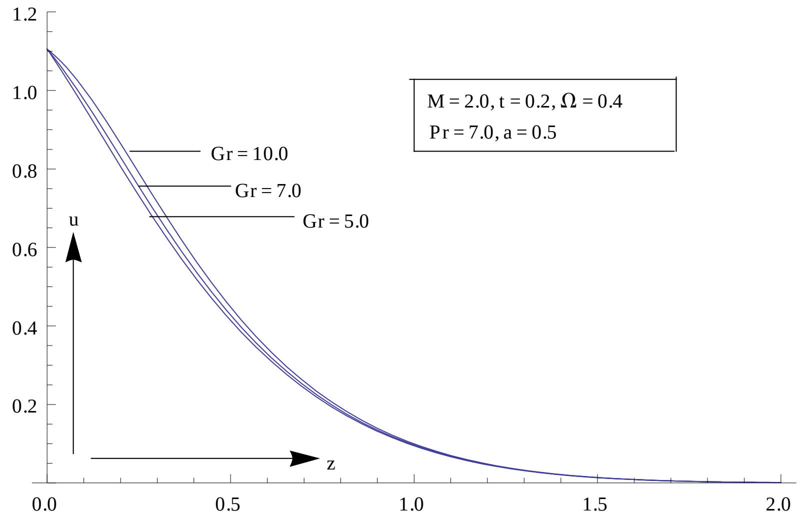

Figure 3: Primary velocity profiles

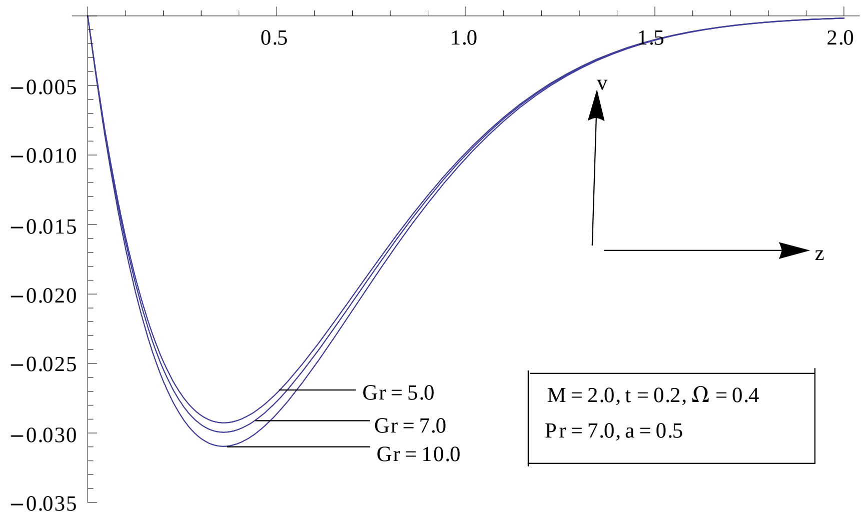

Figure 4: Secondary velocity profiles

Figures 3 and 4 represent primary and secondary velocity profiles due to variations in thermal Grashof number Gr. From these figures it is clear that the primary velocity increases with increasing values of the thermal Grashof number but secondary velocity decreases (taking other parameters $M = 2.0, t = 0.2, \Omega = 0.4, \Pr = 7.0, a = 0.5$ constant).

