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MASS AND HEAT TRANSFER EFFECTS ON MHD FLUID FLOW OF AN EXPONENTIALLY ACCELERATED ISOTHERMAL VERTICAL PLATE WITH VARIABLE MASS DIFFUSION

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Abstract

Flow of an incompressible fluid of an infinite isothermal vertical plate is considered. The plate is exponentially accelerated in the presence of magnetic field is analysed. All partial differential equations in non-dimensional form are got from dimensional form. Laplace transform technique is used to solve all non-dimensional equations. Graphs for velocity, temperature and concentration for different thermophysical parameters like Schmidt number, chemical reaction parameter, radiation parameter, magnetic parameter, mass Grashof number,

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thermal Grashof number are drawn using MATLAB software. Skin friction is also depicted. Due to cooling of the plate, concentration increases for decreasing values of Schmidt number. If the intensiveness of radiation is less, then temperature increases. Velocity increases for decreasing values of radiation parameter, chemical reaction parameter, Schmidt number and magnetic parameter. Velocity also increases for the increase in values of thermal Grashof number, mass Grashof number, accelerating parameter and time. Skin friction increases for decreasing values of mass Grashof number, thermal Grashof number, Schmidt number, chemical reaction parameter and decreasing values of accelerating parameter and magnetic parameter.

Nomenclature

C'	Species concentration in the fluid
C	Dimensionless concentration
C_p	Specific heat at constant pressure
D	Mass diffusion coefficient
Gc	Mass Grashof number
Gr	Thermal Grashof number
g	Acceleration due to gravity
K	Thermal conductivity
Pr	Prandtl number
Sc	Schmidt number
T	Temperature of the fluid near the plate
t'	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

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
τ	Dimensionless skin friction
θ	Dimensionless temperature
η	Similarity parameter
erfc	Complementary error function

Subscripts

w	Conditions at the wall
∞	Free stream conditions

1. Introduction

Convective flow driven by temperature and concentration differences is the objective of extensive research because such processes exist in nature and have engineering applications like chimney effect or stack effect. Cooling towers, solar updraft towers were built by this effect. Natural convection of the fluid motion is set up by buoyancy effects resulting from the density variation caused by the temperature differences within the fluid. This is focussed in many applications such as oceanography, drying processes and geophysics. In the ocean, greater density is associated with colder or saltier water, and it is possible to have thermal convection due to the vertical temperature gradient, haline convection due to the vertical salinity gradient, or thermohaline convection due to the combination.

The mass transfer occurs due to difference in concentration of the species present in the fluid. Molecular diffusion of the species occurs either within or at the boundary. The chemical reaction may be homogeneous or heterogeneous. The mass transfer in such a case occurs due to simultaneous action of convection or diffusion, like mixing of water vapour with air during evaporation of water from a surface.

Effects of mass transfer of an accelerated infinite vertical plate with variable heat transfer by power series method were discussed by Raptis and Tzivanidis [2] studied. Singh [3] analysed the flow of an electrically conducting incompressible viscous fluid due to time varying motion of an infinite vertical plate in the presence of a transverse magnetic field. Gupta [4] studied flow of an electrically conducting viscous incompressible fluid due to the accelerated motion of an infinite flat plate in the presence of a uniform magnetic field using integral method. Jha and Prasad [5] analysed consequences of temperature dependent heat sources on free convection and mass transfer flow past an accelerated plate.

Radiation effect on mixed convection along a isothermal vertical plate was studied by Hossain and Takhar [6]. The skin friction for accelerated vertical plate has been studied analytically by Hossain and Shayo [7]. First order chemical reaction on exponentially accelerated isothermal vertical plate with mass diffusion was studied by Muthucumaraswamy and Valliammal [8]. Rajput and Surendra Kumar [9] studied MHD flow of a vertical plate with variable temperature and mass diffusion without radiation and chemical reaction parameter. Soundalgekar et al. [10] depicted mass transfer effects on the flow past a uniformly accelerated vertical plate which is supplied heat at constant rate.

