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THE EFFECT OF CHEMICAL REACTION ON UNSTEADY HEAT AND MASS TRANFER FLOW PAST AN EXPONENTIALLY ACCELERATED VERTICAL PLATE WITH VARIABLE TEMPERATURE AND MASS DIFFUSION

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ABSTRACT

An exact solution to the problem of unsteady flow past an infinite vertical exponentially accelerated plate with variable temperature and mass diffusion has been presented here, taking into account the homogeneous chemical reaction of first order. The plate temperature is raised linearly with time and species concentration level near the plate is also raised linearly with respect to time. The dimensionless governing equations involved in the present analysis are solved using Laplace-transform technique. The velocity, temperature and concentration fields are studied for different physical parameters like Thermal Grashof number (Gr), Mass Grashof number (Gm), Schmidt number (Sc), Prandtl number (Pr), accelerated parameter (a), chemical reaction parameter (K) and time (t) with the help of graphs.

***Keywords**: Chemical reaction, Heat and mass transfer, Exponential, Accelerated, Vertical plate.*

INTRODUCTION

Mass diffusion rates can be changed tremendously with chemical reactions. The chemical reaction effects depend whether the reaction is homogeneous or heterogeneous. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous, if it takes place at an interface and homogeneous, if it takes place in solution. In majority cases, a chemical reaction depends on the concentration of the species itself. A reaction is said to be first order, if the rate of reaction is directly proportional to the concentration itself (cussler[3]). A few representative areas of interest in which heat and mass transfer combined along with chemical reaction play an important role in chemical industries like in food processing and polymer production. Chambre and Young [2] have analyzed a first order chemical reaction in the neighborhood f a horizontal plate. Das et al. [4] have studied the effect of homogeneous first order chemical reaction on the flow past an impulsively started vertical plate with uniform heat flux and mass transfer. Again, mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction studied by Das et al. [5]. The dimensionless governing equations were solved by the usual Laplace Transform technique.

Gupta et al. [6] studied free convection flow past a linearly accelerated vertical plate in the presence of viscous dissipative heat using perturbation method. Kafousias and Raptis [7] extended this problem to include mass transfer effects subjected to variable suction or injection. Mass transfer effects on flow past an accelerated vertical plate a uniformly accelerated vertical plate was studied by soundalgekar [9] again, Mass transfer effects on flow past an accelerated vertical plate with uniform heat flux was analyzed by the Singh and Singh [8]. Basant kumar Jha and Ravindra Prasad [1] analyzed mass transfer effects on the flow past an accelerated infinite vertical plate with heat sources. Muthucumaraswamy et al. [9] (2009) studied mass transfer with a chemical reaction on unsteady flow past an accelerated isothermal vertical plate. Recently, Rajput and Sahu [11] investigated the effects of rotation and magnetic field on the flow past an exponentially accelerated vertical plate with constant temperature.

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The objective of the present investigation is to study unsteady free convection flow past an exponentially accelerated infinite vertical plate with variable temperature and also with variable mass diffusion in the presence of a homogeneous chemical reaction of first order. The dimensionless governing equations involved in the present analysis are solved using the Laplace Transform technique.

MATHEMATICAL ANALYSIS

Here the unsteady flow of a viscous incompressible fluid past an exponentially accelerated infinite vertical plate with variable temperature and mass diffusion in the presence of chemical reaction of first order has been considered. It is assumed that the effect of viscous dissipation is negligible in the energy equation and there exist a first order chemical reaction between the diffusing species and the fluid. The plate is taken along $\boldsymbol{x'}$-axis in vertically upward direction and $\boldsymbol{y'}$-axis is taken 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 the 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 temperature of the plate is raised linearly with time and species concentration level near the plate is also raised linearly with time t. All the physical properties of the fluid are considered to be constant except the influence of the body-force term, and then under usual Boussinesq's approximation, the unsteady flow is governed by the following equations.

$$\frac{\partial u'}{\partial t'} = g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + v\frac{\partial^2 u'}{\partial y'^2} \tag{1}$$

