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Unsteady MHD free convective Heat and Mass transfer flow near a Moving vertical porous plate with radiation & Thermo diffusion effects

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***Abstract*— The present study deals with Unsteady MHD free convective Heat and Mass transfer flow near an infinite vertical plate embedded in porous medium, which moves with time dependent velocity in a viscous, electrically conducting incompressible fluid, under the influence of uniform magnetic field, applied normal to the plate with radiation and Soret effects. The problem is solved analytically in closed form by Laplace transform technique and the expressions for velocity, temperature, concentration, skin friction, rate of heat and mass transfer has been obtained. The results obtained have also been presented numerically through graphs to observe the effects of various parameters and the physical aspects of the problem .**

Key words: Free convection, MHD flow, heat transfer, mass transfer, 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. when a conductive fluid moves through a magnetic field and an ionized gas is electrically conductive, the fluid may be influenced by the magnetic field. Magnetohydrodynamic free convection heat transfer flow is of considerable interest in the technical field due to its frequent occurrence in industrial technology and geothermal application, liquid metal fluids and MHD power generation systems etc. The phenomenon of heat and mass transfer frequently exist in chemically processed industries such as food processing and polymer production. Free convection flow involving coupled heat and mass transfer occurs frequently in nature. For this flow, the driving forces arise due to the temperature and concentration variations in the fluid. For example, in atmospheric flows, thermal convection resulting from heating of the earth by sunlight is affected by differences in water vapour concentration. Magnetohydrodynamics has attracted the attention of a large number of scholars due to its diversified applications. The study of effects of magnetic field on free convection flow is important in liquid-metals, electrolytes and ionized gases. The thermal physics of hydromagnetic problems with mass transfer is of interest in power engineering and metallurgy. Moreover, there are several engineering situations wherein combined heat and mass transport arise viz. humidifiers, dehumidifiers, desert coolers, chemical reactors etc. The usual way to study these phenomena is to consider a characteristic moving continuous surface.

Free convection flow with mass transfer past a vertical moving plate has been studied by Soundalgeker[1], Revankar[2], Soundalgeker *et al*.[3], Das et al. [4], Muthukumaraswamy et al. [5] and Panda *et al*.[6]. The effects of heat and mass transfer on a free convection flow near an infinite vertical porous plate has been extensively investigated by Takhar *et al*.[7], Hossain *et al*. [8], Israel *et al*.[9], Sahoo *et al*[10] ,Ali[11], Chaudhary and Jain[12]. Das[13] developed the problem by considering the magnetic effect on free convection flow in presence of thermal radiation. Hitesh Kumar [14] has studied the boundary layer steady flow and radiative heat transfer of a viscous incompressible fluid due to a stretching plate with viscous dissipation effect in the presence of a transverse magnetic field. The effects of radiation on unsteady MHD free convection flow of a viscous incompressible electrically conducting fluid past an exponentially accelerated vertical plate in the presence of a uniform transverse magnetic field on taking viscous and Joule dissipations into account have been studied by Maitree Jana et.al [15]. Chaudhary et.al. [16] have studied the MHD flow past an infinite vertical oscillating plate through porous medium, taking account of the presence of free convection and mass transfer. Rajput and Sahu[17] studied the effect of a uniform transverse magnetic field on the unsteady transient free convection flow of an incompressible viscous electrically conducting fluid between two infinite vertical parallel porous plates with constant temperature and variable mass diffusion. Manyonge et al [18] studied steady MHD poiseuille flow between two infinite parallel porous plates in an inclined magnetic field and discover that high magnetic field strength decreases the velocity.

The aim of the present investigation is to analyze the effect of heat and mass transfer on the unsteady free convection flow of a viscous, electrically conducting incompressible fluid near an infinite vertical plate embedded in porous medium which moves with time dependent velocity under the influence of uniform magnetic field, applied normal to the plate with radiation and Soret effects. A general exact solution of the governing partial differential equation is obtained by using Laplace transform technique. Furthermore, this general solution is applied to consider some important cases of the flow: (i) motion of the plate with uniform velocity and (ii) the single accelerated motion of the plate.

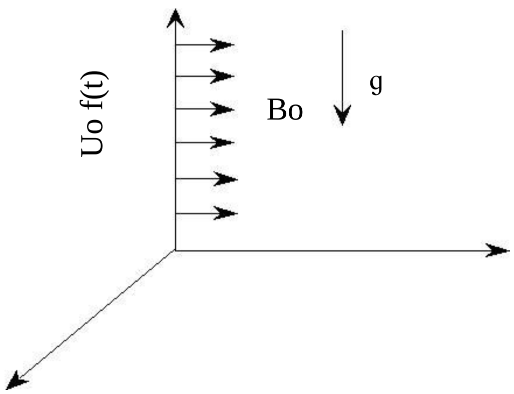

Fig.1 A schematic of the problem and coordinate system

2. Formulation of the problem

Let us consider unsteady free convection and mass transfer flow of a viscous incompressible and electrically conducting fluid along an infinite non-conducting vertical flat plate (or surface) through a porous medium in presence of a uniform transverse magnetic field B_0 applied on this plate. An arbitrary point has been chosen on this plate as the origin of a Cartesian co-ordinate system with the x′-axis along the plate in the upward direction and the y′-axis normal to the plate (Fig.1).

Initially for time $t' \leq 0$, the plate and the fluid are maintained at the same constant temperature T'_∞ in a stationary condition with the same species concentration C'_∞ at all points. Subsequently ($t' > 0$), the plate is assumed to be accelerating with a velocity $U_0 f(t')$ in its own plane along the x′-axis, instantaneously the temperature of the plate and the concentration are raised to T_w' and C'_w respectively, which are hereafter regarded as constant.

For free convection flow, we also assume that : (i) All the physical properties of the fluid such as coefficient of viscosity(μ), kinematic coefficient of viscosity(ν), specific heat at constant pressure (C_P), thermal conductivity(κ), volumetric coefficient of thermal expansion(β_T^*),volumetric coefficient of expansion for concentration(β^*_C), chemical molecular diffusivity(D_M) and Thermal diffusion (Soret), etc remain constant. (ii) The effect of variations of density(ρ) (with temperature) and species concentration are considered only on the body force term, in accordance with the usual Boussinesq approximation. (iii) Since the flow of the fluid is assumed to be in the direction of the x*-axis, so the physical quantities are functions of the space co-ordinate y* and time t* only.

Under the above assumptions, the governing equations for the two dimensional flow can be expressed as follows:

Momentum equation:

$$\frac{\partial u^*}{\partial t^*} = \vartheta \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta^*(T^* - T^*_\infty) + g\beta^*(C^* - C^*_\infty) - \frac{\vartheta}{K^*}u^* - \frac{\sigma B_0^2}{\rho}u^* \qquad (2.1)$$

Energy Equation:

$$\frac{\partial T^*}{\partial t^*} = \frac{K^*}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho C_p}\frac{\partial q_r^*}{\partial y^*} \qquad (2.2)$$

Concentration equation:

$$\frac{\partial C^*}{\partial t^*} = D_M \frac{\partial^2 C^*}{\partial y^{*2}} - D_T \frac{\partial^2 T^*}{\partial y^{*2}} \qquad (2.3)$$

where u* velocity, T* is the temperature, C* is the species concentration and g is the acceleration due to gravity.

