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Laplace Technique on Magnetohydrodynamic Radiating and Chemically Reacting Fluid over an Infinite Vertical Surface

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ABSTRACT

An analysis is carried out to study the nonlinear MHD flow with heat and mass transfer characteristics of an incompressible, viscous, electrically conducting and Boussinesq fluid over a vertical oscillating porous permeable plate in presence of homogeneous chemical reaction of first order and thermal radiation effects. The fluid considered here is a gray, absorbing/emitting radiation, but a non-scattering medium. At time $t > 0$, the plate temperature and concentration levels near the plate raised linearly with time t. An approximate numerical solution for the flow problem has been obtained by solving the governing boundary layer equations using ***Laplace transform technique***. It has been found that, when the chemical reaction parameter (K_r) increased, the fluid velocities as well as concentration profiles were decreased. An increase in conduction-radiation parameter (R_a) is found to escalate temperatures and shear stress in the regime. Applications of the study arise in materials processing and solar energy collector systems.

Keywords: Thermal radiation; Chemical reaction; MHD; shear stress and Variable Mass Diffusion.

2000 Mathematical subject classification: 76D05, 76W05, 80A20, 32 and 76M20

1. INTRODUCTION

The study of heat and mass transfer with chemical reaction is of great practical important to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. In particular, the study of chemical reaction, heat and mass transfer with heat radiation is of considerable importance in chemical and hydrometallurgical industries. A reaction is said to be first-order if the rate of reaction is directly proportional to the concentration itself. In many chemical processes, a chemical reaction occurs between a foreign mass and a fluid in which a plate is moving. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware, and food processing Cussler [1]. Chambre and Young [2] analyzed the diffusion of chemically reactive species in a laminar boundary layer flow. Vajravelu [3] studied the exact solution for hydrodynamic boundary layer flow and heat transfer over a continuous, moving horizontal flat surface with uniform suction and internal heat generation/absorption. Chamkha [4] presented an analytical solution for heat and mass transfer by laminar flow of a Newtonian, viscous, electrically conducting fluid and heat generation/absorption.

If the temperature of surrounding fluid is rather high, radiation effects play an important role and this situation does not exist in space technology. In such cases one has to take into account the effect of thermal radiation and mass diffusion. Boundary layer flow on moving horizontal surfaces was studied by sakiadas [5]. The effects of transversely applied magnetic field on the flow of an electrically conducting fluid past an impulsively started isothermal vertical plate was studied by Soundalgekar *et al.* [6]. MHD effects on impulsively started vertical infinite plate with variable temperature in the presence of transverse magnetic field were studied by Soundalgekar *et al.* [7]. The dimensionless governing equations were solved using Laplace transform technique. Kumari and Nath [8] studied the development of the asymmetric flow of a viscous electrically conducting fluid in the forward stagnation point of a two-dimensional body and over a stretching surface with an applied magnetic field. The governing equations were solved using Laplace transform technique. England and Emery [9] have studied the thermal radiation effects of an optically thin gray gas bounded by a stationary vertical plate. Soundalgekar and Takhar [10] have considered the radiation free convection flow of an optically thin gray- gas past a semi- infinite vertical plate. Radiation effects on mixed convection along isothermal vertical plate were studied by Hossain and Takhar [11]. In all above studies, the stationary vertical plate is considered. Raptis and Perdikis [12] studied the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Also, Sahin and Liu [13] analyzed the effects of mixed convection and mass transfer of three-dimensional oscillatory flow of a viscous incompressible fluid past an infinite vertical porous plate in presence of transverse sinusoidal suction velocity oscillating with time and a constant free stream velocity. Sahin [14] studied effects of radiation and magnetic Prandtl number on the steady mixed convective heat and mass transfer flow of an optically thin gray gas over an infinite vertical porous plate with constant suction in presence of transverse magnetic field. Recently, Sahin [15] investigated the effects of radiation and chemical reaction on a steady mixed convective heat and mass transfer past an infinite vertical permeable plate with constant suction taking into account the induced magnetic field. Sahin and Zueco [16] studied the effect of the transverse magnetic field on a steady mixed convective heat and mass transfer flow past an infinite vertical isothermal porous plate taking into account the induced magnetic field, viscous and magnetic dissipations of energy in presence of chemical reaction and heat generation/absorption, and the non-linear coupled equations are solved by network simulation technique. Sahin and Chamkha [17] investigated the effects of radiation and chemical reaction on steady mixed convective heat and mass transfer flow of an optically thin gray gas over an infinite vertical porous plate with constant suction taking into account the induced magnetic field, and viscous dissipation of energy. Jaiswal and Soundalgekar [18] obtained an approximate solution to the problem of an unsteady flow past an infinite vertical plate with constant suction and embedded in a porous medium with oscillating plate temperature. Kumar and Verma [19] studied the problem of an unsteady flow past an infinite vertical permeable plate with constant suction and transverse magnetic field with oscillating plate temperature.

