Chemically Reacting Unsteady MHD Oscillatory Slip Flow in a Planer Channel with Varying Concentration

R. Sivaraj and B. Rushi Kumar

***Abstract*—This study examines the problem of unsteady MHD mixed convictive oscillatory flow of an electrically conducting optically thin fluid through a planer channel filled with saturated porous medium. The effect of buoyancy, heat source, thermal radiation and chemical reaction are taken into account embedded with slip boundary condition, varying temperature and concentration. The closed-form analytical solutions are obtained for the momentum, energy and concentration equations. The influence of the various parameters entering into the problem in the velocity, temperature and concentration fields are discussed with the help of graphs. The effect of skin friction, the rate of heat and mass transfer coefficients at the walls are shown in the tables.**

***Index Terms* — chemical reaction, MHD, oscillatory flow, planer channel.**

***MSC 2010 Codes* — 34D10, 76S05, 80A20, 80A32.**

Nomenclature

U, V - velocity components in X, Y directions resp.
d - dimensional channel width
t^* - dimensional time
P^* - dimensional pressure
K^* - dimensional porous permeability coefficient
g - gravitational force
T - dimensional fluid temperature
T_1, T_2 - wall temperatures
k - thermal conductivity
c_P - specific heat at constant pressure
q - radiative heat flux
Q - dimensional heat source parameter
C - dimensional fluid concentration
C_1, C_2 - wall concentrations
D - mass diffusivity
K_R - dimensional chemical reaction parameter
L - mean free path
m_1 - Maxwell's reflexion coefficient
$K_{\lambda_r, w}$ - radiation absorption coefficient at the wall
$e_{b\lambda_r}$ - Plank's function
Re - Reynolds number
M^2 - Hartmann number
K - permeability of the porous medium
Gr - thermal Grashof number
Gc - solutal Grashof number
Pe - Peclet number
F - thermal radiation parameter
Sc - Schmidt number
K_r - chemical reaction parameter
A - real constant

Greek symbols

μ - dynamic viscosity
ρ - fluid density
ν - kinematic viscosity coefficient
σ_e - electric conductivity of the fluid
β_T - volumetric thermal expansion
β_C - volumetric concentration expansion
α - heat source parameter
ω - frequency of the oscillation
γ - slip parameter
δ_T - temperature variation parameter
δ_C - concentration variation parameter.

I. INTRODUCTION

Oscillatory flows has known to result in higher rates of heat and mass transfer, many studies have been done to understand its characteristics in different systems such as reciprocating engines, pulse combustors and chemical reactors. Cooper et al.

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[1] have made a detailed study on fluid mechanics of oscillatory and modulated flows and associated applications in heat and mass transfer. Fusegi [2] have numerically studied the influence of convective heat transfer from periodic open cavities in a channel with oscillatory flow. Gomaa and Taweel [3] have examined the effect of oscillatory motion on heat transfer about vertical flat surfaces. The heat transfer enhancement of oscillatory flow in channel with periodically upper and lower walls mounted obstacles has been analyzed by Abdelkader and Lounes [4]. MHD has attracted the attention of many researchers and industrialists due to its rich applications in cosmic fluid dynamics, meteorology, motion of Earth's core and solar physics. El-Hakiem [5] has examined the influence of MHD oscillatory flow on free convection-radiation through a porous medium with constant suction velocity. Makinde and Mhone [6] have investigated the problem of heat transfer to MHD oscillatory flow in a channel filled with porous medium. The effect of slip condition on unsteady MHD oscillatory flow of a viscous fluid in a planer channel has been analyzed by Mehmood and Ali [7]. The wide range of technological and industrial applications have stimulated considerable amount of interest in the study of heat and mass transfer in convection flows. Convection in porous media has applications in geothermal energy recovery, oil extraction, thermal energy storage and flow through filtering devices. Gholizadeh [8] has investigated the MHD oscillatory flow past a vertical porous plate through porous medium in the presence of thermal and mass diffusion with constant heat source. The work of Makinde [9] is of particular interest since it demonstrated the possibility of achieving significant unsteady incompressible flow in a porous channel. Makinde and Aziz [10] have analyzed the MHD mixed convection from a vertical plate embedded in porous medium with convective boundary condition.