The initial and boundary conditions corresponding to the present problem are

$$u^*(y^*,t^*) = 0,\ T^*(y^*,t^*) = T^*_\infty,$$
$$C^*(y^*,t^*) = C^*_\infty \quad for\, y^* \geq 0\ and\ t^* \leq 0$$
$$u^*(0,t^*) = u_0 f(t^*),\ \ T^*(0,t^*) = T^*_w,\ C^*(0,t^*) = C^*_w \ \ for\ t^* \leq 0) \qquad (2.4)$$
$$u^* \to 0,\quad T^* \to T^*_\infty,\quad C^* \to C^*_\infty \qquad y^* \to \infty\ \ and\ for\, t^* > 0$$

To reduce the above equations into non-dimensional form for convenience, let us introduce the following dimensionless variables and parameters:

$$u_0 = \frac{u_0^*}{U_0},\ y = \frac{y^* U_0}{\vartheta},\quad t = \frac{t^* U_0^2}{\vartheta},$$
$$G_r = \frac{\vartheta g \beta_T (T_w^* - T_\infty^*)}{U_0^3},\ M = \frac{\sigma B_0^2 \vartheta}{\rho U_0^2}, \qquad (2.5)$$
$$P_r = \frac{\rho \vartheta C_p}{K^*},\quad G_m = \frac{\vartheta g \beta_C (C_w^* - C_\infty^*)}{U_0^3}$$
$$S_c = \frac{\vartheta}{D_M},\quad S_0 = \frac{(T_w^* - T_\infty^*)D_t}{(C_w^* - C_\infty^*)\vartheta},$$
$$K = \frac{K^* U_0^2}{\vartheta^2},\ \gamma = \frac{k_1^* \vartheta}{U^2},\ S_c = \frac{\vartheta}{D^*},\ \omega = \frac{\omega^* \vartheta}{U_0^2},$$
$$\theta = \frac{(T^* - T_\infty^*)}{T_w^* - T_\infty^*},\quad C = \frac{(C^* - C_\infty^*)}{C_w^* - C_\infty^*},\quad F = \frac{4\vartheta I^*}{K U_0^2}$$

where Gr is the thermal Grashof number, Gm is the mass Grashof number, K is the permeability parameter, M is the magnetic parameter, Pr is Prandtl number, Sc is Schmidt number, β_T is thermal expansion coefficient, β_C is concentration expansion coefficient and ω is frequency of oscillation. Other physical variables have their usual meanings.

With the help of (2.5), the governing equations (2.1) to (2.3) reduce to

With the help of (2.5), the governing equations (2.1) to (2.3) reduce to

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_r\theta + G_m C - Nu \qquad (2.6)$$

$$\frac{\partial^2\theta}{\partial y^2} - P_r\frac{\partial\theta}{\partial t} + G_r\theta + F\theta = 0 \quad (2.7)$$

$$\frac{\partial^2 C}{\partial y^2} - S_c\frac{\partial C}{\partial t} + S_c S_0\frac{\partial^2\theta}{\partial y^2} = 0 \quad (2.8)$$

The corresponding initial and boundary conditions in non-dimensional form are :

$$u(y,t) = 0, \theta(y,t) = 0, C(y,t) = 0 \; for\; y^* \geq 0 \; and\; t^* \leq 0$$
$$u(0,t) = f(t),\; \theta(0,t) = 1,\; C(0,t) = 1 \; for\; t^* > 0)$$
$$u \to 0,\quad \theta \to 0,\quad C \to 0 \quad y \to \infty \quad and\; for\; t > 0 \quad (2.9)$$

3. Solution of the problem

In order to obtain the analytical solutions of the system of differential equations (2.6) to (2.8), we shell use the Laplace transform technique.

Applying the Laplace transform (with respect to time t) to equations (2.6) to (2.9), we get

$$\bar\theta = \frac{1}{s}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) \quad (3.1)$$

$$\bar C = \frac{1}{s}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) - A_2\frac{1}{s+A_3}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) - A_6\frac{1}{s}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) + \frac{A_6}{s+A_5}\exp\left(-y\sqrt{S_c}\sqrt{s}\right)$$
$$+A_2\frac{1}{s+A_3}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) + A_6\frac{1}{s}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) - \frac{A_6}{s+A_5}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) \text{ for } P_r \neq 1 \text{ and } S_c \neq 1 \quad (3.2)$$

$$\bar u(y,s) = \bar f(s)\exp\left(-y\sqrt{s+N}\right) + \frac{A_{29}}{s}\exp\left(-y\sqrt{s+N}\right) + \frac{A_{10}}{s+A_9}\exp\left(-y\sqrt{s+N}\right) + \frac{A_{30}}{s-A_{12}}\exp\left(-y\sqrt{s+N}\right)$$
$$+\frac{A_{31}}{s+A_3}\exp\left(-y\sqrt{s+N}\right) + \frac{A_{32}}{s+A_5}\exp\left(-y\sqrt{s+N}\right) + \frac{A_{33}}{s+A_{21}}\exp\left(-y\sqrt{s+N}\right) + \frac{A_{34}}{s}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right)$$
$$-\frac{A_{10}}{s+A_9}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) - A_{13}\frac{1}{s}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) + \frac{A_{35}}{s-A_{12}}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) + \frac{A_{15}}{s+A_3}\exp\left(-y\sqrt{S_c}\sqrt{s}\right)$$
$$+\frac{A_{18}}{s-A_{12}}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) + \frac{A_{19}}{s+A_5}\exp\left(-y\sqrt{S_c}\sqrt{s}\right) + \frac{A_{36}}{s+A_{21}}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) + \frac{A_{23}}{s+A_3}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right)$$
$$+\frac{A_{28}}{s+A_5}\exp\left(-y\sqrt{P_r}\sqrt{s+F}\right) \text{ for } P_r \neq 1 \text{ and } S_c \neq 1 \quad (3.3)$$

For $P_r = 1$ and $S_c = 1$

$$\bar\theta = \frac{1}{s}\exp\left(-y\sqrt{s+F}\right) \quad (3.4)$$

$$\bar C = \frac{1}{s}\exp\left(-y\sqrt{s}\right) - B_1\frac{1}{s}\exp\left(-y\sqrt{s}\right) + \frac{S_0}{s}\exp\left(-y\sqrt{s}\right) + B_1\frac{1}{s}\exp\left(-y\sqrt{s+F}\right) - \frac{S_0}{s}\exp\left(-y\sqrt{s+F}\right) \quad (3.5)$$

$$\bar u(y,s) = \bar f(s)\exp\left(-y\sqrt{s+N}\right) - B_9\frac{1}{s}\exp\left(-y\sqrt{s+N}\right) + B_8\exp\left(-y\sqrt{s+N}\right) + B_6\frac{1}{s}\exp\left(-y\sqrt{s+F}\right)$$
$$+B_7\frac{1}{s}\exp\left(-y\sqrt{s}\right) - B_8\exp\left(-y\sqrt{s}\right) \quad (3.6)$$

Then, inverting equations (3.1) - (3.6) in the usual way we get the general solution of the problem for the temperature $\theta(y,t)$, the species concentration C(y, t) and velocity u(y, t) for t > 0 in the non dimensional form as

$$\theta = \frac{1}{2}\left[e^{-y\sqrt{P_rA_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{A_1t}\right) + e^{y\sqrt{P_rA_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{A_1t}\right)\right] \text{for } P_r \neq 1 \quad (3.7)$$

$$C = erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}\right) - A_2\{\frac{e^{-A_3t}}{2}[e^{-y\sqrt{S_c}\sqrt{-A_3}}\,erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{-A_3t}\right)$$
$$+e^{y\sqrt{S_c}\sqrt{-A_3}}\,erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{-A_3t}\right)]\} - A_6 erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}\right)$$
$$+A_6\left\{\frac{e^{-A_5t}}{2}\left[e^{-y\sqrt{S_c}\sqrt{-A_5}}\,erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{-A_5t}\right) + e^{y\sqrt{S_c}\sqrt{-A_5}}\,erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{-A_5t}\right)\right]\right\}$$
$$+A_2\{\frac{e^{-A_3t}}{2}[e^{-y\sqrt{P_r}\sqrt{-A_3+A_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_3+A_1)t}\right)]$$
$$+e^{y\sqrt{P_r}\sqrt{-A_3+A_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(-A_3+A_1)t}\right)$$
$$+A_6\{\frac{1}{2}\left[e^{-y\sqrt{P_r}\sqrt{A_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \left(\sqrt{A_1t}\right)\right) + \right.$$
eyPrA1 erfcyPr2t+A1t}

$$-A_6\{\frac{e^{-A_5t}}{2}[e^{-y\sqrt{P_r}\sqrt{-A_5+A_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_5+A_1)t}\right)$$
$$+e^{y\sqrt{P_r}\sqrt{-A_5+A_1}}\,erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(-A_5+A_1)t}\right)]\}$$
$$\text{for } P_r \neq 1 \text{ and for } S_c \neq 1 \quad (3.8)$$

$$\theta = \frac{1}{2}[\exp(-y\sqrt{F})erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Ft}\right) + \exp(y\sqrt{F})erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{Ft}\right)], \text{ for } P_r = 1 \quad (3.9)$$

$$C = B_1\frac{y}{2\sqrt{\pi t^3}}\exp\left(\frac{-y^2}{4t} - Ft\right) - B_1\frac{y}{2\sqrt{\pi t^3}}\exp\left(\frac{-y^2}{4t}\right) + B_2 erfc\left(\frac{y}{2\sqrt{t}}\right) - \frac{S_0}{2}[\exp(-y\sqrt{F})erfc(\frac{y}{2\sqrt{t}} - \sqrt{Ft})$$
$$+\exp(y\sqrt{F})\,erf\left(\frac{y}{2\sqrt{t}} + \sqrt{Ft}\right)] \text{ , for } P_r = 1 \text{ and } S_c = 1 \quad (3.10)$$

Thus the expressions (3.7) - (3.10) are the general solution of the present problem. These general solution include the effects of heating, the diffusion and the motion of the plate. Since the non dimensional temperature $\theta(y,t)$, non dimensional species concentration C(y, t) are clearly described in (3.7) to (3.10), so we shall confine our self to non dimensional velocity u(y, t) for various types of f(t).

