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EFFECTS OF RADIATION, CHEMICAL REACTION AND POROSITY OF THE MEDIUM ON MHD FLOW PAST AN OSCILLATING PLATE WITH HEAT AND MASS TRANSFER

U S Rajput and Gaurav kumar
Department of Mathematics and Astronomy,
University of Lucknow, U.P, India.
Email: rajputgauravlko@gmail.com

ABSTRACT
The present study is carried out to examine the effects of radiation, chemical reaction and porosity of the medium on unsteady MHD flow past an oscillating vertical plate in the presence of Hall current. The fluid considered is viscous, incompressible and electrically conducting. The flow is along an impulsively started oscillating vertical plate with variable wall temperature and mass diffusion. The magnetic field is applied perpendicular to the plate. The plate temperature and the concentration level near the plate increase linearly with time. The model contains equations of motion, diffusion equation and energy equation. The fluid model under consideration has been solved by the Laplace transform technique. 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. The results of the study may find applications in the field related to flow in pipes and channels in petroleum technology, rocket science and missile technology etc.

Keywords: MHD flow, Radiation, chemical reaction, mass diffusion, Hall current.

1 INTRODUCTION

The MHD flow problems play important role in different area of science and technology. These have many applications in industry, for instance, magnetic material processing, glass manufacturing control processes and purification of crude oil. Radiation and chemical reaction effects on isothermal vertical oscillating plate with variable mass diffusion was analyzed by Manivannan et al. [4]. Chaudhary and Arpita [1] have studied combined heat and mass transfer effects on MHD free convection flow past an oscillating plate embedded in porous medium. Effects of chemical reaction, radiation, heat and mass transfer on the MHD flow along a vertical porous wall in the presence of applied magnetic field was considered by Sahin and Chamkha [8]. 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 examined by Damala et al. [2]. MHD boundary layer stagnation point flow with radiation and chemical reaction towards a heated shrinking porous surface was investigated by Etwire et al. [3]. Reddy et al. [7] have worked on analytical study of MHD free convective, dissipative boundary layer flow past a porous vertical surface in the presence of thermal radiation, chemical reaction and constant suction. Diffusion-thermo and radiation effects on MHD free convection flow of chemically reacting fluid past an oscillating plate embedded in porous medium was presented by Swethaa et al. [9]. Molaei and Rouzbahani [5] have analyzed MHD free convection flow of a non-Newtonian power-law fluid over a vertical plate with suction effects. 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 [6]. The objective of the present paper is to study the effects of radiation, chemical reaction and porosity of the medium 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.

2 MATHEMATICAL ANALYSIS

The geometrical model of the problem is shown in Figure-1

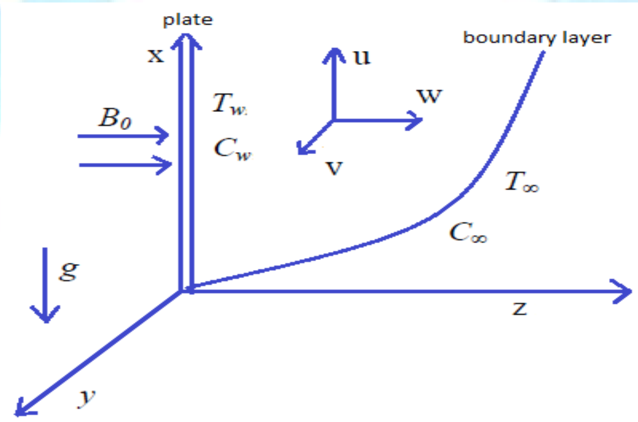

Figure-1. Physical model

The x axis is taken along the vertical plate and z axis is normal to it. 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:

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

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

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

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

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, 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, m - the Hall current parameter, *K*- the permeability parameter, T_w - temperature of the plate at *z= 0*, *T*- temperature of the fluid, β^* - volumetric coefficient of concentration expansion, *k*- thermal conductivity of the fluid, *D*-the mass diffusion coefficient, K_c chemical reaction, C_w -species concentration at the plate *z= 0*, B_0- the uniform magnetic field, *σ* - electrical conductivity.