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa \frac{\partial^2 T'}{\partial y'^2} \tag{2}$$

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

With the following initial and boundary conditions

$$t' \le 0: \quad u' = 0, \qquad T' = T'_\infty, \qquad C' = C'_\infty \quad for\ \ all\ \ y'$$

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

$$and\ \ u' = 0,\ T' \to T'_\infty,\ C' \to C'_\infty\ \ as\ \ y' \to \infty \tag{4}$$

Where $A = \frac{u_0^2}{v}$. On introducing the following non-dimensional quantities

$$u = \frac{u'}{u_0},\ t = \frac{t'u_0^2}{v},\ y = \frac{y'u_0}{v},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ C = \frac{C' - C'_\infty}{C'_w - C'_\infty},\ P_r = \frac{\mu C_\rho}{\kappa}$$

$$G_r = \frac{g\beta v(T'_w - T'_\infty)}{u_0^3}\quad G_m = \frac{g\beta^* v(C'_w - C'_\infty)}{u_0^3},\quad S_c = \frac{v}{D},\ a = \frac{a'v}{u_0^2},\ K = \frac{vK_l}{u_0^2} \tag{5}$$

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

$$\frac{\partial u}{\partial t} = G_r\theta + G_m C + \frac{\partial^2 u}{\partial y^2} \tag{6}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} \tag{7}$$

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

The initial and boundary conditions in dimensionless form are as follows

$$t \le 0: \quad u = 0, \quad \theta = 0, \quad C = 0 \quad for\ \ all\ \ y,$$

$$t > 0: \quad u = exp(at),\ \theta = t, \quad C = t \quad at \quad y = 0, \text{ And}$$

$$u \to 0,\ \theta \to 0,\ \ C \to 0 \quad as \quad y \to \infty \tag{9}$$

METHOD OF SOLUTION:

The solutions are derived for hydrodynamic flow field in the presence of chemical reaction of first order. The equations from (6) to (8), subject to the boundary conditions (9) are solved by the usual Laplace Transform technique and the solutions are derived for temperature, concentration and velocity fields as follows.

$$\theta(y,t) = \left[\left(t + \frac{y^2 Pr}{2}\right) erfc\left(\frac{y\sqrt{Pr}}{2\sqrt{t}}\right) - y\sqrt{\frac{tPr}{\pi}}\, e^{-\frac{y^2 Pr}{4t}}\right]$$

$$C(y,t) = \left[\left(\frac{t}{2} + \frac{y\sqrt{Sc}}{4\sqrt{K}}\right) e^{y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} + \sqrt{Kt}\right) + \left(\frac{t}{2} - \frac{y\sqrt{Sc}}{4\sqrt{K}}\right) e^{-y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} - \sqrt{Kt}\right)\right]$$

$$\begin{aligned}
u(y,t) = {} & \frac{e^{at}}{2}\left[e^{y\sqrt{a}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{at}\right) + e^{-y\sqrt{a}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{at}\right)\right] \\
& + \frac{b}{24}\left[(12t^2 + 12y^2 t + y^4) erfc\left(\frac{y}{2\sqrt{t}}\right) - (2y^3 + 20yt)\sqrt{\frac{t}{\pi}}\, e^{-\frac{y^2}{4t}}\right] \\
& + \frac{c}{d}\left[\left(t + \frac{y^2}{2}\right) erfc\left(\frac{y}{2\sqrt{t}}\right) - y\sqrt{\frac{t}{\pi}}\, e^{-\frac{y^2}{4t}}\right] - \frac{c}{d^2} erfc\left(\frac{y}{2\sqrt{t}}\right) + \frac{c}{2d^2} e^{-dt}\begin{bmatrix} e^{y\sqrt{-d}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{-dt}\right) \\ + e^{-y\sqrt{-d}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{-dt}\right)\end{bmatrix} \\
& - \frac{b}{24}\left[(12t^2 + 12y^2 tPr + y^4 Pr^2) erfc\left(\frac{y\sqrt{Pr}}{2\sqrt{t}}\right) - (2y^3 Pr + 20yt)\sqrt{\frac{tPr}{\pi}}\, e^{-\frac{y^2 Pr}{4t}}\right] \\
& - \frac{c}{d}\left[\left(\frac{t}{2} + \frac{y\sqrt{Sc}}{4\sqrt{K}}\right) e^{y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} + \sqrt{Kt}\right) + \left(\frac{t}{2} - \frac{y\sqrt{Sc}}{4\sqrt{K}}\right) e^{-y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} - \sqrt{Kt}\right)\right] \\
& + \frac{c}{2d^2}\left[e^{y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} + \sqrt{Kt}\right) + e^{-y\sqrt{KSc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} - \sqrt{Kt}\right)\right] \\
& - \frac{c}{2d^2} e^{-dt}\left[e^{y\sqrt{(K-d)Sc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} + \sqrt{(K-d)t}\right) + e^{-y\sqrt{(K-d)Sc}} erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}} - \sqrt{(K-d)t}\right)\right]
\end{aligned}$$