4. Applications of the general solution

In this section we now consider some important cases of flow as given below:

Case(i): Motion of the plate with uniform velocity

Let f(t) = H(t), the Heaviside unit function

Then $\bar{f}(s) = \frac{1}{s}$

In this case we observe that the result (18) and (19) for $\theta(y,t)$, and C(y, t) are unaffected and the expression for u(y,t) is reduced to

$$u(y,t) = \frac{1}{2}\left[e^{-y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Nt}\right) + e^{y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} + \right.\right.$$
$$Nt + \emptyset y,t \qquad (4.1)$$

Case(ii): Motion of the plate with a given acceleration

Let f(t) = tH(t), the Heaviside unit function

Then $\bar{f}(s) = \frac{1}{s^2}$

In this case also we observe that the result (18) and (19) for $\theta(y,t)$, and C(y, t) are unaffected but the expression (3.10) for u(y,t) is reduces to the following analytical form:

$$u(y,t) = \left(\frac{t}{2} - \frac{y}{4\sqrt{N}}\right) e^{-y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Nt}\right) + \left(\frac{t}{2} + \frac{y}{4\sqrt{N}}\right) e^{y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{Nt}\right) + \emptyset(y,t) \qquad (4.2)$$

Where

$$\emptyset(y,t) = \frac{A_{29}}{2}\left[e^{-y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Nt}\right) + e^{y\sqrt{N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{Nt}\right)\right]$$
$$+A_{10}\frac{e^{-A_9 t}}{2}\left[e^{-y\sqrt{-A_9+N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(-A_9+N)t}\right) + e^{y\sqrt{-A_9+N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(-A_9+N)t}\right)\right]$$
$$+A_{30}\frac{e^{-A_{12} t}}{2}\left[e^{-y\sqrt{A_{12}+N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(A_{12}+N)t}\right) + e^{y\sqrt{A_{12}+N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(A_{12}+N)t}\right)\right]$$
$$+A_{31}\frac{e^{-A_3 t}}{2}\left[e^{-y\sqrt{-A_3+N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(-A_3+N)t}\right) + e^{y\sqrt{-A_3+N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(-A_3+N)t}\right)\right]$$
$$+A_{32}\frac{e^{-A_5 t}}{2}\left[e^{-y\sqrt{-A_5+N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(-A_5+N)t}\right) + e^{y\sqrt{-A_5+N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(-A_5+N)t}\right)\right]$$
$$+A_{33}\frac{e^{-A_{21} t}}{2}\left[e^{-y\sqrt{-A_{21}+N}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(-A_{21}+N)t}\right) + e^{y\sqrt{-A_{21}+N}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(-A_{21}+N)t}\right)\right]$$
$$+\frac{A_{34}}{2}\left[e^{-y\sqrt{P_r}\sqrt{A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \left(\sqrt{A_1 t}\right)\right) + e^{y\sqrt{P_r}\sqrt{A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \left(\sqrt{A_1 t}\right)\right)\right]$$
$$-A_{10}\left\{\frac{e^{-A_9 t}}{2}\left[e^{-y\sqrt{P_r}\sqrt{-A_9+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_9+A_1)t}\right) + e^{y\sqrt{P_r}\sqrt{-A_9+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} \sqrt{(-A_9+A_1)t}\right)\right]\right\}$$
$$-A_{13} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}\right)$$
$$+A_{35}\left\{\frac{e^{A_{12} t}}{2}\left[e^{-y\sqrt{S_c}\sqrt{A_{12}}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{A_{12} t}\right) + e^{y\sqrt{S_c}\sqrt{A_{12}}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{A_{12} t}\right)\right]\right\}$$
$$+A_{36}\left\{\frac{e^{-A_{21} t}}{2}\left[e^{-y\sqrt{P_r}\sqrt{-A_{21}+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_{21}+A_1)t}\right) + e^{y\sqrt{P_r}\sqrt{-A_{21}+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(-A_{21}+A_1)t}\right)\right]\right\}$$
$$+A_{23}\left\{\frac{e^{-A_3 t}}{2}\left[e^{-y\sqrt{P_r}\sqrt{-A_3+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_3+A_1)t}\right) + e^{y\sqrt{P_r}\sqrt{-A_3+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(-A_3+A_1)t}\right)\right]\right\}$$
$$+A_{28}\left\{\frac{e^{-A_5 t}}{2}\left[e^{-y\sqrt{P_r}\sqrt{-A_5+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} - \sqrt{(-A_5+A_1)t}\right) + e^{y\sqrt{P_r}\sqrt{-A_5+A_1}} erfc\left(\frac{y\sqrt{P_r}}{2\sqrt{t}} + \sqrt{(-A_5+A_1)t}\right)\right]\right\}$$

for $P_r \neq 1$, $S_c \neq 1$ (4.3)

$$\emptyset(y,t) = B_9 \frac{1}{2}\left[\exp(-y\sqrt{N}) erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Nt}\right) + \exp(y\sqrt{N}) erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{Nt}\right)\right]$$
$$+B_8 \frac{y}{2\sqrt{\pi t^3}} \exp\left(\frac{-y^2}{4t} - Nt\right)$$
$$-B_8 \frac{y}{2\sqrt{\pi t^3}} \exp\left(\frac{-y^2}{4t}\right) + B_7 erfc\left(\frac{y}{2\sqrt{t}}\right)$$
$$+B_6 \frac{1}{2}\left[\exp(-y\sqrt{F}) erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{Ft}\right) + \exp(y\sqrt{F}) erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{Ft}\right)\right]$$

For $P_r = 1$ and $S_c = 1$ (4.4)

5. Skin-friction

Case(i): Motion of the plate with uniform velocity

$$\boldsymbol{\tau} = -\left(\frac{\partial u}{\partial y}\right)_{y=0}$$
$$= \frac{1}{2}\left[\frac{-2}{\sqrt{\pi t}} \exp(-Nt) + \sqrt{N}\left[erfc\left(\sqrt{Nt}\right) - erfc\left(-\sqrt{Nt}\right)\right]\right]$$

$$+\left(\frac{\partial \emptyset}{\partial y}\right)_{y=0} \quad (5.1)$$

Case(ii): Motion of the plate with a given acceleration

$$= \frac{1}{2}\left[\frac{-\sqrt{t}}{\sqrt{\pi}}\exp(-Nt) + \left(\frac{1}{4\sqrt{N}} - \frac{t\sqrt{N}}{2}\right)\left[erfc\left(\sqrt{Nt}\right) - erfc-Nt\right] + \partial\emptyset\partial yy=0 \quad (5.2)$$