The role of thermal radiation is of major importance in engineering areas occurring at high temperatures and knowledge of radiative heat transfer becomes very important in nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles and space vehicles. Hakeem and Sathiyanathan [11] have examined the radiation effect of an oscillatory flow through a porous medium. Srinivas and Muthuraj [12] have studied the effects of thermal radiation and space porosity on MHD mixed convection flow in a vertical channel. Pal and Talukdar [13] have analyzed the unsteady MHD convective heat and mass transfer in a vertical permeable plate with thermal radiation. The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Chamkha [14] has analyzed the significance of chemical reaction on MHD flow of a uniformly stretched vertical permeable surface. Bakr [15] have studied the effects of chemical reaction on oscillatory plate velocity and constant heat source in a rotating frame of reference. The influence of chemical reaction on unsteady MHD mixed convective flow over a moving vertical porous plate has been examined by Prakash et al. [16].

To the best of the author's knowledge, studies pertaining to oscillatory flow investigations in a planer channel with variable temperature and concentration have not received much attention. Therefore, the main goal here is to study the chemical reaction effects on unsteady MHD oscillatory slip flow in an optically thin fluid through a planer channel in the presence of a temperature-dependent heat source. The closed form solutions for velocity, temperature, skin friction, concentration, Nusselt number, and Sherwood number are presented. The effects of pertinent parameters on fluid flow and heat and mass transfer characteristics are studied in detail. This work is presented as follows. First, the problem is formulated, and then the solution of the problem is presented. Following are results and discussion, and finally, conclusions are summarized.

II. FORMULATION OF THE PROBLEM

We consider the unsteady mixed convection, two-dimensional slip flow of an electrically conducting, heat-generating, optically thin and chemically reacting oscillatory fluid flow in a planer channel filled with porous medium in the presence of thermal radiation with temperature and concentration variation. Take a Cartesian coordinate system $\left(X,Y\right)$ where $X-$axis is taken along the flow and $Y-$axis is taken normal to the flow direction. A uniform transverse magnetic field of magnitude B_0 is applied in the presence of thermal and solutal buoyancy effects in the direction of $Y-$axis. Then, assuming a Boussinesq incompressible fluid model, the equations governing the motion are given as:

$$\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$\begin{aligned}\frac{\partial U}{\partial t^*}=-\frac{1}{\rho}\frac{\partial P^*}{\partial X}+\nu\frac{\partial^2 U}{\partial Y^2}-\frac{\sigma_e B_0^2}{\rho}U-\frac{\nu}{K^*}U\\ +g\beta_T\left(T-T_1\right)+g\beta_C\left(C-C_1\right)\end{aligned} \tag{2}$$

$$\frac{\partial T}{\partial t^*}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial Y^2}-\frac{1}{\rho c_p}\frac{\partial q}{\partial Y}+\frac{Q\left(T-T_0\right)}{\rho c_p} \tag{3}$$

$$\frac{\partial C}{\partial t^*}=D\frac{\partial^2 C}{\partial y^2}-K_R\left(C-C_1\right) \tag{4}$$

The appropriate boundary conditions of the problem are

$$\begin{aligned}U=L_1\frac{\partial U}{\partial Y},\ T=T_1+\delta_T{}^*\frac{\partial T}{\partial Y},\\ C=C_1+\delta_C{}^*\frac{\partial C}{\partial Y}\quad at\quad Y=0\end{aligned} \tag{5}$$

$$U = 0,\ T = T_2 + \delta_T^* \frac{\partial T}{\partial Y},$$
$$C = C_2 + \delta_C^* \frac{\partial C}{\partial Y} \ \ at \ \ Y = d \tag{6}$$

The radiative heat flux (Cogley et al. [17]) is given by

$$\frac{\partial q}{\partial Y} = 4\left(T_1 - T\right) I' \tag{7}$$

Introducing the following non-dimensional quantities

$$x = \frac{X}{d},\ y = \frac{Y}{d},\ P = \frac{dP^*}{\mu U_0},\ u = \frac{U}{U_0},\ \theta = \frac{T - T_1}{T_2 - T_1},$$
$$\phi = \frac{C - C_1}{C_2 - C_1},\ t = \frac{U_0 t^*}{d},\ Re = \frac{U_0 d}{\nu},\ \frac{1}{K} = \frac{d^2}{K^*},$$
$$M^2 = \frac{\sigma_e B_0^2 d^2}{\mu},\ Gr = \frac{g\beta_T\left(T_2 - T_1\right)d^2}{\nu U_0},\ F = \frac{4I'd^2}{k},$$
$$Gc = \frac{g\beta_C\left(C_2 - C_1\right)d^2}{\nu U_0},\ Pe = \frac{\rho c_p U_0 d}{k},\ \alpha = \frac{Qd^2}{k},$$
$$Sc = \frac{D}{U_0 d},\ K_r = \frac{K_R d}{U_0},\ \gamma = \frac{\gamma^*}{d},\ \delta_T = \frac{\delta_T^*}{d},\ \delta_C = \frac{\delta_C^*}{d} \tag{8}$$