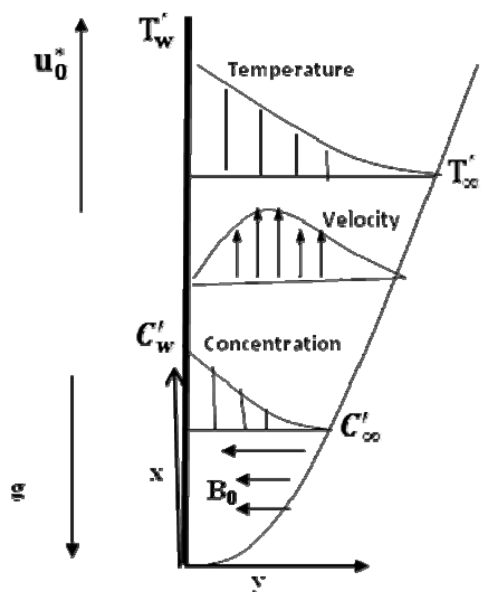
The radiant energy is in direct proportion to the temperatures of substances. Therefore, it is very important to consider thermal radiation effects at high temperature, which has its consequence in nuclear power plants and space vehicles. England and Emery [11] have studied the thermal radiation effects of a optically thin gray gas bounded by a constant vertical plate.

However, the study of thermal radiation and chemical reaction effects on unsteady flow past an exponentially accelerated isothermal vertical plate in the presence of magnetic field has not been studied.

The purpose of the present work is to study the radiation and chemical reaction effects on unsteady flow past an exponentially accelerated isothermal vertical plate with variable mass diffusion, in the presence of magnetic field. Such a study is found useful in energy storage, food processing, freezing. Shear stress is also discussed.

2. Mathematical Analysis

The fluid is assumed to be in the direction of *x*-axis which is taken along the vertical plate in the upward direction. The *y*-axis is taken to be normal to the plate. Initially, the temperature of the plate and the fluid is assumed to be same. Initially, the temperature of the plate is T_∞ and the concentration level in the fluid is assumed to be C'_∞. At time $t' > 0$, the plate temperature is raised to T_w and the concentration level in the fluid is raised to C'_w.



Physical model of the problem

Under usual Boussinesq's approximation, the unsteady free convective flow of an incompressible fluid in dimensional form is given by

$$\frac{\partial u}{\partial t'} = g\beta(T - T_\infty) + g\beta^*(C' - C'_\infty) + \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2 u}{u_0^2}, \tag{1}$$

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

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y^2} - K_l(C' - C'_\infty) \tag{3}$$

with the following initial and boundary conditions:

$$t' \le 0 : u = 0,\ T = T_\infty,\ C' = C'_\infty \text{ for all } y,$$

$$t' > 0 : u = u_0 \exp(a't'),\ T = T_w,\ C' = C'_\infty + (C'_w - C'_\infty)At' \text{ at } y = 0,$$

$$u = 0,\ T \to T_\infty,\ C' \to C'_\infty \text{ as } y \to \infty, \text{ where } A = \frac{u_0^2}{\nu}. \tag{4}$$

Using Taylor series expansion in local radiant energy q_r, (2) reduces to

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} + 16a^*\sigma T_\infty^3(T_\infty - T). \tag{5}$$

On introducing the following non-dimensional quantities

$$U = \frac{u}{u_0}, \quad t = \frac{t'u_0^2}{\nu}, \quad Y = \frac{yu_0}{\nu}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty},$$

$$Gr = \frac{g\beta\nu(T_w - T_\infty)}{u_0^3}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Gc = \frac{\nu g\beta^*(C'_w - C'_\infty)}{u_0^3},$$

$$R = \frac{16a^*\nu^2\sigma T_\infty^3}{ku_0^2}, \quad Pr = \frac{\mu C_p}{k}, \quad Sc = \frac{\nu}{D}, \quad K = \frac{\nu K_l}{u_0^2}, \quad a = \frac{a'\nu}{u_0^2}$$

in (1) to (4), leads to

$$\frac{\partial U}{\partial t} = Gr\theta + GcC + \frac{\partial^2 U}{\partial Y^2} - MU, \tag{6}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial Y^2} - \frac{R}{Pr}\theta, \tag{7}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial Y^2} - KC. \tag{8}$$

The initial and boundary conditions in non-dimensional form are

$$U = 0,\ \theta = 0,\ C = 0,\ \text{for all } Y,\ t \le 0,$$

$$t > 0 : U = \exp(at),\ \theta = 1,\ C = t,\ \text{at } Y = 0,$$

$$U = 0,\ \theta \to 0,\ C \to 0 \ \text{as } Y \to \infty. \tag{9}$$

All the physical variables are defined in the nomenclature.