Where

$$\left(\frac{\partial \emptyset}{\partial y}\right)_{y=0} = \frac{A_{29}}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-Nt} + \sqrt{N}\left(erfc\left(\sqrt{Nt}\right) - erfc\left(-\sqrt{Nt}\right)\right)\right]$$

$$+\frac{A_{10}}{2}e^{-A_9 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(N-A_9)t} + \sqrt{(N-A_9)}\left(erfc\left(\sqrt{(N-A_9)t}\right) - erfc\left(-\sqrt{(N-A_9)t}\right)\right)\right]$$

$$+\frac{A_{30}}{2}e^{A_{12}t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(N+A_{12})t} + N+A12\ erfcN+A12t-erfc-N+A12t\right.$$

$$+\frac{A_{31}}{2}e^{-A_3 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(N-A_3)t} + N-A3\ erfcN-A3t-erfc-N-A3t\right.$$

$$+\frac{A_{32}}{2}e^{-A_5 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(N-A_5)t} + N-A5\ erfcN-A5t-erfc-N-A5t\right.$$

$$+\frac{A_{33}}{2}e^{-A_{21} t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(N-A_{21})t} + N-A21\ erfcN-A21t-erfc-N-A21t\right.$$

$$+\frac{A_{34}}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-A_1 t} + PrA1\ erfcA1t-erfc-A1t\right.$$

$$+\frac{A_{10}}{2}e^{-A_9 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(A_1-A_9)t} + A1-A9Pr\ erfcA1-A9t-erfc-A1-A9t\right.$$

$$+A_{13}\left[\frac{\sqrt{S_c}}{\sqrt{\pi t}}\right]$$

$$+\frac{A_{35}}{2}e^{-A_{12}t}\left[\frac{-2\sqrt{S_c}}{\sqrt{\pi t}}e^{-A_{12}t} + \sqrt{(S_c A_{12})}\left(erfc\left(\sqrt{A_{12}t}\right) - erfc-A12t\right.\right.$$

$$+\frac{A_{15}}{2}e^{-A_3 t}\left[\frac{-2\sqrt{S_c}}{\sqrt{\pi t}}e^{A_3 t} + \sqrt{(-A_3 S_c)}\left(erfc\left(\sqrt{-A_3 t}\right) - erfc--A3t\right.\right.$$

$$+\frac{A_{18}}{2}e^{A_{12}t}\left[\frac{-2\sqrt{S_c}}{\sqrt{\pi t}}e^{-A_{12}t} + \sqrt{(A_{12} S_c)}\left(erfc\left(\sqrt{A_{12}t}\right) - erfc-A12t\right.\right.$$

$$+\frac{A_{19}}{2}e^{-A_5 t}\left[\frac{-2\sqrt{S_c}}{\sqrt{\pi t}}e^{A_5 t} + \sqrt{(-A_5 S_c)}\left(erfc\left(\sqrt{(-A_5)t}\right) - erfc--A5t\right.\right.$$

$$+\frac{A_{36}}{2}e^{-A_{21}t}\left[\frac{-2P_r}{\sqrt{\pi t}}e^{-(A_1-A_{25})t} + A1-A25Pr\ erfcA1-A25t-erfc-A1-A25t\right.$$

$$+\frac{A_{23}}{2}e^{-A_3 t}\left[\frac{-2P_r}{\sqrt{\pi t}}e^{-(A_1-A_3)t} + A1-A3Pr\ erfcA1-A3t-erfc-A1-A3t\right.$$

$$+\frac{A_{28}}{2}e^{-A_5 t}\left[\frac{-2P_r}{\sqrt{\pi t}}e^{-(A_1-A_5)t} + A1-A5Pr\ erfcA1-A5t-erfc-A1-A5t\right.$$

for $P_r \neq 1$, $S_c \neq 1$ (5.3)

$$\left(\frac{\partial \emptyset}{\partial y}\right)_{y=0} = \frac{B_9}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-Nt} + \sqrt{N}\left(erfc\left(\sqrt{Nt}\right) - erfc\left(-\sqrt{Nt}\right)\right)\right] + \frac{B_8}{2\sqrt{\pi t^3}}e^{-Nt} - \frac{B_8}{2\sqrt{\pi t^3}} - \frac{B_7}{\sqrt{\pi t}} - \frac{B_6}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-Ft} + \sqrt{F}\left(erfc\left(\sqrt{Ft}\right) - erfc\left(-\sqrt{Ft}\right)\right)\right]$$

for $P_r = 1$ and $S_c = 1$ (5.4)

6. Nusselt number

An important phenomenon in this study is to understand the effects of t, P_r on the Nusselt number. In non dimensional form, the rate of heat transfer is given by

$$N_u = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0}$$

$$= \frac{1}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-A_1 t} + \sqrt{(P_r A_1)}\left(erfc\left(\sqrt{A_1 t}\right) - erfc\left(-\sqrt{A_1 t}\right)\right)\right]$$

for $P_r \neq 1$ (6.1)

$$= \frac{1}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-A_1 t} + \sqrt{(A_1)}\left(erfc\left(\sqrt{A_1 t}\right) - erfc\left(-\sqrt{A_1 t}\right)\right)\right]$$

for $P_r = 1$ (6.2)

7. Sherwood Number

Another important physical quantities of interest is the Sherwood number which in non-dimensional form is $S_h = -\left(\frac{\partial C}{\partial y}\right)_{y=0}$

$$= -\sqrt{\frac{S_c}{\pi t}} - \frac{A_2}{2}e^{-A_3 t}\left[\frac{-2}{\sqrt{\pi t}}e^{A_3 t} + \sqrt{(-A_3 S_c)}\left(erfc(\sqrt{-A_3 t}) - erfc(-\sqrt{-A_3 t})\right)\right]$$

$$+A_6\left[\frac{\sqrt{S_c}}{\sqrt{\pi t}}\right]$$

$$-\frac{A_6}{2}e^{-A_5 t}\left[\frac{-2}{\sqrt{\pi t}}e^{A_3 t} + \sqrt{(-A_5 S_c)}\left(erfc(\sqrt{-A_5 t}) - erfc(-\sqrt{-A_5 t})\right)\right]$$

$$+\frac{A_2}{2}e^{-A_3 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(A_1 - A_3)t} + \sqrt{(A_1 - A_3)P_r}\left(erfc\left(\sqrt{(A_1 - A_3)t}\right) - erfc\left(-\sqrt{(A_1 - A_3)t}\right)\right)\right]$$

$$+\frac{A_6}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-A_1 t} + \sqrt{(P_r A_1)}\left(erfc(\sqrt{A_1 t}) - erfc(-\sqrt{A_1 t})\right)\right]$$

$$-\frac{A_6}{2}e^{-A_5 t}\left[\frac{-2}{\sqrt{\pi t}}e^{-(A_1 - A_5)t} + \sqrt{(A_1 - A_5)P_r}\left(erfc\left(\sqrt{(A_1 - A_5)t}\right) - erfc\left(-\sqrt{(A_1 - A_5)t}\right)\right)\right]$$

$$\text{for } P_r \neq 1,\ S_c \neq 1 \qquad (7.1)$$

$$= \frac{B_1}{2\sqrt{\pi t^3}}e^{-Ft} - \frac{B_1}{2\sqrt{\pi t^3}} - \frac{B_2}{\sqrt{\pi t}} - \frac{S_0}{2}\left[\frac{-2}{\sqrt{\pi t}}e^{-Ft} + \sqrt{F}\left(erfc(\sqrt{Ft}) - erfc(-\sqrt{Ft})\right)\right]$$

$$\text{for } P_r = 1 \text{ and } S_c = 1 \qquad (7.2)$$

8. Numerical Discussions:

To understand the physical meaning of the problem, we have computed the expression for u, θ, C, τ, N_u and S_h for different values of Prandtl number Pr, magnetic field parameter M, Grashof number Gr, modified Grashof number Gm, Schmidt number Sc, permeability parameter K, Radiation parameter F, and Thermal diffusion (Soret) So. The purpose of the numerical result given here is to assess the effects of different parameters upon the nature of the flow, temperature and concentration etc..

The velocity profiles for different parameters with plate moves uniform velocity (Pr ≠ 1& Sc ≠ 1) are shown in figs. 2 to 9. It is observed that the velocity increases with increasing Pr, Gr, k and t but decreases with increasing F, Sc, So M and Gm.

The velocity profiles for different parameters with plate moves uniform velocity (Pr = 1& Sc = 1) are shown in figs. 10 to 14. It is observed that the velocity increases with increasing F, So Gr, Gm, k and t.

The velocity profiles for different parameters with plate moves a given acceleration (Pr ≠ 1& Sc ≠ 1) are shown in figs.15 to 22. It is observed that the velocity increases with increasing F, Pr, Gr, k and t but decreases with increasing Sc, So, M and Gm.

