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.
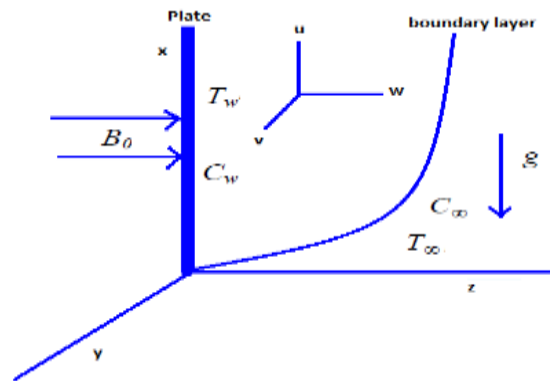
Fig-1: Physical model

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_∞. The species concentration in the fluid is taken as C_∞. At time $t > 0$, the plate starts oscillating in its own plane with frequency ω, 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:

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

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

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

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - \frac{\partial q_r}{\partial z} \tag{4}$$

The initial and boundary conditions are

$$\left. \begin{array}{l} t \le 0 : u = 0,\ v = 0,\ T = T_\infty,\ C = C_\infty,\ \text{for every } z. \\ t > 0 : u = u_0 Cos\omega t,\ v = 0,\ T = T + (T_w - T_\infty)A,\ C = C_\infty + (C_w - C_\infty)A,\ \text{at } z{=}0. \\ u \to 0,\ v = 0,\ T \to T_\infty,\ C \to C_\infty \ \text{as } z \to \infty. \end{array} \right\} \tag{5}$$

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_c chemical reaction, C_w -species concentration at the plate $z{=}0$, B_0- the uniform magnetic field, σ - electrical conductivity. β^* - volumetric coefficient of concentration expansion, ν- the kinematic viscosity, ρ- the density, C_p- the specific heat at constant pressure, g-the acceleration due to gravity, β -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

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

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_∞ and neglecting higher-order terms

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$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

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

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - 16a^* \sigma T_\infty^3 (T - T_\infty) \tag{8}$$

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

$$\left. \begin{array}{l} \bar{z} = \dfrac{z u_0}{\upsilon}, \ \bar{u} = \dfrac{u}{u_0}, \ \bar{v} = \dfrac{v}{u_0}, \ G_m = \dfrac{g\beta^* \upsilon (C_w - C_\infty)}{u_0^3}, G_r = \dfrac{g\beta\upsilon(T_w - T_\infty)}{u_0^3}, R = \dfrac{16a^* \upsilon^2 \sigma T_\infty^3}{k u_0}, \bar{\omega} = \dfrac{\omega\upsilon}{u_0^2}, \\[4mm] \theta = \dfrac{(T - T_\infty)}{(T_w - T_\infty)}, \ M = \dfrac{\sigma B_0^2 \upsilon}{\rho u_0^2}, \ S_c = \dfrac{\upsilon}{D}, K_0 = \dfrac{\upsilon K_c}{u_0^2}, P_r = \dfrac{\mu u_0}{k}, \mu = \rho\upsilon, \overline{C} = \dfrac{(C - C_\infty)}{(C_w - C_\infty)}, \ \bar{t} = \dfrac{t u_0^2}{\upsilon}. \end{array} \right\} \tag{9}$$

The symbols in dimensionless form are as under:

$\bar{u}$ - primary velocity, $\bar{v}$ - secondary velocity, P_r - Prandtl number, S_c - Schmidt number, R-Radiation parameter, $\bar{t}$ - time, θ- temperature, $\overline{C}$ - concentration, G_r - thermal Grashof number, G_m - mass Grashof number, μ- coefficient of viscosity, M- magnetic parameter.