The solutions are obtained for flow field in the presence of first order chemical reaction and radiation. Equations (6) to (8), subject to the boundary conditions (9), are solved by the usual Laplace transform technique and the expressions for temperature, velocity and concentration are as follows:

$$L(\theta) = \left[\frac{\exp(-\sqrt{Pr(s+b)}\,y)}{s^2}\right],$$

$$\theta = \frac{t}{2}[\exp(2\eta\sqrt{btPr})erfc(\eta\sqrt{Pr} + \sqrt{bt})$$

$$+ \exp(-2\eta\sqrt{btPr})erfc(\eta\sqrt{Pr} - \sqrt{bt})]$$

$$- \frac{\sqrt{Pr}\sqrt{t}\eta}{2\sqrt{b}}[\exp(-2\eta\sqrt{btPr})erfc(\eta\sqrt{Pr} - \sqrt{bt})$$

$$- \exp(2\eta\sqrt{btPr})erfc(\eta\sqrt{Pr} + \sqrt{bt})]. \tag{10}$$

Temperature profiles are plotted using (10).

$$L(C) = \left[\frac{\exp(-\sqrt{Sc(k+s)}\,y)}{s}\right],$$

$$C = \frac{1}{2}[\exp(2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc} + \sqrt{Kt})$$

$$+ \exp(-2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc} - \sqrt{Kt})]. \tag{11}$$

Concentration profiles are plotted using (11).

$$L(u) = \frac{\exp(-\sqrt{s+M}\,y)}{s-a} + 2e\frac{\exp(-\sqrt{s+M}\,y)}{s} - 2e\frac{\exp(-\sqrt{s+M}\,y)}{s-C}$$

$$+ 2g\frac{\exp(-\sqrt{s+M}\,y)}{s} + 2f\frac{\exp(-\sqrt{s+M}\,y)}{s^2} - 2g\frac{\exp(-\sqrt{s+M}\,y)}{s-d}$$

$$- 2e\frac{\exp(-\sqrt{sPr+R}\,y)}{s} + 2e\frac{\exp(-\sqrt{Sc(k+s)}\,y)}{s-C}$$

$$- 2g\frac{\exp(-\sqrt{Sc(k+s)}\,y)}{s} - 2f\frac{\exp(-\sqrt{Sc(k+s)}\,y)}{s^2}$$

$$+ 2g\frac{\exp(-\sqrt{Sc(k+s)}\,y)}{s-d},$$

$$U = \frac{\exp(at)}{2}[\exp(2\eta\sqrt{(M+a)t})erfc(\eta + \sqrt{(M+a)t})$$

$$+ \exp(-2\eta\sqrt{(M+a)t})erfc(\eta - \sqrt{(M+a)t})]$$

$$+ (e+g)[\exp(2\eta\sqrt{Mt})erfc(\eta + \sqrt{Mt}) + \exp(-2\eta\sqrt{Mt})erfc(\eta - \sqrt{Mt})]$$

$$- e\exp(Ct)[\exp(2\eta\sqrt{(M+C)t})erfc(\eta + \sqrt{(M+C)t})$$

$$+ \exp(-2\eta\sqrt{(M+C)t})erfc(\eta - \sqrt{(M+C)t})]$$

$$+ f\Big[t[\exp(-2\eta\sqrt{Mt})erfc(\eta - \sqrt{Mt}) + \exp(2\eta\sqrt{Mt})erfc(\eta + \sqrt{Mt})]$$

$$- \frac{\eta\sqrt{t}}{\sqrt{M}}[\exp(-2\eta\sqrt{Mt})erfc(\eta - \sqrt{Mt}) - \exp(2\eta\sqrt{Mt})erfc(\eta + \sqrt{Mt})]\Big]$$

$$- g\exp(dt)[\exp(2\eta\sqrt{(M+d)t})erfc(\eta + \sqrt{(M+d)t})$$

$$+\exp(-2\eta\sqrt{(M+d)t})erfc(\eta-\sqrt{(M+d)t})]$$

$$-e[\exp(2\eta\sqrt{Rt})erfc(\eta\sqrt{Pr}+\sqrt{bt})+\exp(-2\eta\sqrt{Rt})erfc(\eta\sqrt{Pr}-\sqrt{bt})]$$

$$+ee^{Ct}[\exp(2\eta\sqrt{Pr(b+C)t})erfc(\eta\sqrt{Pr}+\sqrt{(b+C)t})$$

$$+\exp(-2\eta\sqrt{Pr(b+C)t})erfc(\eta\sqrt{Pr}-\sqrt{(b+C)t})]$$

$$-g[\exp(2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}+\sqrt{Kt})$$

$$+\exp(-2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}-\sqrt{Kt})]$$

$$-f\left[t[\exp(2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}+\sqrt{Kt})\right.$$

$$+\exp(-2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}-\sqrt{Kt})]$$

$$-\frac{\eta\sqrt{Sc}\sqrt{t}}{\sqrt{K}}[\exp(-2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}-\sqrt{Kt})$$