Where $\boldsymbol{b} = \frac{\boldsymbol{Gr}}{\boldsymbol{Pr-1}}$, $\boldsymbol{c} = \frac{\boldsymbol{Gm}}{\boldsymbol{Sc-1}}$, $\boldsymbol{d} = \frac{\boldsymbol{KSc}}{\boldsymbol{Sc-1}}$

RESULTS AND DISCUSSION

For physical understanding of the problem numerical computations are carried out for different physical parameters $\boldsymbol{a}, \boldsymbol{Gr}, \boldsymbol{Gm}, \boldsymbol{Pr}, \boldsymbol{Sc}, \boldsymbol{K}$ and *t* upon the nature of the flow and transport. The value of Schmidt parameter $\boldsymbol{Sc}$ is taken to be 0.6 which corresponds to the water-vapor. Also, the value of the Prandtl number $\boldsymbol{Pr}$ are chosen such that they represent air $(\boldsymbol{Pr = 0.71})$. The numerical values of the velocity are computed for different physical parameters like $\boldsymbol{a}$ (accelerated parameter), $\boldsymbol{Gr}$(thermal grashof number), $\boldsymbol{Gm}$(mass grashof number), $\boldsymbol{Pr}$(prandtl number), $\boldsymbol{Sc}$(Schmidt number), $\boldsymbol{K}$(chemical reaction parameter), and *t* (time).

The velocity profiles for different values of accelerated parameter $(\boldsymbol{a = 0.2, 0.5, 0.9})$ and $\boldsymbol{Gr = 20, Gm = 5, K = 5}$ at time $\boldsymbol{t = 0.2}$ & 0.4 are exhibited through figures (1) & (2) respectively for the cases of cooling and heating of the plate. It is observed that the velocity increases with an increase in $\boldsymbol{a}$ in both cases of cooling and heating of the plate. Figure (3) & (4) demonstrate that the effect of velocity fields for different values of thermal Grashof number and mass Grashof number at time $\boldsymbol{t = 0.2}$ & 0.4 respectively. It is observed that the velocity u increases with increasing values of thermal Grashof number or mass Grashof number in the case of cooling of the plate. It is due to the fact increase 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. And a reverse effect is identified in the heating of the plate.

The effect of velocity for different values of Prandtl number $(\boldsymbol{Pr = 0.5, 0.71, 7.0})$ at time $\boldsymbol{t = 0.2}$ & 0.4 are respectively shown in figures (5) & (6) for the cases of cooling and heating of the plate. It is noticed that, the velocity decreases with increase of Prandtl number in the case of cooling of the plate. Physically, it meets the logic that, the fluids with high prandtl number have high viscosity and hence move slowly. But an opposite phenomenon is identified in the case of heating of the plate. Figure (7) represents the effect of velocity profiles for different values of Schmidt number $(\boldsymbol{Sc = 0.16, 0.22, 0.60})$ and $\boldsymbol{a = 0.5, K = 5}$ at time $\boldsymbol{t = 0.4}$ in the cases of cooling and heating of the plate. It is observed that, in the case of cooling of the plate, the velocity increases with decreasing Schmidt number. The reverse effect is observed in the case of heating of the plate. The variation in velocity for different time ($\boldsymbol{t =}$ ***0.2, 0.4, 0.6, 0.8*** and ***K=5, a=0.5,*** are shown in figure (8) for the cases of cooling and heating of the plate. It is observed that in the case of cooling of the plate the velocity gradually increases an increase in time t. But in the case of heating, the velocity increases with increase in t near the plate and the reverse effect is notified moving far away from the plate.