The flow model in dimensionless form is

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + G_r \theta + G_m \overline{C} - \frac{M(\bar{u} + m\bar{v})}{(1 + m^2)} \tag{10}$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + \frac{M(m\bar{u} - \bar{v})}{(1 + m^2)} \tag{11}$$

$$\frac{\partial \overline{C}}{\partial \bar{t}} = \frac{1}{S_c} \frac{\partial^2 \overline{C}}{\partial \bar{z}^2} - K_0 \overline{C} \tag{12}$$

$$\frac{\partial \theta}{\partial \bar{t}} = \frac{1}{P_r} \frac{\partial^2 \theta}{\partial \bar{z}^2} - \frac{R\theta}{P_r} \tag{13}$$

The corresponding boundary conditions (5) become:

$$\left. \begin{array}{l} \bar{t} \le 0 : \bar{u} = 0, \ \bar{v} = 0, \ \theta = 0, \ \overline{C} = 0, \text{ for every } \bar{z}. \\[2mm] \bar{t} > 0 : \bar{u} = Cos\,\overline{\omega}\bar{t}, \bar{v} = 0, \ \theta = \bar{t}, \ \overline{C} = \bar{t}, \text{ at } \bar{z} = 0. \\[2mm] \bar{u} \to 0, \ \bar{v} \to 0, \ \theta \to 0, \ \overline{C} \to 0, \text{ as } \bar{z} \to \infty. \end{array} \right\} \tag{14}$$

Dropping bars in the above equations, we get

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + G_r \theta + G_m C - \frac{M(u + mv)}{(1 + m^2)} \tag{15}$$

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} + \frac{M(mu - v)}{(1 + m^2)} \tag{16}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c} \frac{\partial^2 C}{\partial z^2} - K_0 C \tag{17}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r} \frac{\partial^2 \theta}{\partial z^2} - \frac{R\theta}{P_r} \tag{18}$$

The boundary conditions become

$$t \leq 0 : u = 0, v = 0, \theta = 0, C = 0, \text{ for every } z.$$
$$t > 0 : u = Cos\omega t, , v = 0, \ \theta = t, \ C = t, \text{ at z=0.} \left. \right\}$$
$$u \rightarrow 0, \ v \rightarrow 0, \ \theta \rightarrow 0, \ C \rightarrow 0, \text{ as } z \rightarrow \infty.$$

(19)

Writing the equations (15) and (16) in combined form (using $q = u + i \, v$)

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} + G_r \, \theta + G_m \, C - qa$$

(20)

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

(21)

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

(22)

Finally, the boundary conditions become:

$$t \leq 0 : q = 0, \theta = 0, C = 0, \quad \text{for every z.}$$
$$t > 0 : q = Cos\omega t, \theta = t, C = t, \text{ at z=0.} \left. \right\}$$
$$q \rightarrow 0, \ \theta \rightarrow 0, \ C \rightarrow 0, \quad \text{as } z \rightarrow \infty.$$

(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:

$$q = \frac{e^{-it\omega}A_{33}}{4} + \frac{G_r}{4(a\text{-}R)^2}((\exp(-\sqrt{a}z)(2RtA_1 - 2atA_1 + z\sqrt{a}A_2 + 2A_1(P_r+1)) - \frac{A_2 z}{\sqrt{a}}) - \frac{2A_5 P_r z}{\sqrt{A_{32}A_{11}}}(at - Rt + P_r - 1)$$

$$+ \frac{2A_{28}A_6 P_r z}{A_{11}}(P_r - 1) - 2A_{26}A_3(P_r - 1) - \frac{P_r z\sqrt{A_{32}P_r}}{A_{10}\pi\sqrt{R}}(\frac{1}{a} - \frac{1}{R})) + \frac{G_m}{4(a - K_0 S_c)^2}((\exp(-\sqrt{a}z)(z\sqrt{a}A_2 - 2atA_1$$

$$- 2A_1(S_c - 1) + 2tA_1 K_0 S_c) - \frac{z\exp(-\sqrt{a}z)A_2 K_0 S_c}{\sqrt{a}} - 2A_{27}A_4(S_c - 1)) + \exp(-z\sqrt{S_c K_0})(-\frac{aA_8 z\sqrt{S_c}}{\sqrt{K_0}} - 2atA_7$$