$$\left.-\exp(2\eta\sqrt{KtSc})erfc(\eta\sqrt{Sc}+\sqrt{Kt})]\right]$$

$$+g\exp(dt)[\exp(2\eta\sqrt{Sc(K+d)t})erfc(\eta\sqrt{Sc}+\sqrt{(K+d)t})$$

$$+\exp(-2\eta\sqrt{Sc(K+d)t})erfc(\eta\sqrt{Sc}-\sqrt{(K+d)t})]. \tag{12}$$

Velocity profiles are plotted using (12), where $b=\frac{R}{Pr}$, $C=\frac{R-M}{1-Pr}$, $d=\frac{KSc-M}{1-Sc}$, $e=\frac{Gr}{2C(1-Pr)}$, $f=\frac{Gc}{2d(1-Sc)}$, $g=\frac{Gc}{2d^2(1-Sc)}$ and $\eta=Y/2\sqrt{t}$, where *erfc* is called *complementary error function*.

3. Shear Stress (Skin Friction)

The fluid layer in contact with the surface will try to drag the plate along via friction, exerting a friction force on it. A faster fluid layer will try to drag the adjacent slower layer and exert a friction force because of the friction between the two layers. Friction force per unit area is called *shear stress*. We now study skin friction from velocity. It is given in non-dimensional form as

$$\tau = -\frac{dU}{dY}\bigg|_{Y=0}. \tag{13}$$

From equations (12) and (13), we have

$$\begin{aligned}
\tau = {} & \exp(at)\left[\sqrt{M+a}\,erf\sqrt{(M+a)t} + \frac{1}{\sqrt{t\pi}}\exp[-(M+a)t]\right] \\
& + 2(e+g)\left[\sqrt{M}\,erf\sqrt{Mt} + \frac{1}{\sqrt{t\pi}}\exp(-Mt)\right] \\
& - 2e\exp(Ct)\left[\sqrt{M+C}\,erf\sqrt{(M+C)t} + \frac{1}{\sqrt{t\pi}}\exp[-(M+C)t]\right] \\
& + 2f\left[t\sqrt{M}\,erf\sqrt{Mt} + \frac{2\sqrt{t}}{\sqrt{\pi}}\exp(-Mt) + \frac{1}{2\sqrt{M}}\exp(\sqrt{Mt})\right] \\
& - 2g\exp(dt)\left[\sqrt{M+d}\,erf\sqrt{(M+d)t} + \frac{1}{\sqrt{t\pi}}\exp[-(M+d)t]\right] \\
& - 2e\left[\sqrt{R}\,erf\sqrt{bt} + \frac{\sqrt{Pr}}{\sqrt{t\pi}}\exp(-bt)\right] \\
& + 2e\exp(Ct)\left[\sqrt{Pr(b+C)}\,erf\sqrt{(b+C)t} + \frac{\sqrt{Pr}}{\sqrt{t\pi}}\exp[-(b+C)t]\right] \\
& + 2g\left[\sqrt{KSc}\,erf\sqrt{Kt} + \frac{\sqrt{Sc}}{\sqrt{t\pi}}\exp(-Kt)\right] \\
& - 2f\left[t\sqrt{KSc}\,erf\sqrt{Kt} + \frac{\sqrt{t}}{\sqrt{\pi}}\exp(-Kt) - \frac{\sqrt{Sc}}{\sqrt{t\pi}}\exp(-(K+d)t)\right] \\
& + 2e\exp(dt)\left[\sqrt{Sc(K+d)}\,erf\sqrt{(K+d)t} + \frac{\sqrt{Sc}}{\sqrt{t\pi}}\exp[-(K+d)t]\right].
\end{aligned}$$

4. Discussion of Results

4.1. Analysis of temperature, concentration and velocity profiles

The purpose of the calculations given here is to assess the effects of the parameters a, R, K, Gr, Gc, Sc and M upon the nature of the flow and transport. Skin friction is also calculated for different values of a, R, K, Gr, Gc, Sc and M.

Radiation becomes the only mechanism of heat transfer between the surface under consideration and the surroundings. The temperature profiles for different values of thermal radiation parameter $R = 2, 5, 7, 10$ are shown in Figure 1. It is observed that increase in intensity of radiation decreases the temperature.

Figure 2 demonstrates the effect of concentration profiles for different values of time $t = 0.4, 0.6, 0.8, 1$. It is observed that the concentration near the wall increases with increasing values of t.

Schmidt number gives the relationship between momentum diffusivity and mass diffusivity. It governs both velocity and concentration boundary layer. The concentration profiles for different values of the Schmidt number Sc 0.16(Hydrogen), 0.3(Helium), 0.6(Water Vapor), 2.01(Ethyl Benzene) are shown in Figure 3. With decreasing values of Schmidt number, there is more diffusion and hence concentration is more.