The effect of velocity for different values of the chemical reaction parameter ($\boldsymbol{K = 0.2, 5, 10, 15, 20}$) are presented in Tables 1-4 at time *t=0.2 &0.4* in cases of cooling and heating of the plate. It is observed that the increase in chemical reaction parameter leads to fall in velocity in the case of cooling of the plate. And a reverse effect is identified in the case of heating of the plate.

The temperature profiles for air(*Pr=0.71)* and water (*Pr=7.0)* are studied at different time (*t=0.2, 0.4 and0.6)* in figure 9. It is observed that the heat transfer is more in air than in water. It is clear that there is a sudden drop in temperature in water compared to that in air Figure (10) demonstrates the effect of Schmidt number on the concentration field at time *t=0.2 &0.4*. The concentration decreases with an increase in Sc. And it is noticed that concentration decreases slowly for *Sc=0.22(hydrogen)* in comparison of other gases *Sc=0.60(water vapour)* and *Sc=0.78(ammonia).* The effect of concentration profiles for different values of chemical reaction parameter (*K=2, 5& 10)* at time *t=0.2 &0.4* are presented in Figure (11). It is observed that the concentration increases with decreasing chemical reaction parameter and finally, from figure (12) it is observed that the concentration increases with an increase in time t.

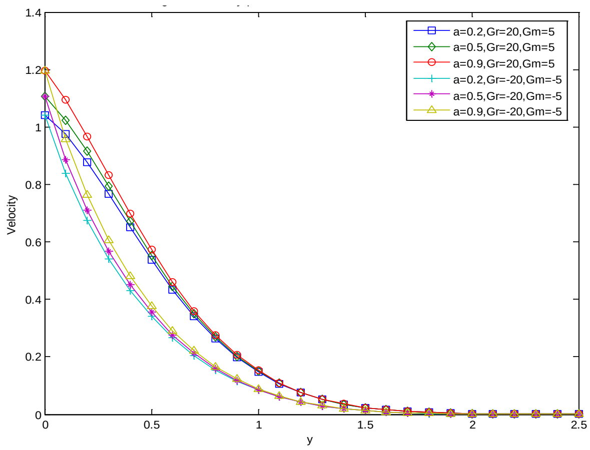

Figure 1: Velocity profiles when K=5, Pr=0.71, Sc=0.6 and t=0.2

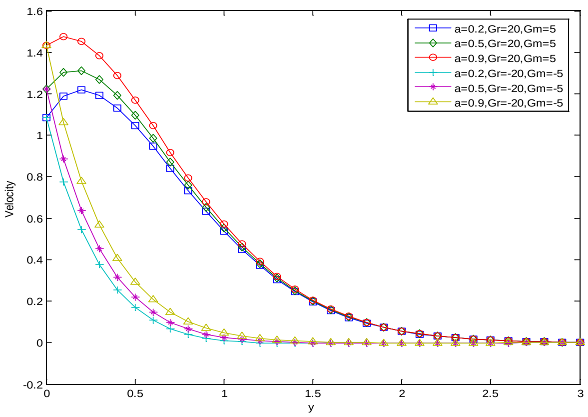

Figure 2: Velocity profiles when K=5, Pr=0.71, Sc=0.6 and t=0.4

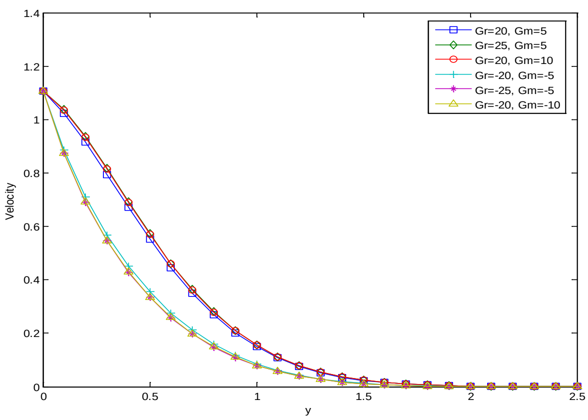

Figure 3: Velocity profiles when a=0.5, K=5, Pr=0.71, Sc=0.6 and t=0.2

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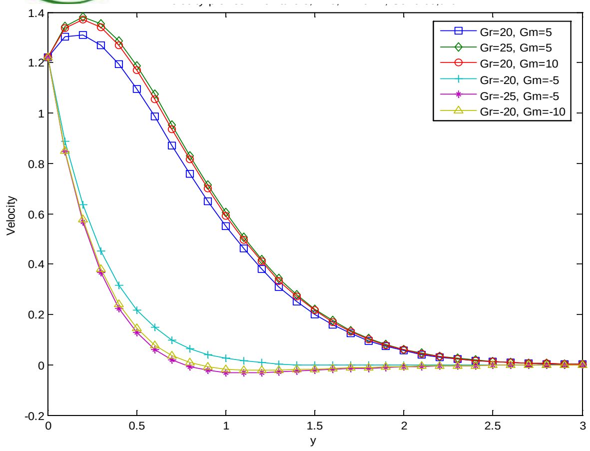