The velocity profiles for different parameters with plate moves a given acceleration (Pr = 1& Sc = 1) are shown in figs. 23 to 27 . It is observed that the velocity increases with increasing F, So Gr, Gm, k and t. Figures 28 & 29 depicts the temperature profiles for Radiation parameter F and Prandtl number Pr. It is noticed that the temperature decreases with increasing F and Pr respectively. We observe that the temperature for air is greater than that of water, which is due to the fact that thermal conductivity of fluid decreases with increasing Pr.

For various values of Radiation parameter F, Prandtl number Pr , Schmidt number(Sc), Thermal diffusion (Soret) So, the concentration profiles are shown in figures 30 to 33.

It is seen from figures 30, 32, 33 that an increase in F, Pr, So leads to an increase in the concentration. While it decreases with the increase of Sc as given in figure 31.

From Table 1 it is noticed that an increase in Pr, F, Sc, So, M, Gr, and Gm results in a increase in the surface skin friction due to uniform velocity. From Table 2, the same effect was observed with given acceleration.

From Table 3, it is noticed that an increase in Pr and F, leads to an increase in the rate of heat transfer expressed in terms of Nusselt number.

From Table 4, it is noticed that an increase in Pr, F, Sc, So, and Gr, leads to an increase in the rate of Mass transfer expressed in terms of Sherwood number.

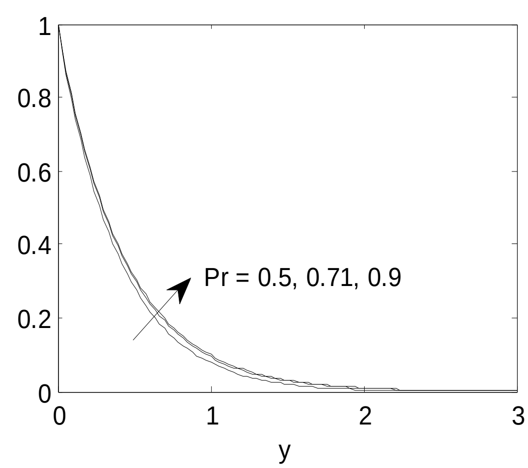

Fig. 2: Velocity profile for Pr when the plate moves with uniform

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Vol.4, No.6, June 2015 DOI:10.15693/ijaist/2015.v4i6.124-137

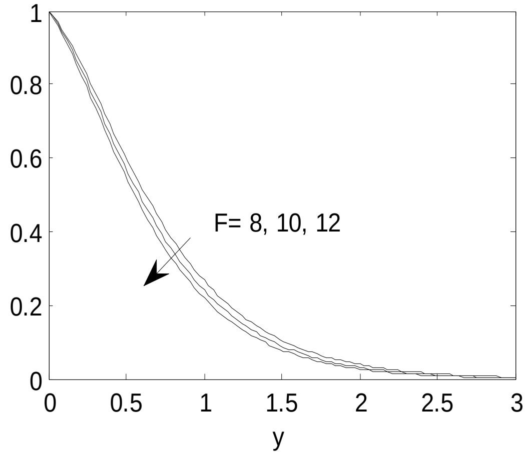

Fig. 3: Velocity profile for F when the plate moves with uniform velocity

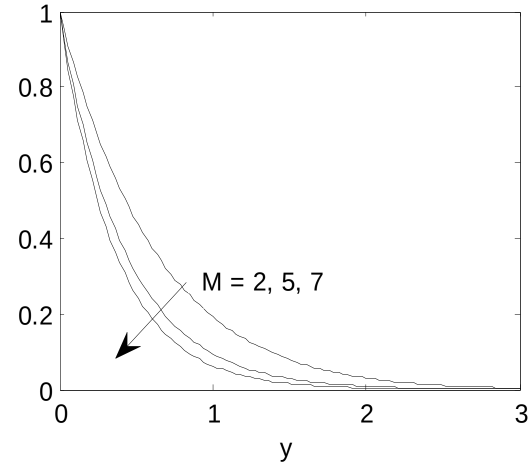

Fig.6: Velocity profile for M when the plate moves with uniform velocity

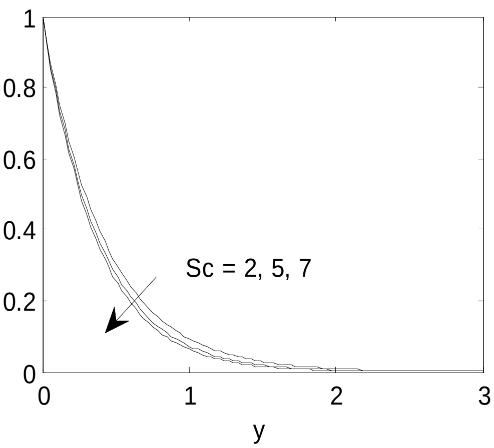

Fig.4: Velocity profile for Sc when the plate moves with uniform velocity

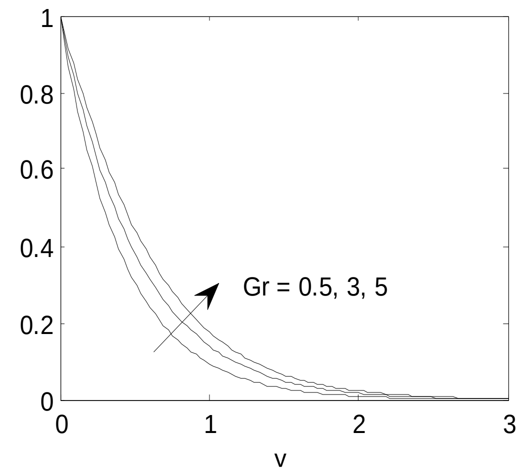

Fig.7: Velocity profile for Gr when the plate moves with uniform velocity

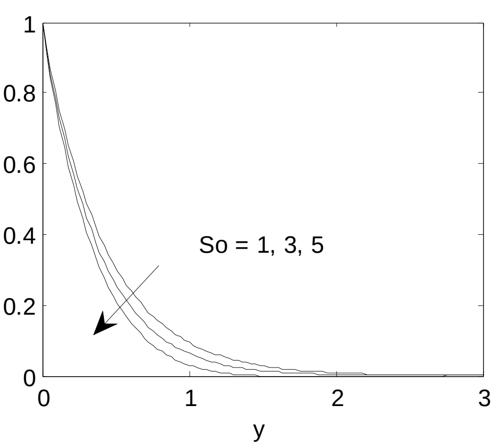

Fig.5: Velocity profile for So when the plate moves with uniform velocity

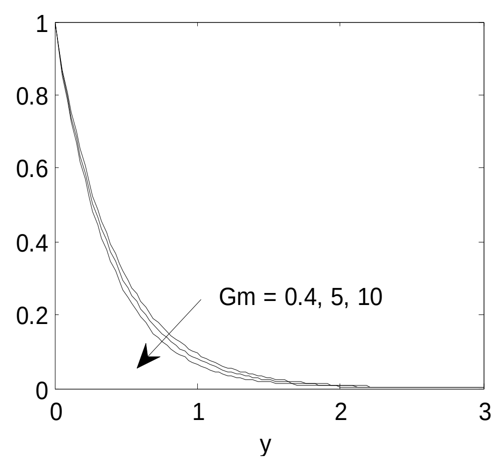

Fig.8: Velocity profile for Gm when the plate moves with uniform velocity

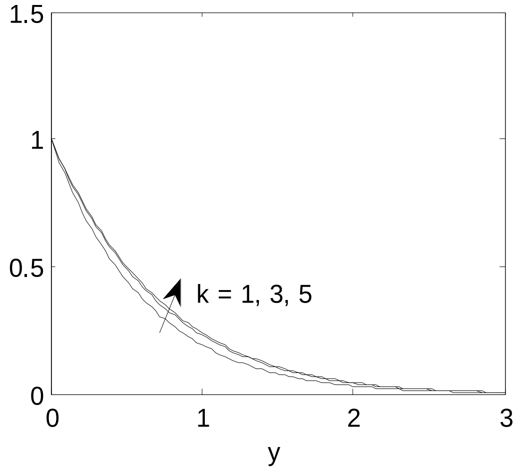

Fig.9: Velocity profile for k when the plate moves with uniform velocity

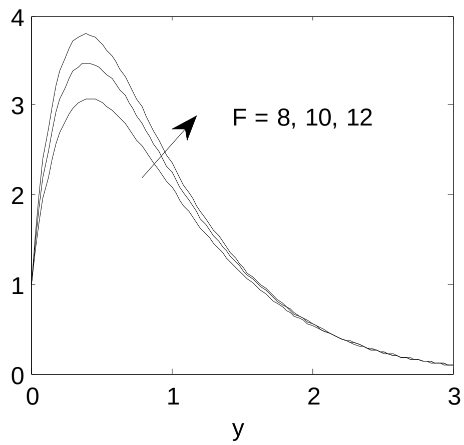

Fig.10: Velocity profile for M when the plate moves with uniform velocity (Pr =1 & Sc =1)

