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MASS TRANSFER WITH CHEMICAL REACTION EFFECTS ON MHD FREE CONVECTIVE FLOW PAST AN ACCELERATED VERTICAL PLATE EMBEDDED IN A POROUS MEDIUM

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ABSTRACT

This paper presents an analytical study of MHD heat and mass transfer flow by natural convection through an accelerated infinite vertical plate embedded in a porous medium in the presence of chemical reaction. The plate accelerates in its own plane. The governing equations of motion are solved in closed form by the Laplace-transform technique. The flow phenomenon has been characterized with the help of flow parameters such as porosity parameter, Schmidt number (Sc) and Prandtl number (Pr). The effects of various flow parameters have been studied and results are presented graphically and discussed qualitatively. The problem assumes greater importance in several geo-physicals and astrophysical studies hence the analysis.

KEYWORDS: Chemical Reaction, Heat and Mass Transfer, MHD, Natural Convection, Porous Medium

1. INTRODUCTION

Natural convection flows are frequently encountered in physical and engineering problems such as chemical catalytic reactors, nuclear waste materials etc. Transient free convection is important in many practical applications, such as furnaces, electronic components, solar collectors, thermal regulation process, security of energy systems etc. MHD free convective heat transfer flow is considerable interest in the technical field due its frequent occurrence in industrial technology and geothermal application, liquid metal fluids and MHD power generation systems etc. Transport processes in porous media are encountered in a board range of scientific and engineering problems associated with the fiber and granular insulation materials, packed-bed chemical reactors and transpiration cooling. Simultaneous heat and mass transfer from different geometries embedded in porous media has many engineering and geophysical applications such as geothermal reservoirs, drying of porous solids, thermal insulation and underground energy transport.

The effect of chemical and thermal diffusion in Hall current on the unsteady Hydro magnetic flow near an infinite vertical porous plate was studied by Acharya et al. [1]. Recently Aldoss et al. [2] investigated MHD transient free convection flow over a surface by finite difference method. Chamkha et al. [3] examined the effect of thermophoresis of aerosol practical in the laminar boundary layer on a vertical plate. Free convection effects on flow past a moving vertical plate embedded in porous medium by Laplace-transform technique analyzed by Chaudhary and Jain [4]. Chin et al. [5] studied the effect of variable viscosity on mixed convection boundary layer over a vertical surface. The effects of heat and mass transfer laminar boundary layer flow over a wedge have been concluded by Gebhart and Pera [6]. Hady et al. [7] investigated the effect of temperature-dependent viscosity on the mixed convection flow from vertical plate. Mixed convection flow from a vertical flat plate with temperature dependent viscosity has been studied by Hossain and Munir [8].

Chemical reactions usually accompany a large amount of exothermic and endothermic reactions. These characteristics can be easily seen in a lot of industrial processes. It has been realized that it is not always permissible to neglect the convection effects in porous constructed chemical reactors. The reaction produced in a porous medium was extraordinarily in common, such as the topic of PEM fuel cells modules and the polluted underground water because of discharging the toxic substance etc. In recent years, Kandasamy et al. [9] studied the heat and mass transfer under a chemical reaction with a heat source. Kim [10] reported the investigating results in the problem of unsteady of MHD convective heat transfer a semi infinite vertical porous moving plate by considering variable suction. The problem of unsteady free convective flow and mass transfer of a rotating elastico-viscous fluid through porous media past a vertical porous plate was presented by Panda et al. [11]. Sattar [12] had discussed the free convection and the mass transfer through a porous medium past an infinite vertical plate with time dependent temperature and concentration. Seddeek [13] studied the thermal radiation and buoyancy effect on MHD free convection heat generation flow over an accelerating permeable surface with influence temperature dependent viscosity and later chemical reaction, variable viscosity, radiation, variable suction on hydromagnetic convection flow problems were included by Seddeek et al. [14]. The problem of MHD free convection flow an accelerated vertical porous plate by finite difference approximation was presented by Singh [15]. Soundalgekar [16] had discussed the free convection effects on steady MHD flow past a vertical plate. Alharbi et al. [18] investigated heat and mass transfer characteristics of an incompressible MHD visco-elastic fluid flow immersed in a porous medium with chemical reaction and thermal stratification effects.

