Effects of Radiation and Chemical Reaction on MHD Flow Past Over Vertical Plate with Variable Temperature and Mass Diffusion

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Abstract: In the present paper, we study the effects of radiation and chemical reaction on flow past an oscillating vertical plate with variable wall temperature and mass diffusion in the presence of transversely applied uniform magnetic field and Hall current. The flow model consists of unsteady flow of a viscous, incompressible and electrically conducting fluid. The plate temperature and the concentration level near the plate increase linearly with time. The fluid model under consideration has been solved by Laplace transform technique. The model contains equations of motion, diffusion equation and equation of energy. To analyze the solution of the model, desirable sets of the values of the parameters have been considered. The numerical data obtained is discussed with the help of graphs and tables. The numerical values obtained for skin-friction, Sherwood number and Nusselt number have been tabulated. We found that the values obtained for velocity, concentration and temperature are in concurrence with the actual flow of the fluid.

Keywords: MHD flow, radiation, chemical reaction, variable temperature, Hall current

INTRODUCTION

The application of hydromagnetic incompressible viscous flow with heat and mass transfer under the influence of chemical reaction and radiation is of great importance to many areas of science and technology. These have many applications in industry, for instance, magnetic material processing, MHD generators, ion propulsion, MHD bearings, the three-dimensional free convective channel flow MHD pumps, MHD boundary layer control of re-entry vehicles, glass manufacturing control processes and purification of crude oil etc. Radiation heat and mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction was analyzed by Muthucumaraswamy and Chandrakala [1]. Manivannan et al. [2] have studied radiation and chemical reaction effects on isothermal vertical oscillating plate with variable mass diffusion. Radiation, absorption, chemical reaction and magnetic field effects on the free convection and mass transfer flow through porous medium with constant suction and constant heat flux was considered by Damala et al. [3]. Seini and Makinde [4] have worked on MHD boundary layer flow due to exponential stretching surface with radiation and chemical reaction. MHD boundary layer stagnation point flow with radiation and chemical reaction towards a heated shrinking porous surface was examined by Etwire et al. [5]. Radiation effect on unsteady MHD convective heat and mass transfer past a vertical plate with chemical reaction and viscous dissipation was presented by Balla and Naikoti [6]. Malapati and Polarapu [7] have investigated unsteady MHD free convection heat and mass transfer in a boundary layer flow past a vertical permeable plate with thermal radiation and chemical reaction. Singh et al. [8] have worked on heat transfer due to permeable stretching wall in presence of transverse magnetic field. Chemical reaction effect on unsteady MHD flow past an impulsively started oscillating inclined plate with variable temperature and mass diffusion in the presence of Hall current was studied by us [9]. The objective of the present paper is to study the effects of radiation, chemical reaction on flow past an oscillating vertical plate with variable wall temperature and mass diffusion in the presence of transversely applied uniform magnetic field and Hall current. The model has been solved using the Laplace transforms technique. The effects of various parameters on the velocity, temperature and concentration as well as on the skin-friction, Nusselt number and Sherwood number are presented graphically and discussed quantitatively.

MATHEMATICAL ANALYSIS

The geometric model of the problem is shown in figure-1.
Fig-1: Physical model

The x axis is taken along the vertical plate and z axis is normal to it. Thus the z axis lies in the horizontal plane. The magnetic field $B_0$ of uniform strength is applied perpendicular to the flow. Initially it has been considered that the plate as well as the fluid is at the same temperature $T_\infty$. The species concentration in the fluid is taken as $C_\infty$. At time $t > 0$, the plate starts oscillating in its own plane with frequency $\omega$, and temperature of the plate is raised to $T_w$. The concentration $C_w$ near the plate is raised linearly with respect to time.