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

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

Here a^* is absorption constant. The temperature difference within the flow is considered sufficiently small, hence 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

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

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:

$$\left.\begin{array}{l} \bar{z} = \frac{zu_0}{\upsilon},\ \bar{u} = \frac{u}{u_0},\ \bar{v} = \frac{v}{u_0}, S_c = \frac{\upsilon}{D}, \mu = \rho\upsilon, G_m = \frac{g\beta^*\upsilon(C_w - C_\infty)}{u_0^3},\ R = \frac{16a^*\upsilon^2\sigma T_\infty^3}{ku_0}, P_r = \frac{\mu u_0}{k}, \\ \bar{C} = \frac{(C - C_\infty)}{(C_w - C_\infty)}, G_r = \frac{g\beta\upsilon(T_w - T_\infty)}{u_0^3}, M = \frac{\sigma B_0^2\upsilon}{\rho u_0^2},\ K_0 = \frac{\upsilon K_c}{u_0^2}, \bar{\omega} = \frac{\omega\upsilon}{u_0^2}, \theta = \frac{(T - T_\infty)}{(T_w - T_\infty)},\ \bar{t} = \frac{tu_0^2}{\upsilon}. \end{array}\right\} \tag{9}$$

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, $\bar{C}$ - 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

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

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

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

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

The corresponding boundary conditions (5) become:

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

Dropping bars in the above equations, we get

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

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

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

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

The boundary conditions become

$$\left.\begin{array}{l} t \le 0: u=0, v=0, \theta=0, C=0, \text{ for every } z. \\ t > 0: u = Cos\omega t, , v=0,\ \theta = t,\ C = t, \text{ at } z=0. \\ u \to 0, v \to 0, \theta \to 0, C \to 0, \text{ as } z \to \infty. \end{array}\right\} \tag{19}$$

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

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} + G_r\,\theta + G_m\,C - qa \tag{20}$$

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}-K_0 C \tag{21}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2}-\frac{R\theta}{P_r} \tag{22}$$

Finally, the boundary conditions become:

$$\left.\begin{array}{l} t\le 0: q=0,\theta=0,C=0,\ \text{for every z.} \\ t>0: q=Cos\,\omega t,\theta=t,C=t,\ \text{at z=0.} \\ q\to 0,\ \theta\to 0,\ C\to 0,\ \text{as}\ z\to\infty. \end{array}\right\} \tag{23}$$

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:

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

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

$$q=\frac{e^{-it\omega}A_{33}}{4}+\frac{G_r}{4(a-R)^2}((\exp(-\sqrt{a}z)(2RtA_1-2atA_1+z\sqrt{a}A_2+2A_1(P_r+1))-\frac{A_2 z}{\sqrt{a}})$$
$$-\frac{2A_5P_r z}{\sqrt{A_{32}A_{11}}}(at-Rt+P_r-1)+\frac{2A_{28}A_6P_r z}{A_{11}}(P_r-1)-2A_{26}A_3(P_r-1)-\frac{P_r z\sqrt{A_{32}P_r}}{A_{10}\pi\sqrt{R}}(\frac{1}{a}-\frac{1}{R}))$$
$$+\frac{G_m}{4(a-K_0S_c)^2}((\exp(-\sqrt{a}z)(z\sqrt{a}A_2-2atA_1-2A_1(S_c-1)+2tA_1K_0S_c)-\frac{z\exp(-\sqrt{a}z)A_2K_0S_c}{\sqrt{a}}$$
$$-2A_{27}A_4(S_c-1))+\exp(-z\sqrt{S_cK_0})(-\frac{aA_8z\sqrt{S_c}}{\sqrt{K_0}}-2atA_7-2A_7-2A_7(S_c-1)+2tA_7K_0S_c$$
$$+zA_8S_c\sqrt{S_cK_0})+2A_{27}A_9(S_c-1))$$

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

3 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.

4 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.

4 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.

5 RESULTS AND DISCUSSION

The present study is carried out to examine the effects of radiation, chemical reaction and permeability of porous medium on the flow. The behavior of other parameters like magnetic field, Hall current and thermal buoyancy is almost similar to the earlier model studied by us [6]. The analytical results are shown graphically in figures 2 to 11. 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. From figures 4 and 5, it is observed that primary and secondary velocities increase with permeability parameter *(K)*. This result is due to the fact that increases in the value of *(K)* results in reducing the drag force, and hence increasing the fluid velocities. Figures 6 and 7, indicates that the 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 8 and 9. 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 decrease when radiation and chemical reaction parameters are increased (figures 10 and 11).