Figure 4: Velocity profiles when a=0.5, K=5, Pr=0.71, Sc=0.6 and t=0.4

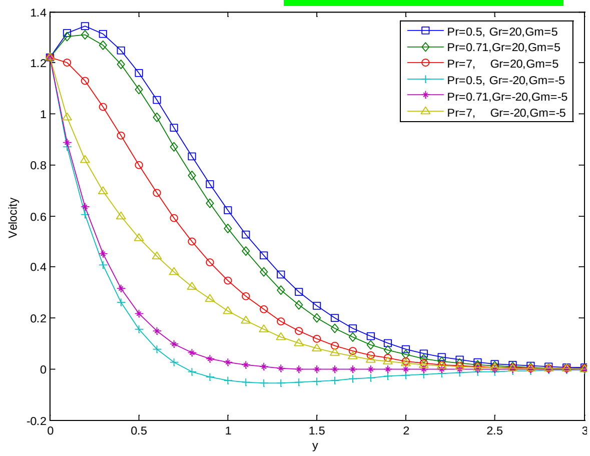

Figure 6: Velocity profiles when k=5, Sc=0.6, a=0.5 and t=0.4

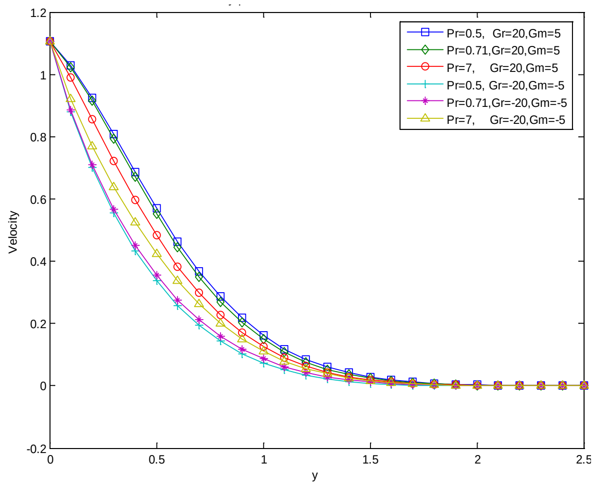

Figure 5: Velocity profiles when K=5, Sc=0.6, a=0.5 and t=0.2

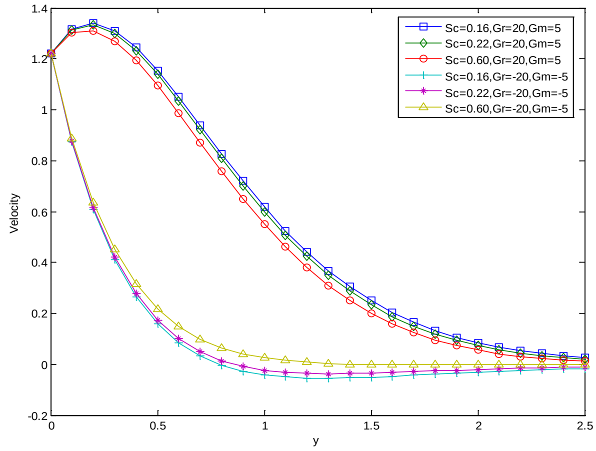

Figure 7: Velocity profiles when K=5, Pr=0.71, a=0.5 and t=0.4

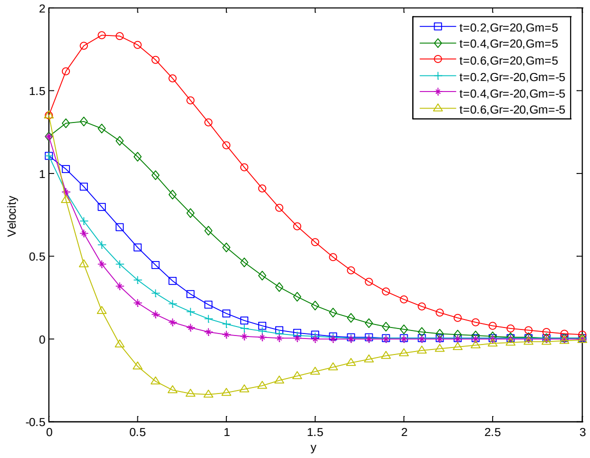

Figure 8: Velocity profiles when Pr=0.71, Sc=0.6, a=0.5 and K=5

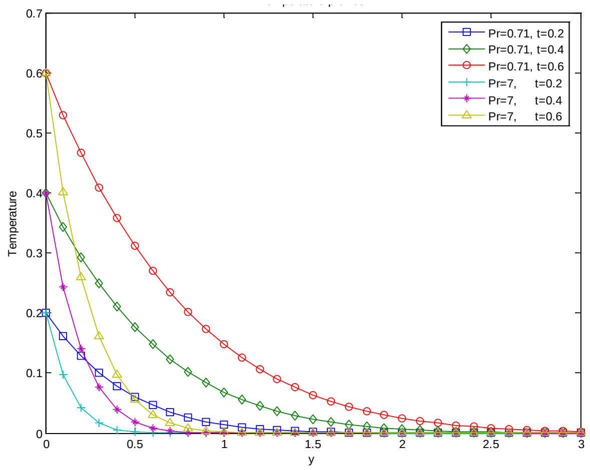

Figure 9: Temperature profiles

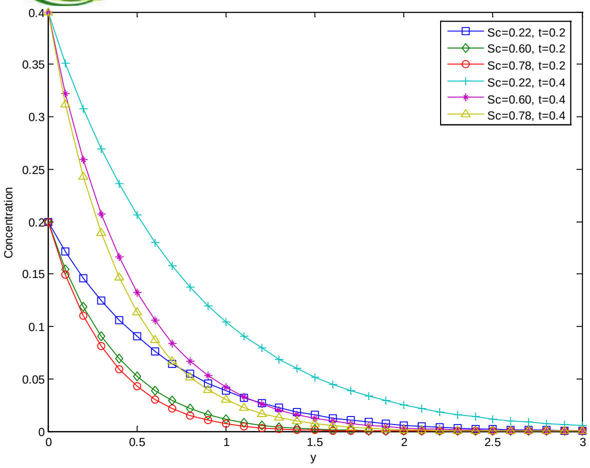