Hence, based on the above mentioned investigations and applications, the objective of this paper is to study MHD heat and mass transfer flow by natural convection past an accelerated infinite vertical plate embedded in porous medium in the presence of chemical reaction when the plate is accelerated in its own plane. The results obtained are presented graphically and discussed.

2. MATHEMATICAL ANALYSIS

We consider a two-dimensional flow of an incompressible and electrically conducting viscous fluid along an infinite vertical plate that is embedded in porous medium. The x' - axis is taken along the infinite plate and y' - axis normal to it. Initially, the plate and the fluid are at same temperature T'_∞ with concentration level C'_∞ at all points. At time $t' > 0$, the plate temperature is raised to T'_w and the concentration level at the plate is raised to C'_w. A magnetic field of uniform strength is applied perpendicular to the plate. Let us assume the plate is accelerating with a velocity $u' = Ut'$ in its own plane at time $t' > 0$. Under these conditions and assuming variation of density in the body force term (Boussinesq's approximation), the problem can be governed by the following set of equations:

$$\frac{\partial u'}{\partial t'} = g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + \upsilon\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho}u' - \frac{\upsilon}{K^*}u' \tag{2.1}$$

$$\rho C_p\frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} \tag{2.2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} - K'C' \tag{2.3}$$

The necessary boundary conditions are:

$$\left.\begin{array}{l} t' \le 0, u' = 0, T' = T'_\infty, C' = C'_\infty \;\; for\ all\ y' \\ t' > 0, \begin{bmatrix} u' = Ut', T' = T'_w, C' = C'_w \ at\ y' = 0 \\ u' \to 0, T' \to T'_\infty, C' \to C'_\infty \ as\ y' \to \infty \end{bmatrix} \end{array}\right\} \tag{2.4}$$

Where, $U = \dfrac{u_0^3}{\upsilon}$

Introducing the following non-dimensional quantities:

$$\left.\begin{array}{l} u = \dfrac{u'}{u_0}, t = \dfrac{t'u_0^2}{\upsilon}, y = \dfrac{y'u_0}{\upsilon}, \theta = \dfrac{T' - T'_\infty}{T'_w - T'_\infty}, C = \dfrac{C' - C'_\infty}{C'_w - C'_\infty}, G_r = \dfrac{g\beta\upsilon\left(T'_w - T'_\infty\right)}{u_0^3} \\ G_c = \dfrac{g\beta^*\upsilon\left(C'_w - C'_\infty\right)}{u_0^3}, P_r = \dfrac{\mu C_p}{k}, S_c = \dfrac{\upsilon}{D}, K = \dfrac{\upsilon K'}{u_0^2}, \alpha = \dfrac{u_0^2 K^*}{\upsilon^2}, M = \dfrac{\sigma B_0^2 \upsilon}{\rho u_0^2} \end{array}\right\} \tag{2.5}$$

The equations (2.1) to (2.4) reduce to following non-dimensional form:

$$\frac{\partial u}{\partial t} = G_r\theta + G_c C + \frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{\alpha}\right)u \tag{2.6}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial y^2} \tag{2.7}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} - KC \tag{2.8}$$

With the following boundary conditions:

$$\left.\begin{array}{l} t \le 0, u = 0, \theta = 0, C = 0 \;\; for\ all\ y \\ t > 0, \begin{bmatrix} u = t, \theta = 1, C = 1\, at\ y = 0 \\ u \to 0, \theta \to 0, C \to 0\ as\ y \to \infty \end{bmatrix} \end{array}\right\} \tag{2.9}$$

All the physical variables are defined in the nomenclature.

The dimensionless governing equations (2.6) to (2.8), subject to the boundary conditions (2.9), are solved by the usual Laplace-transform technique and the solutions are derived as follows:

$$\theta\left(y,t\right) = erfc\left(\frac{y}{2}\sqrt{\frac{P_r}{t}}\right) \tag{2.10}$$

$$C(y,t)=\frac{1}{2}\left[\exp\left(y\sqrt{KS_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}+\sqrt{Kt}\right)+\exp\left(-y\sqrt{KS_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}-\sqrt{Kt}\right)\right] \tag{2.11}$$