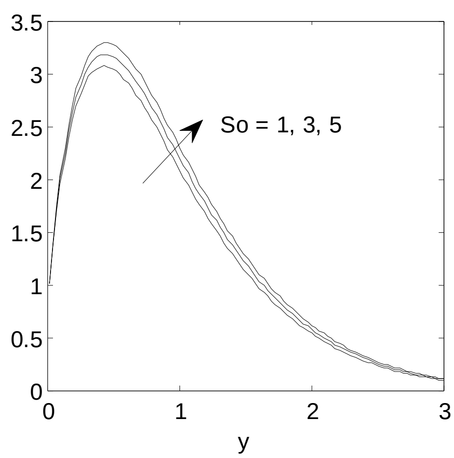

Fig.11: Velocity profile for So when the plate moves with uniform velocity (Pr =1 & Sc =1)

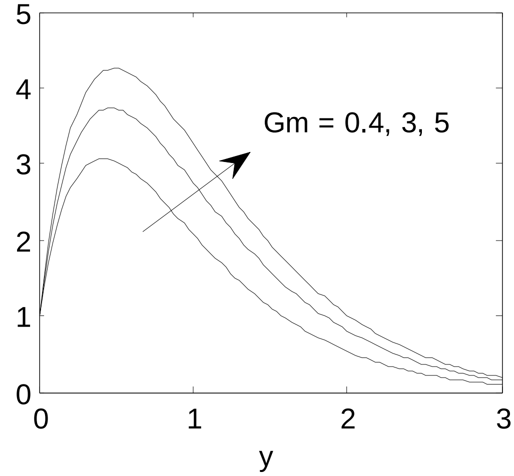

Fig.12: Velocity profile for Gm when the plate moves with uniform velocity (Pr =1 & Sc =1)

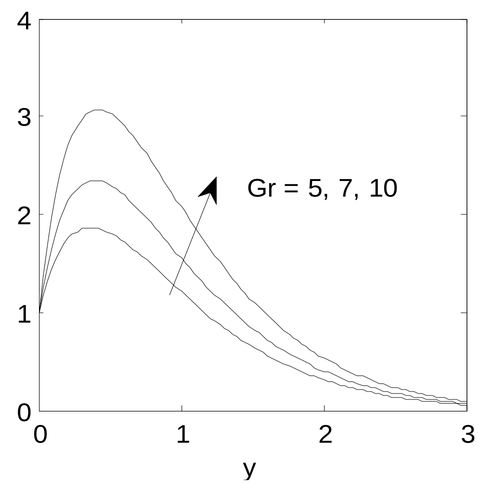

Fig.13: Velocity profile for Gr when the plate moves with uniform velocity (Pr =1 & Sc =1)

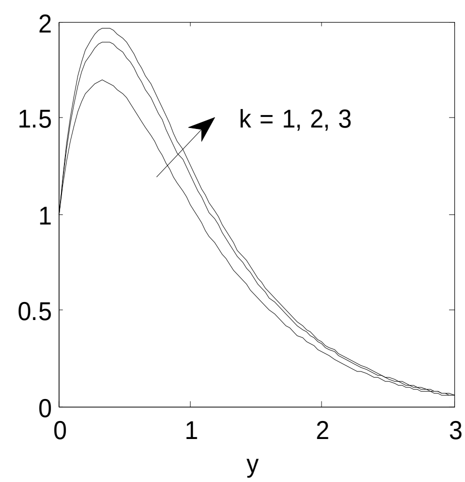

Fig.14: Velocity profile for k when the plate moves with uniform velocity (Pr =1 & Sc =1)

