Radiation and Chemical Reaction Effects on Unsteady Slip Flow over a Semi Infinite Vertical Porous Plate Embedded in a Porous Medium in The Presence of Inclined Magnetic Field

P. R. Sharma[1], Sushila Choudhary[2]

Department of Mathematics, University of Rajasthan, Rajasthan, India

***Abstract*-Unsteady free convective viscous slip flow of an incompressible, electrically conducting and radiating fluid over a semi infinite vertical porous plate embedded in a porous medium in the presence of inclined magnetic field is investigated. The resulting non-linear system of coupled partial differential equations is solved by using regular perturbation technique. The effects of various physical parameters on velocity, temperature and concentration profiles as well as on the skin friction coefficient, Nusselt number and Sherwood number are discussed numerically and shown through graphs and table.**

Key words: Unsteady, MHD, radiation, porous medium, skin friction coefficient, Nusselt number, Sherwood number.

I. INTRODUCTION

Free convective fluid motion has been studied most extensively because of its existence in nature very frequently as well as plays an important role in engineering, geophysical and astrophysical environment. In recent years, radiative heat transfer in the presence of chemical reaction has received much attention due to its wide applications in practical engineering such as the design and operation of chemical processing equipment, design of heat exchangers, chemical vapour deposition of solid layers and many manufacturing processes like wire drawing, fiber drawing and hot rolling. The influence of a magnetic field in viscous incompressible flow of electrically conducting fluid is of use in extrusion of plastics in the manufacture of rayon, nylon etc. Sparrow and Cess [1] analyzed the effect of a magnetic field on free convention heat transfer. Radiation effects on free convection flow past a moving plate has been discussed by Raptis and Perdikis [2]. Kim [3] studied unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. Unsteady flow of liquid through a channel with pressure gradient changing exponentially under the influence of inclined magnetic field was considered by Singh [4]. Chamka [5] investigated MHD flow of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Heat transfer to unsteady magneto-hydrodynamic flow past an infinite moving vertical plate with variable suction was studied by Ogulu and Prakash [6]. Sharma and Sharma [7] analyzed effect of oscillatory suction and heat source on heat and mass transfer in MHD flow along a vertical moving porous plate bounded by porous medium. Radiation effect on MHD flow in a porous space was examined by Hayat and Abbas [8]. Sharma and Singh [9] discussed unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation. Radiation effects on unsteady MHD free convective flow with hall current and mass transfer through viscous incompressible fluid past a vertical porous plate immersed in porous medium with heat source/sink were studied by Sharma et al. [10]. Sharma and Mehta [11] discussed radiative and free convective effects on MHD flow through porous medium between infinite porous plates with periodic cross flow velocity. Unsteady MHD convective flow and heat transfer between heated inclined plates with magnetic field in the presence of radiation effects were investigated by Sharma et al. [12]. Turkyilmazoglu and Pop [13] discussed Soret and heat source effects on the unsteady radiation MHD free convection flow from an impulsively started infinite vertical plate. Effect of inclined magnetic field on unsteady free convective flow of dissipative fluid past a vertical plate has been analyzed by Sandeep and Sugunamma [14]. Sugunamma et al. [15] presented the inclined magnetic field and chemical reaction effects on flow over a semi infinite vertical porous plate through porous medium.

Aim of this paper is to investigate unsteady radiative MHD free convective viscous slip flow of incompressible dissipative fluid over a semi infinite vertical porous plate embedded in a porous medium in the presence of inclined magnetic field. The governing non-linear coupled partial differential equations are first transformed into a dimensionless form and then approximate solutions are obtained using perturbation technique. The effects of various physical parameters on velocity, temperature and concentration are discussed and shown through graphs. Numerical values for skin friction, Nusselt number and Sherwood number for various values of physical parameters are obtained and shown through tables.

II. FORMULATION OF THE PROBLEM

Consider two dimensional MHD free convective unsteady flow of a viscous incompressible, electrically conducting and radiating fluid past a semi infinite vertical porous plate through a porous medium, in the presence of thermal and concentration buoyancy effects. The x^*-axis is taken along the plate in vertical direction and y^* -axis is taken perpendicular to the plate. An inclined magnetic field is applied in the direction of y^*-axis. Flow is fully developed under the assumptions that the Joule heating effects and Soret and Dufour effects are assumed to be negligible and the electric field is absent since no voltage is applied externally.

Under these assumptions as well as Boussinesq approximation, the governing equations for unsteady free convective flow are given by

$$\frac{\partial v^*}{\partial y^*}=0, \tag{1}$$

$$\frac{\partial u^*}{\partial t^*}-V_0(1+\varepsilon Ae^{i\omega^* t^*})\frac{\partial u^*}{\partial y^*}=\frac{\partial U_\infty^*}{\partial t^*}+g\beta(T^*-T_\infty)-g\beta^*(C^*-C_\infty)+\nu\frac{\partial^2 u^*}{\partial y^{*2}}-\left(\frac{\nu}{K^*}+B\sin^2\psi\right)(u^*-U_\infty^*), \tag{2}$$