Chemical reaction plays a vital role in changing concentration of the fluid. Figure 4 illustrates the effect of the concentration profiles for different values of the chemical reaction parameter $K = 2, 5, 10$ at $t = 0.2$. It is observed that the concentration increases with decreasing chemical reaction parameter.

The effects of the different values of the radiation parameter $R = 2, 5, 10$ are shown in Figure 5. Decreasing intensity of radiation results in increase in velocity.

Figure 6 illustrates the effect of the velocity for different values of the chemical reaction parameter $K = 0.2, 8, 20$. The trend shows that the velocity increases with decreasing chemical reaction parameter.

The velocity profiles for different time $t = 0.6, 0.4, 0.2$ are shown in Figure 7. This shows that the velocity increases gradually with respect to time *t*.

Grashof number which represents the ratio of the buoyancy force to the viscous force acting on the fluid. Figure 8 demonstrates the effect of the velocity profiles for different values of thermal Grashof number $Gr = 15, 10$ and mass Grashof number $Gc = 20, 15$. It is clear that the velocity increases with increasing thermal Grashof number and mass Grashof number.

The velocity profiles for different values of $a = 0.2, 0.5, 0.9$ are studied and presented in Figure 9. It is observed that the velocity increases with increasing values of *a*.

The velocity profiles for different values of $Sc = 0.16, 0.3, 0.6$ are given and presented in Figure 10. For increasing values of Schmidt number, there is a gradual fall in the velocity.

The velocity profiles for different values of magnetic parameter $M = 0.2, 2, 10$ are shown in Figure 11. It depicts that for decreasing values of *M*, velocity increases.

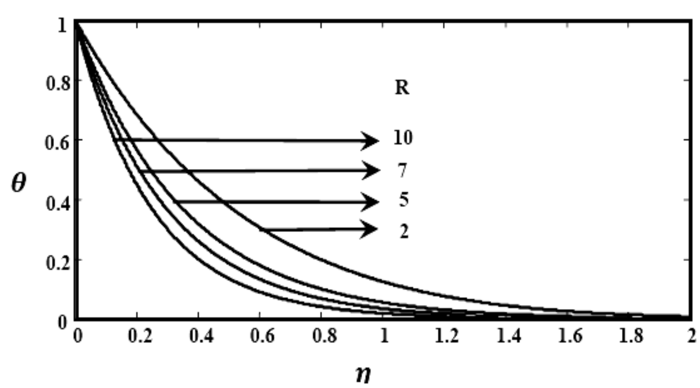


Figure 1. Temperature profile for different values of *R*.

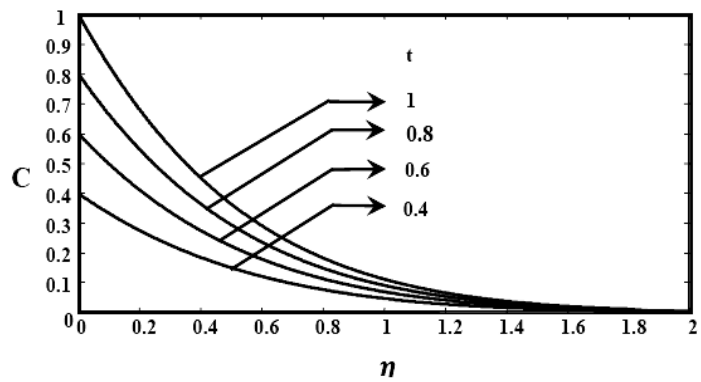


Figure 2. Concentration profiles for different values of *t*.

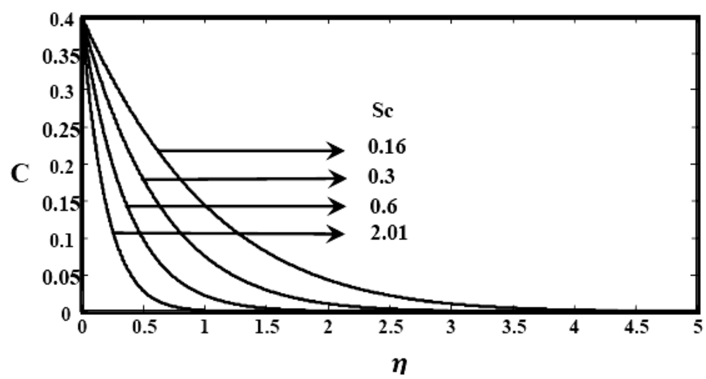


Figure 3. Concentration profile for different values of *Sc*.