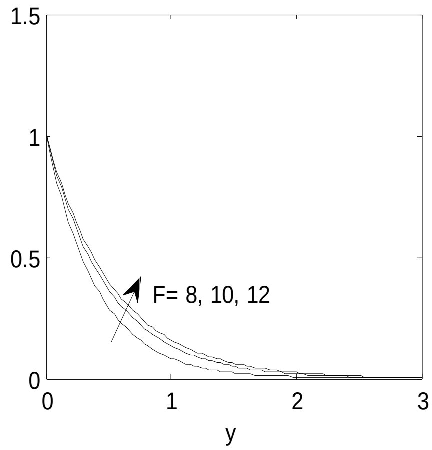

Fig.15: Velocity profile for F when the plate moves with given acceleration

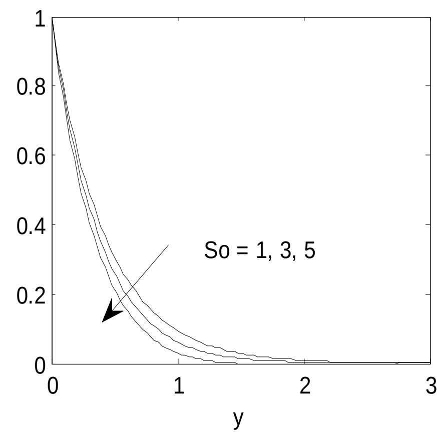

Fig.18: Velocity profile for So when the plate moves with given acceleration

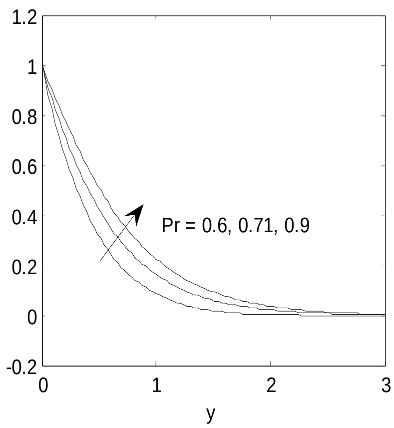

Fig.16: Velocity profile for Pr when the plate moves with given acceleration

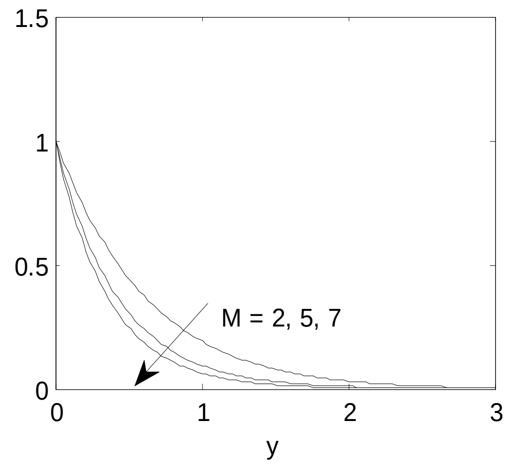

Fig.19: Velocity profile for M when the plate moves with given acceleration

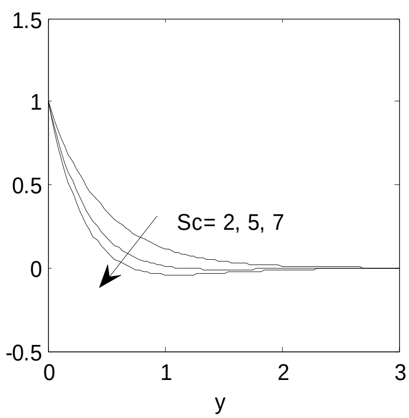

Fig.17: Velocity profile for Sc when the plate moves with given acceleration

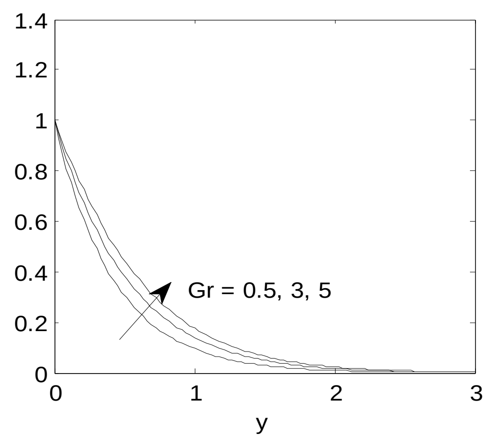

Fig.20: Velocity profile for Gr when the plate moves with given acceleration

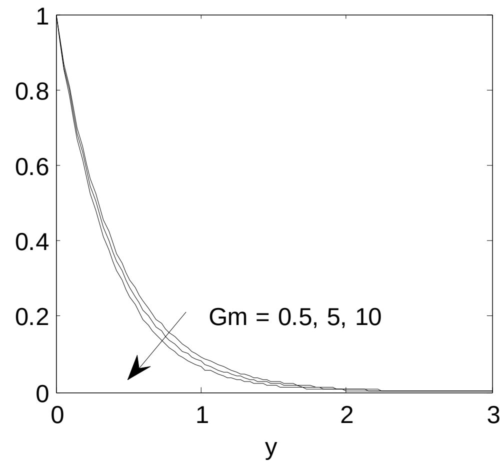

Fig.21: Velocity profile for Gm when the plate moves with given acceleration

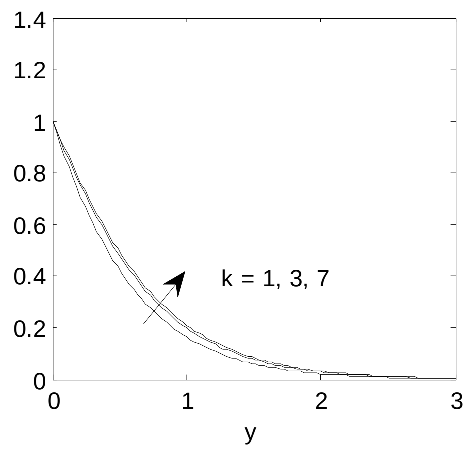

Fig.22: Velocity profile for k when the plate moves with given acceleration

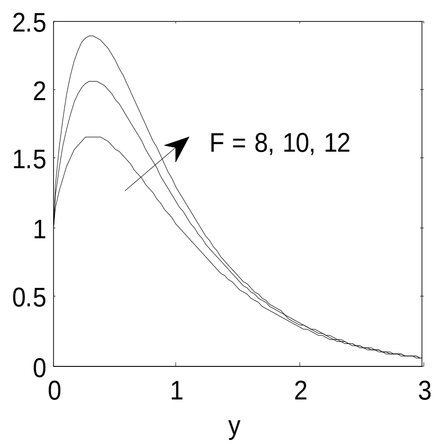

Fig.23: Velocity profile for F when the plat moves with given acceleration (Pr =1 & Sc =1)

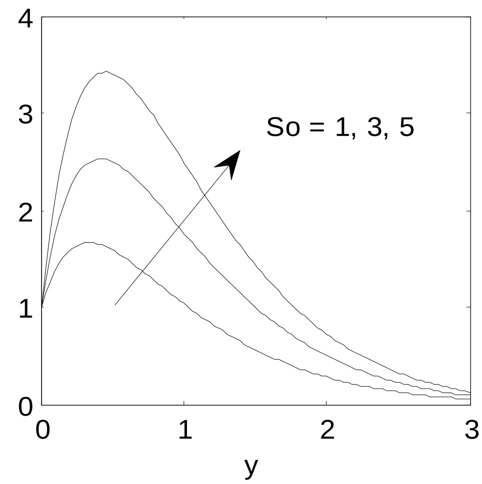

Fig.24: Velocity profile for So when the plate moves with given acceleration (Pr =1 & Sc =1)

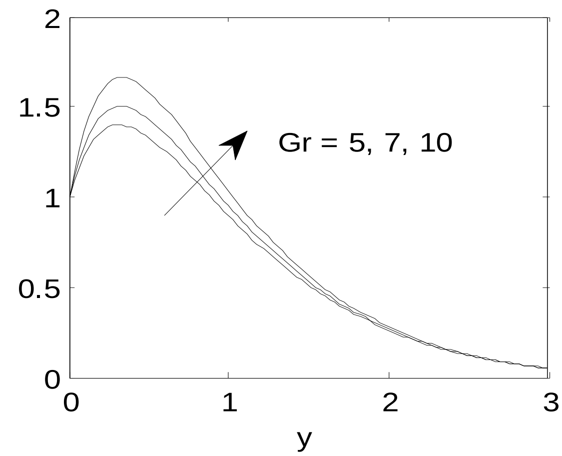

Fig.25: Velocity profile for Gr when the plate moves with given acceleration (Pr =1 & Sc =1)

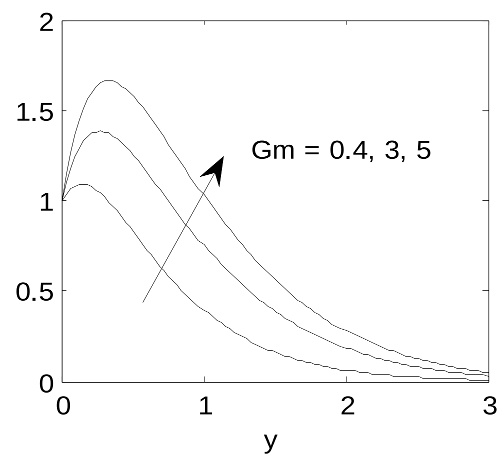

Fig.26: Velocity profile for Gm when the plate moves with given acceleration (Pr =1 & Sc =1)

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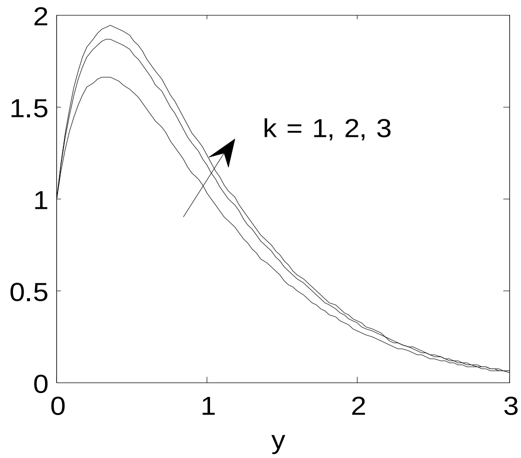

Fig.27: Velocity profile for k when the plate moves with given acceleration (Pr =1 & Sc =1)