$$\frac{\partial T^*}{\partial t^*}-V_0(1+\varepsilon Ae^{iw^* t^*})\frac{\partial T^*}{\partial y^*}=\frac{\kappa}{\rho C_p}\left(\frac{\partial^2 T^*}{\partial y^{*2}}-\frac{1}{\kappa}\frac{\partial q_r^*}{\partial y^*}\right)+\frac{\mu}{\rho C_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2, \tag{3}$$

$$\frac{\partial C^*}{\partial t^*}-V_0(1+\varepsilon Ae^{iw^* t^*})\frac{\partial C^*}{\partial y^*}=D\frac{\partial^2 C^*}{\partial y^{*2}}-k_1^*(C^*-C_\infty). \tag{4}$$

where u^* and v^* are the velocity components in x^* and y^*-directions, respectively; t^* is the time, g is the acceleration due to gravity, β is the thermal expansion coefficient, T^* is the temperature of the fluid in the boundary layer, T_∞ is the temperature of the fluid far away from the plate, β^* is the concentration expansion coefficient, C^* is the species concentration in the boundary layer, C_∞ is the species concentration in the fluid far away from the plate, B is the magnetic field intensity, ρ is the fluid density, ν is the kinematic viscosity, K^* is the permeability of porous medium, U_∞^* is the free stream velocity, κ is the thermal conductivity, C_p is the specific heat at constant pressure, D is the mass diffusivity, k_1^* is the chemical reaction coefficient, q_r^* is the radiative heat flux and $V_0(>0)$ is the constant suction velocity, $\varepsilon>0, A<1$, and $0<\varepsilon A \ll 1$.

The boundary conditions are

$$y^*=0:\ u^*=S^*(\frac{\partial u^*}{\partial y^*}),\ T^*=T_w+\varepsilon(T_w-T_\infty)e^{iw^* t^*},$$
$$C^*=C_w+\varepsilon(C_w-C_\infty)e^{iw^* t^*};$$
$$y^*\to\infty:\ u^*\to U_\infty(t^*)=U_0(1+\varepsilon Ae^{iw^* t^*}),\ T^*\to T_\infty,\ C^*\to C_\infty. \tag{5}$$

where T_w and C_w are the temperature and species concentration at the plate, respectively, S^* is the slip parameter and U_∞ is the free stream velocity.

From the equation (1), it is noted that the suction velocity at the plate is either a constant or a function of time only. Here, the suction velocity normal to the plate is assumed to be in the form

$$v^*=-V_0(1+\varepsilon Ae^{iw^* t^*})\ . \tag{6}$$

III. METHOD OF SOLUTION

Introducing the following non-dimensional quantities

$$y=\frac{V_0 y^*}{\nu},u=\frac{u^*}{V_0},t=\frac{t^* V_0^2}{4\nu},\omega=\frac{4\omega^*\nu}{V_0^2},\theta=\frac{T^*-T_\infty}{T_w-T_\infty},C=\frac{C^*-C_\infty}{C_w-C_\infty},$$
$$Gr=\frac{\nu g\beta(T_w-T_\infty)}{V_0^3},Gc=\frac{\nu g\beta^*(C_w-C_\infty)}{V_0^3},M=\frac{B\nu}{V_0^2},\Pr=\frac{\mu C_p}{\kappa},$$
$$K=\frac{K^* V_0^2}{\nu^2},R=\frac{\kappa k_e}{4\sigma_s T_\infty^3},Ec=\frac{V_0^2}{C_p\left(T_w^*-T_\infty\right)},Sc=\frac{\nu}{D},U=\frac{U_\infty^*}{V_0},$$
$$S=\frac{V_0 S^*}{\nu},k_1=\frac{\nu k_1^*}{V_0^2},v=\frac{v^*}{V_0}; \tag{7}$$

into the equations (2) to (4), we get

$$\frac{1}{4}\frac{\partial u}{\partial t}-(1+\varepsilon Ae^{i\omega t})\frac{\partial u}{\partial y}=\frac{1}{4}\frac{\partial U}{\partial t}+\frac{\partial^2 u}{\partial y^2}+Gr\theta+GcC-\left(M\sin^2\psi+\frac{1}{K}\right)(u-U), \tag{8}$$

$$\frac{1}{4}\frac{\partial\theta}{\partial t}-\left(1+\varepsilon Ae^{i\omega t}\right)\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\left(1+\frac{4}{3R}\right)\frac{\partial^2\theta}{\partial y^2}+Ec\left(\frac{\partial u}{\partial y}\right)^2, \tag{9}$$

$$\frac{1}{4}\frac{\partial C}{\partial t}-(1+\varepsilon Ae^{i\omega t})\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-k_1 C, \tag{10}$$

where u is the dimensionless velocity along x-axis, U is the free stream velocity, θ is the dimensionless temperature, t is the time, C is the dimensionless concentration of the fluid, Gr is the Grashof number for heat transfer, Gc is the Grashof number for mass transfer, M is the Hartmann number, K is the permeability parameter, Pr is the Prandtl number, R is the radiation parameter, Ec is the Eckert number, Sc is the Schimdt number and k_1 is the chemical reaction parameter.