In this paper, we consider the effects of chemical reaction as well as magnetic field on the heat and mass transfer of Newtonian fluids over an infinite vertical oscillating permeable plate with variable mass diffusion. The magnetic field is imposed transversely to the plate. The temperature and concentration of the plate is oscillating with time about a constant non-zero mean value. The dimensionless governing equations involved in the present analysis are solved using ***Laplace transform technique***.

2. MATHEMATICAL ANALYSIS

Thermal radiation and mass transfer effects on unsteady MHD flow of a viscous incompressible fluid past along a vertical oscillating plate with variable temperature and also with variable mass diffusion in the presence of transverse applied magnetic field has been studied. The $\bar{x}$ axis is taken along the plate in the vertical upward direction and the $\bar{y}$ axis is taken normal to the plate. Initially it is assumed that the plate and fluid are at the same temperature $\bar{T}_\infty$ in the stationary condition with concentration level $\bar{C}_\infty$ at all the points. At time, $\bar{t} > 0$ the plate is given an oscillatory motion in its own plane with velocity $U_0 \cos(\bar{\omega}\bar{t})$. At the same time the plate temperature is raised linearly with time $\bar{t}$ and also mass is diffused from the plate linearly with time. A transverse magnetic field of uniform strength B_0 is assumed to be applied normal to the plate. The ***induced magnetic field*** and ***viscous dissipation*** is assumed to be negligible as the ***magnetic Reynolds number*** of the flow is taken to be very small. The fluid considered here is gray, absorbing/emitting radiation but a non-scattering medium. Then by usual Boussinesq's approximation, the unsteady flow is governed by the following equations.

Figure 1: Physical configuration and coordinate system

$$\frac{\partial \bar{u}}{\partial \bar{t}} = g\beta(\bar{T} - \bar{T}_\infty) + g\bar{\beta}(\bar{C} - \bar{C}_\infty) + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{\sigma B_0^2}{\rho}\bar{u} \tag{1}$$

$$\rho C_P \frac{\partial \bar{T}}{\partial \bar{t}} = \kappa \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{\partial q_r}{\partial \bar{y}} \tag{2}$$

$$\frac{\partial \bar{C}}{\partial \bar{t}} = D\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} - \bar{K}_r(\bar{C} - \bar{C}_\infty) \tag{3}$$

The initial and boundary conditions are:

$$\left.\begin{array}{l} \bar{t} \le 0: \bar{u} = 0\,, \bar{T} = \bar{T}_\infty\,, \bar{C} = \bar{C}_\infty \ \ \forall y \\ \bar{t} > 0: \bar{u} = U_0 \cos(\bar{\omega}\bar{t}),\ \ \bar{T} = \bar{T}_\infty + (\bar{T}_w - \bar{T}_\infty)A\bar{t}\,,\ \ \bar{C} = \bar{C}_\infty + (\bar{C}_w - \bar{C}_\infty)A\bar{t} \ \text{ at } y = 0 \\ \bar{t} > 0: \bar{u} \to 0\,,\ \ \bar{T} \to \bar{T}_\infty\,,\ \ \bar{C} \to \bar{C}_\infty \ \text{ as } y \to \infty \end{array}\right\} \tag{4}$$

The local radiant absorption for the case of an optically thin gray gas is expressed as

$$\frac{\partial q_r}{\partial \bar{y}} = -4\bar{a}\,\bar{\sigma}\left(\bar{T}_\infty^4 - \bar{T}^4\right) \tag{5}$$