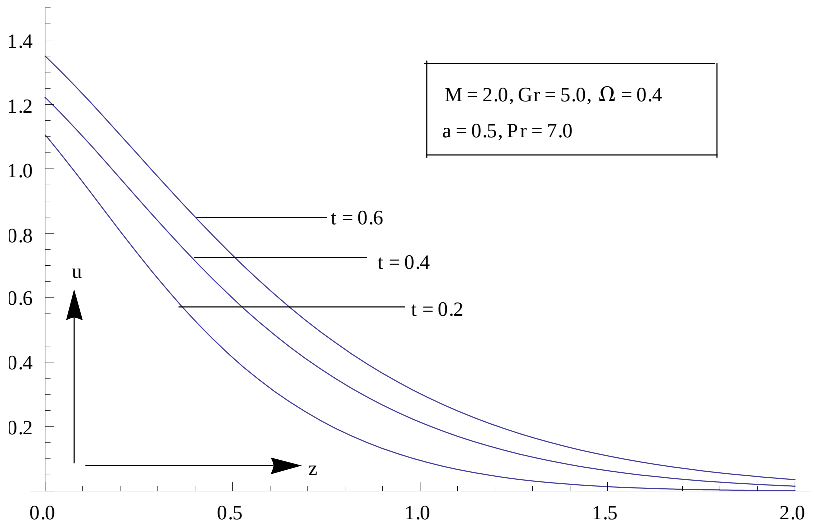

Figure 5: Primary velocity profiles

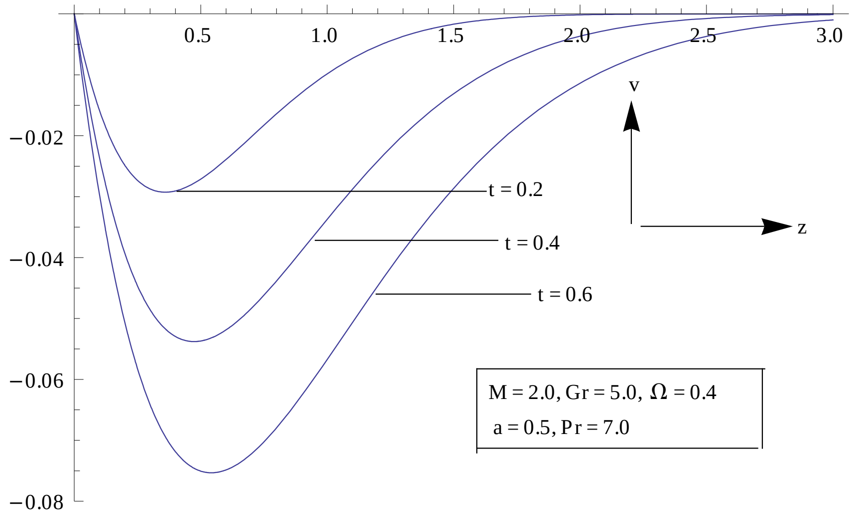

Figure 6: Secondary velocity profiles

Figures 5 and 6 represent primary and secondary velocity profiles due to variations in time t. From these figures, it is clear that the primary velocity increases with increasing values of the time but secondary velocity decreases (taking other parameters $M = 2.0, Gr = 5.0,\ \Omega = 0.4, \Pr = 7.0, a = 0.5$ constant).