The boundary conditions in dimensionless form are reduced to

$$y=0:\ u=S\frac{\partial u}{\partial y},\ \theta=1+\varepsilon e^{i\omega t},\ \ C=1+\varepsilon e^{i\omega t};$$

$$y\to\infty:\ u\to\lambda(1+\varepsilon Ae^{i\omega t}),\ \ \theta\to 0,\ \ C\to 0. \qquad (11)$$

where $\lambda=\frac{U_0}{V_0}$ and S is the slip parameter.

In view of boundary conditions, the velocity, temperature and concentration distributions are separated into steady and unsteady parts as given below

$$u(y,t)=u_0(y)+\varepsilon e^{i\omega t}u_1(y),$$
$$\theta(y,t)=\theta_0(y)+\varepsilon e^{i\omega t}\theta_1(y),$$
$$C(y,t)=C_0(y)+\varepsilon e^{i\omega t}C_1(y), \qquad (12)$$

Substituting (12) into the equations (8) to (10) and equating the harmonic and non-harmonic terms, we obtain

$$u_0''+u_0'-\left(M\sin^2\psi+\frac{1}{K}\right)u_0=-Gr\theta_0-Gc\phi_0-\left(M\sin^2\psi+\frac{1}{K}\right)\lambda, \qquad (13)$$

$$u_1''+u_1'-\left(M\sin^2\psi+\frac{1}{K}+\frac{i\omega}{4}\right)u_1=-Gr\theta_1-Gc\phi_1-\left(M\sin^2\psi+\frac{1}{K}+\frac{i\omega}{4}\right)A\lambda, \qquad (14)$$

$$\theta_0''+\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_0'=-Ec\Pr\left(1+\frac{4}{3R}\right)^{-1}u_0'^2, \qquad (15)$$

$$\theta_1''+\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_1'-\frac{i\omega\Pr}{4}\left(1+\frac{4}{3R}\right)^{-1}\theta_1=-A\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_0'-2Ec\Pr\left(1+\frac{4}{3R}\right)^{-1}u_0'u_1', \qquad (16)$$

$$C_0''+ScC_0'-k_1ScC_0=0, \qquad (17)$$

$$C_1''+ScC_1'-Sc\left(\frac{i\omega}{4}+k_1\right)C_1=-ScAC_0'; \qquad (18)$$

where prime denotes the differentiation with respect to y.

Now, the corresponding boundary conditions are reduced to

$$y=0:\ u_0=S\left(\frac{\partial u_0}{\partial y}\right),u_1=S\left(\frac{\partial u_1}{\partial y}\right),\theta_0=1,\theta_1=1,\phi_0=1,\phi_1=1;$$
$$y\to\infty: u_0\to\lambda,u_1\to A\lambda,\theta_0\to 0,\theta_1\to 0,\phi_0\to 0,\phi_1\to 0. \qquad (19)$$

The equations (13) to (18) are still coupled ordinary second order differential equations. Since the Eckert number Ec is very small for incompressible fluid flows, therefore $u_0,u_1,\theta_0,\theta_1,C_0,C_1$ can be expanded in the powers of Ec as given below

$$F(y)=F_0(y)+Ec\,F_1(y)+O\left(Ec^2\right)+\ldots\ , \qquad (20)$$

where F stands for any $u_0,u_1,\theta_0,\theta_1,C_0$ or C_1. Substituting (20) into the equations (13) to (18), equating the coefficients of like powers of Ec and neglecting terms of $O\left(Ec^2\right)$, we get

Zeroth order equations:

$$u_{00}''+u_{00}'-\left(M\sin^2\psi+\frac{1}{K}\right)u_{00}=-Gr\theta_{00}-GcC_{00}-\left(M\sin^2\psi+\frac{1}{K}\right)\lambda, \qquad (21)$$

$$u_{10}''+u_{10}'-\left(M\sin^2\psi+\frac{1}{K}+\frac{i\omega}{4}\right)u_{10}=-Au_{00}'-Gr\theta_{10}-GcC_{10}-\left(M\sin^2\psi+\frac{1}{K}+\frac{i\omega}{4}\right)A\lambda, \qquad (22)$$

$$\theta_{00}''+Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{00}'=0, \qquad (23)$$

$$\theta_{10}''+\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{10}'-\frac{i\omega}{4}\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{10}=-A\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{00}', \qquad (24)$$

$$C_{00}''+ScC_{00}'-k_1ScC_{00}=0, \qquad (25)$$

$$C_{10}''+ScC_{10}'-Sc\left(k_1+\frac{i\omega}{4}\right)C_{10}=-ScAC_{00}' \qquad (26)$$

First-order equations:

$$u_{01}''+u_{01}'-\left(M\sin^2\psi+\frac{1}{K}\right)u_{01}=-Gr\theta_{01}-GcC_{01}, \qquad (27)$$

$$u_{11}''+u_{11}'-\left(M\sin^2\psi+\frac{1}{K}+\frac{i\omega}{4}\right)u_{11}=-Au_{01}'-Gr\theta_{11}-GcC_{11}, \qquad (28)$$

$$\theta_{01}''+Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{01}'=-\Pr u_{00}'^2\left(1+\frac{4}{3R}\right)^{-1}, \qquad (29)$$

$$\theta_{11}''+\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{11}'-\frac{i\omega}{4}\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{11}=-A\Pr\left(1+\frac{4}{3R}\right)^{-1}\theta_{01}'-2\Pr\left(1+\frac{4}{3R}\right)^{-1}u_{00}'u_{10}', \qquad (30)$$

$$C_{01}''+ScC_{01}'-k_1ScC_{01}=0, \qquad (31)$$

$$C_{11}''+ScC_{11}'-Sc\left(k_1+\frac{i\omega}{4}\right)C_{11}=-ScAC_{01}'. \qquad (32)$$