Where $\bar{\sigma}$ and $\bar{a}$ are the ***Stefan-Boltzmann constant*** and the ***Mean absorption coefficient***, respectively. Following Chamkha [5] and others, we assume that the temperature differences within the flow are sufficiently small so that $\bar{T}^4$ can be expressed as a linear function of $\bar{T}$ after using Taylor's series to expand $\bar{T}^4$ about the free stream temperature $\bar{T}_\infty$ and neglecting higher-order terms. This results in the following approximation:

$$\bar{T}^4 \cong 4\bar{T}_\infty^3\bar{T} - 3\bar{T}_\infty^4 \tag{6}$$

$$\rho C_P \frac{\partial \bar{T}}{\partial \bar{t}} = \kappa \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - 16\bar{a}\,\bar{\sigma}\,\bar{T}_\infty^3(\bar{T} - \bar{T}_\infty) \tag{7}$$

Introducing the following non-dimensional quantities:

$$\left.\begin{array}{l} y = \dfrac{u_0\bar{y}}{\nu}\,,\ \ u = \dfrac{\bar{u}}{u_0}\,,\ \ \theta = \dfrac{\bar{T} - \bar{T}_\infty}{\bar{T}_w - \bar{T}_\infty}\,,\ \ \phi = \dfrac{\bar{C} - \bar{C}_\infty}{\bar{C}_w - \bar{C}_\infty}\,,\ \ Sc = \dfrac{\nu}{D}\,,\ \ Pr = \dfrac{\rho\nu C_P}{\kappa}\,, \\ Gr = \dfrac{\nu g\beta(\bar{T}_w - \bar{T}_\infty)}{u_0^3}\,,\ \ Gr_m = \dfrac{\nu g\bar{\beta}(\bar{C}_w - \bar{C}_\infty)}{u_0^3}\,,\ \ t = \dfrac{u_0^2\bar{t}}{\nu}\,,\ \ M = \dfrac{\sigma B_0^2\nu}{\rho u_0^2}\,, \\ R_a = \dfrac{16\,\bar{a}\,\nu\,\bar{\sigma}\,\bar{T}_\infty^3}{\kappa u_0^2}\,,\ \ \omega = \dfrac{\bar{\omega}\nu}{u_0^2}\,,\ \ K_r = \dfrac{\nu\bar{K}_r}{u_0^2}\,,\ \ A = \dfrac{u_0^2}{\nu} \end{array}\right\} \tag{8}$$

Using the transformations (8), the non-dimensional forms of (1), (3) and (7) are

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - Mu + Gr\theta + Gr_m\phi \tag{9}$$

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

$$\frac{\partial\phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-K_r\phi \tag{11}$$

The corresponding initial and boundary conditions are transformed to:

$$\left.\begin{array}{l} t\leq 0:\ u=0\,,\ \ \theta=0\,,\ \ \phi=0 \qquad \forall\, y \\ y>0:\ u=\cos(\omega t)\,,\ \ \theta=t\,,\ \ \phi=t \qquad \text{at}\ \ y=0 \\ \qquad y>0:\ u\to 0\,,\ \ \theta\to 0\,,\ \ \phi\to 0\ \ \text{as}\ \ y\to\infty \end{array}\right\} \tag{12}$$

3. METHOD OF SOLUTION

The unsteady, non-linear, coupled partial differential equations (9) to (11) along with their boundary conditions (12) have been solved analytically using usual ***Laplace transform technique*** and the solutions for hydromagnetic flow in the presence of radiation and first order chemical reaction are obtained as follows:

$$\theta(y,t)=\left(\frac{t}{2}+\frac{yPr}{4\sqrt{R_a}}\right)\mathrm{e}^{y\sqrt{R_a}}erfc\left(\eta\sqrt{Pr}+\sqrt{\frac{R_a t}{Pr}}\right)$$
$$+\left(\frac{t}{2}-\frac{yPr}{4\sqrt{R_a}}\right)\mathrm{e}^{y\sqrt{R_a}}erfc\left(\eta\sqrt{Pr}-\sqrt{\frac{R_a t}{Pr}}\right), \tag{13}$$