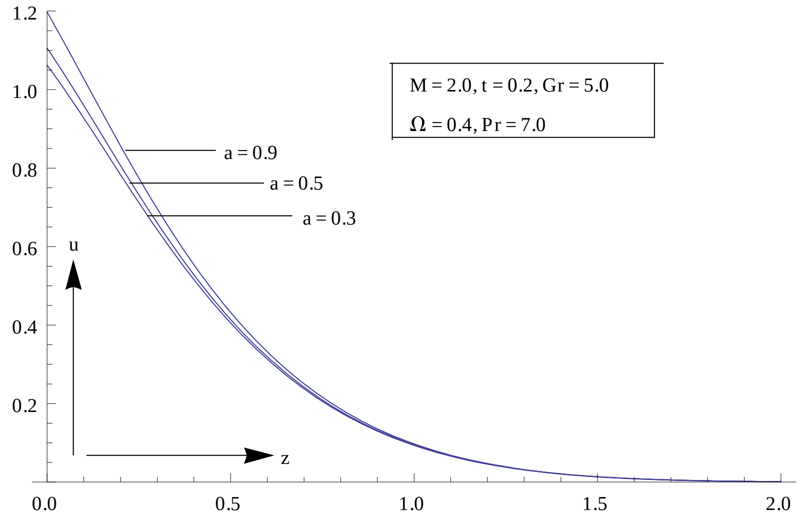

Figure 7: Primary velocity profiles

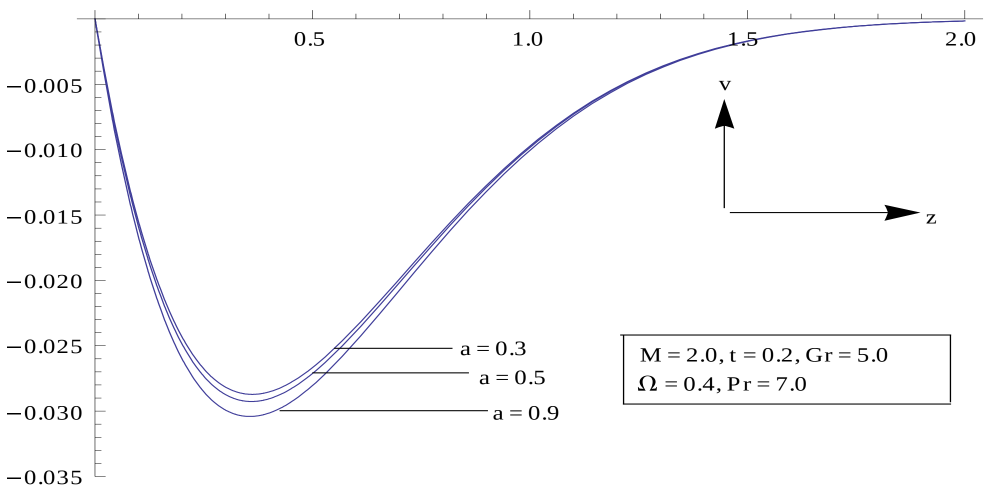

Figure 8: Secondary velocity profiles

Figure 7 and 8 display the effects of accelerating parameter a on primary and secondary velocity profiles. From these figures it is observed that the primary velocity increases with increasing values of accelerating parameter but secondary velocity decreases (taking other parameters $M = 2.0, Gr = 5.0,\ \Omega = 0.4, \Pr = 7.0, t = 0.2$ fixed). Further, as we move far away from the moving plate the effect of accelerating parameter is almost negligible in both cases.