$$\begin{aligned}
u(y,t)=&\frac{1}{2}\left(t-\frac{a_1}{a_2}-\frac{a_3}{a_4-K}\right)\left[\exp\left(y\sqrt{a}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{at}\right)+\exp\left(-y\sqrt{a}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{at}\right)\right]\\
&-\frac{y}{4\sqrt{a}}\left[\exp\left(-y\sqrt{a}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{at}\right)-\exp\left(y\sqrt{a}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{at}\right)\right]\\
&+\frac{a_1\exp(a_2t)}{2a_2}\left[\begin{array}{l}\exp\left(y\sqrt{a+a_2}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(a+a_2)t}\right)\\+\exp\left(-y\sqrt{a+a_2}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(a+a_2)t}\right)\end{array}\right]\\
&+\frac{a_3\exp\left((a_4-K)t\right)}{2(a_4-K)}\left[\begin{array}{l}\exp\left(y\sqrt{a+a_4-K}\right)erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(a+a_4-K)t}\right)\\+\exp\left(-y\sqrt{a+a_4-K}\right)erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(a+a_4-K)t}\right)\end{array}\right]\\
&-\frac{a_1\exp(a_2t)}{2a_2}\left[\begin{array}{l}\exp\left(y\sqrt{a_2P_r}\right)erfc\left(\frac{y}{2}\sqrt{\frac{P_r}{t}}+\sqrt{a_2t}\right)\\+\exp\left(-y\sqrt{a_2P_r}\right)erfc\left(\frac{y}{2}\sqrt{\frac{P_r}{t}}-\sqrt{a_2t}\right)\end{array}\right]\\
&-\frac{a_3\exp\left((a_4-K)t\right)}{2(a_4-K)}\left[\begin{array}{l}\exp\left(y\sqrt{a_4S_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}+\sqrt{a_4t}\right)\\+\exp\left(-y\sqrt{a_4S_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}-\sqrt{a_4t}\right)\end{array}\right]\\
&+\frac{a_3}{2(a_4-K)}\left[\begin{array}{l}\exp\left(y\sqrt{KS_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}+\sqrt{Kt}\right)\\+\exp\left(-y\sqrt{KS_c}\right)erfc\left(\frac{y}{2}\sqrt{\frac{S_c}{t}}-\sqrt{Kt}\right)\end{array}\right]+\frac{a_1}{a_2}erfc\left(\frac{y}{2}\sqrt{\frac{P_r}{t}}\right)
\end{aligned} \tag{2.12}$$

Where, $a=M+\frac{1}{\alpha}, a_1=\frac{G_r}{P_r-1}, a_2=\frac{a}{P_r-1}, a_3=\frac{G_c}{S_c-1}, a_4=\frac{a-K}{S_c-1}$

In order to get the physical insight into the problem, the numerical values of u have been computed from (2.12).

$erfc(x)$ Being the complementary error function defined by

$erfc(x) = 1 - erf(x), erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-\eta^2) d\eta$ and $erfc(X_1 + iY_1)$ is the complementary error function of the complex argument which can be calculated in terms of tabulated numerical values of the auxiliary function $W_1(z)$, $z = X_1 + iY_1$ [24]. The table given in [24] does not give $erfc(X_1 + iY_1)$ directly but an auxiliary function $W_1(X_1 + iY_1)$ that is defined as:

$$erfc(X_1 + iY_1) = W_1(-Y_1 + iX_1) \exp\left(-(X_1 + iY_1)^2\right)$$

Some properties of $W_1(X_1 + iY_1)$ are

$$W_1(-X_1 + iY_1) = W_2(X_1 + iY_1)$$

$$W_1(X_1 - iY_1) = 2\exp\left(-(X_1 - iY_1)^2\right) - W_2(X_1 + iY_1)$$

Where, $W_2(X_1 + iY_1)$ is complex conjugate of $W_1(X_1 + iY_1)$.

Nusselt Number

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = \sqrt{\frac{P_r}{\pi t}} \qquad \dots (2.13)$$

Sherwood Number

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = \sqrt{KS_c} erf\left(\sqrt{Kt}\right) + \sqrt{\frac{S_c}{\pi t}} \exp(-Kt) \qquad \dots (2.14)$$

