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EFFECTS OF THERMAL RADIATION AND MHD ON THE UNSTEADY FREE CONVECTION AND MASS TRANSFORM FLOW PAST AN EXPONENTIALLY ACCELERATED VERTICAL PLATE WITH VARIABLE TEMPERATURE

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ABSTRACT

The effect of a uniform transverse magnetic field on the free convection and mass- transform flow of an electrically-conducting fluid past an exponentially accelerated infinite vertical plate is discussed. The fluid considered here is a gray, absorbing/emitting radiation but a non-scattering medium. The plate temperature is raised linearly with time and the concentration level near the plate is raised to C'_w. *The magnetic lines of force are assumed to be fixed relative to the plate. Expressions for the velocity field and skin friction are obtained by the Laplace transform technique. The influence of the various parameters, entering into the problem, on the velocity field and skin friction is extensively discussed with the help of graphs.*

***Keywords**: MHD, thermal radiation, free convection, mass diffusion, vertical plate, variable temperature.*

1. INTRODUCTION

Gupta [1] studied free convection on flow past a linearly accelerated vertical plate in the presence of viscous dissipative heat using perturbation method. Kafousias and Raptis [2] extended this problem to include mass transfer effects subjected to variable suction or injection. Free convection effects on flow past an exponentially accelerated vertical plate was studied by Singh and Naveen kumar [3]. The skin friction for accelerated vertical plate has been studied analytically by Hossain and Shayo [4]. Basant kumar Jha [5] studied MHD free convection and mass transform flow through a porous medium. Later Basant kumar Jha et al. [6] analyzed mass transfer effects on exponentially accelerated infinite vertical plate with constant heat flux and uniform mass diffusion. Recently Muthucumaraswamy et al. [7] studied mass transfer effects on exponentially accelerated isothermal vertical plate.

Soundalgekar and Takhar [8] have considered the radiative free convective flow of an optically thin gray-gas past a semi-infinite vertical plate. Radiation effects on mixed convection along an isothermal vertical plate were studied by Hossain and Takhar [9]. Raptis and Perdikis [10] studied the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Das et al. [11] have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate. The governing equations were solved by the Laplace transform technique. Muthucumaraswamy and Janakiraman [12] studied MHD and radiation effects on moving isothermal vertical plate with variable mass diffusion.

Natural convection induced by the simultaneous action of buoyancy forces from thermal and mass diffusion is of considerable interest in many industrial applications such as geophysics, oceanography, drying processes and solidification of binary alloy. The effect of the magnetic field on free convection flows is important in liquid metals, electrolytes and ionized gases. The thermal physics of MHD problems with mass transfer is of interest in power engineering and metallurgy. When free convection flows occur at high temperature, radiation effects on the flow become significant. Many processes in engineering areas occur at high temperatures, and knowledge of radiative heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines, and the various propulsion devices for aircraft, missiles, and space vehicles are examples of such engineering areas. In view of

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these applications, it is proposed to study the effects of thermal radiation and uniform transverse magnetic field (fixed relative to the plate) on the unsteady free convection and mass transform flow past an exponentially accelerated infinite vertical plate with variable temperature. The dimensionless governing equations are solved using the Laplace transform technique. The solutions are in terms of exponential and complementary error function.

2. MATHEMATICAL ANALYSIS

The unsteady flow of an incompressible and electrically conducting viscous fluid past an infinite isothermal vertical plate with variable temperature has been considered. A magnetic field (fixed relative to the plate) of uniform strength B_o is applied transversely to the plate. The induced magnetic field is neglected as the magnetic Reynolds number of the flow is taken to be very small. The flow is assumed to be in x'-direction which is taken along the vertical plate in the upward direction. The y'-axis is taken to be normal to the plate. Initially the plate and the fluid are at the same temperature T'_∞ in the stationary condition with concentration level C'_∞ at all points. At time $t'>0$, the plate is exponentially accelerated with a velocity $u = u_0 \exp(a't')$ in its own plane and the plate temperature is raised linearly with time t and the level of concentration near the plate is raised to C'_w. The fluid considered here is a gray, absorbing/emitting radiation but a non-scattering medium. The viscous dissipation is assumed to be negligible. Then by usual Boussinesq's approximation, the unsteady flow is governed by the following equations.

$$\frac{\partial u'}{\partial t'} = g\beta(T'-T'_\infty) + g\beta^*(C'-C'_\infty) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho}\left(u' - u_0\exp(a't')\right) \quad (1)$$

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} \quad (2)$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} \quad (3)$$

With the following initial and boundary conditions

$$\begin{aligned} &t' \le 0:\ u'=0,\ T'=T'_\infty,\ C'=C'_\infty \ \text{for all}\ y' \\ &t'>0:\ u'=u_0\exp(a't'),\ T'=T'_\infty+(T'_w-T'_\infty)At',\ C'=C'_w \quad \text{at} \quad y'=0 \\ &u'=0,\ T'\to T'_\infty,\ C'\to C'_\infty,\ \text{as}\ y'\to\infty. \end{aligned} \quad (4)$$

Where $A = \frac{u_0^2}{\nu}$. Equation (1) is valid when the magnetic lines of force are fixed relative to the plate. The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^*\sigma\left(T'^4_\infty - T'^4\right) \quad (5)$$

It is assumed that the temperature differences with in the flow are sufficiently small 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 the higher order terms, thus

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \quad (6)$$

By using equations (5) and (6), equation (2) reduces to

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} + 16a^*\sigma T'^3_\infty\left(T'_\infty - T'\right) \quad (7)$$