Figure 10: Concentration profiles when K=5

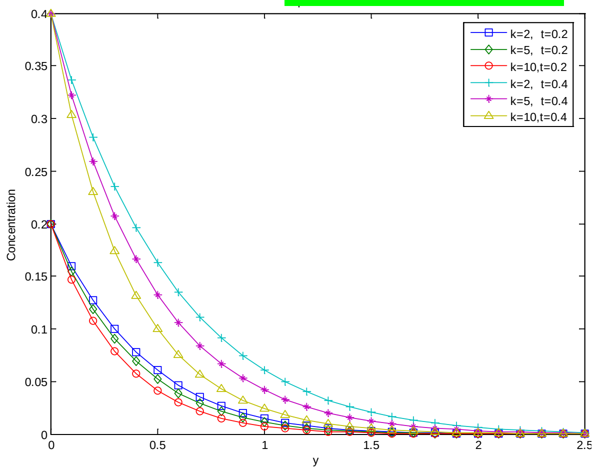

Figure 11: Concentration profiles when

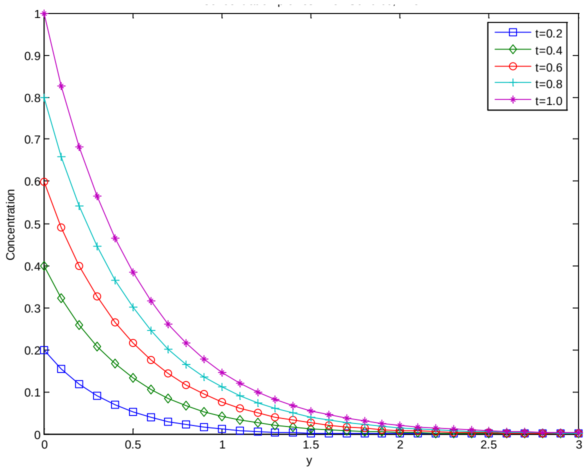

Figure 12: Concentration profiles when Sc=0.6 and K=5, Sc=0.6

Table 1: Velocity for different values of Pr=0.71, Sc=0.60, a=0.5, t=0.2, Gr=20, Gm=5

y	K=0.2	K=5	K=10	K=15	K=20
0	1.1052	1.1052	1.1052	1.1052	1.1052
0.2	0.9174	0.9150	0.9131	0.9115	0.9102
0.4	0.6739	0.6704	0.6677	0.6655	0.6638
0.6	0.4477	0.4444	0.4419	0.4399	0.4385
0.8	0.2716	0.2690	0.2671	0.2657	0.2646
1.0	0.1510	0.1492	0.1479	0.1470	0.1464
1.2	0.0771	0.0760	0.0752	0.0747	0.0743
1.4	0.0361	0.0355	0.0351	0.0348	0.0346
1.6	0.0156	0.0152	0.0150	0.0149	0.0148
1.8	0.0062	0.0060	0.0059	0.0058	0.0058
2.0	0.0022	0.0022	0.0021	0.0021	0.0021

Table 2: Velocity for different values of Pr=0.71, Sc=0.60, a=0.5, t=0.2, Gr=-20, Gm=-5

y	K=0.2	K=5	K=10	K=15	K=20
0	1.1052	1.1052	1.1052	1.1052	1.1052
0.2	0.7087	0.7111	0.7131	0.7147	0.7160
0.4	0.4477	0.4511	0.4539	0.4560	0.4577
0.6	0.2726	0.2759	0.2785	0.2804	0.2819
0.8	0.1570	0.1596	0.1615	0.1630	0.1640
1.0	0.0843	0.0860	0.0873	0.0882	0.0889
1.2	0.0417	0.0428	0.0435	0.0440	0.0444
1.4	0.0188	0.0194	0.0199	0.0201	0.0203
1.6	0.0077	0.0080	0.0082	0.0084	0.0085