$$- 2A_7 - 2A_7(S_c - 1) + 2tA_7 K_0 S_c + zA_8 S_c \sqrt{S_c K_0}) + 2A_{27}A_9(S_c - 1))$$

$$\theta = \frac{e^{-\sqrt{R}z}}{4\sqrt{R}}\{erfc[\frac{-2\sqrt{R}t + zP_r}{\sqrt{P_r}t}](2\sqrt{R}t - zR) + e^{2\sqrt{R}z}erfc[\frac{2\sqrt{R}t + zP_r}{\sqrt{P_r}t}](2\sqrt{R}t + zR)\},$$

$$C = \frac{e^{-z\sqrt{S_c K_0}}}{4\sqrt{K_0}}\left\{erfc[\frac{z\sqrt{S_c} - 2t\sqrt{K_0}}{2\sqrt{t}}](-z\sqrt{S_c} + 2t\sqrt{K_0}) + e^{2z\sqrt{S_c K_0}}erfc[\frac{z\sqrt{S_c} + 2t\sqrt{K_0}}{2\sqrt{t}}](z\sqrt{S_c} + 2t\sqrt{K_0})\right\}$$

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

$$\left(\frac{dq}{dz}\right)_{z=0} = \tau_x + i\tau_y.$$

The numerical values of τ_x and τ_y, for different parameters are given in table-1.

Nusselt Number

The dimensionless Nusselt number at the plate is given by

$$Nu = \left(\frac{\partial \theta}{\partial z}\right)_{z=0} = erfc[\frac{\sqrt{Rt}}{\sqrt{tP_r}}](\sqrt{Rt} - \frac{\sqrt{R}}{2}t + \frac{P_r}{4\sqrt{R}}) - erfc[-\frac{\sqrt{Rt}}{\sqrt{tP_r}}](\frac{\sqrt{R}}{2}t + \frac{P_r}{4\sqrt{R}}) - \frac{e^{-\frac{Rt}{P_r}}\sqrt{tP_r}}{\sqrt{\pi}}.$$

The numerical values of *Nu* for different parameters are given in table-2.

Sherwood Number

The dimensionless Sherwood number at the plate is given by

$$S_h = \left(\frac{\partial C}{\partial z}\right)_{z=0} = erfc[-\sqrt{tK_0}](-\frac{1}{4\sqrt{K_0}}\sqrt{S_c} - \frac{t\sqrt{S_cK_0}}{2}) + \sqrt{S_c}\,erfc[\sqrt{tK_0}](\frac{1}{4\sqrt{K_0}} + t\sqrt{K_0}) - \frac{e^{-tK_0}\sqrt{tS_cK_0}}{\sqrt{\pi K_0}}.$$

The numerical values of S_h for different parameters are given in table-3.

RESULTS AND DISCUSSION

The present study is carried out to examine the effects of radiation and chemical reaction on the unsteady MHD flow. The behavior of other parameters like magnetic field, Hall current and thermal buoyancy is almost similar to the earlier model studied by us [9]. The analytical results are shown graphically in figures 2 to 10. The numerical values of skin-friction, Sherwood number and Nusselt number are presented in Table-1, 2 and 3 respectively. Chemical reaction effect on fluid flow behavior is shown by figures 2 and 3. It is seen here that when chemical reaction parameter (K_0) increases, primary and secondary velocities decrease throughout the boundary layer region. Figures 4 and 5, indicates that effect of radiation (*R*) in the boundary layer region near the plate tends to accelerate primary and secondary velocities. Effect of oscillation on flow behavior is shown by figures 6 and 7. It is observed that if phase angle *ωt is* increased then velocities of fluid are decreased throughout the boundary layer region. Further, it is observed that the temperature and concentration of the fluid near the plate decreases when radiation and chemical reaction parameters are increased (figures 8 and 9).