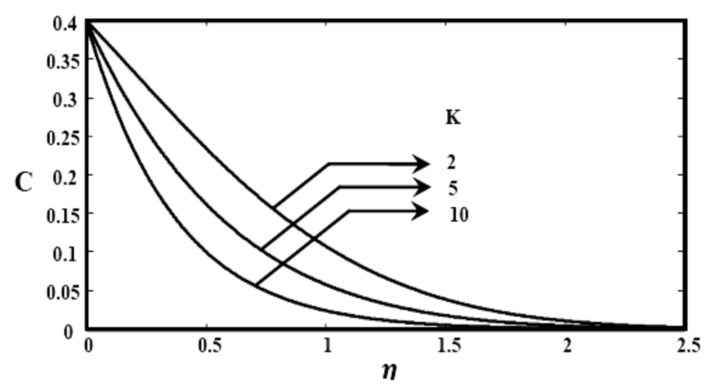


Figure 4. Concentration profiles for different values of *K*.

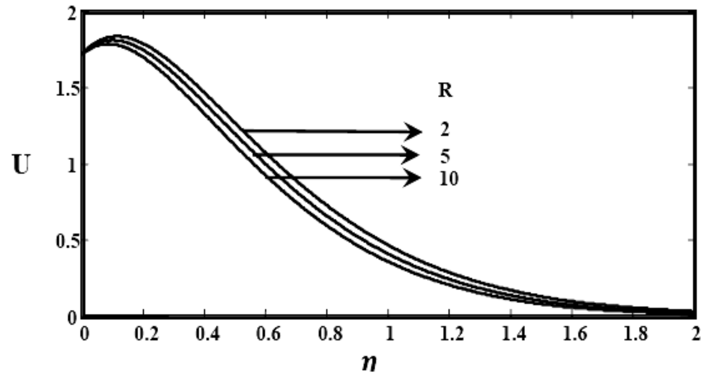


Figure 5. Velocity profile for different values of "*R*".

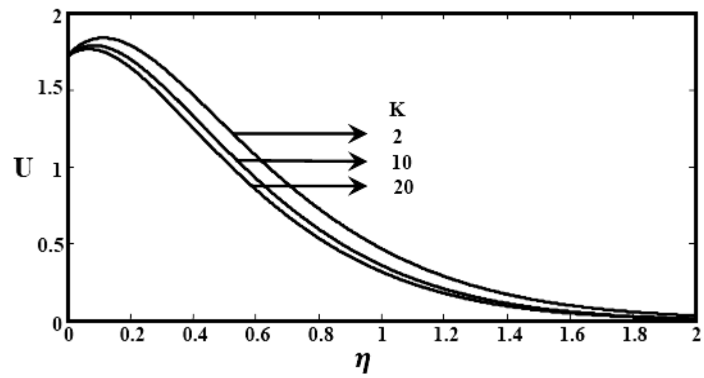


Figure 6. Velocity profile for different values of *K*.

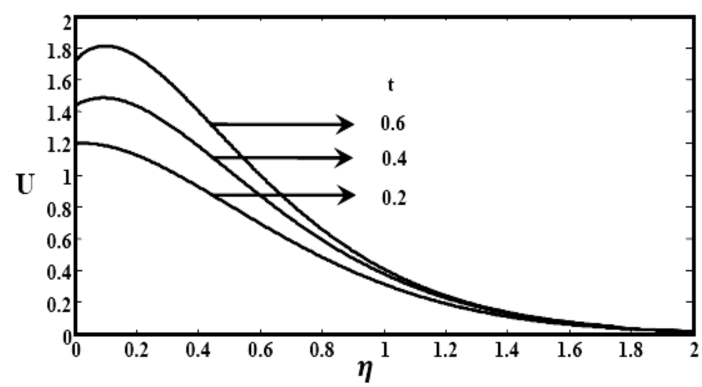


Figure 7. Velocity profile for different values of *t*.

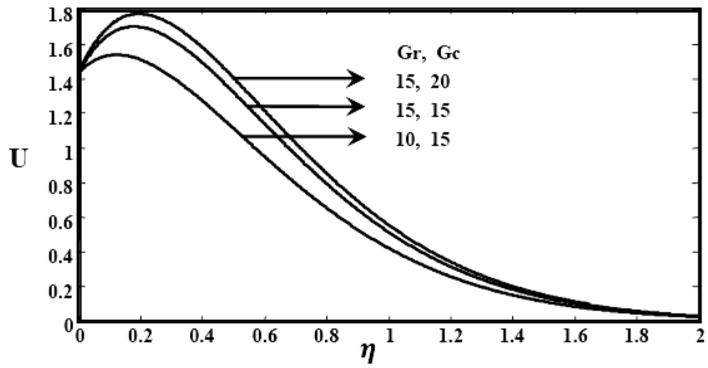


Figure 8. Velocity profile for different values of *Gr* and *Gc*.