The flow model is as under:

$$\frac{\partial u}{\partial t} = v \frac{\partial^2 u}{\partial z^2} + g \beta (T - T_\infty) + g \beta^* (C - C_\infty) - \frac{\sigma B_0^2 (u + mv)}{\rho(1 + m^2)} \quad (1)$$

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} + \frac{\sigma B_0^2 (mu - v)}{\rho(1 + m^2)} \quad (2)$$

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - k (C - C_\infty) \quad (3)$$

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - \frac{\partial q_l}{\partial z} \quad (4)$$

The initial and boundary conditions are

$$t \leq 0: u = 0, \quad v = 0, \quad T = T_\infty, \quad C = C_\infty, \quad \text{for every } z.$$  
$$t > 0: \begin{cases} 
 u = u_0 \cos \omega t, \quad v = 0, \quad T = T_\infty + (T_w - T_\infty) A, \quad C = C_\infty + (C_w - C_\infty) A, \quad \text{at } z = 0. \\
 u \to 0, \quad v \to 0, \quad T \to T_\infty, \quad C \to C_\infty \quad \text{as } z \to \infty. 
\end{cases} \quad (5)$$

Here $u$ and $v$ are the primary and secondary velocities along x and z directions respectively, $C$- species concentration in the fluid, $m$-the Hall current parameter, $T$-temperature of the fluid, $T_w$ - temperature of the plate at $z = 0$, $K_e$ -chemical reaction, $C_w$ -species concentration at the plate $z = 0$, $B_0$- the uniform magnetic field, $\sigma$ - electrical conductivity, $\beta^*$ - volumetric coefficient of concentration expansion, $\nu$ - the kinematic viscosity, $\rho$ - the density, $C_p$ - the specific heat at constant pressure, $g$-the acceleration due to gravity, $\beta$ - volumetric coefficient of thermal expansion, $t$-time, $k$- thermal conductivity of the fluid, $D$-the mass diffusion coefficient.

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

$$\frac{\partial q_l}{\partial z} = -4 a^* \sigma (T_\infty^4 - T^4), \quad (6)$$

where $a^*$ is absorption constant. Considered the temperature difference within the flow sufficiently small, $T^4$ can be expressed as the linear function of temperature. This is accomplished by expanding $T^4$ in a Taylor series about $T_\infty$ and neglecting higher-order terms.
\[ T^4 \cong 4T_x^3T - 3T_x^4 \]  

Using equations (6) and (7), equation (4) becomes

\[ \rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - 16a^* \sigma T_x^3(T - T_x) \]  

The following non-dimensional quantities are introduced to transform equations (1), (2), (3) and (8) into dimensionless form:

\[ \tilde{\zeta} = \frac{2z}{u_0}, \quad \tilde{u} = \frac{u}{u_0}, \quad \tilde{v} = \frac{v}{u_0}, \quad G_m = \frac{g\beta u_0}{u_0^3}, \quad G_r = \frac{g\beta u(T_w - T_x)}{u_0}, \quad R = \frac{16a^* \sigma T_x^3}{k u_0}, \quad \tilde{t} = \frac{t u_0^2}{v^2} \]  

The symbols in dimensionless form are as under:

- \( \tilde{u} \) - primary velocity, \( \tilde{v} \) - secondary velocity, \( P_r \) - Prandtl number, \( S_c \) - Schmidt number, \( R \) - Radiation parameter, \( \tilde{t} \) - time,
- \( \theta \) - temperature, \( C \) - concentration, \( G_r \) - thermal Grashof number, \( G_m \) - mass Grashof number, \( \mu \) - coefficient of viscosity, \( M \) - magnetic parameter.

The flow model in dimensionless form is

\[ \frac{\partial \tilde{u}}{\partial \tilde{t}} = \frac{\partial^2 \tilde{u}}{\partial \tilde{z}^2} + G_r, \quad \theta + G_m \tilde{C} = \frac{M(\tilde{u} + m\tilde{v})}{(1 + m^2)} \]  

\[ \frac{\partial \tilde{v}}{\partial \tilde{t}} = \frac{\partial^2 \tilde{u}}{\partial \tilde{z}^2} + \frac{M(m\tilde{u} - \tilde{v})}{(1 + m^2)} \]  

\[ \frac{\partial \tilde{C}}{\partial \tilde{t}} = \frac{1}{S_c} \frac{\partial^2 \tilde{C}}{\partial \tilde{z}^2} - K_0 \tilde{C} \]  

\[ \frac{\partial \theta}{\partial \tilde{t}} = \frac{1}{P_r} \frac{\partial^2 \theta}{\partial \tilde{z}^2} - \frac{R \theta}{P_r} \]  