Skin-Friction

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = \left(t - \frac{a_1}{a_2} - \frac{a_3}{a_4 - K}\right)\left[\sqrt{a}\, erf\left(\sqrt{at}\right) + \frac{1}{\sqrt{\pi t}} \exp(-at)\right] + \frac{1}{2\sqrt{a}} erf\left(\sqrt{at}\right)$$

$$+ \frac{a_1 \exp(a_2 t)}{a_2}\left[\sqrt{a + a_2}\, erf\left(\sqrt{(a + a_2)t}\right) + \frac{1}{\sqrt{\pi t}} \exp\left(-(a + a_2)t\right)\right]$$

$$+ \frac{a_3 \exp\left((a_4 - K)t\right)}{(a_4 - K)}\left[\sqrt{a + a_4 - K}\, erf\left(\sqrt{(a + a_4 - K)t}\right) + \frac{1}{\sqrt{\pi t}} \exp\left(-(a + a_4 - K)t\right)\right]$$

$$-\frac{a_1 \exp(a_2 t)}{a_2}\left[\sqrt{P_r a_2}\, erf\left(\sqrt{a_2 t}\right)+\sqrt{\frac{P_r}{\pi t}}\exp(-a_2 t)\right]$$

$$-\frac{a_3 \exp((a_4-K)t)}{(a_4-K)}\left[\sqrt{a_4 S_c}\, erf\left(\sqrt{a_4 t}\right)+\sqrt{\frac{S_c}{\pi t}}\exp(-a_4 t)\right]$$

$$+\frac{a_3}{(a_4-K)}\left[\sqrt{KS_c}\, erf\left(\sqrt{Kt}\right)+\sqrt{\frac{S_c}{\pi t}}\exp(-Kt)\right]+\frac{a_1}{a_2}\sqrt{\frac{P_r}{\pi t}} \tag{2.15}$$

3. RESULT AND DISCUSSION

The convection flows driven by combinations of diffusion effects are very important in many applications. The foregoing formulations may be analyzed to indicate the nature of interaction of the various contributions to buoyancy. In order to gain physical insight into the problem, the values of Prandtl number are chosen 0.71 and 7.0 which represents air and water respectively at $20^0 C$ temperature and 1 atmospheric pressure and the values of Schmidt number are chosen to represent the presence of species by hydrogen (0.22), water vapour (0.60), ammonia (0.78) at $25^0 C$ temperature and 1 atmospheric pressure.