On introducing the following non-dimensional quantities:

$$u=\frac{u'}{u_0},t=\frac{t'u_0^2}{\nu},y=\frac{y'u_0}{\nu},\theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},G_r=\frac{g\beta\nu\left(T'_w-T'_\infty\right)}{u_0^3},C=\frac{C'-C'_\infty}{C'_w-C'_\infty}\ G_m=\frac{g\beta^*\nu\left(C'_w-C'_\infty\right)}{u_0^3},$$

$$P_r=\frac{\mu C_p}{\kappa},S_c=\frac{\nu}{D},M=\frac{\sigma B_0^2\nu}{\rho u_0^2},R=\frac{16a^*\nu^2\sigma T_\infty'^3}{\kappa u_0^2},\ a=\frac{a'\nu}{u_0^2} \tag{8}$$

in equations (1) to (4), leads to

$$\frac{\partial u}{\partial t}=G_r\theta+G_mC+\frac{\partial^2 u}{\partial y^2}-M\left(u-\exp\left(at\right)\right) \tag{9}$$

$$\frac{\partial\theta}{\partial t}=\frac{1}{P_r}\frac{\partial^2\theta}{\partial y^2}-\frac{R}{P_r}\theta \tag{10}$$

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} \tag{11}$$

With the initial and boundary conditions

$$\begin{aligned}&t\le 0:\quad u=0,\ \theta=0,\ C=0\ \text{ for all } \ y\\&t>0:\quad u=\exp\left(at\right),\ \theta=t,\ C=1\ \text{ at } y=0\\&u=0,\ \theta\to 0,\ C\to 0\ \text{ as } y\to\infty\end{aligned} \tag{12}$$

All the physical parameters are defined in the nomenclature. The dimensionless governing equations (9) to (11), subject to the boundary conditions (12), are solved by the usual Laplace transform technique and the solutions are derived as follows.

$$C=erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}\right) \tag{13}$$

$$\begin{aligned}\theta=&\left(\frac{t}{2}+\frac{yP_r}{4\sqrt{R}}\right)\left[\exp\left(y\sqrt{R}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}+\sqrt{\frac{Rt}{P_r}}\right)\right]\\&+\left(\frac{t}{2}-\frac{yP_r}{4\sqrt{R}}\right)\left[\exp\left(-y\sqrt{R}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}-\sqrt{\frac{Rt}{P_r}}\right)\right]\end{aligned} \tag{14}$$

$$\begin{aligned}u=&\frac{a\exp(at)}{2\left(a+M\right)}\left[\exp\left(-y\sqrt{a+M}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\left(a+M\right)t}\right)\right.\\&\left.+\exp\left(y\sqrt{a+M}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\left(a+M\right)t}\right)\right]\\&+\left[\exp\left(-y\sqrt{M}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{Mt}\right)\right]\left[\frac{ctG_r}{2d}-\frac{cyG_r}{4d\sqrt{M}}-\frac{1}{2}\left(\frac{G_r}{d}+\frac{G_m}{M}\right)\right]\\&+\left[\exp\left(y\sqrt{M}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{Mt}\right)\right]\left[\frac{ctG_r}{2d}+\frac{cyG_r}{4d\sqrt{M}}-\frac{1}{2}\left(\frac{G_r}{d}+\frac{G_m}{M}\right)\right]\\&+\frac{G_r\exp\left(-ct\right)}{2d}\left[\exp\left(-y\sqrt{M-c}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\left(M-c\right)t}\right)\right.\end{aligned}$$

$$+\exp\left(y\sqrt{M-c}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(M-c)t}\right)\Bigg]$$

$$+\frac{G_m\exp(bt)}{2M}\Bigg[\exp\left(-y\sqrt{b+M}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(b+M)t}\right)$$

$$+\exp\left(y\sqrt{b+M}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(b+M)t}\right)\Bigg]$$

$$+\left[\exp\left(-y\sqrt{R}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}-\sqrt{\frac{Rt}{P_r}}\right)\right]\left[\frac{G_r}{2d}-\frac{ctG_r}{2d}+\frac{cyG_rP_r}{4d\sqrt{R}}\right]$$

$$+\left[\exp\left(y\sqrt{R}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}+\sqrt{\frac{Rt}{P_r}}\right)\right]\left[\frac{G_r}{2d}-\frac{ctG_r}{2d}-\frac{cyG_rP_r}{4d\sqrt{R}}\right]$$

$$-\frac{G_r\exp(-ct)}{2d}\Bigg[\exp\left(-y\sqrt{R-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}-\sqrt{\frac{(R-cP_r)t}{P_r}}\right)$$

$$+\exp\left(y\sqrt{R-cP_r}\right)erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}}+\sqrt{\frac{(R-cP_r)t}{P_r}}\right)\Bigg]$$

$$-\frac{G_m\exp(bt)}{2M}\Bigg[\exp\left(-y\sqrt{bS_c}\right)erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}-\sqrt{bt}\right)$$

$$+\exp\left(y\sqrt{bS_c}\right)erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}+\sqrt{bt}\right)\Bigg]+\frac{G_m}{M}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}\right)$$

$$+\frac{M\left(\exp(at)-\exp(-Mt)\right)}{a+M}+\frac{M\exp(-Mt)}{a+M}erfc\left(\frac{y}{2\sqrt{t}}\right) \tag{15}$$