Now, the corresponding boundary conditions are reduced to

$$y=0: u_{00}=S\left(\frac{\partial u_{00}}{\partial y}\right),u_{01}=S\left(\frac{\partial u_{01}}{\partial y}\right),u_{10}=S\left(\frac{\partial u_{10}}{\partial y}\right),u_{11}=S\left(\frac{\partial u_{11}}{\partial y}\right),$$
$$\theta_{00}=1,\theta_{01}=0,\theta_{10}=1,\theta_{11}=0,C_{00}=1,C_{01}=0,C_{10}=1,C_{11}=0;$$
$$y\to\infty: u_{00}\to\lambda,u_{01}\to 0,u_{10}\to A\lambda,u_{11}\to 0,\theta_{00}\to 0,\theta_{01}\to 0,$$
$$\theta_{10}\to 0,\theta_{11}\to 0,C_{00}\to 0,C_{01}\to 0,C_{10}\to 0,C_{11}\to 0. \qquad (33)$$

Now, the equations (21) to (32) are ordinary second order linear coupled differential equations and solved under the boundary conditions (33). Through straight forward calculations, the solutions of $u_{00}, u_{01}, u_{10}, u_{11}, \theta_{00}, \theta_{01}, \theta_{10}, \theta_{11}, C_{00}, C_{01}, C_{10}, C_{11}$ are known and given as

$$u_{00} = A_8 e^{-A_5 y} - A_6 e^{-\gamma y} - A_7 e^{-A_1 y} + \lambda, \tag{34}$$

$$u_{01} = A_{29} e^{-A_5 y} - A_{22} e^{-\gamma y} + A_{23} e^{-2A_5 y} + A_{24} e^{-2\gamma y} + A_{25} e^{-2A_1 y} - A_{26} e^{-A_{12} y} + A_{27} e^{-A_{14} y} - A_{28} e^{-A_{16} y}, \tag{35}$$

$$u_{10} = A_{38} e^{-A_{30} y} + A_{31} e^{-A_5 y} - A_{39} e^{-\gamma y} - A_{40} e^{-A_1 y} - A_{34} e^{-A_{19} y} - A_{36} e^{-A_2 y} + A\lambda, \tag{36}$$

$$u_{11} = B_{69} e^{-A_{30} y} + B_{51} e^{-\gamma y} + B_{52} e^{-2\gamma y} + B_{53} e^{-2A_1 y} + B_{54} e^{-A_5 y} + B_{55} e^{-2A_5 y} - B_{56} e^{-A_{12} y} + B_{57} e^{-A_{14} y} - B_{58} e^{-A_{16} y} + B_{59} e^{-A_{49} y} - B_{60} e^{-A_{51} y} - B_{61} e^{-A_{53} y} - B_{62} e^{-A_{55} y} + B_{63} e^{-A_{57} y} + B_{64} e^{-A_{59} y} - B_{65} e^{-A_{61} y} + B_{66} e^{-A_{63} y} + B_{67} e^{-A_{65} y} - B_{68} e^{-A_{19} y}, \tag{37}$$

$$\theta_{00} = e^{-\gamma y}, \tag{38}$$

$$\theta_{01} = A_{18} e^{-\gamma y} - A_9 e^{-2A_5 y} - A_{10} e^{-2\gamma y} - A_{11} e^{-2A_1 y} + A_{13} e^{-A_{12} y} - A_{15} e^{-A_{14} y} + A_{17} e^{-A_{16} y}, \tag{39}$$

$$\theta_{10} = A_{20} e^{-A_{19} y} + A_{21} e^{-\gamma y}, \tag{40}$$

$$\theta_{11} = B_{32} e^{-A_{19} y} + B_1 e^{-\gamma y} - B_3 e^{-2A_5 y} - B_5 e^{-2\gamma y} - B_7 e^{-2A_1 y} + B_9 e^{-A_{12} y} - B_{11} e^{-A_{14} y} + B_{13} e^{-A_{16} y} - B_{15} e^{-A_{49} y} + B_{17} e^{-A_{51} y} + B_{19} e^{-A_{53} y} + B_{21} e^{-A_{55} y} - B_{23} e^{-A_{57} y} - B_{25} e^{-A_{59} y} + B_{27} e^{-A_{61} y} - B_{29} e^{-A_{63} y} - B_{31} e^{-A_{65} y}, \tag{41}$$

$$C_{00} = e^{-A_1 y}, \tag{42}$$

$$C_{01} = 0, \tag{43}$$

$$C_{10} = A_4 e^{-A_2 y} + A_3 e^{-A_1 y}, \tag{44}$$

$$C_{11} = 0, \tag{45}$$

where A_1 to A_{65} and B_1 to B_{69} are constants, whose expressions are not given here due to sake of brevity.