In view of the above dimensionless variables, the basic field equations (2) to (4) can be expressed in non-dimensionless form as

$$Re\frac{\partial u}{\partial t} = -\frac{\partial P}{\partial x} + \frac{\partial^2 u}{\partial y^2} - \left(\frac{1}{K} + M^2\right)u + Gr\theta + Gc\phi \tag{9}$$

$$Pe\frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} - \left(F + \alpha\right)\theta \tag{10}$$

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

The boundary conditions becomes

$$u = \gamma\frac{\partial u}{\partial y},\ \theta = \delta_T\frac{\partial \theta}{\partial y},\ \phi = \delta_C\frac{\partial \phi}{\partial y} \ \ at \ \ y = 0 \tag{12}$$

$$u = 0,\ \ \theta = 1 + \delta_T\frac{\partial \theta}{\partial y},\ \phi = 1 + \delta_C\frac{\partial \phi}{\partial y} \ \ at \ \ y = 1 \tag{13}$$

III. Solution of the Problem

In order to solve equations (9) - (11) with respect to the boundary conditions (12) and (13) for purely oscillatory flow, let us take

$$-\frac{\partial P}{\partial x} = Ae^{i\omega t},\ u\left(y,t\right) = u_0\left(y\right)e^{i\omega t},$$
$$\theta\left(y,t\right) = \theta_0\left(y\right)e^{i\omega t},\ \phi\left(y,t\right) = \phi_0\left(y\right)e^{i\omega t} \tag{14}$$

Substituting the above expressions in equation (14) into equations (9) - (13), we obtain:

$$u_0'' - A_1^2 u = -\left(\lambda + Gr\theta_0 + Gc\phi_0\right) \tag{15}$$

$$\theta_0'' + A_2^2\theta_0 = 0 \tag{16}$$

$$\phi_0'' - A_3^2\phi_0 = 0 \tag{17}$$

Together with boundary conditions

$$u_0 = \gamma u_0',\ \theta_0 = \delta_T\theta_0',\ \phi_0 = \delta_C\phi_0' \ \ at \ \ y = 0 \tag{18}$$

$$u_0 = 0,\ \theta_0 = 1 + \delta_T\theta_0',\ \phi_0 = 1 + \delta_C\phi_0' \ \ at \ \ y = 1 \tag{19}$$

Equations (15) - (19) are solved and the solution for fluid velocity, temperature and concentration are given as:

$$u\left(y,t\right) = \left[A_7 + A_8\sinh\left(A_3 y\right) + A_9\cosh\left(A_3 y\right) + A_{10}\sin\left(A_2 y\right) + A_{11}\sinh\left(A_1 y\right) + A_{12}\cosh\left(A_1 y\right)\right]e^{i\omega t} \tag{20}$$

$$\theta\left(y,t\right) = A_6\sin\left(A_2 y\right)e^{i\omega t} \tag{21}$$

$$\phi\left(y,t\right) = \left[A_4\sinh\left(A_3 y\right) + A_5\cosh\left(A_3 y\right)\right]e^{i\omega t} \tag{22}$$

The shear stress, the coefficient of the rate of heat transfer and the rate of mass transfer at any point in the fluid can be characterized by

$$\tau^* = -\mu u';\ Nu^* = -kT';\ Sh^* = -DC' \tag{23}$$

In dimensionless form

$$\tau = \frac{\tau^* d}{\mu U_0} = -u';\ Nu = \left(\frac{Nu^* d}{k\left(T_1 - T_0\right)}\right) = -\theta';$$
$$Sh = \left(\frac{Sh^* d}{C_1 - C_0}\right) = -\phi' \tag{24}$$

The skin friction (τ), the Nusselt number (Nu) and the Sherwood number (Sh) at the walls $y = 0$ and $y = 1$ are given by

$$\tau_0 = -u'\big|_{y=0} \qquad \tau_1 = -u'\big|_{y=1} \tag{25}$$

$$Nu_0 = -\theta'\big|_{y=0} \qquad Nu_1 = -\theta'\big|_{y=1} \tag{26}$$

$$Sh_0 = \phi'\big|_{y=0} \qquad Sh_1 = \phi'\big|_{y=1} \tag{27}$$

where the primes are with respect to y and A's are given in the appendix.