Where $b=\frac{M}{S_c-1}, c=\frac{R-M}{P_r-1}, d=c\left(R-M\right)$

Skin-Friction

We now study skin-friction from velocity field. It is given in non-dimensional form as

$$\tau=\frac{-du}{dy}\Bigg]_{y=0} \tag{16}$$

Then from equations (15) and (16), we have

$$\tau=\frac{a\exp(at)}{a+M}\left[\sqrt{a+M}\,erf\left(\sqrt{(a+M)t}\right)+\frac{\exp\left(-(a+M)t\right)}{\sqrt{\pi t}}\right]$$

$$+\left[\frac{ctG_r}{d}-\frac{G_r}{d}-\frac{G_m}{M}\right]\left[\sqrt{M}\,erf\left(\sqrt{Mt}\right)+\frac{\exp(-Mt)}{\sqrt{\pi t}}\right]$$

$$+\frac{cG_r}{2d\sqrt{M}}erf\left(\sqrt{Mt}\right)+\frac{G_r\exp(-ct)}{d}\left[\sqrt{M-c}\,erf\left(\sqrt{(M-c)t}\right)+\frac{\exp\left(-(M-c)t\right)}{\sqrt{\pi t}}\right]$$

$$
+\frac{G_m \exp(bt)}{M}\left[\sqrt{b+M}\, erf\left(\sqrt{(b+M)t}\right)+\frac{\exp(-(b+M)t)}{\sqrt{\pi t}}\right]-\frac{cP_rG_r}{2d\sqrt{R}}erf\left(\sqrt{\frac{Rt}{P_r}}\right)
$$

$$
+\left[\frac{G_r}{d}-\frac{ctG_r}{d}\right]\left[\sqrt{R}erf\left(\sqrt{\frac{Rt}{P_r}}\right)+\sqrt{\frac{P_r}{\pi t}}\exp\left(\frac{-Rt}{P_r}\right)\right]+\frac{M}{a+M}\frac{\exp(-Mt)}{\sqrt{\pi t}}
$$

$$
-\left[\frac{G_r\exp(-ct)}{d}\right]\left[\sqrt{R-cP_r}\, erf\left(\sqrt{\frac{(R-cP_r)t}{P_r}}\right)+\sqrt{\frac{P_r}{\pi t}}\exp\left(\frac{-(R-cP_r)t}{P_r}\right)\right] \tag{17}
$$

$$
-\left[\frac{G_m\exp(bt)}{M}\right]\left[\sqrt{bS_c}\, erf\left(\sqrt{bt}\right)+\sqrt{\frac{S_c}{\pi t}}\exp(-bt)\right]+\frac{G_m}{M}\sqrt{\frac{S_c}{\pi t}}
$$

3. RESULTS AND DISCUSSION

In order to get the physical insight into the problem, we have plotted velocity profiles for different physical parameters M(Magnetic field parameter), R(Radiation parameter), Sc(Schmidt number), Pr(prandtl number), Gr(Thermal grashof number), Gm(Mass grashof number), a(accelerating parameter) and t(time) in figures (1) to (13) for the cases of heating (Gr<0) and cooling (Gr>0) of the plate. The heating and cooling take place by setting up free convection current due to temperature and concentration gradient. The value of prandtl number Pr is chosen as 0.71, which represents air.

Figures (1) and(2) represent the velocity profiles due to variations in M(Magnetic field parameter) in cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. It is found that the velocity increases with increase of magnetic parameter M for the cases of both cooling and heating of the plate. It is also found that the velocity is maximum near the plate and decreases away from the plate.

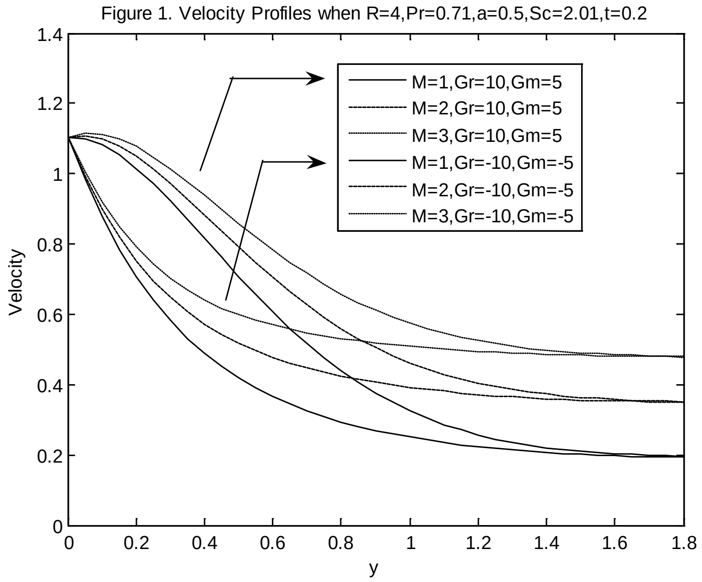
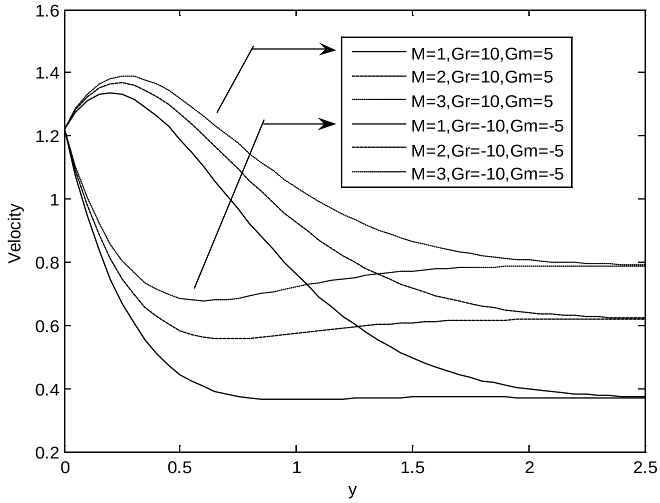


Figure 2. Velocity Profiles when R=4,Pr=0.71,a=0.5,Sc=2.01,t=0.4



Figures (3) and (4) illustrate the influences of R (Radiation parameter) on the velocity field in cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. It is observed that the velocity decreases with increase of radiation parameter R for the case of cooling of the plate. The reverse effect is observed in the case of heating of the plate. It is also observed that the velocity is maximum near the plate and decreases away from the plate.