$$\phi(y,t)=\left(\frac{t}{2}+\frac{\eta\sqrt{Sc\,t}}{2\sqrt{K_r}}\right)\mathrm{e}^{2\eta\sqrt{K_r t\,Sc}}erfc\left(\eta\sqrt{Sc}+\sqrt{K_r t}\right)$$
$$+\left(\frac{t}{2}-\frac{\eta\sqrt{Sc\,t}}{2\sqrt{K_r}}\right)\mathrm{e}^{-2\eta\sqrt{K_r t\,Sc}}erfc\left(\eta\sqrt{Sc}-\sqrt{K_r t}\right), \tag{14}$$

$$u(y,t)=\frac{1}{4}e^{i\omega t}\left[\mathrm{e}^{y\sqrt{M+i\omega}}\,erfc\left\{\eta+\sqrt{(M-i\omega)t}\right\}+e^{-y\sqrt{M+i\omega}}erfc\left\{\eta-\sqrt{(M+i\omega)t}\right\}\right]$$

$$+\frac{1}{4}e^{-i\omega t}\left[e^{y\sqrt{M-i\omega}}erfc\left\{\eta+\sqrt{(M+i\omega)t}\right\}+e^{-y\sqrt{M-i\omega}}erfc\left\{\eta-\sqrt{(M-i\omega)t}\right\}\right]$$

$$-\frac{A}{2}\left[e^{y\sqrt{M}}erfc\left(\eta+\sqrt{Mt}\right)+e^{-y\sqrt{M}}erfc\left(\eta-\sqrt{Mt}\right)\right]$$

$$+B\left[\left(\frac{t}{2}+\frac{y}{4\sqrt{M}}\right)e^{y\sqrt{M}}erfc\left(\eta+\sqrt{Mt}\right)+\left(\frac{t}{2}-\frac{y}{4\sqrt{M}}\right)e^{-y\sqrt{M}}erfc\left(\eta-\sqrt{Mt}\right)\right]$$

$$+\frac{E}{2}e^{Ct}\left[e^{y\sqrt{M-C}}erfc\left\{\eta+\sqrt{(M-C)t}\right\}+e^{-y\sqrt{M-C}}erfc\left\{\eta-\sqrt{(M-C)t}\right\}\right]$$

$$+\frac{G}{2}e^{et}\left[e^{y\sqrt{M+e}}erfc\left\{\eta+\sqrt{(M+e)t}\right\}+e^{-y\sqrt{M+e}}erfc\left\{\eta-\sqrt{(M+e)t}\right\}\right]$$

$$+\frac{E}{2}e^{et}\left[e^{y\sqrt{R_a}}erfc\left\{\eta\sqrt{Pr}+\sqrt{\frac{R_a t}{Pr}}\right\}+e^{-y\sqrt{R_a}}erfc\left\{\eta\sqrt{Pr}-\sqrt{\frac{R_a t}{Pr}}\right\}\right]$$

$$+D\theta(y,t)-\frac{E}{2}e^{-Ct}\left[e^{y\sqrt{R_a-CPr}}erfc\left\{\eta\sqrt{Pr}+\sqrt{\left(\frac{R_a}{Pr}-C\right)t}\right\}\right.$$

$$\left.+e^{-y\sqrt{R_a-CPr}}erfc\left\{\eta\sqrt{Pr}-\sqrt{\left(\frac{R_a}{Pr}-C\right)t}\right\}\right]+F\phi(y,t)+Gerfc\left(y\sqrt{Sc}\right)$$

$$-\frac{G}{2}\left[e^{y\sqrt{eSc}}erfc\{\eta\sqrt{Sc}+\sqrt{et}\}+e^{-y\sqrt{eSc}}erfc\{\eta\sqrt{Sc}-\sqrt{et}\}\right] \tag{15}$$

where $\eta=\dfrac{y}{2\sqrt{t}}$, $b=\dfrac{Gr}{Pr-1}$, $C=\dfrac{R_a-M}{Pr-1}$, $d=\dfrac{Gr_m}{Sc-1}$, $e=\dfrac{M}{Sc-1}$,

$A=\dfrac{Gr(Pr-1)}{(R_a-M)^2}+\dfrac{Gr_m(Sc-1)}{M^2}$, $B=\dfrac{M(Gr+Gr_m)-R_aGr_m}{M(R_a-M)}$, $D=\dfrac{Gr}{R_a-M}$,