Skin friction is given in table1. The values of τ_x and τ_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.
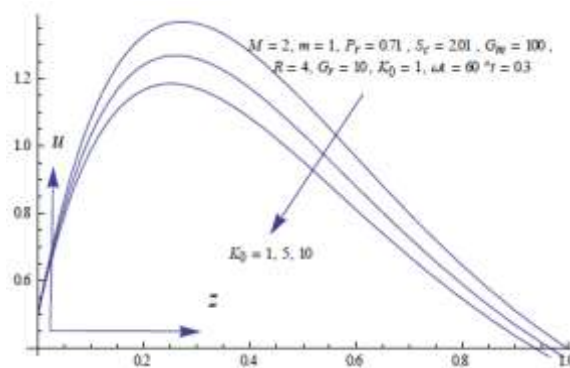

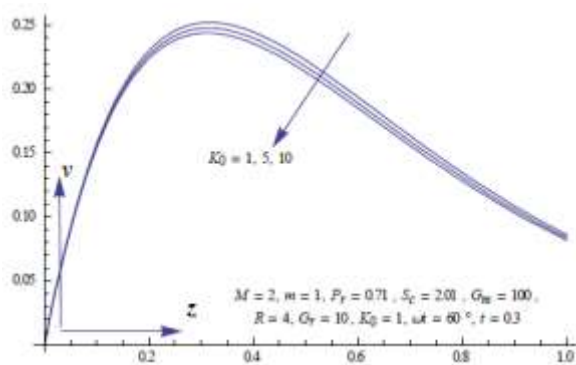**Fig-2: velocity *u* for different values of K_0**
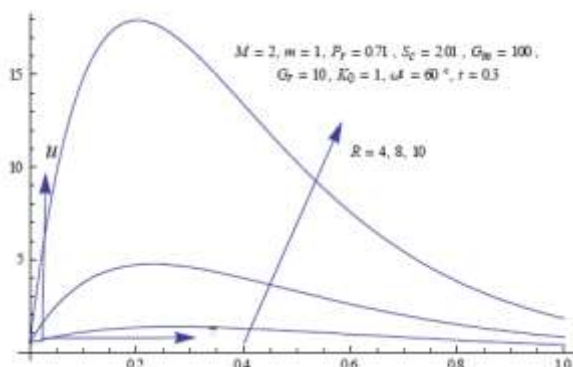
Fig-3: velocity *v* for different values of *K₀*
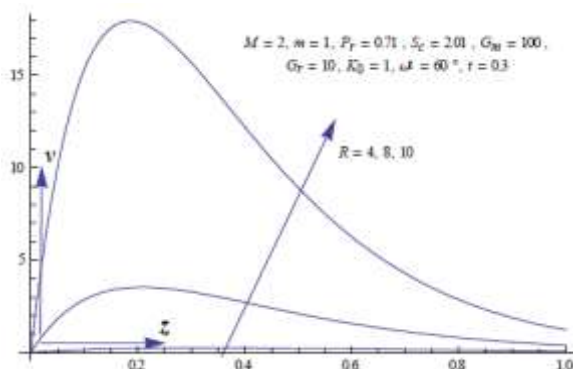

Fig-4: velocity *u* for different values of *R*

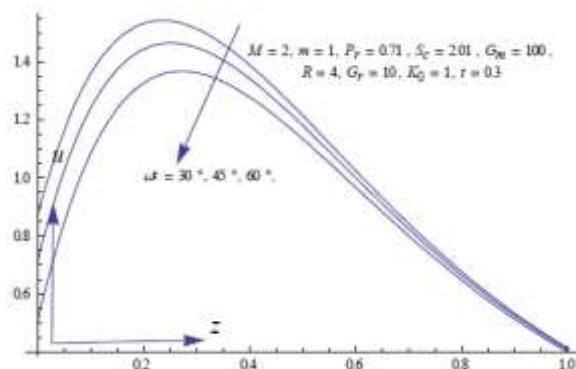**Fig-5: velocity *v* for different values of *R***