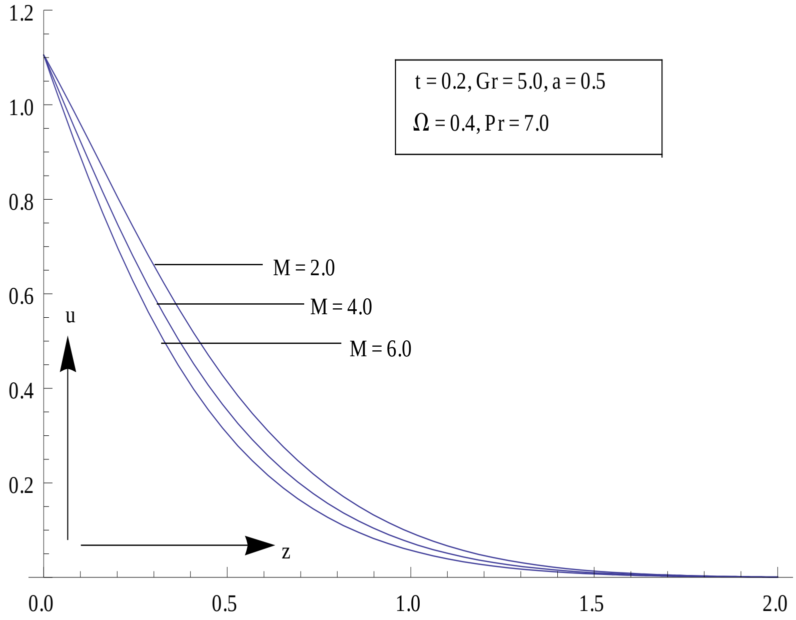

Figure 9: Primary velocity profiles

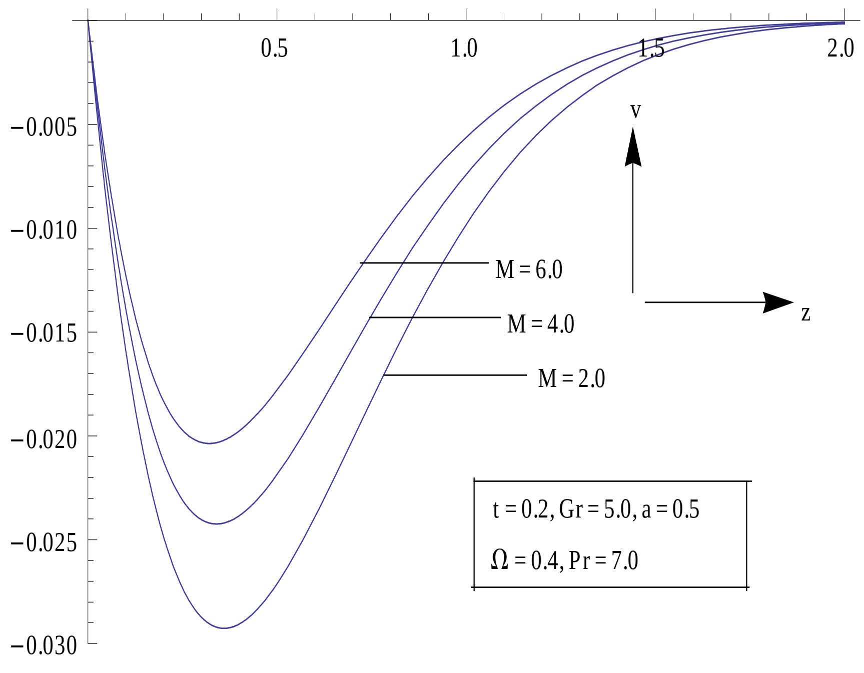

Figure 10: Secondary velocity profiles

Figures 9 and 10 represent primary and secondary velocity profiles due to variations in magnetic parameter M . From these figures it is observed that the primary velocity decreases with increasing values of the magnetic parameter but secondary velocity increases (taking other parameters $Gr = 5.0, t = 0.2, \Omega = 0.4,\ \Pr = 7.0, a = 0.5$ constant).