Figure 3. Velocity Profiles when M=1,Pr=0.71,a=0.5,Sc=2.01,t=0.2

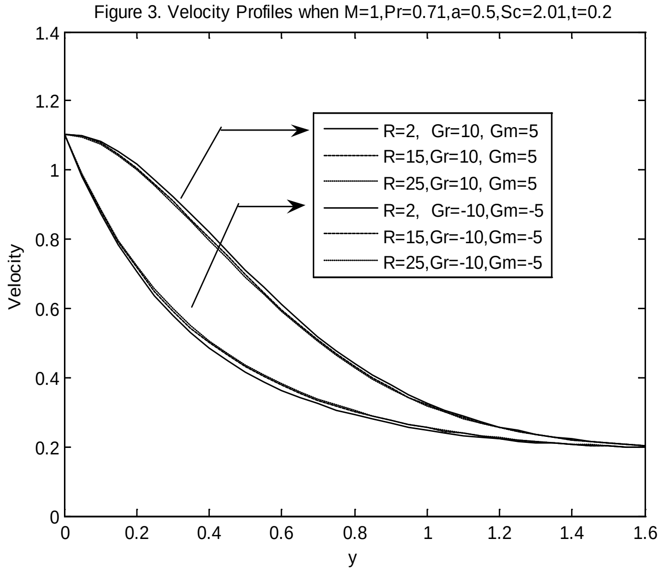
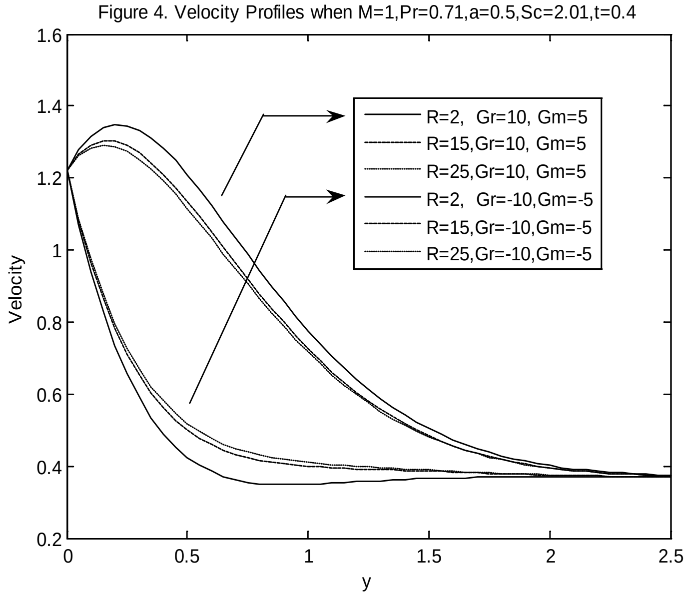


Figure 4. Velocity Profiles when M=1,Pr=0.71,a=0.5,Sc=2.01,t=0.4



Figures (5) and (6) reveal velocity variations with Sc (Schmidt number) in cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. In the case of cooling of the plate, the velocity is observed to increase with decreasing Schmidt number. But the opposite phenomenon is observed for heating of the plate. It is also observed that the velocity is maximum near the plate and decreases away from the plate.

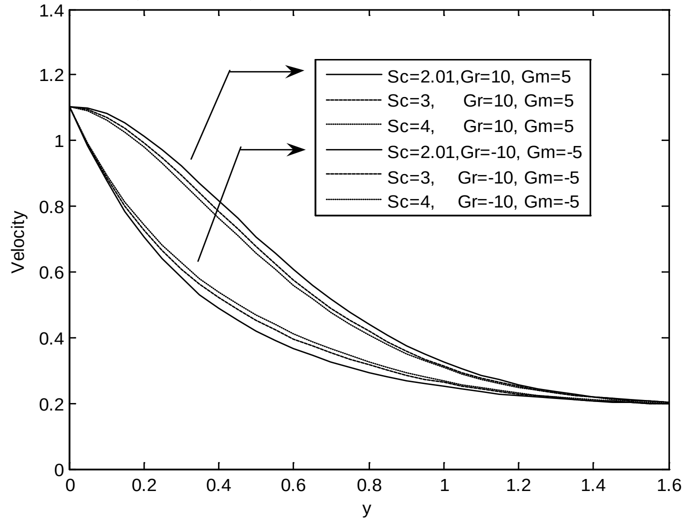


Figure 5. Velocity Profiles when M=1,Pr=0.71,a=0.5,R=4,t=0.2

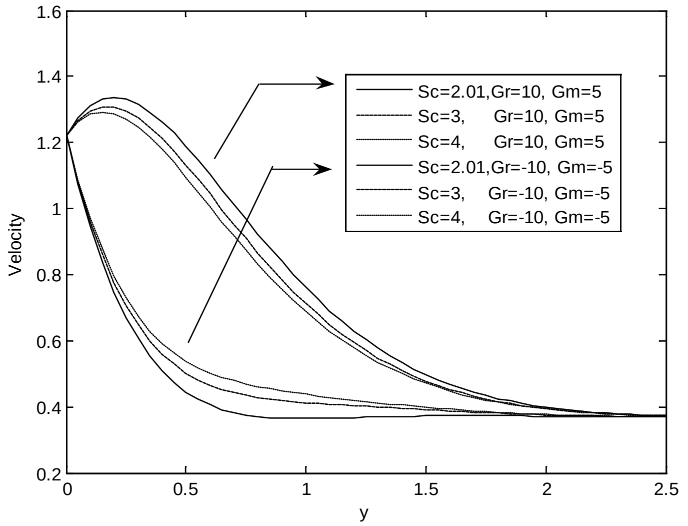


Figure 6. Velocity Profiles when M=1,Pr=0.71,a=0.5,R=4,t=0.4

Figures (7) and (8) display the effects of Pr (Prandtl number) on the velocity field for the cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. In the case of cooling of the plate, the velocity decreases with increasing prandtl number. Physically, it is possible because fluids with high prandtl number have high viscosity and hence move slowly. The reverse effect is observed in the case of heating of the plate.