$E=\dfrac{Gr(Pr-1)}{(R_a-M)^2}$, $F=\dfrac{Gr_m}{M}$, $G=Gr_m\left(\dfrac{Sc-1}{M}\right)^2$

4. SKIN FRICTION

The boundary layer produces a ***drag force*** on the plate due to the ***viscous stresses*** which are developed at the wall. The ***viscous stress*** at the surface of the plate is given by:

$$\tau=-\left[\frac{\partial u(y,t)}{\partial y}\right]_{y=0}$$

$$=\frac{1}{2}\left[e^{i\omega t}\left\{\frac{e^{-(M+i\omega)t}}{\sqrt{\pi t}}+\sqrt{(M+i\omega)t}\,\mathrm{erf}\left(\sqrt{(M+i\omega)t}\right)\right\}\right.$$

$$+ e^{-i\omega t}\left\{\frac{e^{-(M-i\omega)t}}{\sqrt{\pi t}} + \sqrt{(M-i\omega)t}\ \text{erf}\left(\sqrt{(M-i\omega)t}\right)\right\}\Bigg]$$

$$+e^{-Ct}\left[\frac{e^{-(M-C)t}}{\sqrt{\pi t}} + \sqrt{M-C}\ \text{erf}\left(\sqrt{(M-C)t}\right)\right]$$

$$+Ge^{et}\left[\frac{e^{-(M+e)t}}{\sqrt{\pi t}} + \sqrt{M+e}\ \text{erf}\left(\sqrt{(M+e)t}\right)\right] + E\left[\sqrt{\frac{Pr}{\pi t}}e^{-R_a t/Pr} + \sqrt{R_a}\ \text{erf}\left(\sqrt{\frac{R_a t}{Pr}}\right)\right]$$

$$-D\left[t\sqrt{R_a}\ \text{erf}\left(\sqrt{\frac{R_a t}{Pr}}\right) + \sqrt{\frac{tPr}{\pi}}e^{-R_a t/Pr} + \frac{Pr}{2\sqrt{R_a}}\ \text{erf}\left(\sqrt{\frac{R_a t}{Pr}}\right)\right]$$

$$-Ee^{Ct}\left[\sqrt{\frac{Pr}{\pi t}}e^{-R_a t/Pr} + \sqrt{R_a - CPr}\ \text{erf}\left(\sqrt{\frac{R_a t}{Pr}}\right)\right] + G\sqrt{\frac{Sc}{\pi t}} + 2F\sqrt{\frac{tSc}{\pi}}$$

$$-Ge^{et}\left[\sqrt{\frac{Sc}{\pi t}}e^{-et} + \sqrt{eSc}\ \text{erf}\left(\sqrt{et}\right)\right] \qquad (16)$$

5. RESULTS AND DISCUSSION

To gain a perspective of the physics of the flow regime, we have numerically evaluated the effects of Hartmann number (M), Grashof number (Gr), radiation-conduction parameter (R_a), dimensionless time (t) and chemical reaction parameter (K_r), on the velocity, u, temperature, θ, shear stress function, $\left.\frac{\partial u}{\partial y}\right|_{y=0}$. Here we consider $Gr = 5 = Gr_m > 0$ (cooling of the plate) i.e. free convection currents convey heat away from the plate in to the boundary layer, $t = 0.5$, $R_a = 10$ throughout the discussion. The Prandtl number Pr is taken for air at 20°C ($Pr = 0.71$), electrolytic solution ($Pr = 1.0$) and water ($Pr = 7.0$). To ascertain the accuracy of the numerical results, the present study is compared with the previous study. The velocity and concentration profiles are compared with the available solutions of Soundalgekar and Jaiswal [18]; Kumar and Verma [19]. It is observed that the present results are in good agreement with those of [18] and [19].