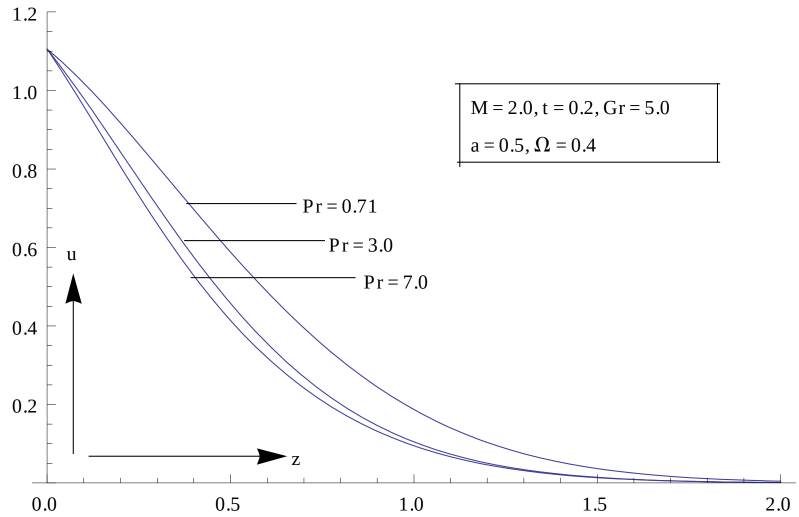

Figure 11: Primary velocity profiles

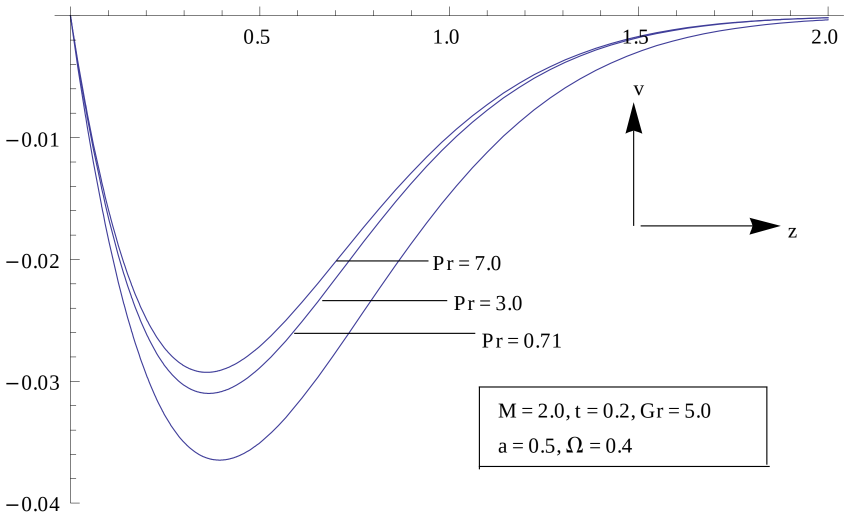

Figure 12: Secondary velocity profiles

Figures 11 and 12 represent the effects of Prandtl number Pr on primary and secondary velocity profiles. From these figures it is observed that the primary velocity decreases with increasing values of the Prandtl number but secondary velocity increases (keeping other parameters $Gr = 5.0, t = 0.2, \Omega = 0.4,\ M = 2.0, a = 0.5$ constant).