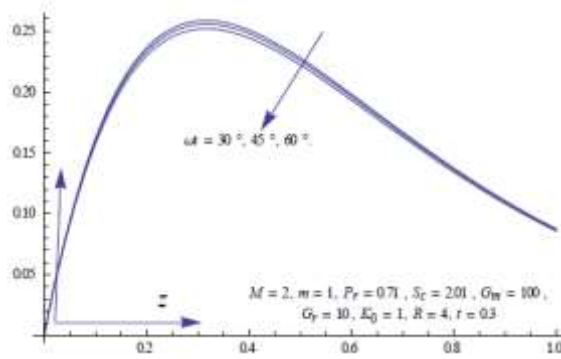**Fig-6: velocity *u* for different values of *ωt***

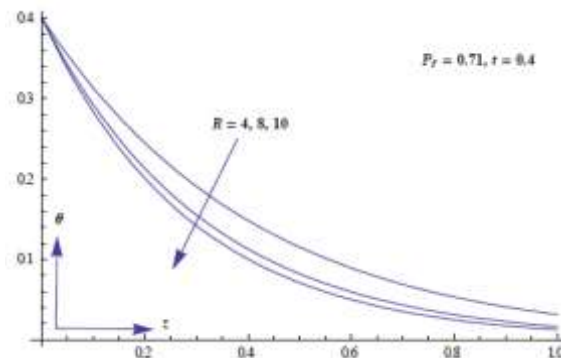**Fig-7: velocity *u* for different values of *ωt***
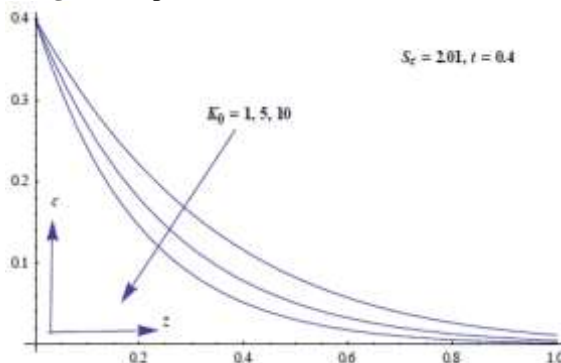
Fig-8: temperature θ for different values of *R*

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

Table 1: Skin friction for different parameter (*ωt in degree*)

M	m	Pr	Sc	Gm	Gr	R	K_0	ωt	t	τ_x	τ_y
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	0490.851	0295.442
2	1	0.71	2.01	100	10	04	10	60	0.3	0490.375	*0295.406*
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	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

Table 3: Nusselt number for different parameter

Pr	R	t	Nu
0.71	2	0.4	-0.805273
7.00	2	0.4	-1.959260
0.71	3	0.4	-0.894014
0.71	4	0.4	-0.976083
0.71	2	0.5	-0.950956
0.71	2	0.6	-1.094940

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:

$$A = \frac{u_0^2 t}{\upsilon}, \qquad a = \frac{M(1-im)}{1+m^2}, \qquad A_1 = (1 + A_{12} + e^{2\sqrt{az}}(1 - A_{13})), \qquad A_2 = (1 + A_{12} - e^{2\sqrt{az}}(1 - A_{13})),$$

$$A_3 = (A_{14} - 1 + A_{29}(A_{15} - 1)), \qquad A_4 = (A_{16} - 1 + A_{30}(A_{17} - 1)), \qquad A_5 = (A_{18} - 1 + A_{33}(A_{19} - 1)),$$

$$A_6 = (A_{20} - 1 + A_{31}(A_{21} - 1)), \qquad A_7 = (e^{2z\sqrt{K_0 S_c}}(A_{23} - 1) - A_{22} - 1)), \qquad A_8 = (e^{2z\sqrt{K_0 S_c}}(A_{23} - 1) + A_{22} + 1)),$$

$$A_9 = (A_{30}(A_{25} - 1) - A_{24} - 1), \qquad A_{10} = (1 - A_{18} + A_{32}(A_{19} - 1)), \qquad A_{11} = Abs[z]Abs[P_r],$$