IV. Results and Discussion

Numerical evaluation for the analytical solution of this problem is performed and the results are illustrated graphically in Figs. 1–16 to show the interesting features of significant parameters on velocity, temperature, concentration, skin friction, Nusselt number and Sherwood number distributions in the planer channel. Throughout the computations we employ $t = 1$, $\lambda = 1$, $\omega = 0.5$ $M = 2$, $K = 2$, $Re = 1$, $Gr = 2$,

$Gc = 1$, $F = 2$, $\alpha = 3$, $Pe = 4$, $K_r = 2$, $Sc = 1$, $\gamma = 0.1$, $\delta_T = 0.002$ and $\delta_C = 0.002$ unless otherwise stated. Figure 1 illustrates that the presence of transverse magnetic field produces a resistive force on the fluid flow. This force is called the Lorentz force, which slows down the motion of the fluid. It is obvious that the increases in the frequencies of oscillation decrease the velocity and this is presented in Fig. 2. Increases in thermal and solutal Grashof numbers significantly increase the boundary layer thickness which resulted into rapid enhancement of fluid velocity which is displayed in Figs. 3 & 4. Figure 5 displays that the increases in the permeability coefficient of porous medium act against the porosity of the porous medium which increase the fluid velocity. Figure 6 represents that the increase in the slip parameter has the tendency to reduce the friction forces which increases the fluid velocity. Figure 7 illustrates that increase in the radiation parameter increases the temperature distribution because large values of radiation parameter oppose the conduction over radiation, thereby which increases the buoyancy force and increases the thickness of the thermal boundary layer. Figure 8 represents that the increase in the heat source parameter significantly increase the thermal buoyancy effects which raise fluid temperature. It is observed from Fig. 9 that the effect of raising Peclet number develop the thermal conductivities and therefore heat is able to diffuse away and the heat transfer falls monotonically. Increase in temperature variation parameter coincides with the decrease of heat transfer and the curves could be seen in Fig. 10. Figure 11 shows that we obtain a destructive type chemical reaction because the concentration decreases for increasing the chemical reaction parameter which indicates that the diffusion rates can be tremendously changed by the chemical reaction. Figs. 12 & 13 illustrate that Schmidt number and concentration variation parameter are used to increase the mass transfer. Figure 14 is plotted to illustrate the effects of frequency parameter in the skin friction with respect to thermal Grashof number. The magnitude of skin friction increases with an increase of frequency parameter at the wall $y = 0$ but this trend is reversed at the other wall $y = 1$. We display the significance of thermal radiation in the Nusselt number against the heat source parameter in Fig. 15. We observe that increase in the thermal radiation gradually diminishes the Nusselt number at the both walls. Figure 16 displays the effect of Schmidt number in Sherwood number with respect to the chemical reaction parameter. The Sherwood number decreases for the higher values of Schmidt number at the wall $y = 0$ while we obtain a reverse trend at the other wall $y = 1$.

Table I shows that the effect of thermal radiation parameter, heat source parameter, Peclet number and temperature variation parameter in skin friction and Nusselt number at the walls. The influence of frequency of oscillation parameter, chemical reaction parameter, Schmidt number and concentration variation parameter in skin friction and Sherwood number at the walls are present in table II.