The corresponding boundary conditions (5) become:

\[ \tilde{t} \leq 0 : \tilde{u} = 0, \tilde{v} = 0, \theta = 0, \tilde{C} = 0, \text{ for every } \tilde{z}. \]  

\[ \tilde{t} > 0 : \tilde{u} = \cos \tilde{t}, \tilde{v} = 0, \theta = \tilde{t}, \tilde{C} = \tilde{t}, \text{ at } \tilde{z} = 0. \]  

\[ \tilde{u} \to 0, \tilde{v} \to 0, \theta \to 0, \tilde{C} \to 0, \text{ as } \tilde{z} \to \infty. \]  

Dropping bars in the above equations, we get

\[ \frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + G_r, \quad \theta + G_m C = \frac{M(u + mv)}{(1 + m^2)} \]  

\[ \frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} + \frac{M(mu - v)}{(1 + m^2)} \]  

\[ \frac{\partial C}{\partial t} = \frac{1}{S_c} \frac{\partial^2 C}{\partial z^2} - K_0 C \]  

\[ \frac{\partial \theta}{\partial t} = \frac{1}{P_r} \frac{\partial^2 \theta}{\partial z^2} - \frac{R \theta}{P_r} \]  

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The boundary conditions become
\begin{align*}
& t \leq 0 : u = 0, v = 0, \theta = 0, C = 0, \text{ for every } z, \\
& t > 0 : u = \cos(\alpha), v = 0, \theta = t, C = t, \text{ at } z = 0. \\
& u \to 0, v \to 0, \theta \to 0, C \to 0, \text{ as } z \to \infty.
\end{align*}
(19)

Writing the equations (15) and (16) in combined form (using \( q = u + iv \))
\begin{align*}
\frac{\partial q}{\partial t} &= \frac{\partial q}{\partial z} + G, \quad \theta + G_m C - qa \\
\frac{\partial C}{\partial t} &= \frac{1}{S_c} \frac{\partial^2 C}{\partial z^2} - K_0 C \\
\frac{\partial \theta}{\partial t} &= \frac{1}{P_r} \frac{\partial^2 \theta}{\partial z^2} - R \theta
\end{align*}
(20)
(21)
(22)

Finally, the boundary conditions become:
\begin{align*}
& t \leq 0 : q = 0, \theta = 0, C = 0, \text{ for every } z, \\
& t > 0 : q = \cos(\alpha), \theta = t, C = t, \text{ at } z = 0. \\
& q \to 0, \theta \to 0, C \to 0, \text{ as } z \to \infty.
\end{align*}
(23)