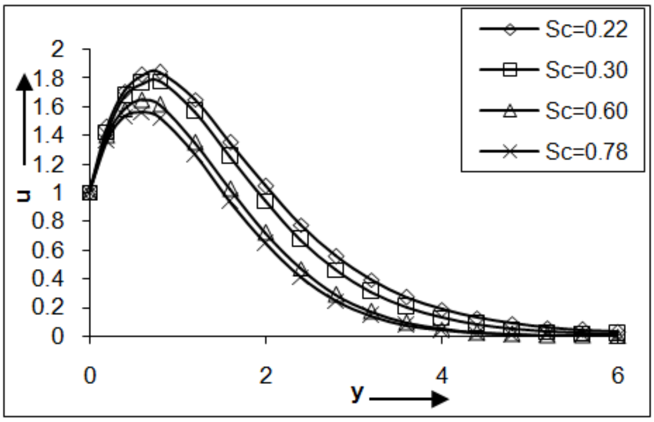

Figure 1: Velocity Distribution for Various Values of Sc

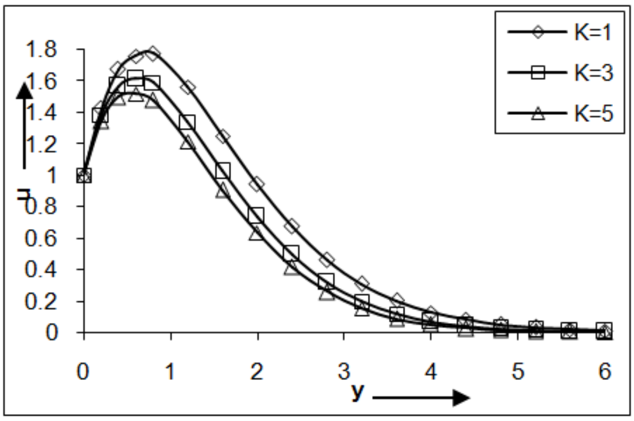

Figure 2: Velocity Distribution for Various Values of K

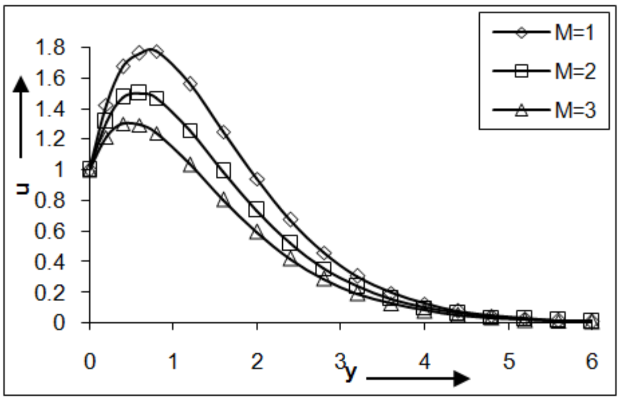

Figure 3: Velocity Distribution for Various Values of M

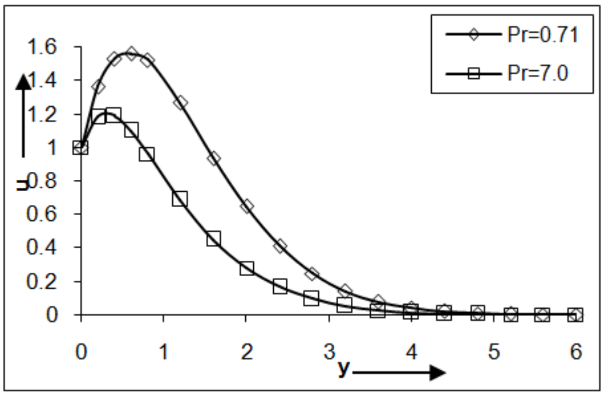

Figure 4: Velocity Distribution for Various Values of Pr

Figures 1, 2, 3 and 4, represent the velocity profiles against y for different values of Schmidt number (Sc), Chemical reaction parameter (K), Magnetic parameter (M) and Prandtl number (Pr). It is evident from all the figures that the velocity increases sharply and attains its maximum value in the vicinity of the plate and then leads to zero as $y \to \infty$. The velocity decreases owing to an increase in the value of Sc and chemical reaction parameter (K) as shown in figures 1 and 2 respectively. In figure 3, we observe that an increase in value of M leads to fall in the velocity. It is because that the application of transverse magnetic field will result a resistive type of force (Lorentz force) similar to drag force which tends to resist the flow and thus reducing its velocity. In figure 4, the velocity for Pr = 0.71 is higher than that of Pr = 7.0. Physically, it is possible because fluids with higher Prandtl number have high viscosity and hence move slowly.