Thus, the expressions for velocity, temperature and concentration are known and given by

$$u(y,t) = u_{00} + Ec\,u_{01} + \varepsilon e^{i\omega t}\left(u_{10} + Ec\,u_{11}\right), \tag{46}$$

$$\theta(y,t) = \theta_{00} + Ec\,\theta_{01} + \varepsilon e^{i\omega t}\left(\theta_{10} + Ec\,\theta_{11}\right), \tag{47}$$

$$C(y,t) = C_{00} + Ec\,C_{01} + \varepsilon e^{i\omega t}\left(C_{10} + Ec\,C_{11}\right). \tag{48}$$

A. Skin-friction Coefficient

The coefficient of skin-friction at the plate is given by

$$C_f = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -A_5 A_8 + \gamma A_6 + A_1 A_7 + Ec(-A_5 A_{29} + \gamma A_{22} - 2A_5 A_{23} - 2\gamma A_{24} - 2A_1 A_{25} + A_{12} A_{26} - A_{14} A_{27} + A_{16} A_{28}) + \varepsilon e^{i\omega t}\{-A_{30} A_{38} - A_5 A_{31} + \gamma A_{39} + A_1 A_{41} + A_{19} A_{34} + A_2 A_{36} + Ec(-A_{30} B_{60} - \gamma B_{51} - 2\gamma B_{52} - 2A_1 B_{53} - A_5 B_{54} - 2A_5 B_{55} + A_{12} B_{56} - A_{14} B_{57} + A_{16} B_{58} - A_{49} B_{59} + A_{51} B_{60} + A_{53} B_{61} + A_{55} B_{62} - A_{57} B_{63} - A_{59} B_{64} + A_{61} B_{65} - A_{63} B_{66} - A_{65} B_{67} + A_{19} B_{68})\}. \tag{49}$$

B. Nusselt Number

The rate of heat transfer in terms of Nusselt number at the plate is given by

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = \gamma - Ec(-\gamma A_{18} + 2A_5 A_9 + 2\gamma A_{10} + 2A_1 A_{11} - A_{12} A_{13} + A_{14} A_{15} - A_{16} A_{17}) - \varepsilon e^{i\omega t}\{-A_{19} A_{20} - \gamma A_{21} + Ec(-A_{19} B_{32} - \gamma B_1 + 2A_5 B_3 + 2\gamma B_5 + 2A_1 B_7 - A_{12} B_9 + A_{14} B_{11} - A_{16} B_{13} + A_{49} B_{15} - A_{51} B_{17} - A_{53} B_{19} - A_{55} B_{21} + A_{57} B_{23} + A_{59} B_{25} - A_{61} B_{27} + A_{63} B_{29} + A_{65} B_{31})\}. \tag{50}$$

C. Sherwood Number

The rate of mass transfer in terms of Sherwood Number at the plate is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = A_1 + \varepsilon e^{i\omega t}(A_2 A_4 + A_1 A_3). \tag{51}$$

IV. RESULTS AND DISCUSSION

The effects of physical parameters on velocity, temperature and mass distribution are shown through figures when $\delta = 0.01, A = 0.5, t = 0.1, S = 0.2, \lambda = 0.5$ and $\omega = 1$. It is depicted from figures 1 to 3 that fluid velocity increases with an increase of Grashof number for heat transfer, Grashof number for mass transfer or permeability parameter, while an opposite phenomenon is observed in case of radiation parameter, Prandtl number, Hartmann number, chemical reaction parameter, angle of inclination or Schmidt number as shown from figures 4 to 9.

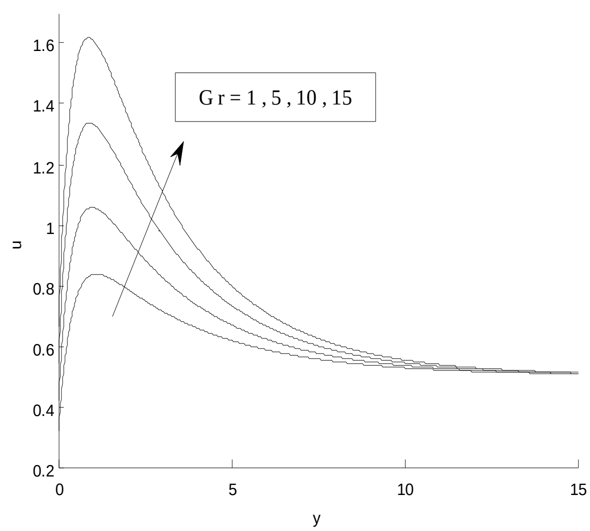

Fig-1: Velocity distribution versus y when $R = 1.6, Ec = 0.01, \Pr = 0.71, Gc = 5, K = 0.1, k_1 = 0.1, M = 1, \psi = \frac{\pi}{2}, Sc = 0.22.$