Skin friction is given in table1. The values of τ_x and τ_y increase with the increase in radiation and permeability parameter. Sherwood number is given in table2. The value of S_h decreases with the increase in the chemical reaction parameter, Schmidt number and time. Nusselt number is given in table 3. The value of *Nu* decrease with increase in Prandtl number, radiation parameter and time.

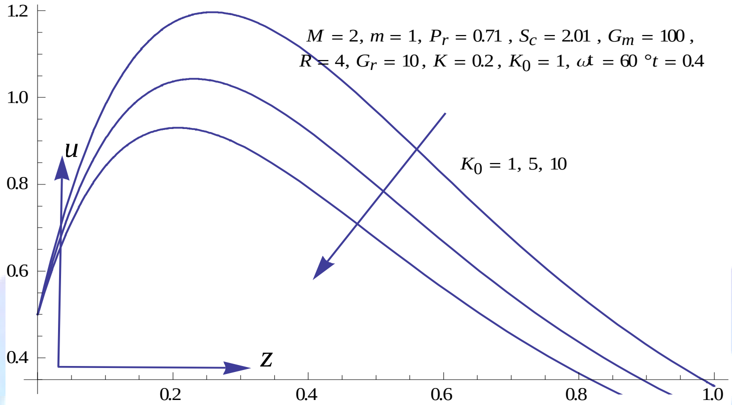

Figure 2: velocity *u* for different values of K_0

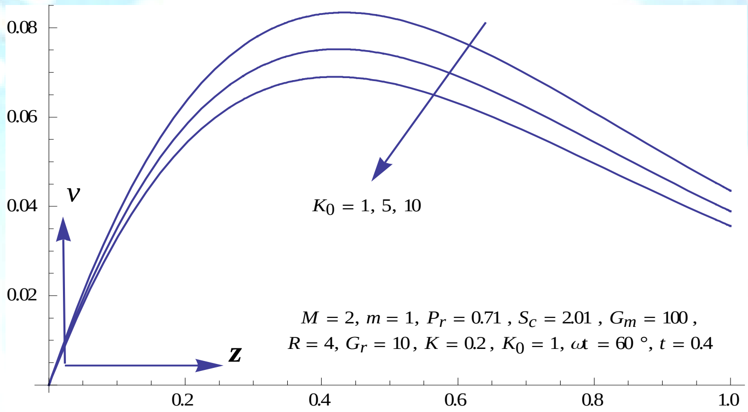

Figure 3: velocity *v* for different values of K_0

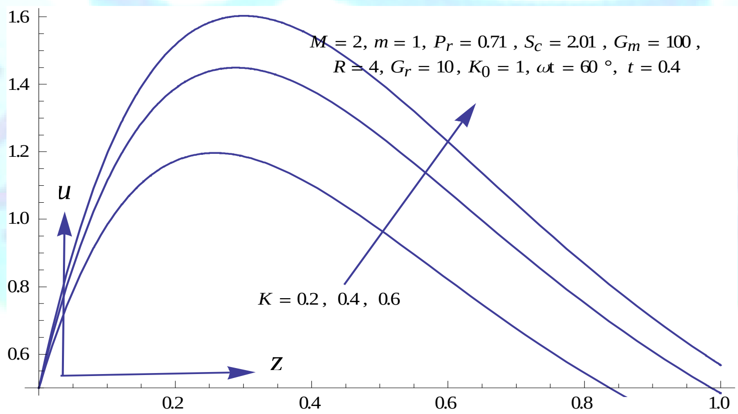

Figure 4: velocity *u* for different values of *K*

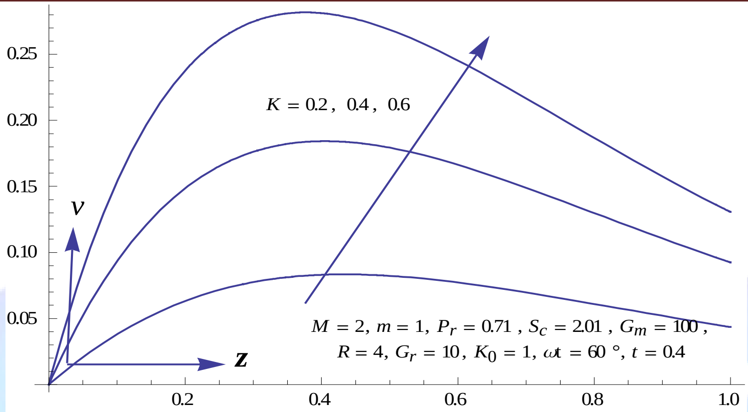

Figure 5: velocity *v* for different values of *K*

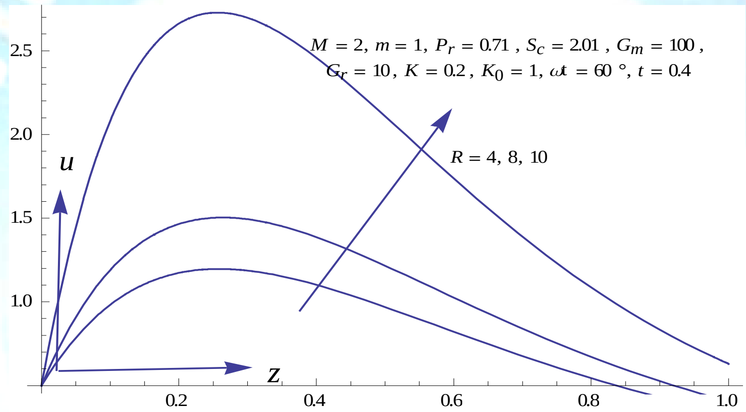

Figure 6: velocity *u* for different values of *R*

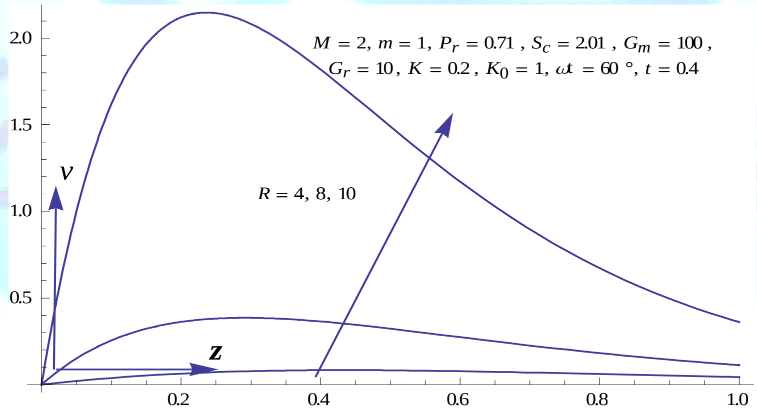