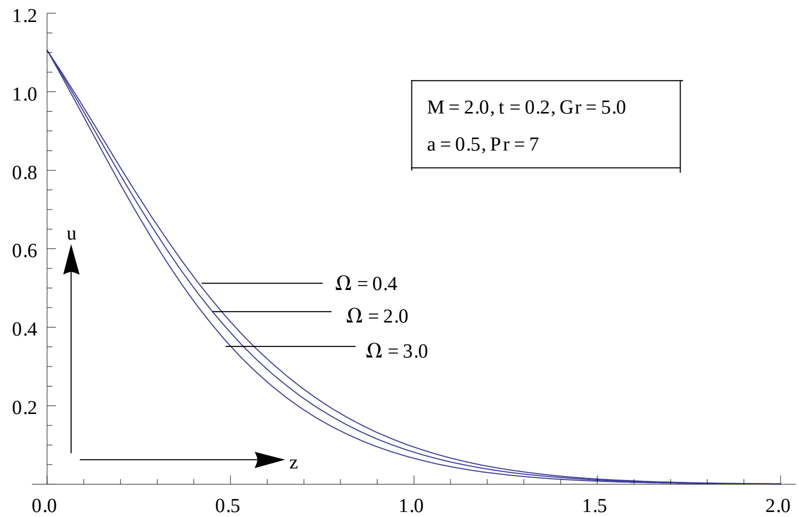

Figure 13: Primary velocity profiles

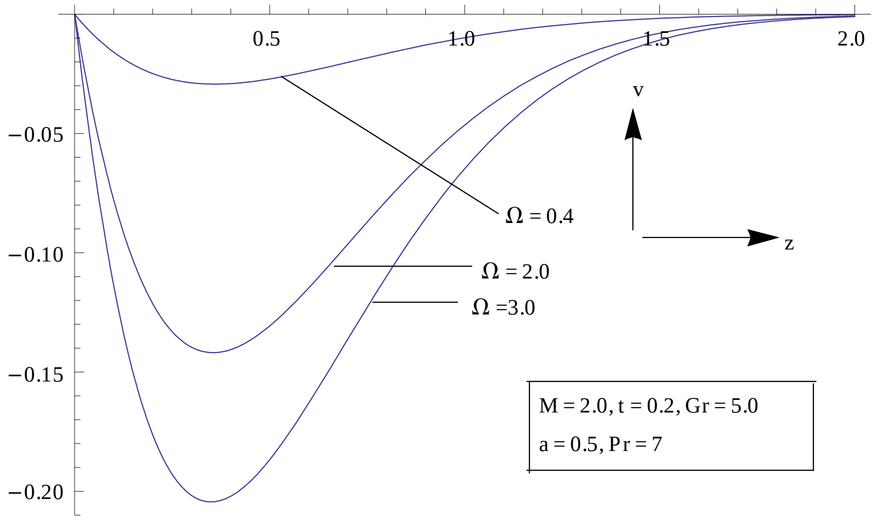

Figure 14: Secondary velocity profiles

Figures 13 and 14 represent the effects of rotation parameter Ω on primary and secondary velocity profiles. From these figures it is observed that the primary and secondary velocity decrease with increasing values of the rotation parameter (taking other parameters $Gr = 5.0, t = 0.2, M = 2.0, \Pr = 7.0, a = 0.5$ constant).

.**Table 1:** Skin-friction for different parameters

M	a	Ω	$\Pr$	t	Gr	τ_x	τ_y
2.0	0.5	0.4	7.0	0.2	5.0	1.37502	0.199713
2.0	0.5	0.4	7.0	0.2	7.0	1.10780	0.203303
2.0	0.5	0.4	7.0	0.2	10.0	0.70698	0.208687
2.0	0.5	0.4	7.0	0.4	5.0	1.12476	0.282442
2.0	0.5	0.4	7.0	0.6	5.0	1.10708	0.349112
2.0	0.3	0.4	7.0	0.2	5.0	1.24889	0.194390
2.0	0.9	0.4	7.0	0.2	5.0	1.64716	0.210898
2.0	0.5	2.0	7.0	0.2	5.0	1.48436	0.982172
2.0	0.5	3.0	7.0	0.2	5.0	1.62044	1.442400
2.0	0.5	0.4	3.0	0.2	5.0	1.16207	0.206487
2.0	0.5	0.4	0.71	0.2	5.0	0.76617	0.224400
4.0	0.5	0.4	7.0	0.2	5.0	1.84668	0.178860
6.0	0.5	0.4	7.0	0.2	5.0	2.27156	0.162002

The values of skin-friction are tabulated in table 1 for different parameters like magnetic parameter M, thermal Grashof number Gr, Prandtl number $\Pr$, rotation parameter Ω, accelerating parameter a and time t. Skin-friction τ_x decreases when the values of thermal Grashof number and time increase but it increases when the values of accelerating parameter, Prandtl number, rotation parameter and magnetic parameter increase. On the other hand Skin-friction τ_y increases when the values of thermal Grashof number, accelerating parameter, rotation parameter and time increase but it decreases when the values of Prandtl number and magnetic parameter increase.

CONCLUSIONS:

In this paper, a theoretical analysis has been done to study the effects of rotation and magnetic field on the flow past an exponentially accelerated vertical plate with constant temperature. The dimensionless governing partial differential equations are solved by the usual Laplace transform technique. The effects of different parameters such as magnetic parameter M, thermal Grashof number Gr, Prandtl number $\Pr$, rotation parameter Ω, accelerating parameter a and time t have been investigated. The conclusions of the paper can be summarized as follows.

- The temperature decreases as $\Pr$ increases while it increases with increase of time t.
- The primary velocity increases with increasing values of Gr, t and a, and secondary velocity decreases with increasing values of Gr, t and a.

- The primary velocity increases with decreasing values of M and $\Pr$, and secondary velocity increases with increasing values of M and $\Pr$.
- The primary and secondary velocity decrease with increasing values of Ω.
- Skin-friction:

(i) Skin-friction τ_x decreases when the values of Gr and t are increased but it increases when the values of a, $\Pr$, Ω and M are increased.

(ii) Skin-friction τ_y increases when the values of Gr, a, Ω and t are increased but it decreases when the values of $\Pr$ and M are increased.

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