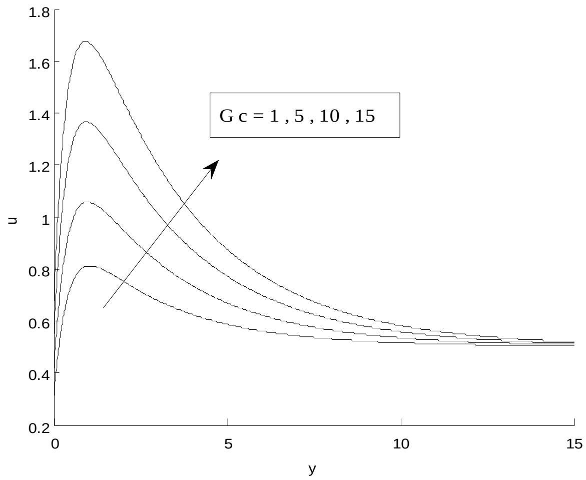

Fig-2: Velocity distribution versus y when $R=1.6,\ Ec=0.01,\ \Pr=0.71,\ Gr=5,\ K=0.1,\ k_1=0.1,\ M=1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

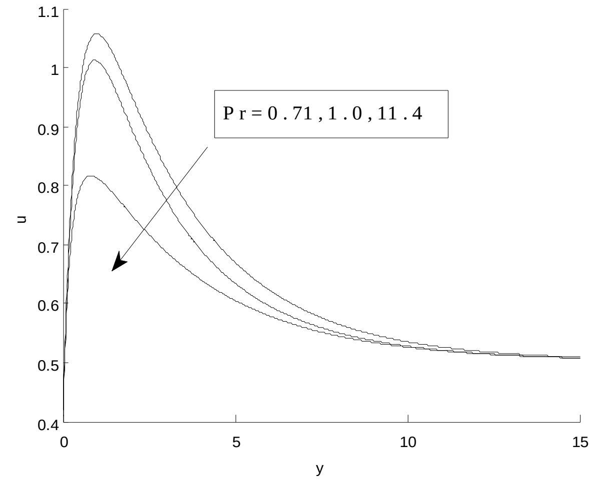

Fig-5: Velocity distribution versus y when $R=1.6,\ Ec=0.01,\ Gr=5,\ Gc=5,\ K=0.1,\ k_1=0.1,\ M=1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

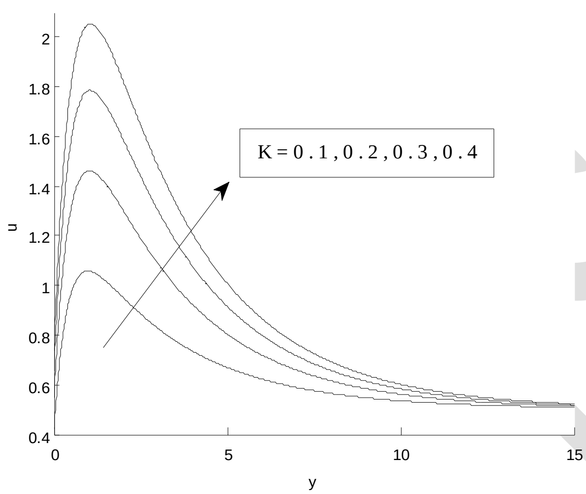

Fig-3: Velocity distribution versus y when $R=1.6,\ Ec=0.01,\ \Pr=0.71,\ Gr=5,\ Gc=5,\ k_1=0.1,\ M=1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

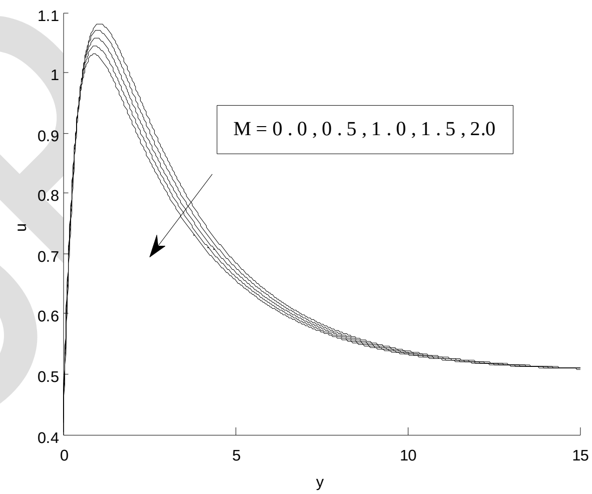

Fig-6: Velocity distribution versus y when $R=1.6,\ Ec=0.01,\ \Pr=0.71,\ Gr=5,\ Gc=5,\ K=0.1,\ k_1=0.1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

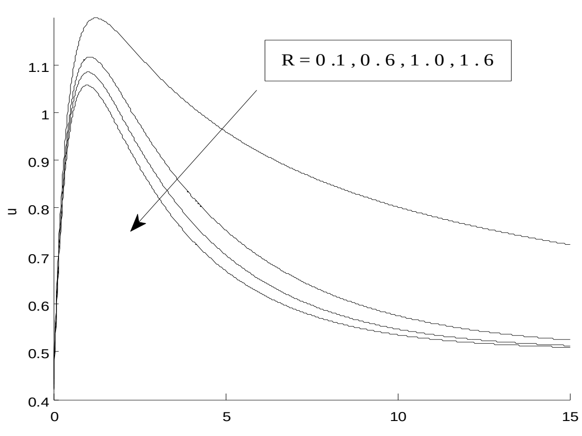

Fig-4: Velocity distribution versus y when $M=1,\ Ec=0.01,\ \Pr=0.71,\ Gr=5,\ Gc=5,\ K=0.1,\ k_1=0.1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