Figure 7: velocity *v* for different values of *R*

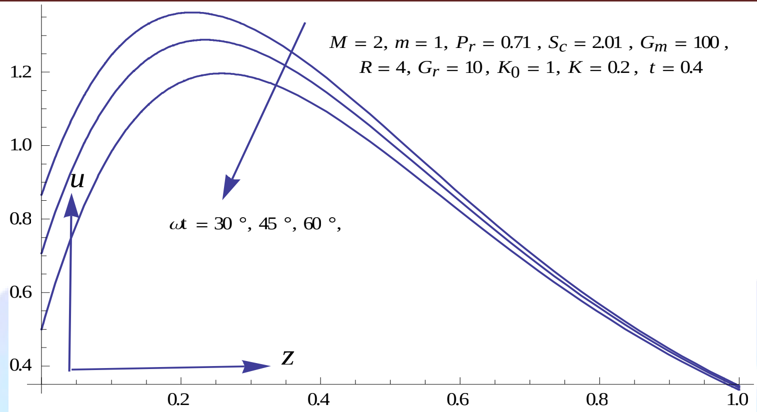

Figure 8: velocity u for different values of ωt

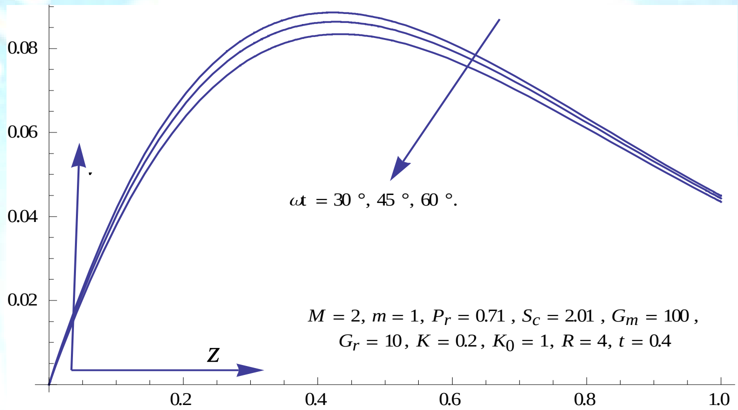

Figure 9: velocity v for different values of ωt

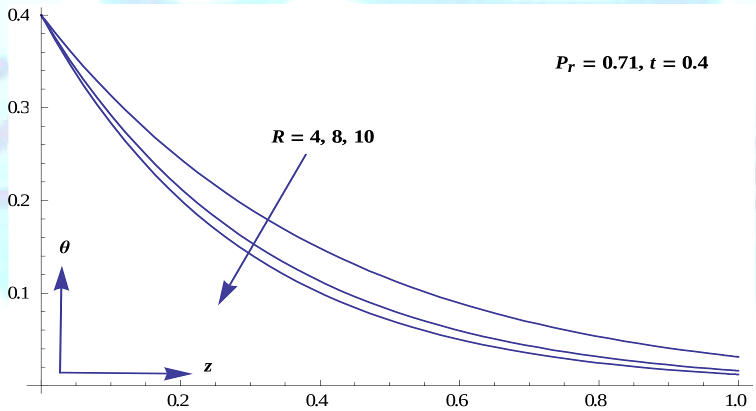

Figure 10: Temperature θ for different values of R

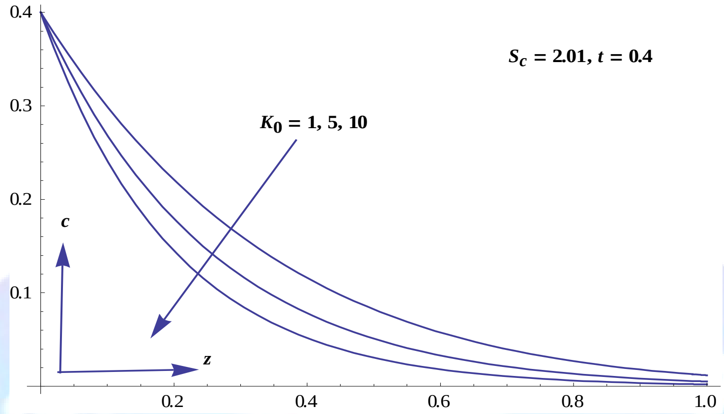

Figure 11: Concentration *c* for different values of K_0

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

M	*m*	*Pr*	*Sc*	*Gm*	*Gr*	*K*	*R*	K_0	ωt	*t*	τ_x	τ_y
02	01	0.71	2.01	100	10	0.2	04	01	60	0.3	086.554	020.670
02	01	0.71	2.01	100	10	0.4	04	01	60	0.3	172.607	066.377
02	01	0.71	2.01	100	10	0.6	04	01	60	0.3	233.916	105.400
02	01	0.71	2.01	100	10	0.2	08	01	60	0.3	307.037	156.594
02	01	0.71	2.01	100	10	0.2	10	01	60	0.3	837.344	583.277
02	01	0.71	2.01	100	10	0.2	04	05	60	0.3	086.096	020.657
02	01	0.71	2.01	100	10	0.2	04	10	60	0.3	085.687	020.646
02	01	0.71	2.01	100	10	0.2	04	01	45	0.3	085.852	020.696

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 parameters.

Pr	*R*	*t*	*Nu*
0.71	02	0.4	-0.805273
7.00	02	0.4	-1.959260

0.71	03	0.4	-0.894014
0.71	04	0.4	-0.976083
0.71	02	0.5	-0.950956
0.71	02	0.6	-1.094940

6 CONCLUSION

In this paper a theoretical analysis has been done to study the unsteady MHD flow through porous medium past a moving 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 permeability parameter and radiation parameter. But the trend is reversed with chemical reaction parameter and phase angle. It is also observed that the drag at the plate surface is increased by permeability parameter and radiation parameter Sherwood number and Nusselt number decrease with increase in radiation parameter and chemical reaction parameter.

Appendix

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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