The dimensionless governing equations (20) to (22), subject to the boundary conditions (23), are solved by the usual Laplace transform technique. The solution obtained is as under:
\begin{align*}
q &= \frac{e^{-sta}A_{13}}{4} + \frac{G}{4(a - R)}(\exp(-\sqrt{a}z)(2RtA_1 - 2atA_1 + \sqrt{a}A_2 + 2A_1(P_r + 1)) - \frac{A_3}{\sqrt{a}} - \frac{2A_4P_c}{\sqrt{a}}(at - Rt + P_r - 1)) \\
&+ \frac{2A_2A_5P_c}{A_{11}}(P_r - 1) - 2A_2tA_3(P_r - 1) - \frac{P_c\sqrt{a}A_{12}P_r}{A_0\otimes \sqrt{a}}(1 - \frac{1}{R}) + \frac{G_m}{4(a - K_0S_c)}((\exp(-\sqrt{a}z)(z\sqrt{a}A_2 - 2atA_1)) \\
&- 2A_1(S_c - 1) + 2tA_1K_0S_c) - \frac{z\exp(-\sqrt{a}z)A_1K_0^2S_c}{\sqrt{a}} - 2A_2tA_1(S_c - 1) + \exp(-z\sqrt{K_0}(-(\frac{aA_1}{\sqrt{K_0}} - 2atA_1)) \\
&- 2A_2 - \frac{A_3(S_c - 1) + 2tA_1K_0S_c + \frac{zA_1\sqrt{K_0}}{A_2}(S_c, K_0) + 2A_2}{}
\end{align*}
\begin{align*}
\theta &= \frac{e^{-\sqrt{a}z}}{4\sqrt{R}}\left\{\text{erfc}\left(\frac{-2\sqrt{Rt} + zP_c}{P_r}\right)(2\sqrt{Rt} - zR) + e^{z\sqrt{a}z}\text{erfc}\left(\frac{2\sqrt{Rt} + zP_c}{P_r}\right)(2\sqrt{Rt} + zR), \right. \\
&\left.\text{erfc}\left(\frac{\sqrt{a}S_c - 2t\sqrt{K_0}}{2\sqrt{a}}\right)(-\sqrt{a}S_c + 2t\sqrt{K_0}) + e^{z\sqrt{a}z}\text{erfc}\left(\frac{\sqrt{a}S_c + 2t\sqrt{K_0}}{2\sqrt{a}}\right)(\sqrt{a}S_c + 2t\sqrt{K_0})\right\}
\end{align*}
\begin{align*}
C &= \frac{e^{-\sqrt{a}z}}{4\sqrt{K_0}}\left\{\text{erfc}\left(\frac{\sqrt{a}S_c - 2t\sqrt{K_0}}{2\sqrt{a}}\right)(-\sqrt{a}S_c + 2t\sqrt{K_0}) + e^{z\sqrt{a}z}\text{erfc}\left(\frac{\sqrt{a}S_c + 2t\sqrt{K_0}}{2\sqrt{a}}\right)(\sqrt{a}S_c + 2t\sqrt{K_0})\right\}
\end{align*}

The expressions for the symbols involved in the above solutions are given in the appendix.

Skin Friction

The dimensionless skin friction at the plate is
\[\left(\frac{du}{dz}\right)_{z=0} = \tau_s + i \tau_r.\]

The numerical values of \( \tau_s \) and \( \tau_r \) for different parameters are given in table-1.

Nusselt Number

The dimensionless Nusselt number at the plate is given by
RESULTS AND DISCUSSION

Sherwood Number

The dimensionless Sherwood number at the plate is given by

\[ S_h = \left( \frac{\partial c}{\partial z} \right)_{z=0} = \text{erf}\left(\frac{\sqrt{K_0}}{t^{1/2}}\right)\left(\frac{1}{4\sqrt{K_0}}SS, K_0 - \frac{t}{2\sqrt{K_0}}\right) + \text{erf}\left(\frac{\sqrt{K_0}}{t^{1/2}}\right)\left(\frac{1}{4\sqrt{K_0}}SS, K_0 + \frac{t}{2\sqrt{K_0}}\right) - \frac{1}{2\sqrt{\pi K_0}}. \]

The numerical values of \( S_h \) for different parameters are given in table-2.

Skin friction is given in table1. The values of \( \tau_x \) and \( \tau_y \) increase with the increases in radiation parameter. However, both decrease with chemical reaction parameter and phase angle. Sherwood number is given in table 2. The value of \( S_h \) decreases with the increase in the chemical reaction parameter, Schmidt number and time. Nusselt number is given in table2. The value of \( Nu \) decreases with increase in Prandtl number, radiation parameter and time.
Fig-3: velocity $v$ for different values of $K_0$

Fig-4: velocity $u$ for different values of $R$

Fig-5: velocity $v$ for different values of $R$

Fig-6: velocity $u$ for different values of $\omega t$
Fig-7: velocity $u$ for different values of $\omega t$