$$A_{12} = erf[\frac{1}{2\sqrt{t}}(2\sqrt{at} - z)], \qquad A_{13} = erf[\frac{1}{2\sqrt{t}}(2\sqrt{at} + z)], \qquad A_{14} = erf[\frac{1}{2\sqrt{t}}(z - 2t\sqrt{\frac{aP_r - R}{P_r - 1}})],$$

$$A_{15} = erf[\frac{1}{2\sqrt{t}}(z + 2t\sqrt{\frac{aP_r - R}{P_r - 1}})], \qquad A_{16} = erf[\frac{1}{2\sqrt{t}}(z - 2t\sqrt{\frac{(a - K_0)S_c}{S_c - 1}})], \qquad A_{17} = erf[\frac{1}{2\sqrt{t}}(z + 2t\sqrt{\frac{(a - K_0)S_c}{S_c - 1}})],$$

$$A_{18} = erf[\frac{A_{11}}{2\sqrt{t}} - \sqrt{\frac{tR}{P_r}}], \qquad A_{19} = erf[\frac{A_{11}}{2\sqrt{t}} + \sqrt{\frac{tR}{P_r}}], \qquad A_{20} = erf[\frac{A_{11}}{2\sqrt{t}} - \sqrt{\frac{(R - aP_r)t}{P_r - P_r^2}})],$$

$$A_{21} = erf[\frac{A_{11}}{2\sqrt{t}} + \sqrt{\frac{(R - aP_r)t}{P_r - P_r^2}})], \qquad A_{22} = erf[\frac{1}{2\sqrt{t}}(2t\sqrt{K_0} - z\sqrt{S_c})], \qquad A_{23} = erf[\frac{1}{2\sqrt{t}}(2t\sqrt{K_0} + z\sqrt{S_c})],$$

$$A_{24} = erf[\frac{1}{2\sqrt{t}}(2t\sqrt{\frac{(a - K_0)S_c}{S_c - 1}} - z\sqrt{S_c})], \qquad A_{25} = erf[\frac{1}{2\sqrt{t}}(2t\sqrt{\frac{(a - K_0)S_c}{S_c - 1}} + z\sqrt{S_c})],$$

$$A_{26} = \exp(\frac{at}{P_r - 1} - \frac{Rt}{P_r - 1} - z\sqrt{\frac{aP_r - R}{P_r - 1}}), \qquad A_{27} = \exp(\frac{at}{S_c - 1} - \frac{tS_c K_0}{S_c - 1} - z\sqrt{\frac{(a - K_0)S_c}{S_c - 1}}),$$

$$A_{28} = \frac{1}{A_{31}}\exp(\frac{at}{P_r - 1} - \frac{Rt}{P_r - 1}), \quad A_{29} = \exp(2z\sqrt{\frac{-R + aP_r}{P_r - 1}}), \quad A_{30} = \exp(2z\sqrt{\frac{(a - K_0)S_c}{S_c - 1}}),$$

$$A_{31} = \exp(2Abs[z]\sqrt{\frac{P_r(aP_r - R)}{P_r - 1}}), \quad A_{32} = \exp(2Abs[z]\sqrt{P_r R}), \quad A_{34} = e^{-z\sqrt{a + i\omega}} + e^{-z\sqrt{a - i\omega}},$$

$$A_{33} = A_{34} + A_{35} - e^{-z\sqrt{a+i\omega}}A_{36} - e^{-z\sqrt{a+i\omega}+2it\omega}A_{37}, \qquad\qquad A_{35} = e^{-z\sqrt{a+i\omega}+2it\omega} + e^{z\sqrt{a-i\omega}+2it\omega},$$

$$A_{36} = erf\left[\frac{z - 2t\sqrt{a-i\omega}}{2\sqrt{t}}\right] + erf\left[\frac{z + 2t\sqrt{a-i\omega}}{2\sqrt{t}}\right], \quad A_{37} = erf\left[\frac{z - 2t\sqrt{a+i\omega}}{2\sqrt{t}}\right] + erf\left[\frac{z + 2t\sqrt{a+i\omega}}{2\sqrt{t}}\right],$$

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