In **Figure 2** we have presented the influence of Hartmann number square root M on the velocity u distributions with distance normal to the plate (transverse coordinate, y). The hydromagnetic term in the dimensionless equation (2.9), $-Mu$ is a linear drag force term. With increasing magnetic field strength, B_0, M is increased and this serves to decelerate the flow along the plate. In accordance with this, we observe in **Figure 1** that u profile values are strongly reduced with increasing M. We also note that as M rises, the profiles decay to zero progressively for shorter distances from the plate surface. The strong inhibiting effect of magnetic field is therefore evident. Also it is noticed that the velocity distribution increases with the increase in time parameter.

Figure 3 and **4** displays the effects of the chemical reaction parameter K_r on the velocity u and concentration ϕ profiles, respectively. As expected, the presence of the chemical reaction significantly affects the concentration profiles as well as the velocity profiles. It should be mentioned that the studied case is for a destructive chemical reaction K_r. In fact, as K_r increases, the considerable reduction in the velocity profiles is predicted, and the presence of the peak indicates that the maximum value of the velocity occurs in the body of the fluid close to the surface but not at the surface. Also, with an increase in the chemical reaction parameter, the concentration decreases. It is evident that the increase in the chemical reaction K_r significantly alters the concentration boundary layer thickness but does not alter the momentum boundary layers.

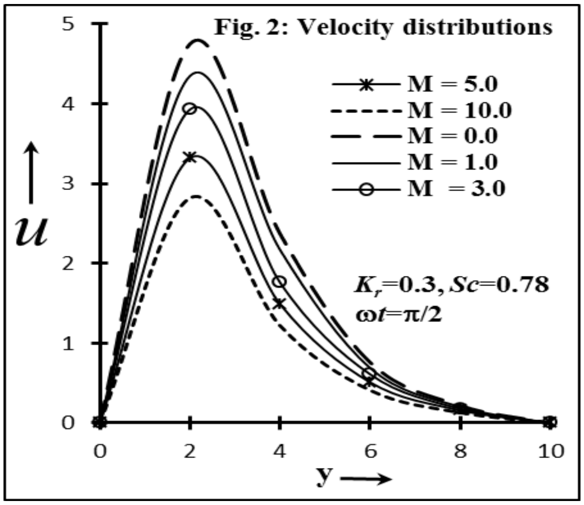

Fig. 2: Velocity distributions

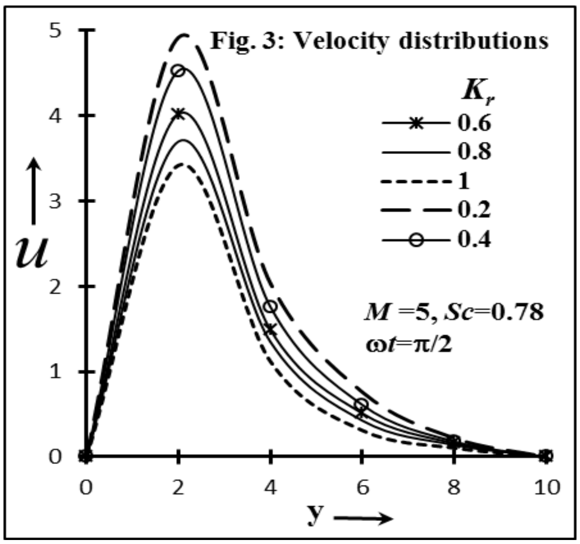

Fig. 3: Velocity distributions

The effect of time (t) and radiation-conduction parameter $R_a$on spatial distribution of the dimensionless temperature function (θ) is shown in **Fig. 5**. Temperature is seen to decrease from a maximum value at the wall (1.0) to a minimum value with maximum distance, y. However with increasing time (t) we observe that there is a clear increase in temperatures. This trend is maintained at all locations in the flow regime. At fixed time, $t = 0.2$, an increase in thermal radiation-conduction parameter (R_a) is observed to strongly increase temperatures throughout the fluid with distance normal to the wall in the fluid regime. Larger (R_a) values correspond to an increased dominance of thermal radiation over conduction. As such thermal radiation supplements the thermal diffusion and increases the overall thermal diffusivity of the regime since the local radiant diffusion flux model adds radiation conductivity to the conventional thermal conductivity. As a result the temperatures in the fluid regime flow are significantly increased.