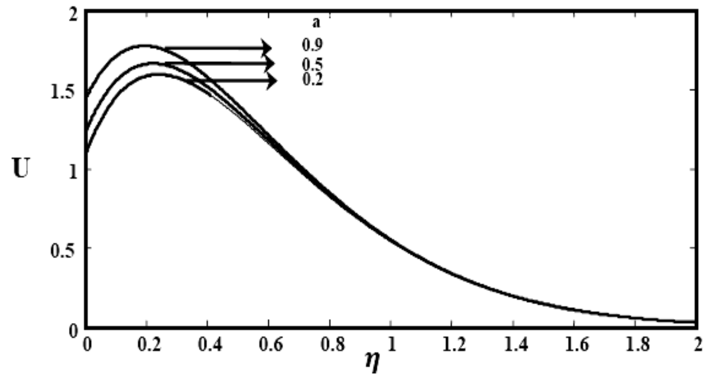


Figure 9. Velocity profile for different values of "*a*".

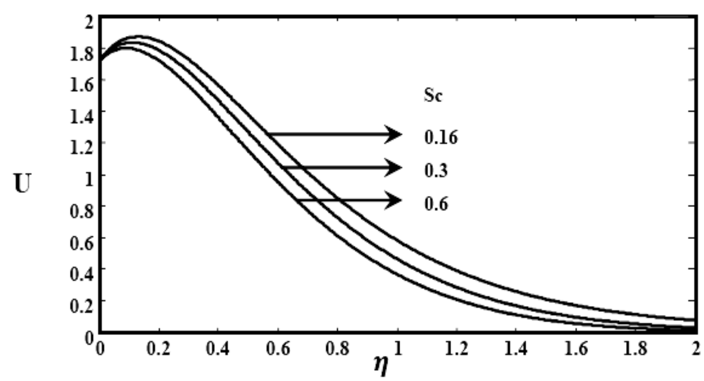


Figure 10. Velocity profile for different values of *Sc*.

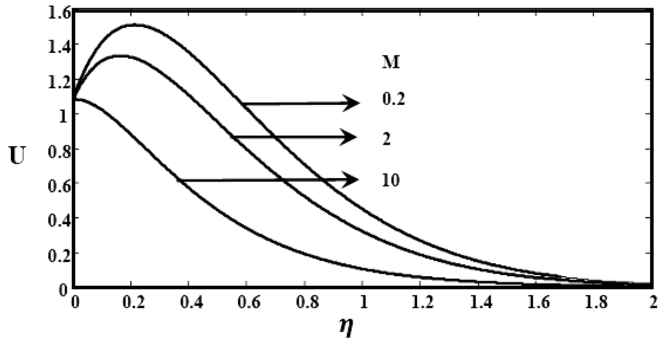


Figure 11. Velocity profile for different values of *M*.

4.2. Analysis of skin friction

Figure 12 shows skin friction for different values of "*a*". It is observed that skin friction increases for increasing values of "*a*".

Figure 13 shows skin friction for different values of *Gr*, *Gc*. The observations depict that the skin friction decreases for increasing values of mass Grashof number and thermal Grashof number.

Skin friction values for different values of Schmidt number are shown in Figure 14. The skin friction decreases for increasing values of *Sc*.

Figure 15 shows skin friction for different values of chemical reaction parameter *K*. The skin friction decreases with increasing values of *K*.

Figure 16 shows skin friction for different values of the magnetic parameter *M*. The skin friction increases for increasing values of *M*.

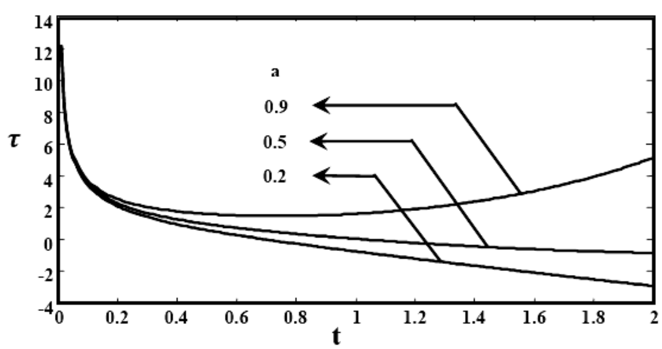


Figure 12. Skin friction for different values of *a*.