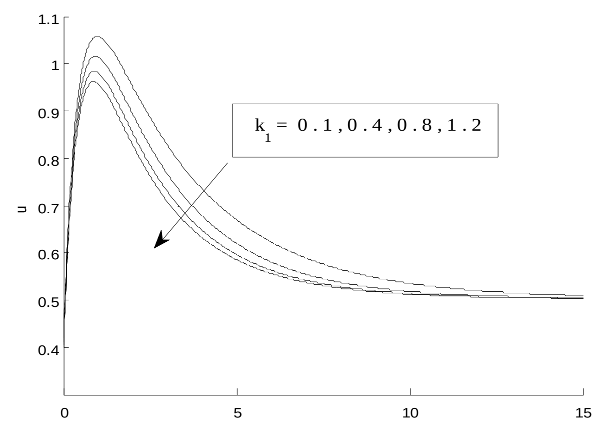

Fig-7: Velocity distribution versus y when $R=1.6, Ec=0.01,\ \Pr=0.71,\ Gr=5,\ Gc=5,\ K=0.1,\ M=1,\ \psi=\frac{\pi}{2},\ Sc=0.22.$

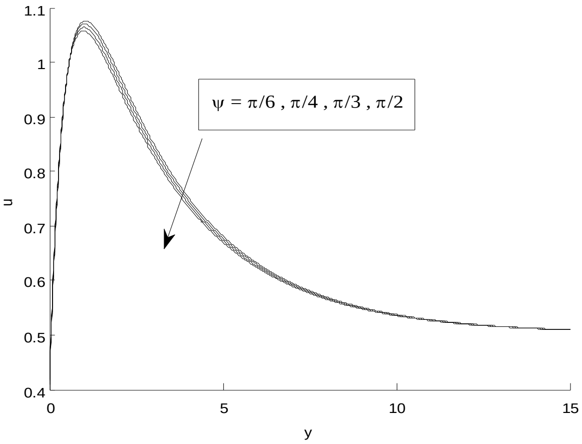

Fig-8: Velocity distribution versus y when $R = 1.6, Ec = 0.01$, $\Pr = 0.71$, $Gr = 5$, $Gc = 5$, $K = 0.1$, $k_1 = 0.1$, $M = 1$, $Sc = 0.22$.

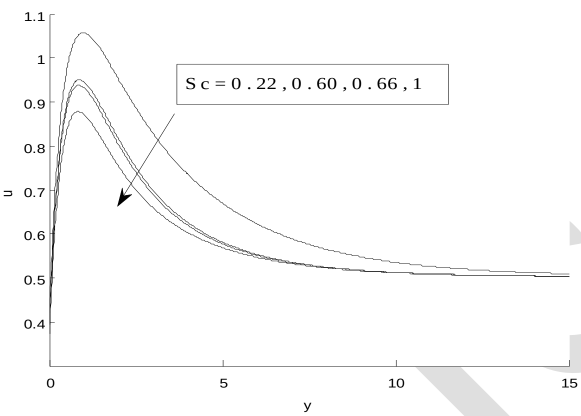

Fig-9: Velocity distribution versus y when $R = 1.6$, $Ec = 0.01$, $\Pr = 0.71$, $Gr = 5$, $Gc = 5$, $K = 0.1$, $k_1 = 0.1$, $M = 1$, $\psi = \frac{\pi}{2}$,

The variation of temperature profile for different values of radiation parameter and Prandtl number are shown in figures 10 and 11. It is depicted that temperature profile decreases with an increase of radiation parameter or Prandtl number.

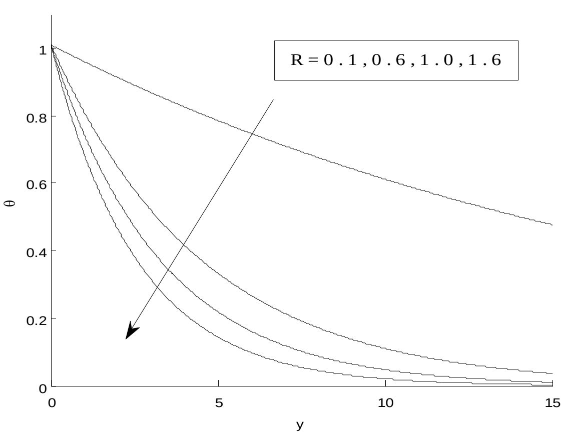

Fig-10: Temperature distribution versus y when $Ec = 0.01$, $\Pr = 0.71$, $Gr = 5$, $Gc = 5$, $K = 0.1$, $k_1 = 0.1$, $M = 1$, $\psi = \frac{\pi}{2}$, $Sc = 0.22$.