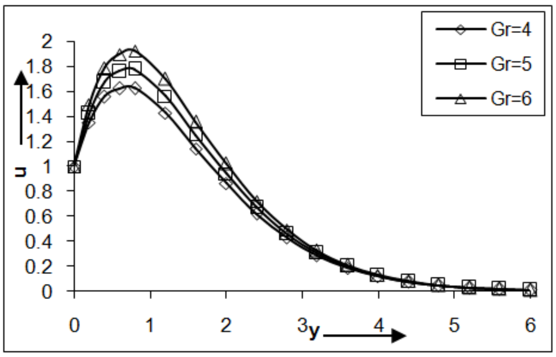

Figure 5: Velocity Distribution for Various Values of Gr

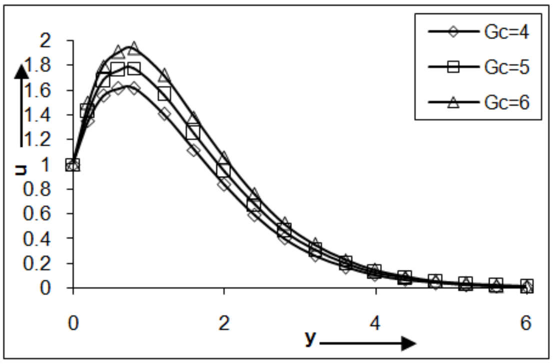

Figure 6: Velocity Distribution for Various Values of Gc

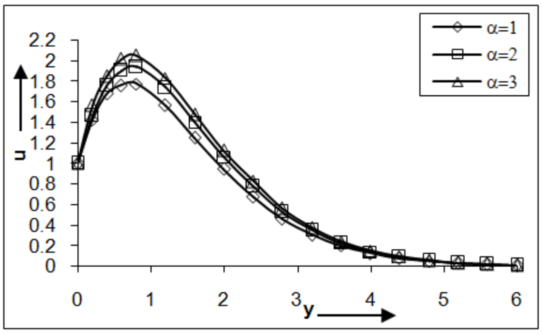

Figure 7: Velocity Distribution for Various Values of

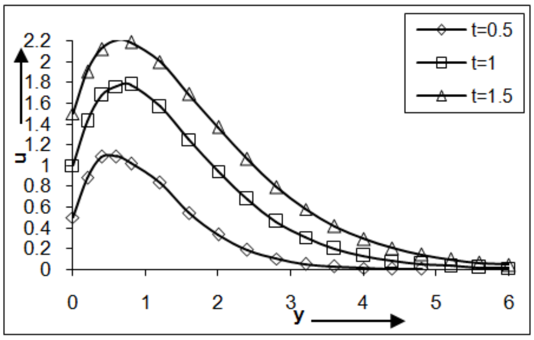

Figure 8: Velocity Distribution for Various Values of t

Figures 5, 6, 7 and 8, show the effects of thermal Grashof number (Gr), the solutal Grashof number (Gc), the porosity parameter (α) and time (t) on velocity profiles against y respectively. It is obvious from all the figures that the maximum velocity attains in the vicinity of the plate then decreases to zero as $y \to \infty$. It is noted that the velocity increases with increasing Gr and t as shown in figures 5 and 8 respectively. Further, the magnitude of velocity leads to an increase with an increase in Gc as shown in figure 6. It is due to the fact an increase in the value of the solutal Grashof number has the tendency to increase the mass buoyancy effect. The presence of a porous medium increases the resistance to flow resulting in decrease in the flow velocity. This behaviour is depicted by the decrease in the velocity as □ decreases as shown in figure 7.

Figures 9 and 10, reveal the temperature profiles against y for different values of Pr and t respectively. In both figures, the magnitude of temperature is maximum at the plate and then decays to zero asymptotically. In figure 9, the magnitude of temperature for air (Pr = 0.71) is greater than that of water (Pr = 7.0). This is due to fact that thermal conductivity of fluid decreases with increasing Pr, resulting a decrease in thermal boundary layer thickness. In figure 10, the temperature profile increases with increasing t.