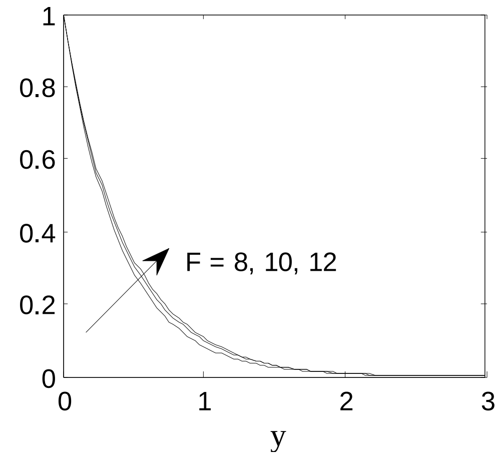

Fig.30: Concentration profile for F

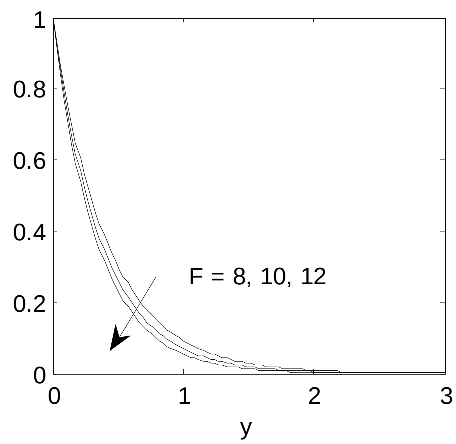

Fig.28: Temperature profile for F

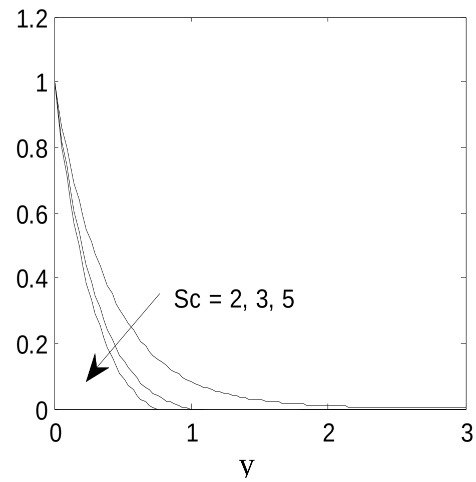

Fig.31: Concentration profile for Sc

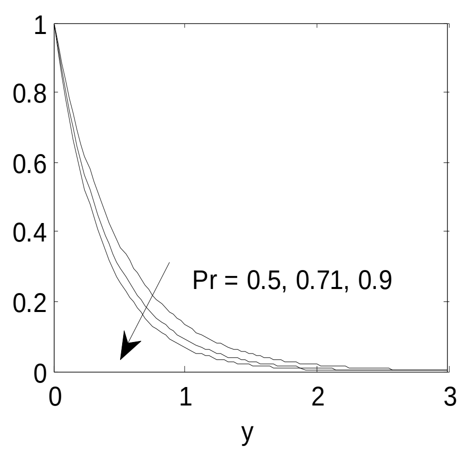

Fig.29: Temperature profile for Pr

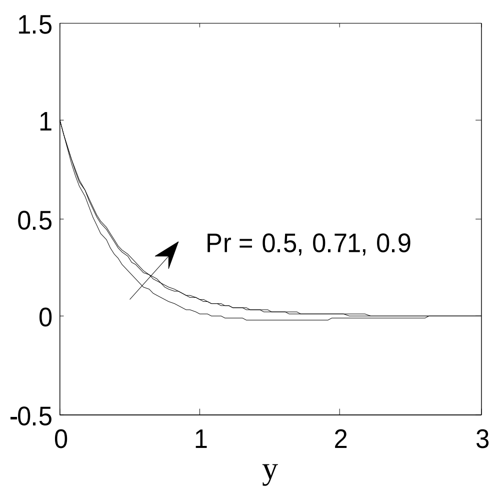

Fig.32: Concentration profile for Pr

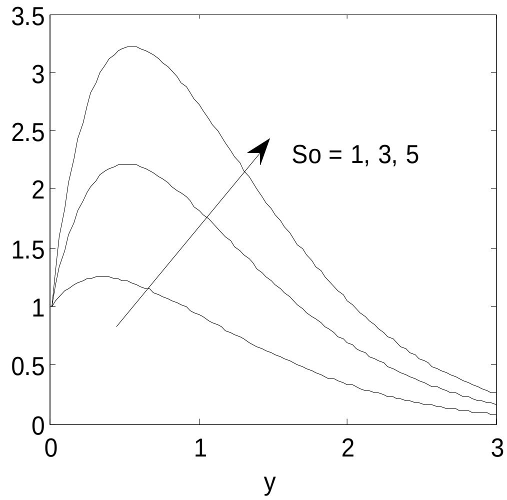

Fig.33: Concentration profile for So (when Pr= 1& Sc = 1)

Table 1:

Pr	F	Sc	S0	M	Gr	Gm	T1
0.50	8.00	1.50	1.00	2.00	0.50	0.40	558.36
0.71	8.00	1.50	1.00	2.00	0.50	0.40	17852.35
0.71	**9.00**	1.50	1.00	2.00	0.50	0.40	180863.29
0.71	8.00	**2.0**	1.00	2.00	0.50	0.40	14619.02
0.71	8.00	1.50	**2.00**	2.00	0.50	0.40	22149.91
0.71	8.00	1.50	1.00	**5.00**	0.50	0.40	90977.50
0.71	8.00	1.50	1.00	2.00	**3.00**	0.40	13322.74
0.71	8.00	1.50	1.00	2.00	0.50	**1.00**	24264.85

Table 2: Skin-friction (Case 2)

Pr	F	Sc	S0	M	Gr	Gm	T1
0.50	8.00	1.50	1.00	2.00	0.50	0.40	563.19
0.71	8.00	1.50	1.00	2.00	0.50	0.40	17857.18
0.71	**9.00**	1.50	1.00	2.00	0.50	0.40	180868.13
0.71	8.00	**2.0**	1.00	2.00	0.50	0.40	14623.85
0.71	8.00	1.50	**2.00**	2.00	0.50	0.40	22154.75
0.71	8.00	1.50	1.00	**5.00**	0.50	0.40	90984.64
0.71	8.00	1.50	1.00	2.00	**3.00**	0.40	13327.17
0.71	8.00	1.50	1.00	2.00	0.50	**1.00**	24269.69

Table 3: Nusselt number

Pr	F	N_u
0.50	8.00	4.00
0.71	8.00	4.77
0.71	**9.00**	5.06

Table 4: Sherwood number

Pr	F	Sc	S0	Gr	Sh
0.50	8.00	1.50	1.00	0.50	-120.07
0.71	8.00	1.50	1.00	0.50	1641.41
0.71	**9.00**	1.50	1.00	0.50	6260.57
0.71	8.00	**2.00**	1.00	0.50	-55.73
0.71	8.00	1.50	**2.00**	0.50	3275.57
0.71	8.00	1.50	1.00	**3.00**	396.31

9. Conclusion:

In this study, a general analytical solution for the problem of unsteady MHD free convection flow with heat and mass transfer near a moving vertical plate has been determined. Some important application from the point of view of physical interest was discussed. Also we investigate some physical examples for evaluation of the numerical values of the velocity, temperature, concentration etc. of water (Pr = 7) and air (Pr = 0.71). To our knowledge, this study gives in close form the actual analytical solution of MHD free convection flow with heat and mass transfer problem which have wide application in different fields of Engineering.

Appendix:

$A_1 = F = \frac{R}{P_r}$, $A_2 = \frac{-S_c S_0 P_r}{P_r - S_c}$, $A_3 = \frac{A_1 P_r}{P_r - S_c}$, $A_4 = \frac{-S_c S_0 R}{P_r - S_c}$,

$A_5 = A_3 = \frac{A_1 P_r}{P_r - S_c}$, $A_6 = \frac{A_4}{A_5}$, $A_7 = 1 - A_6$, $A_8 = \frac{-G_r}{P_r - 1}$,

$A_9 = \frac{P_r A_1 - N}{P_r - 1}$, $A_{10} = \frac{A_8}{A_9}$, $A_{11} = \frac{-G_m A_7}{S_c - 1}$, $A_{12} = \frac{N}{S_c - 1}$,

$A_{13} = \frac{-G_m A_7}{N}$, $A_{14} = \frac{G_m A_2}{S_c - 1}$, $A_{15} = \frac{A_{14}}{-(A_3 + A_{12})}$, $A_{16} = -A_{15}$,

$A_{17} = \frac{-G_m A_6}{S_c - 1}$, $A_{18} = \frac{A_{17}}{A_3 + A_{12}}$, $A_{19} = -A_{18}$, $A_{20} = \frac{-G_m A_2 - N}{P_r - 1}$,

$A_{21} = A_9 = \frac{P_r A_1 - N}{P_r - 1}$, $A_{22} = \frac{A_{20}}{A_3 - A_{21}}$, $A_{23} = -A_{22} = \frac{A_{20}}{A_{21} - A_3}$

$A_{24} = \frac{-G_m A_6}{P_r - 1}$, $A_{25} = \frac{-G_m A_6}{P_r A_1 - N}$, $A_{26} = \frac{G_m A_6}{P_r - 1}$, $A_{27} = \frac{A_{26}}{A_5 - A_{21}}$,

$A_{28} = -A_{27} = \frac{A_{26}}{A_{21} - A_5}$, $A_{29} = -(A_{10} - A_{13} + A_{25})$,

$A_{30} = -(A_{13} + A_{16} + A_{18})$, $A_{31} = -(A_{15} + A_{23})$

$A_{32} = -(A_{19} + A_{28})$, $A_{33} = -(A_{22} - A_{25} + A_{27})$,

$A_{34} = (A_{10} + A_{25})$, $A_{35} = (A_{13} + A_{16})$,

$A_{36} = -A_{33} = (A_{22} - A_{25} + A_{27})$

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