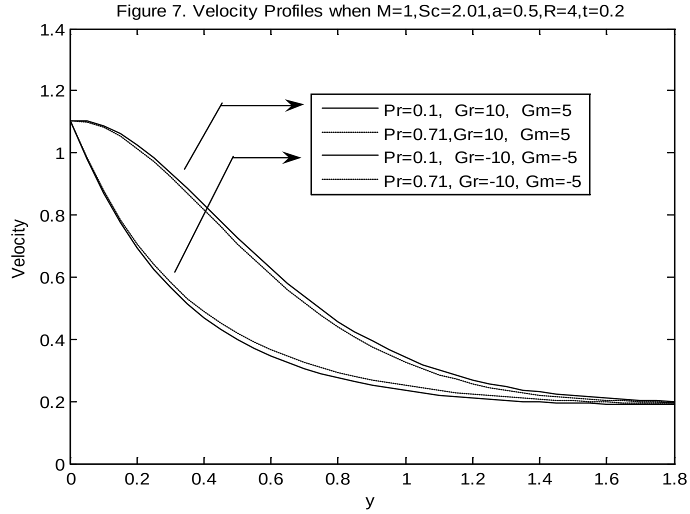
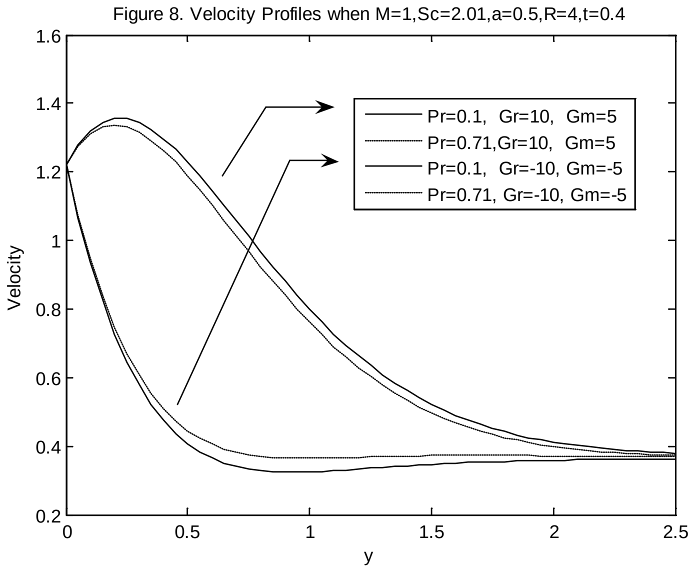
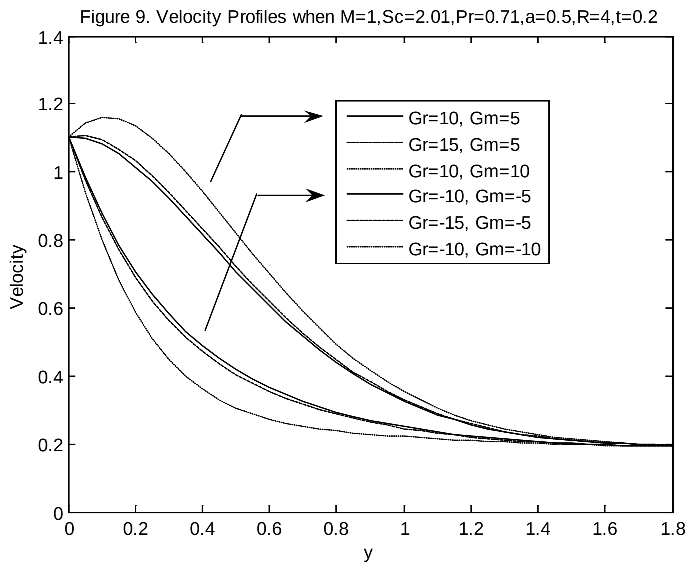
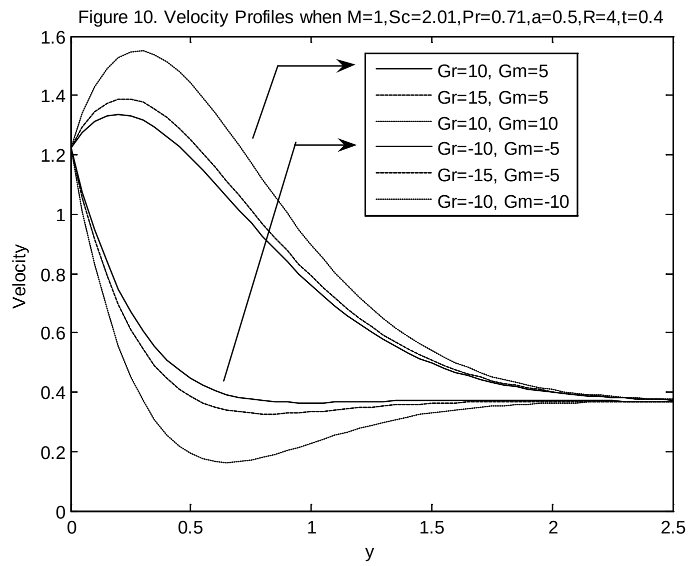