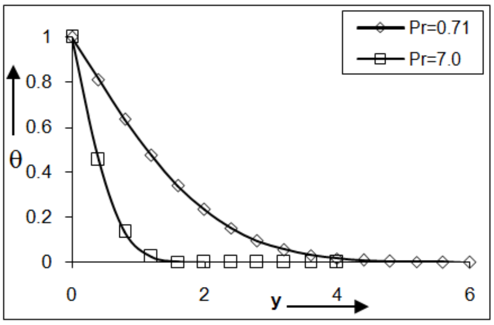

Figure 9: Temperature Dist. for Various Values of Pr

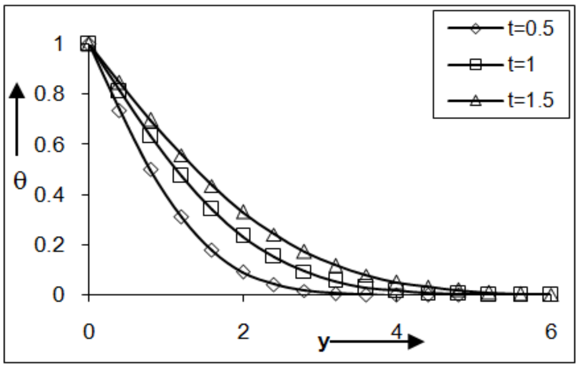

Figure 10: Temperature Dist. for Various Values of t

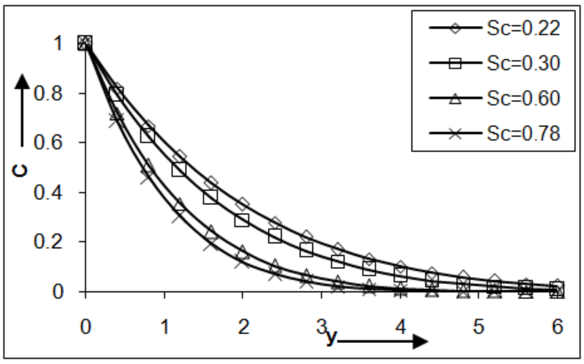

Figure 11: Concentration Dist. for Various Values of Sc

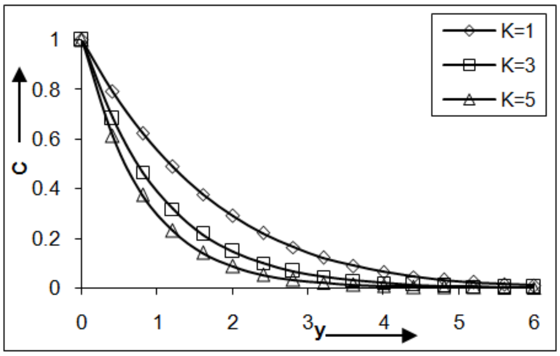

Figure 12: Concentration Dist. for Various Values of K

Figures 11, 12 and 13, concern with the effects of Schmidt number (Sc), chemical reaction parameter (α) and time (t) on the concentration respectively. It is noted from all the figures that the concentration at all points in the flow field decreases exponentially with y and tends to zero as $y \rightarrow \infty$. A comparison of curves in the figure 11, shows a decrease in concentration with an increase in Schmidt number. Physically, it is true, since the increase of Sc means decrease of molecular diffusivity. That results in decrease of concentration boundary layer. Hence, the concentration of species is higher for small values of Sc and lower for large values of Sc. Further, in figure 12, we observe that the concentration profile decreases as increasing chemical reaction parameter (K), whereas, in figure 13, it increases with increasing t.

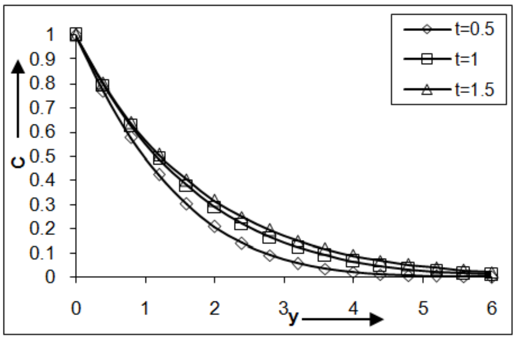

Figure 13: Concentration Dist. for Various Values of t

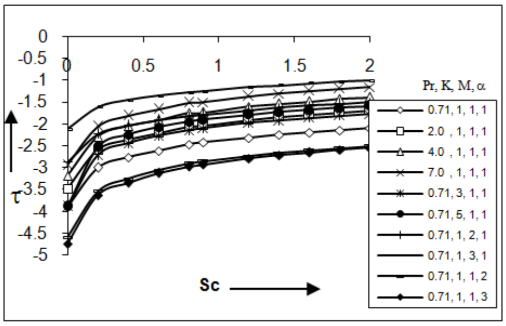

Figure 14: Skin-Friction for Various Values of Pr, K, M,

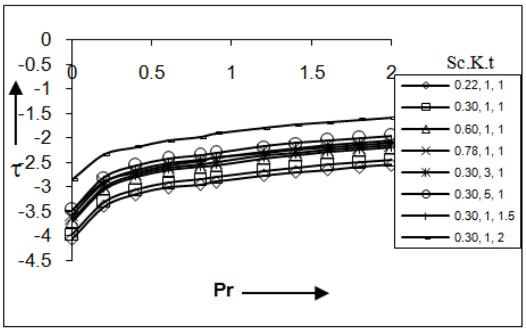

Figure 15: Skin-Friction for Various Values of Sc, K, t

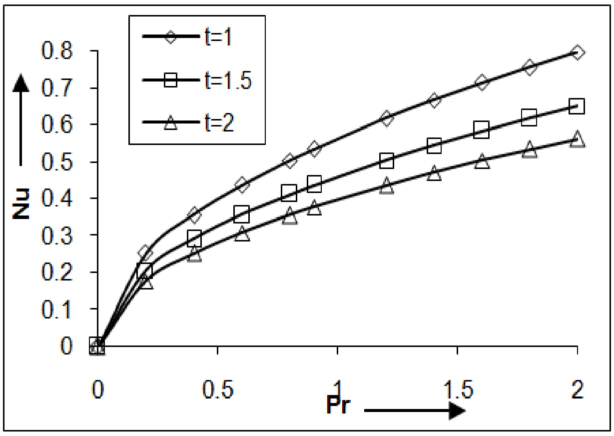

Figure 16: Nusselt Number for Various Values of t

Figure 14, reveals the skin-friction against Sc for various values of Pr, K, M and α. It is concluded that the skin-friction increases as increasing Sc as shown in the figure14. It is also observed that an increase in Pr, K, and M results to an increase in skin-friction, while, the skin-friction decreases with increasing K. Figure 15, represents the effects of Sc, K and t on skin-friction against Pr. It is noted that the skin-friction increases with Sc, K and t.