Fig-8: temperature $\theta$ for different values of $R$

Fig-9: concentration $c$ for different values of $K_0$

Table 1: Skin friction for different parameter ($\omega t$ in degree)

| $M$ | $m$ | $Pr$ | $Sc$ | $Gm$ | $Gr$ | $R$ | $K_0$ | $\omega t$ | $t$ | $r_1$ | $r_2$ |
|-----|-----|------|------|------|------|-----|-------|----------|-----|-------|-------|
| 2   | 1   | 0.71 | 2.01 | 100  | 10   | 04  | 01    | 60       | 0.3 | 0491.386 | 0295.441 |
| 2   | 1   | 0.71 | 2.01 | 100  | 10   | 08  | 01    | 60       | 0.3 | 5914.074 | 5567.552 |
| 2   | 1   | 0.71 | 2.01 | 100  | 10   | 04  | 05    | 60       | 0.3 | 0490.375 | 0295.406 |
| 2   | 1   | 0.71 | 2.01 | 100  | 10   | 04  | 10    | 60       | 0.3 | 0491.386 | 0295.441 |
| 2   | 1   | 0.71 | 2.01 | 100  | 10   | 04  | 01    | 45       | 0.3 | 0490.828 | 0295.473 |

Table 2: Sherwood number for different Parameters

| $K_0$ | $Sc$ | $t$ | $S_h$ |
|-------|------|-----|-------|
| 01    | 2.01 | 0.2 | -0.762200 |
| 05    | 2.01 | 0.2 | -0.933049 |
| 10    | 2.01 | 0.2 | -1.118240 |
| 01    | 3.00 | 0.2 | -0.931175 |
| 01    | 4.00 | 0.2 | -1.075230 |
| 01    | 2.01 | 0.3 | -0.961323 |
| 01    | 2.01 | 0.4 | -1.141570 |
CONCLUSION

In this paper a theoretical analysis has been done to study the unsteady MHD flow past an oscillating vertical plate with variable wall temperature and mass diffusion in the presence of Hall current, radiation and chemical reaction. The results obtained are in agreement with the usual flow. It has been found that the velocity in the boundary layer increases with the values of radiation parameter. But trend is reversed with chemical reaction parameter and phase angle. That is the velocity decreases when chemical reaction parameter and phase angle are increased. It is also observed that the permeability parameter and radiation parameter increase the drag at the plate surface, and decrease with chemical reaction parameter and phase angle. Sherwood number and Nusselt number decrease with increase in radiation parameter and chemical reaction parameter.

Appendix:

\[ A = \frac{u_0^2 t}{2}, \quad a = \frac{M(1-im)}{1+m^2}, \quad A_1 = (1 + A_{i2} + e^{2\sqrt{im}} (1 - A_{i3})), \quad A_2 = (1 + A_{i2} - e^{2\sqrt{im}} (1 - A_{i3})), \]

\[ A_3 = (A_{i4} - 1 + A_{i3} (A_{i5} - 1)), \quad A_4 = (A_{i6} - 1 + A_{i0} (A_{i7} - 1)), \quad A_5 = (A_{i8} - 1 + A_{i3} (A_{i9} - 1)), \]

\[ A_6 = (A_{i20} - 1 + A_{i3} (A_{i21} - 1)), \quad A_7 = (e^{2\sqrt{K_{e0}S_p}} (A_{i23} - 1) - A_{i22} - 1)), \quad A_8 = (e^{2\sqrt{K_{e0}S_p}} (A_{i23} - 1) + A_{i22} + 1)), \]

\[ A_9 = (A_{i0} (A_{i23} - 1) - A_{i24} - 1)), \quad A_{10} = (1 - A_{i8} + A_{i2} (A_{i9} - 1)), \quad A_{11} = Abs[z]Abs(P_{x}'], \]

\[ A_{12} = erf[\frac{1}{2\sqrt{t}} (2\sqrt{at} - z)], \quad A_{13} = erf[\frac{1}{2\sqrt{t}} (2\sqrt{at} + z)], \quad A_{14} = erf[\frac{1}{2\sqrt{t}} (z - 2t \sqrt{ap - R} \sqrt{P_{x}'} - 1)], \]