Figure 7. Velocity Profiles when M=1,Sc=2.01,a=0.5,R=4,t=0.2

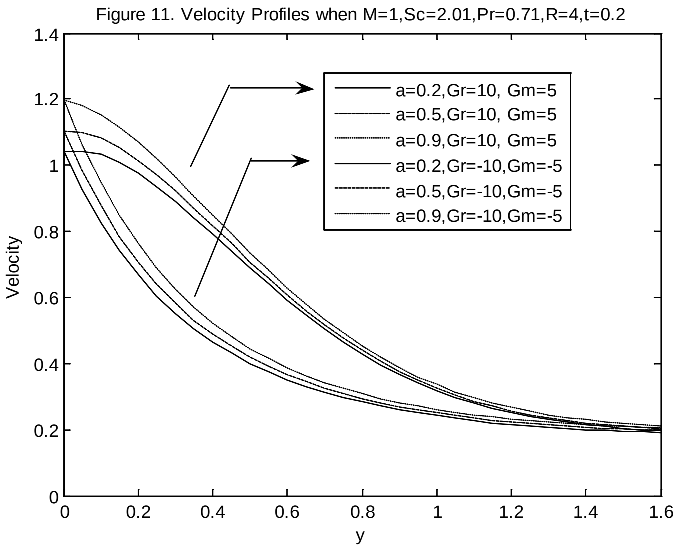


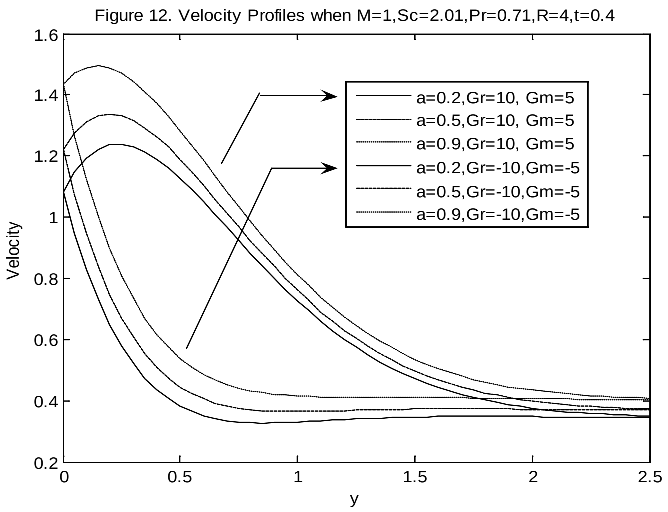
Figures (9) and (10) reveal velocity variations with Gr(Thermal grashof number) and Gm(Mass grashof number) in cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. It is observed that greater cooling of surface (an increase in Gr) and increase in Gm results in an increase in the velocity. It is due to the fact increase in the values of thermal grashof number and mass grashof number has the tendency to increase the thermal and mass buoyancy effect. This gives rise to an increase in the induced flow. But the opposite phenomenon is observed in the case of heating of the plate.





Figures (11) and (12) represent the velocity profiles for different values of the accelerating parameter a in cases of cooling and heating of the plate at t=0.2 and t=0.4 respectively. It is evident from figures that the velocity increases with an increase in a in cases of both cooling and heating of the plate.





The velocity profiles for different values of t (time) are presented in figures (13a) and (13b) for the cases of cooling and heating of the plate. From figure (13a) it is observed that in the case of cooling of the plate the velocity increases with an increase in t (time). From figure (13b) it is found that in the case of heating of the plate the velocity increases with an increase in t(time) upto certain time. Later, as time t increases, the velocity increases near the plate and then decreases away from the plate and finally increases far away from the plate.

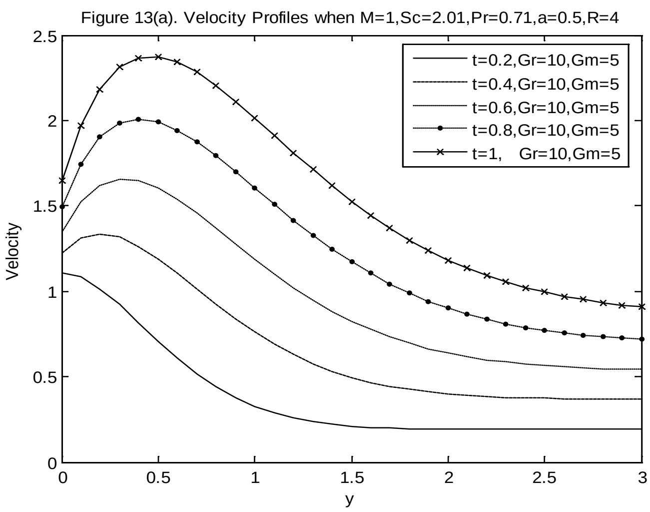
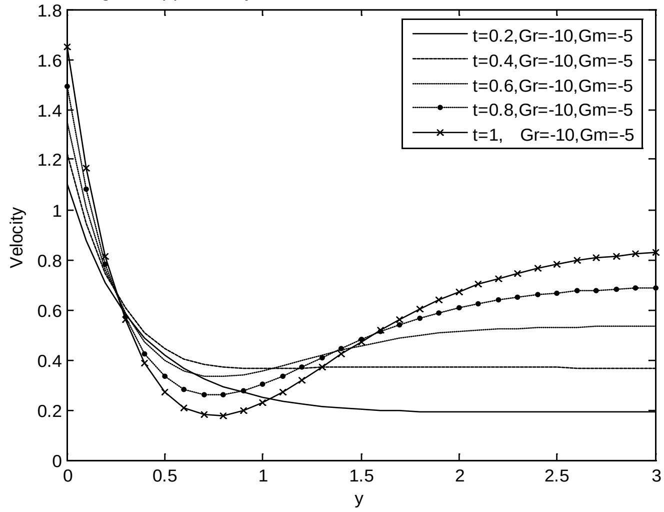