Figure 16, depicts the Nusselt number against Pr for various values of t. It is found that Nusselt number decreasing with increasing t, whereas, it increases with increasing Pr. The reason is that smaller values of Pr are equivalent to increasing thermal conductivities and therefore heat is able to diffuse away from the plate more rapidly than higher values of Prandtl number. Hence, the rate of heat transfer is reduced.

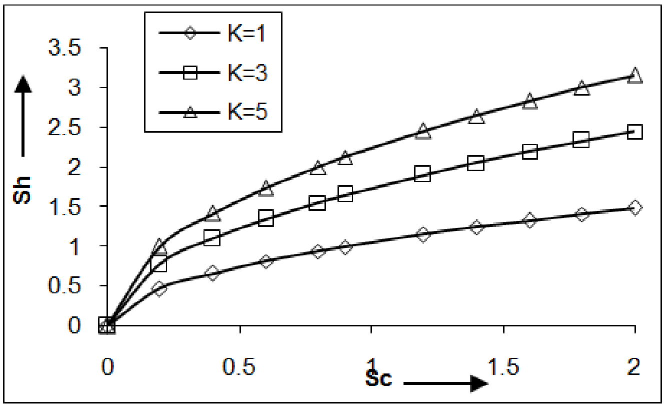

Figure 17: Sherwood Number for Various Values of K

Figure 17, represents the Sherwood number against Sc. It is observed that the Sherwood number increases with Sc and it also increases with increasing the chemical reaction parameter.

CONCLUSIONS

In this paper, we study MHD heat and mass transfer by free convection past an accelerated infinite vertical plate in the presence of chemical reaction. The non-dimensional equations are solved using Laplace-transform technique. From results we concluded that:

- The fluid velocity decreases with increasing Sc, K, M and Pr, while, it increases as increasing Gr, Gc, α and t.

- Temperature profile for air (Pr = 0.71) is higher than that of water (Pr = 7.0).
- An increase in Sc and K leads to decrease in the concentration, whereas, it increases with time t.
- Skin-friction against Sc, increases with increasing Pr, K and M, while, it decreases with increasing α and skin-friction against Pr, increases as increasing Sc, K and t.
- Nu increases with Pr, while decreases as increasing t and Sherwood number increases with Sc and K.

Nomenclature

C' - Concentration in the fluid, $mol.m^{-3}$; C - Dimensionless concentration

C_p - Specific heat at constant pressure, $J.Kg^{-1}.K^{-1}$; D - Mass diffusion coefficient, $m^2.s^{-1}$

G_c - The solutal Grashof number; G_r - The thermal Grashof number

g - Acceleration due to gravity, $m.s^{-1}$; k - Thermal conductivity, $Wm^{-1}K^{-1}$

K' -Chemical reaction parameter, J; K - Dimensionless chemical reaction parameter

K^* -The porosity parameter; M - The magnetic parameter; P_r - Prandtl number; S_c - Schmidt number

T' - Temperature of the fluid near the plate, K; t' - Time, s; t - Dimensionless time

u' - Velocity of the fluid in the x' - direction, $m.s^{-1}$; u_0 - Velocity of the plate, $m.s^{-1}$; u - Dimensionless velocity

y' - Coordinate axis normal to the plate, m; y - Dimensionless coordinate axis normal to the plate

Greek Symbols

α - Dimensionless porosity parameter; β - Volumetric coefficient of thermal expansion, K^{-1}

β^* - Volumetric coefficient of expansion with concentration, K^{-1}; μ - Coefficient of viscosity, Pa.s

υ - Kinematic viscosity, $m^2.s^{-1}$; ρ - Density of the fluid, $Kg.m^{-3}$; τ - Dimensionless skin-friction

θ - Dimensionless temperature; $erfc$ - Complementary error function; erf - Error function

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