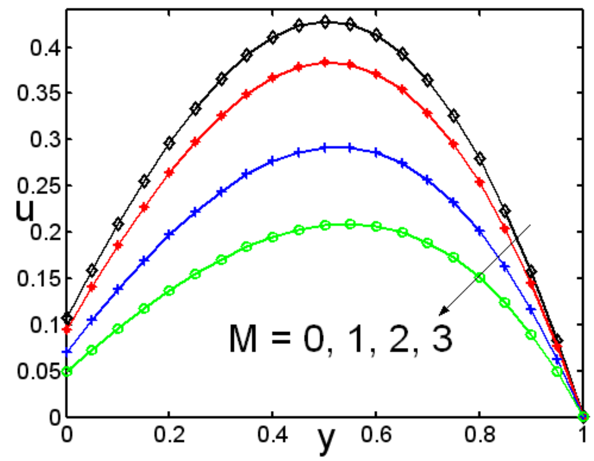

Fig. 1. Velocity profiles for different values of M

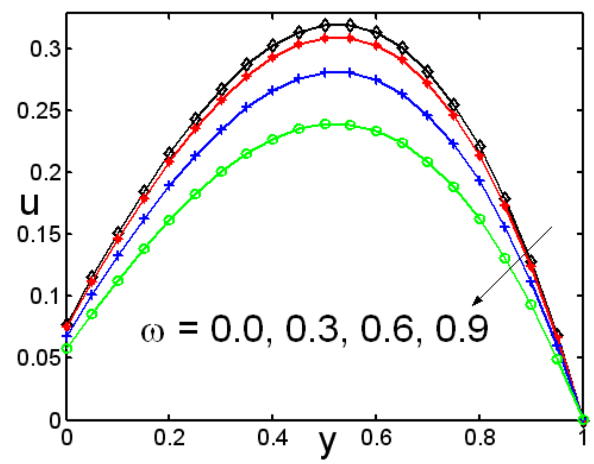

Fig. 2. Velocity profiles for different values of ω

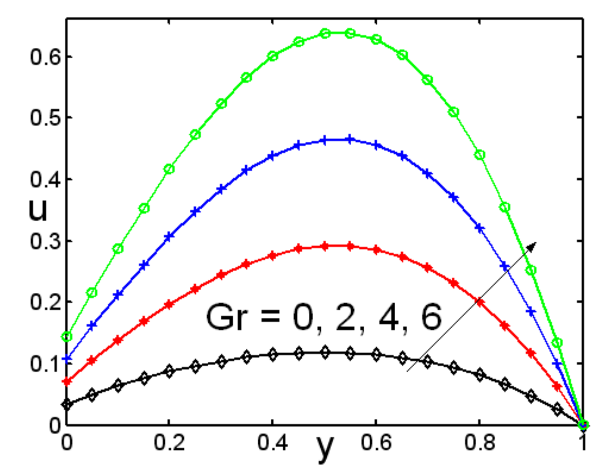

Fig. 3. Velocity profiles for different values of Gr

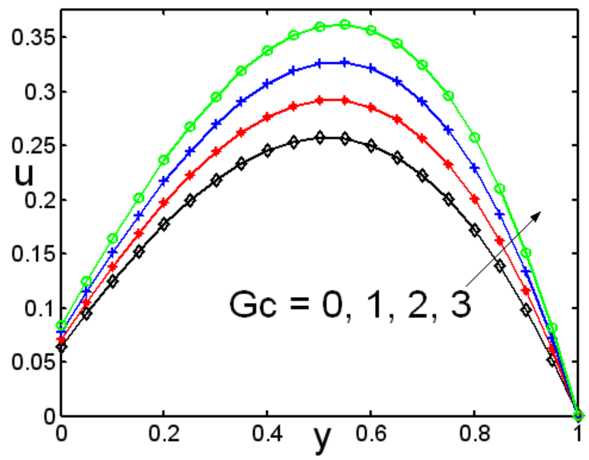

Fig. 4. Velocity profiles for different values of Gc

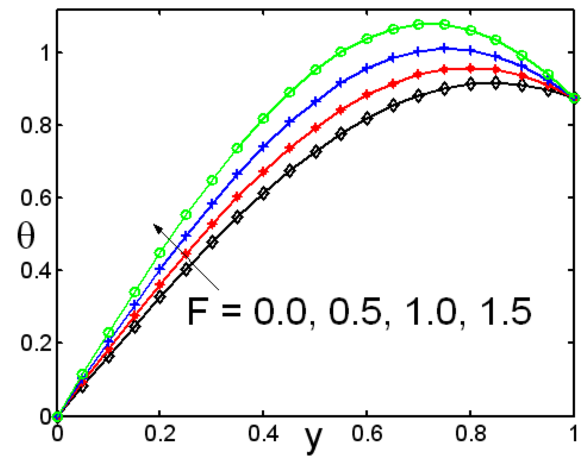

Fig. 7. Temperature profiles for different values of F

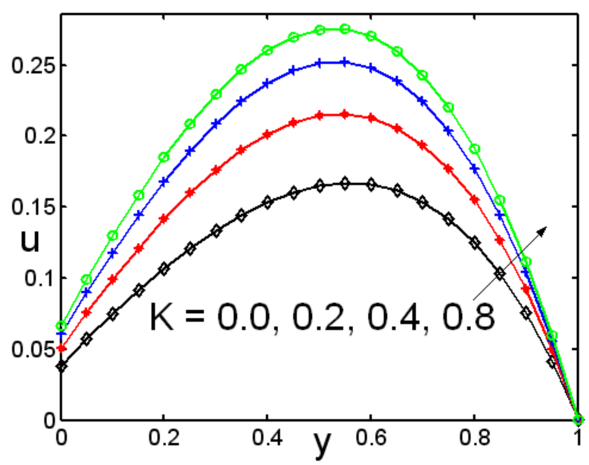

Fig. 5. Velocity profiles for different values of K

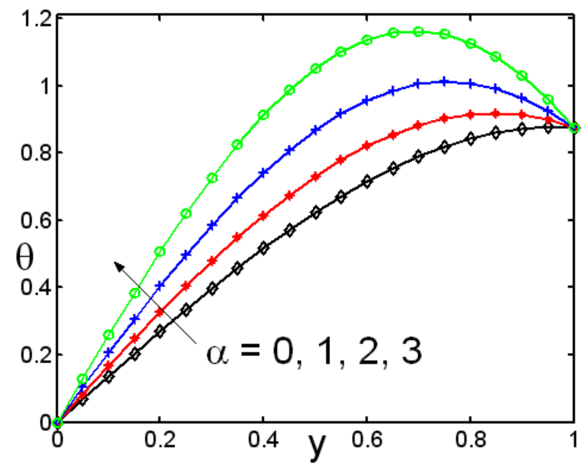

Fig. 8. Temperature profiles for different values of α

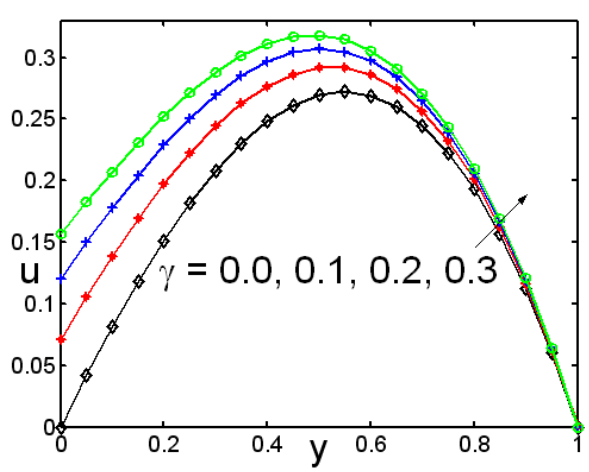

Fig. 6. Velocity profiles for different values of γ

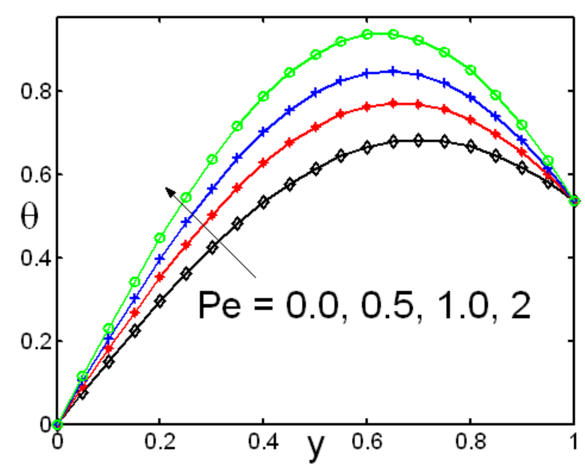

Fig. 9. Temperature profiles for different values of Pe

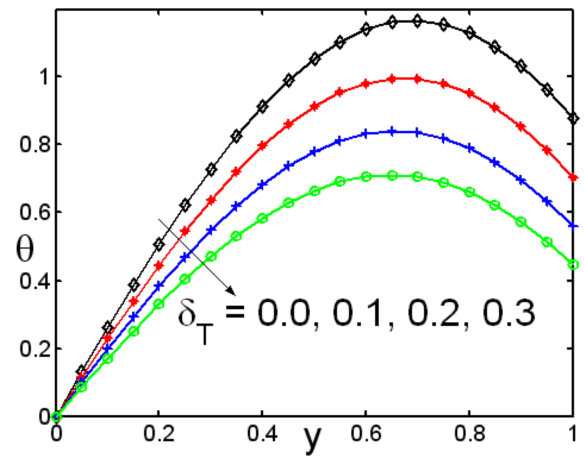

Fig. 10. Temperature profiles for different values of δ_T

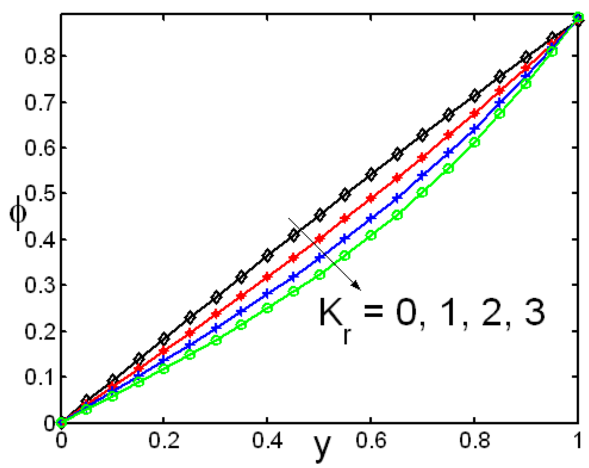

Fig. 11. Concentration profiles for different values of K_r

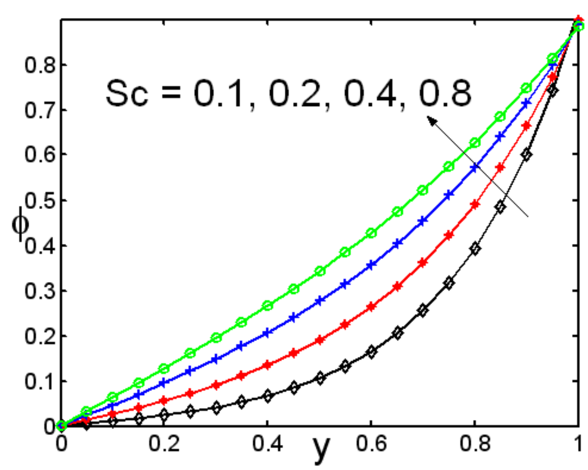

Fig. 12. Concentration profiles for different values of Sc

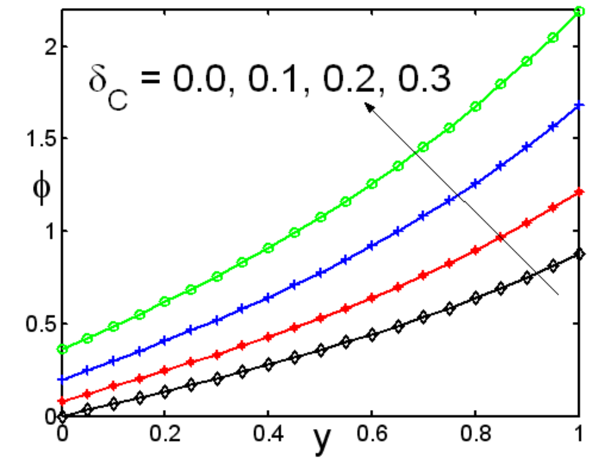