1.8	0.0028	0.0030	0.0031	0.0032	0.0032
2.0	0.0009	0.0010	0.0010	0.0011	0.0011

Table 3: Velocity for different values of Pr=0.71, Sc=0.60, a=0.5, t=0.4, Gr=20, Gm=5

y	K=0.2	K=5	K=10	K=15	K=20
0	1.2214	1.2214	1.2214	1.2214	1.2214
0.2	1.3239	1.3109	1.3021	1.2959	1.2913
0.4	1.2151	1.1938	1.1799	1.1704	1.1635
0.6	1.0103	0.9860	0.9707	0.9606	0.9536
0.8	0.7821	0.7586	0.7445	0.7356	0.7296
1.0	0.5712	0.5509	0.5392	0.5322	0.5276
1.2	0.3965	0.3803	0.3714	0.3662	0.3629
1.4	0.2627	0.2506	0.2442	0.2406	0.2384
1.6	0.1666	0.1580	0.1536	0.1513	0.1499
1.8	0.1013	0.0955	0.0926	0.0912	0.0903
2.0	0.0592	0.0553	0.0536	0.0527	0.0522

Table 4: Velocity for different values of Pr=0.71, Sc=0.60, a=0.5, t=0.4, Gr=-20, Gm=-5

y	K=0.2	K=5	K=10	K=15	K=20
0	1.2214	1.2214	1.2214	1.2214	1.2214
0.2	0.6244	0.6374	0.6462	0.6523	0.6570
0.4	0.2949	0.3162	0.3301	0.3396	0.3465
0.6	0.1236	0.1480	0.1633	0.1733	0.1804
0.8	0.0409	0.0644	0.0786	0.0874	0.0934
1.0	0.0048	0.0251	0.0368	0.0439	0.0485
1.2	-0.0085	0.0077	0.0167	0.0218	0.0251
1.4	-0.0115	0.0006	0.0070	0.0106	0.0128
1.6	-0.0106	-0.0019	0.0025	0.0048	0.0062
1.8	-0.0084	-0.0025	0.0003	0.0018	0.0026
2.0	-0.0061	-0.0023	-0.0005	0.0003	0.0008

CONCLUSIONS

An exact solution for hydrodynamic flow of a viscous incompressible fluid past an exponentially accelerated infinite vertical plate with variable temperature and mass diffusion in the presence of a homogeneous chemical reaction of first order has been studied. The dimensionless governing equations are solved by the usual Laplace Transform technique. The effect of different physical parameters like accelerated parameter, Thermal grashof number, mass grashof number, prandtl number, Schmidt number and time are studied graphically while the effect of chemical reaction parameter is presented with numerical computations through tables. It is observed that the velocity increases with increasing values a in both cases of cooling and heating of the plate. It is found that the velocity increases with increasing values of thermal Grashof number or mass Grashof number in the case of cooling of the plate with a reverse effect in the case of heating of the plate. It is also observed that, in the case of cooling, the velocity increases with decrease of Prandtl number or Schmidt number or chemical reaction parameter but the trend is just reversed in the case of heating of the plate. It is interesting to note that there is a sudden drop in temperature in water compared to that in air. Finally, it is also observed that, the concentration falls slowly and steadily for hydrogen comparatively other gases ammonia and water vapor. And here we conclude that the concentration increases with decreasing chemical reaction parameter and it increases with respect to time.

NOMENCLATURE

A Constant
C' Species concentration
C'_w. Concentration of the plate
C'_∞ Concentration of the fluid far away from the plate.
C Dimensionless concentration
C_p Specific heat at constant pressure.
g Acceleration due to gravity.
G_r Thermal Grashof number
G_m Mass Grashof number
K Thermal conductivity of the fluid
K Chemical reaction parameter
Pr Prandtl number
Sc 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' Co-ordinate axis normal to the plate
y Dimensionless co-ordinate axis normal to the plate
α Thermal diffusivity
β Volumetric Coefficient of thermal expansion
β^* Volumetric Coefficient of expansion with concentration
μ Coefficient of viscosity
υ Kinematic viscosity
ρ Density of the fluid
θ Dimensionless temperature
erf Error function
$erfc$ Complementary error function

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