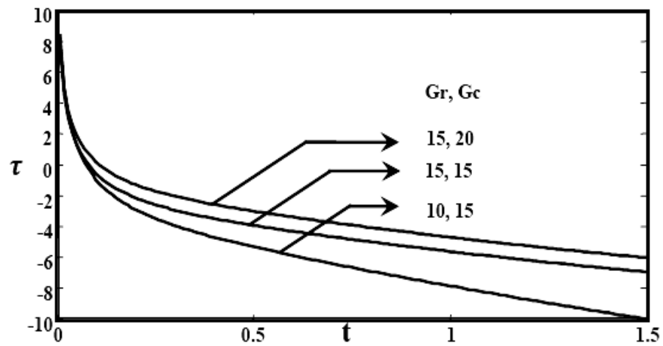


Figure 13. Skin friction for different values of *Gr*, *Gc*.

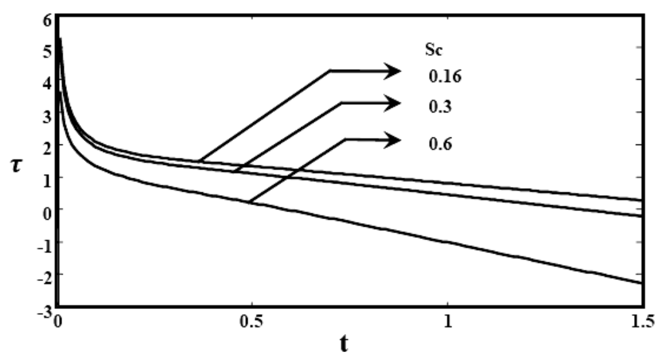


Figure 14. Skin friction for different values of *Sc*.

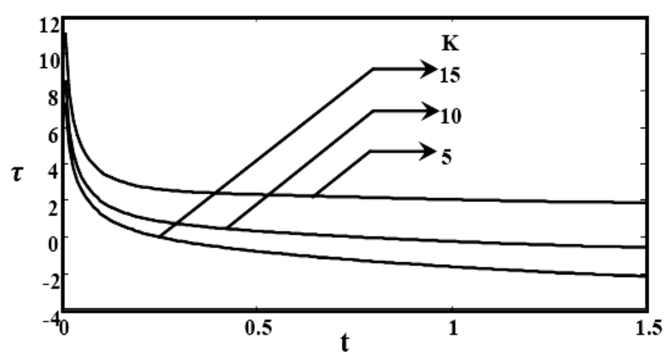


Figure 15. Skin friction for different values of *K*.

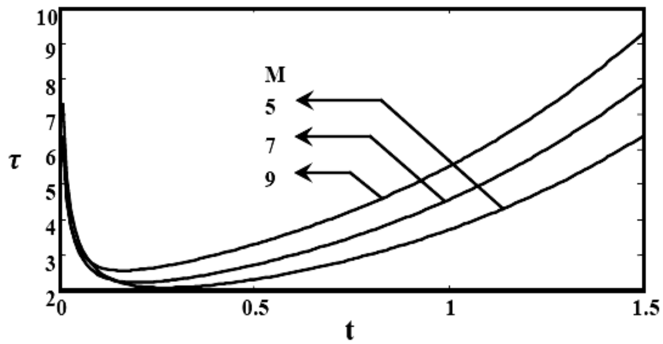


Figure 16. Skin friction for different values of *M*.

5. Conclusion

In paper [8], chemical reaction effects on exponentially accelerated vertical plate with mass diffusion were carried out. Radiation effects in the presence of magnetic field were not taken into account. In this paper, both radiation and chemical reaction effects on exponentially accelerated vertical plate are carried out with variable mass diffusion.

An exact analysis of thermal radiation and chemical reaction effects on unsteady flow past an exponentially accelerated infinite isothermal vertical plate with variable mass diffusion, in the presence of chemical reaction of first order has been studied. It is concluded that concentration increases for decreasing values of Schmidt number (*Sc*) and chemical reaction parameter (*K*) and increasing values of time *t*. Temperature increases for decreasing values of radiation parameter (*R*). Velocity increases for decreasing values of radiation parameter (*R*), chemical reaction parameter (*K*), Schmidt number (*Sc*), magnetic parameter (*M*) and increasing values of time (*t*), thermal Grashof number (*Gr*), mass Grashof number (*Gc*), accelerating parameter (*a*). Skin friction increases for decreasing values of *Gr*, *Gc*, *Sc*, *K* and increasing values of '*a*', *M*.

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