Figure 13(b). Velocity Profiles when M=1,Sc=2.01,Pr=0.71,a=0.5,R=4



The skin friction is presented against time t for different parameters in figures (14) to (19). Figure (14) represents the effects of M (Magnetic parameter) on Skin friction against t in cases of cooling and heating of the plate. It is observed that the skin friction Sk decreases with increasing M for the case of the heating of the plate. But in the case of cooling, the skin friction Sk decreases upto certain t (time) and then increases with increasing magnetic field parameter M. It is also observed that Sk decreases with increasing time t in the case of cooling of the plate. The reverse effect is observed in the case of heating of the plate.

Figure 14. Skin friction when a=0.5,Sc=2.01,Pr=0.71,R=4

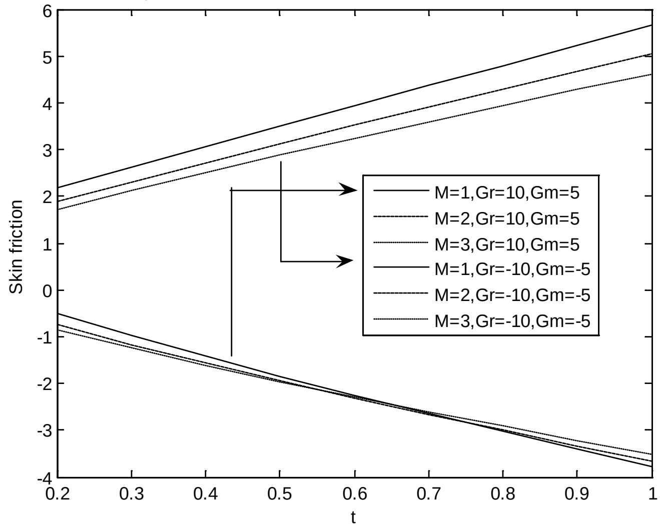


Figure (15) illustrates the effects of R (Radiation parameter) on the skin friction Sk against time t in cases of cooling and heating of the plate. It is found that initially the effect of R on Sk (Skin friction) is negligible. As time t increases Sk increases with an increase in R for the case of cooling. But the reverse effect is observed for the case of heating.

Figure 15. Skin friction when a=0.5,Sc=2.01,Pr=0.71,M=1

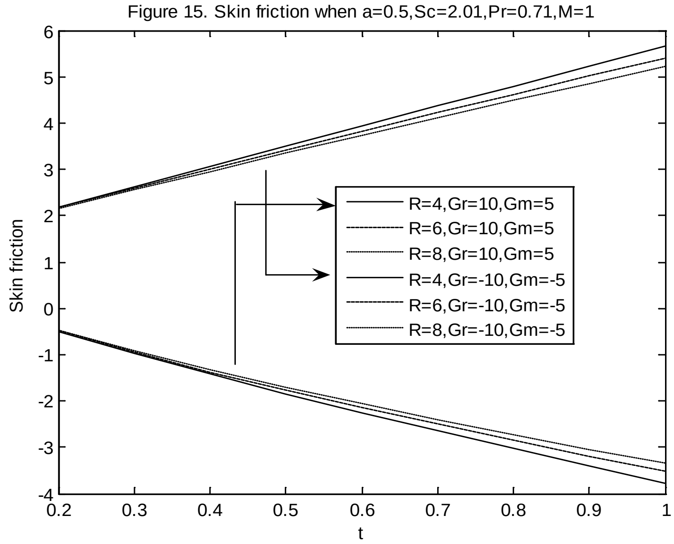


Figure (16) represents the skin friction against t (time) for different values of Sc (Schmidt number) in cases of cooling and heating of the plate. It is observed that Sk (Skin friction) increases with an increase in Sc for the case of cooling of the plate. But the opposite phenomenon is observed for heating of the plate.

Figure 16. Skin friction when a=0.5,R=4,Pr=0.71,M=1

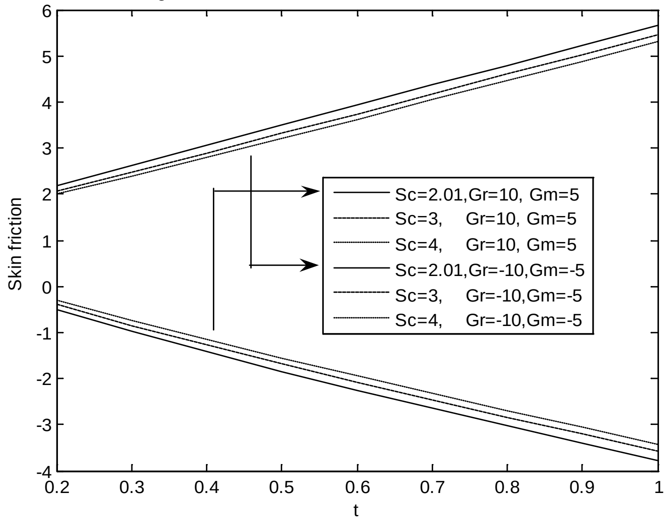


Figure (17) illustrates the influences of Pr (Prandtl number) on the skin friction against t in cases of cooling and heating of the plate. It is noticed that the skin friction Sk increases with an increase in Pr for the case of cooling but decreases for the case of heating.