\[ A_{15} = erf[\frac{1}{2\sqrt{t}} (z + 2t \sqrt{ap - R} \sqrt{P_{x}'} - 1)], \quad A_{16} = erf[\frac{1}{2\sqrt{t}} (z - 2t \sqrt{a - K_{0}S_{p}} \sqrt{S_{e} - 1}), \quad A_{17} = erf[\frac{1}{2\sqrt{t}} (z + 2t \sqrt{a - K_{0}S_{p}} \sqrt{S_{e} - 1}), \]

\[ A_{18} = erf[\frac{A_{i1}}{2\sqrt{t}} - \frac{tR}{P_{x}'}, \quad A_{19} = erf\left[\frac{A_{i1}}{2\sqrt{t}} + \frac{tR}{P_{x}'}\right], \quad A_{20} = erf\left[\frac{A_{i1}}{2\sqrt{t}} - \frac{(R - aP_{x}')}{P_{x}' - 1}\right], \]

\[ A_{21} = erf\left[\frac{A_{i1}}{2\sqrt{t}} + \frac{(R - aP_{x}')}{P_{x}' - 1}\right], \quad A_{22} = erf\left[\frac{1}{2\sqrt{t}} (2t \sqrt{K_{0}S_{p}} - z \sqrt{S_{e} - 1})\right], \quad A_{23} = erf\left[\frac{1}{2\sqrt{t}} (2t \sqrt{K_{0}S_{p}} + z \sqrt{S_{e} - 1})\right], \]

\[ A_{24} = erf\left[\frac{1}{2\sqrt{t}} (2t \sqrt{\frac{(a - K_{0}S_{p})S_{e} - 1} - z \sqrt{S_{e} - 1})\right], \quad A_{25} = erf\left[\frac{1}{2\sqrt{t}} (2t \sqrt{\frac{(a - K_{0}S_{p})S_{e} - 1} + z \sqrt{S_{e} - 1})\right], \]

\[ A_{26} = \exp\left(\frac{at}{P_{x}' - 1} - \frac{Rt}{P_{x}' - 1} - z \sqrt{\frac{ap - R}{P_{x}' - 1}}\right), \quad A_{27} = \exp\left(\frac{at}{P_{x}' - 1} - \frac{tS_{K_{0}}K_{0}}{S_{e} - 1} - \frac{z \sqrt{(a - K_{0}S_{p})}}{S_{e} - 1}\right), \]

\[ A_{28} = \frac{1}{A_{i1}} \exp\left(\frac{at}{P_{x}' - 1} - \frac{Rt}{P_{x}' - 1}\right), \quad A_{29} = \exp(2z \sqrt{-R + aP_{x}'} \sqrt{P_{x}' - 1}), \quad A_{30} = \exp(2z \sqrt{(a - K_{0}S_{p})} \sqrt{S_{e} - 1}), \]

\[ A_{31} = \exp(2Abs[z] \sqrt{P_{x}' (aP_{x}' - R)}/P_{x}' - 1)), \quad A_{32} = \exp(2Abs[z] \sqrt{PR}), \quad A_{33} = e^{-z \sqrt{(a - im)}} + e^{-z \sqrt{(a + im)}}, \]
\[
A_{33} = A_{34} + A_{35} - e^{-z\sqrt{a+i\omega}} A_{36} - e^{-z\sqrt{a+i\omega}+2it\omega} A_{37}, \\
A_{36} = \text{erf}\left[\frac{z-2t\sqrt{a-i\omega}}{2\sqrt{t}}\right] + \text{erf}\left[\frac{z+2t\sqrt{a-i\omega}}{2\sqrt{t}}\right], \\
A_{37} = \text{erf}\left[\frac{z-2t\sqrt{a+i\omega}}{2\sqrt{t}}\right] + \text{erf}\left[\frac{z+2t\sqrt{a+i\omega}}{2\sqrt{t}}\right], \\
A_{35} = e^{-z\sqrt{a+i\omega}+2it\omega} + e^{z\sqrt{a-i\omega}+2it\omega},
\]

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