Fig. 13. Concentration profiles for different values of δ_C

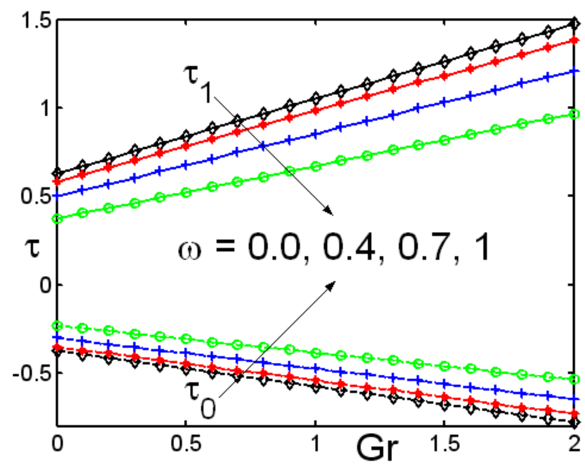

Fig. 14. Skin friction profiles for different values of ω

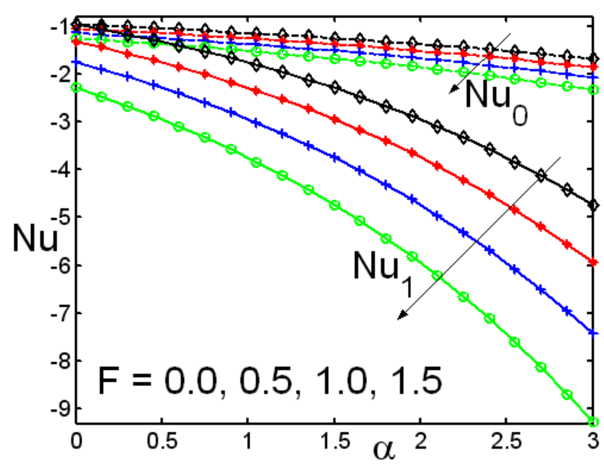

Fig. 15. Nusselt number profiles for different values of F

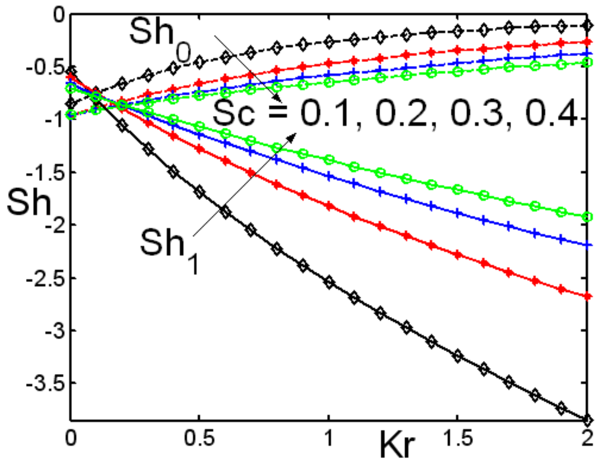

Fig. 16. Nusselt number profiles for different values of Sc

TABLE I

EFFECT OF F, α, Pe AND δ_T IN SKIN FRICTION AND NUSSELT NUMBER AT THE WALLS

Physical parameters	values	τ_0	τ_1	Nu_0	Nu_1
F	0.0	-0.5952	1.1810	-1.6757	-4.7299
	0.5	-0.6433	1.2472	-2.0741	-7.4340
	1.0	-0.7075	1.3343	-2.6165	-11.5432
α	0.0	-0.5584	1.1293	-1.3764	-2.9424
	1.0	-0.5952	1.1810	-1.6757	-4.7299
	2.0	-0.6433	1.2472	-2.0741	-7.4340
Pe	0.5	-0.6971	1.3146	-2.4855	-11.7606
	1.0	-0.7129	1.3363	-2.6331	-12.9329
	1.5	-0.7195	1.3463	-2.7012	-13.2520
δ_T	0.0	-0.7084	1.3366	-2.6223	-11.5504
	1.0	-0.6157	1.1117	-1.9902	-9.9019
	2.0	-0.5436	0.9532	-1.4861	-7.9653

TABLE II

EFFECT OF ω, K_r, Sc AND δ_C IN SKIN FRICTION AND SHERWOOD NUMBER AT THE WALLS

Physical parameters	values	τ_0	τ_1	Sh_0	Sh_1
ω	0.0	-0.7760	1.4749	-0.7338	-1.6023
	0.5	-0.7075	1.3343	-0.6672	-1.3441
	1.0	-0.5370	0.9682	-0.4800	-0.6456