Figure 17. Skin friction when a=0.5,R=4,Sc=2.01,M=1

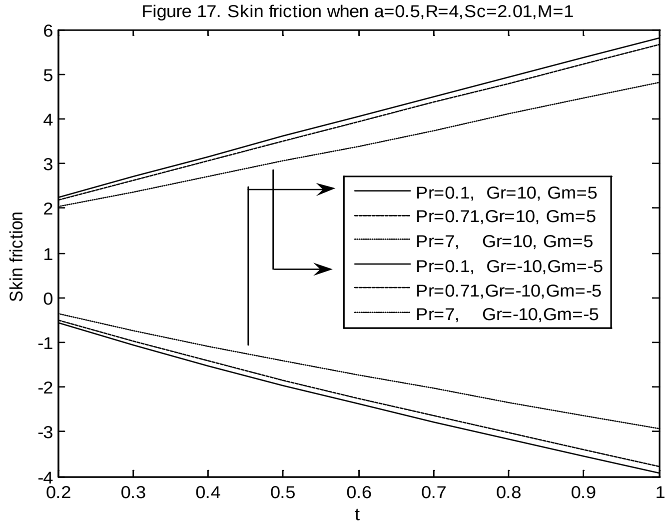


Figure (18) displays the effects of Gr (Thermal grashof number) and Gm (Mass grashof number) on Sk (Skin friction) against t (time) in cases of cooling and heating of the plate. The skin friction is observed to decrease with an increase in Gr or Gm for the case of cooling of the plate. The reverse effect is observed for the case of heating of the plate.

Figure 18. Skin friction when a=0.5,R=4,Sc=2.01,Pr=0.71,M=1

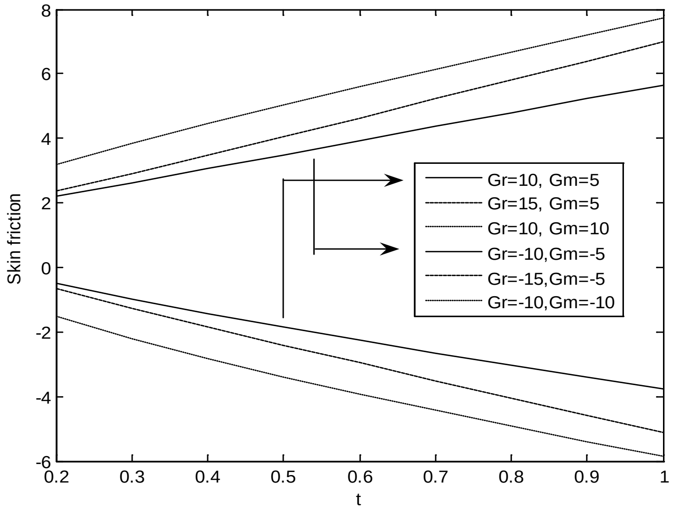
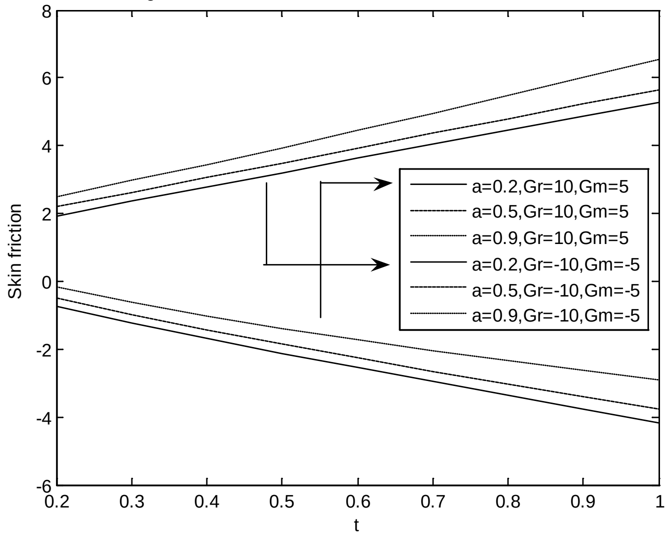


Figure (19) represents the skin friction against t (time) for different values of a (Accelerating parameter) in cases of cooling and heating of the plate. The Skin friction is found to increase with increasing a (Accelerating parameter) for the cases of both cooling and heating of the plate.

Figure 19. Skin friction when R=4,Sc=2.01,Pr=0.71,M=1



APPENDIX

Nomenclature

a^*	Absorption coefficient
A	Constant
B_0	External magnetic field
C'	Species concentration in the fluid
C'_w	Concentration of the plate
C'_∞	Concentration in the fluid far away from the plate
C	Dimensionless concentration
C_p	Specific heat at constant pressure
D	Chemical Molecular diffusivity
g	Acceleration due to gravity
G_r	Thermal Grashof number
G_m	Mass Grashof number
κ	Thermal conductivity of the fluid
M	Magnetic field parameter
P_r	Prandtl number
q_r	Radiative heat flux in the y direction
R	Radiation parameter
S_c	Schmidt number
T'	Temperature of the fluid near the plate
T'_w	Temperature of the plate
T'_∞	Temperature of the fluid far away from the plate
t'	Time
t	Dimensionless time
u'	Velocity of the fluid in the x' -direction
u_0	Velocity of the plate
u	Dimensionless velocity
y'	Coordinate axis normal to the plate
y	Dimensionless coordinate axis normal to the plate

Greek symbols

α	Thermal diffusivity
β	Volumetric coefficient of thermal expansion
β^*	Volumetric coefficient of expansion with concentration
μ	Coefficient of viscosity
ν	Kinematic viscosity
ρ	Density of the fluid
σ	Electric conductivity
τ	Dimensionless skin friction
θ	Dimensionless temperature
erf	Error function
$erfc$	Complementary error function

Subscripts

w	Conditions on the wall
∞	Free stream conditions

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