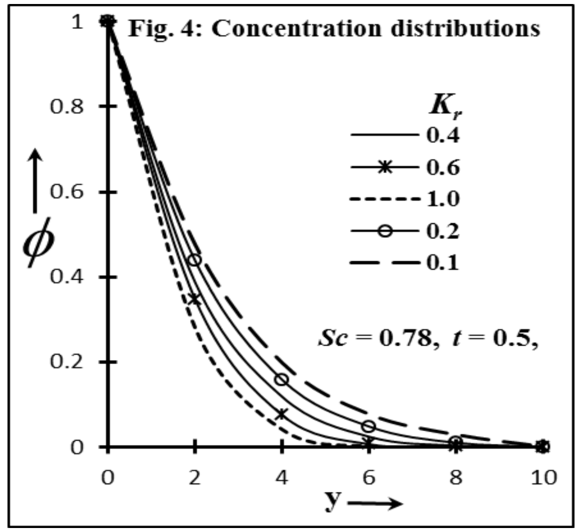

Fig. 4: Concentration distributions

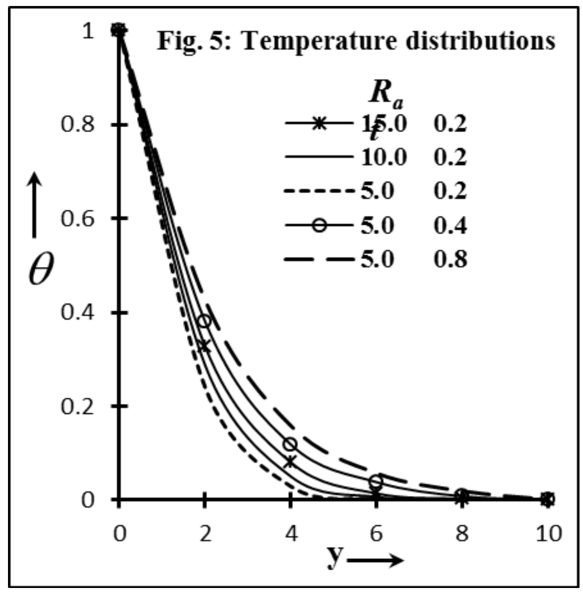

Fig. 5: Temperature distributions

In **Fig. 6** the collective influence of the Grashof number (Gr) and thermal radiation-conduction parameter (R_a) on the shear stress function variation against Hartmann number is shown. Increasing Gr clearly increases shear stress function $\left.\frac{\partial u}{\partial y}\right|_{y=0}$ values i.e. increasing buoyancy serves to accelerate the flow which increases shear stress function values. Similarly in consistency with previous computations, an increase in thermal radiation also serves to accelerate the flow which increases shear stress function values i.e. the maximum shear stress function, $\left.\frac{\partial u}{\partial y}\right|_{y=0}$, corresponds to the maximum M value (highest magnetic body force).