K_r	0.0	-0.7239	1.3586	-0.9128	-0.8016
	1.0	-0.7149	1.3454	-0.7767	-1.0882
	2.0	-0.7075	1.3343	-0.6672	-1.3441
Sc	0.5	-0.6970	1.3181	-0.5172	-1.7400
	1.0	-0.7075	1.3343	-0.6672	-1.3441
	1.5	-0.7118	1.3407	-0.7294	-1.1978
δ_C	0.0	-0.7068	1.3327	-0.6649	-1.3366
	0.1	-0.7487	1.4250	-0.8043	-1.7735
	0.2	-0.8094	1.5548	-0.9966	-2.3454

V. CONCLUSIONS

This paper investigates the effect of heat and mass transfer on MHD oscillatory slip flow in planer channel with variable temperature and concentration. The velocity, temperature and concentration distributions are obtained analytically and used to compute the wall shear stress and rate of heat and mass transfer at the channel walls. It is observed that the velocity profiles accelerate for increasing the value of Grashof number and permeability of the porous medium whereas decrease for magnetic field and frequency of oscillation parameter. It is found that temperature profiles enhance for increasing radiation parameter and the Peclet number but temperature variation parameter reverses the trend. Further it is noticed that increase in chemical reaction parameter decreases the fluid concentration whereas the Schmidt number and concentration variation parameter reverse the effect. It is observed that the agreement of all profiles with the theoretical solution is excellent.