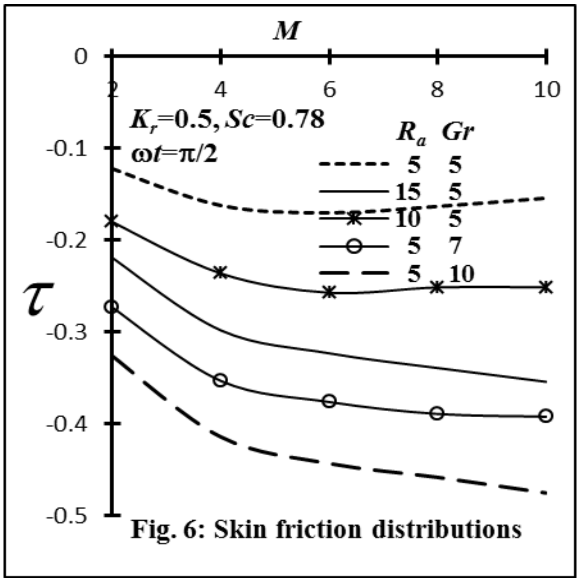

Fig. 6: Skin friction distributions

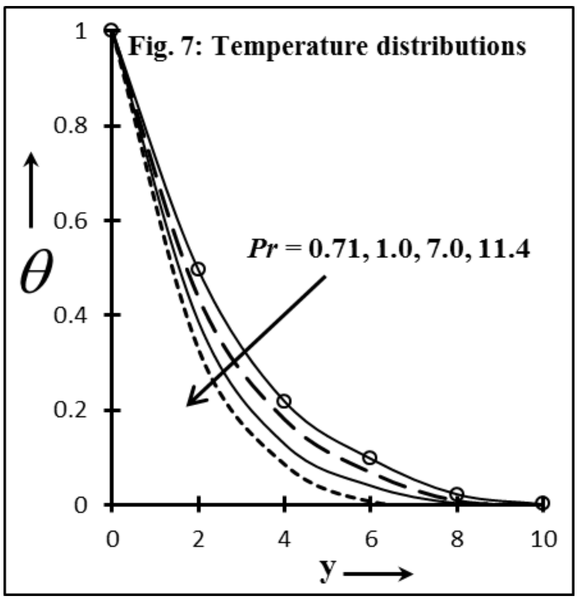

Fig. 7: Temperature distributions

Figures 7 illustrate the temperature (θ) profiles for different Prandtl numbers Pr. The results show that the increasing Prandtl number results in a decrease in the thermal boundary layer and in general lower average temperature within the boundary layer. The reason is that smaller Pr is equivalent to the increase in the thermal conductivity of the fluid, and heat is able to diffuse away from the heated surface more rapidly for higher values of Pr. Therefore, in the case of smaller Prandtl numbers, the thermal boundary layer is thicker, and the rate of heat transfer is reduced.

6. CONCLUSION

A mathematical analysis has been presented of the transient free convection-radiation magnetohydrodynamic viscous flow along an infinite vertical permeable plane under a transverse magnetic field in presence of chemical reaction. A flux model has been employed to simulate thermal radiation effects, valid for optically-thick gases. Laplace transform solutions have been derived for the dimensionless momentum, energy and mass conservations equations. The study has shown that the flow is accelerated with a decrease in Hartmann number square root (M). The velocity as well as the concentration decreases with an increase in the chemical reaction parameter. Temperature of the gas is shown to be enhanced both with the elapse of time (t) and increasing conduction-radiation (R_a)i.e. greater thermal radiation heat transfer contribution. The current study has employed a Newtonian viscous model. Presently the authors are extending this work to examine several non-Newtonian fluids of interest in glass rheological thermal processing including viscoelastic models; the results of these investigations will be communicated imminently.

NOMENCLATURE

$(\overline{u},\overline{v})$ Velocity components along $(\overline{x},\overline{y})$-directions (m. s^{-1}),

U_0 Dimensionless plate velocity (m. s^{-1}),

$\overline{C}$ Species concentration (kg. m^{-3}),

C_P Specific heat at constant pressure (J. kg^{-1}. K),

$\overline{C}_\infty$ Species concentration in the free stream (kg. m^{-3}),

$\overline{C}_w$ Species concentration at the surface (kg. m^{-3}),

D Chemical molecular diffusivity (m^2.s^{-1}),

g Acceleration due to gravity (m.s^{-2}),

Gr Thermal Grashof number,

Gr_m Mass Grashof number,

M Hartmann number parameter,

$\overline{a}$ Absorption coefficient,

Pr Prandtl number,

$\overline{\sigma}$ Stefan-Boltzmann constant,

Sc Schmidt number,

$\overline{T}$ Temperature (K),

$\overline{T}_w$ Fluid temperature at the plate (K),

$\overline{T}_\infty$ Fluid temperature in the free stream (K),

q_r Radiative heat flux,

K_r Chemical reaction coefficient,

R_a Thermal radiation,

t Time parameter,

Nu Nusselt number,

A A constant,

$erfc$ Complementary error function,

erf Error function

Greek symbols

β Coefficient of volume expansion for heat transfer (K^{-1}),

$\overline{\beta}$ Coefficient of volume expansion for mass transfer (K^{-1}),

μ Viscosity of fluid,

θ Dimensionless fluid temperature,

κ Thermal conductivity ($W.\ m^{-1}.\ K^{-1}$),

ν Kinematic viscosity ($m^2.s^{-1}$),

ρ Density ($kg.\ m^{-3}$),

σ Electrical conductivity,

τ Shearing stress ($N.\ m^{-2}$),

ϕ Dimensionless species concentration.

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