APPENDIX

$$I' = \int_0^\infty K_{\lambda w} \frac{\partial e_{b\lambda}}{\partial T} d\lambda; \; A_1 = \sqrt{\frac{1}{K} + M^2 + i\omega Re};$$

$$A_2 = \sqrt{F + \alpha - i\omega Pe}; \; A_3 = \sqrt{\frac{K_r + i\omega}{Sc}};$$

$$A_4 = \frac{1}{\left(1 - \delta_C A_3^2\right)\sinh\left(A_3\right)}; \; A_5 = \delta_C A_3 A_4;$$

$$A_6 = \frac{1}{\sin\left(A_2\right) - \delta_T A_2 \cos\left(A_2\right)}; \; A_7 = \frac{\lambda}{A_1^2};$$

$$A_8 = \frac{A_4 Gc}{A_1^2 - A_3^2};; \; A_9 = \frac{A_5 Gc}{A_1^2 - A_3^2} \; A_{10} = \frac{A_6 Gr}{A_1^2 + A_2^2};$$

$$A_{11} = \frac{\begin{bmatrix} A_7\left(\cosh\left(A_1\right) - 1\right) - A_8\left(A_3\gamma\cosh\left(A_1\right) + \sinh\left(A_3\right)\right) + \\ A_9\left(\cosh\left(A_1\right) - \cosh\left(A_3\right)\right) - A_{10}\left(A_2\gamma\cosh\left(A_1\right) + \sin\left(A_2\right)\right) \end{bmatrix}}{A_1\gamma\cosh\left(A_1\right) + \sinh\left(A_1\right)}$$

$$A_{12} = \left(A_1 A_{11} + A_2 A_{10} + A_3 A_8\right)\gamma - A_7 - A_9.$$

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