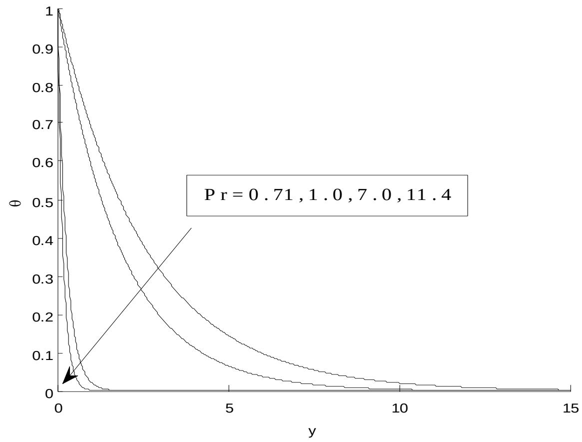

Fig-11: Temperature distribution versus y when $R = 1.6$, $Ec = 0.01$, $Gr = 5$, $Gc = 5$, $K = 0.1$, $k_1 = 0.1$, $M = 1$, $\psi = \frac{\pi}{2}$, $Sc = 0.22$.

The variation of concentration profiles for different values of Schmidt number and chemical reaction parameter are shown in figures 12 and 13. It is observed that the increasing values of Schmidt number or chemical reaction parameter leads to fall in the concentration profile**.**

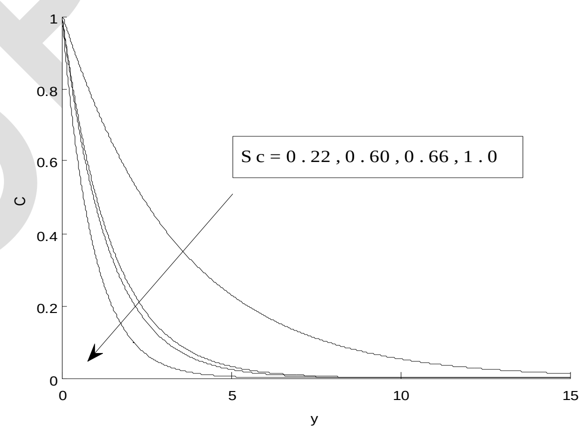

Fig-12: Concentration distribution versus y when $k_1 = 0.1$.

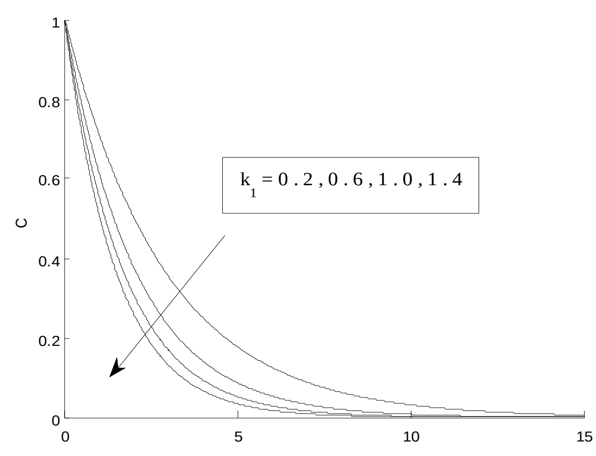

Fig-13: Concentration distribution versus y when $Sc = 0.22$.

TABLE I

Numerical values of skin friction coefficient, Nusselt number and Sherwood number at the plate for various values of physical parameters when $\delta = 0.01,\ t = 0.1,\ A = 0.5,\ S = 0.2,\ \lambda = 0.5$ and $\omega = 1$.

Pr	R	Ec	k_1	Gr	Gc	M	Sc	K	ψ	Cf	Nu	Sh
0.71	1.6	0.01	0.1	5	5	1	0.22	0.1	$\pi/2$	2.0979	0.3895	0.2978
1.0	1.6	0.01	0.1	5	5	1	0.22	0.1	$\pi/2$	2.0490	0.5485	0.2978
0.71	1.0	0.01	0.1	5	5	1	0.22	0.1	$\pi/2$	2.1248	0.3062	0.2978
0.71	1.6	0.04	0.1	5	5	1	0.22	0.1	$\pi/2$	2.0950	0.3807	0.2978
0.71	1.6	0.01	0.4	5	5	1	0.22	0.1	$\pi/2$	2.0569	0.3897	0.4307
0.71	1.6	0.01	0.1	10	5	1	0.22	0.1	$\pi/2$	2.7169	0.3876	0.2978
0.71	1.6	0.01	0.1	5	10	1	0.22	0.1	$\pi/2$	2.7496	0.3874	0.2978
0.71	1.6	0.01	0.1	5	5	0.5	0.22	0.1	$\pi/2$	2.0646	0.3895	0.2978
0.71	1.6	0.01	0.1	5	5	1	0.66	0.1	$\pi/2$	1.9653	0.3901	0.7554
0.71	1.6	0.01	0.1	5	5	1	0.22	0.2	$\pi/2$	2.7397	0.3868	0.2978
0.71	1.6	0.01	0.1	5	5	1	0.22	0.1	$\pi/6$	2.0436	0.3894	0.2978

The effects of various physical parameters on skin friction, Nusselt number and Sherwood number are shown through TABLE I. It is observed that skin friction increases with the increase of Grashof number for heat transfer, Grashof number for mass transfer, permeability parameter, Hartmann number or angle of inclination of magnetic field, while it decreases with the increase of Prandtl number, Eckert number, chemical reaction parameter, radiation parameter or Schmidt number. It is depicted that increasing values of Prandtl number, Hartmann number, radiation parameter, Schmidt number, chemical reaction parameter or angle of inclination of magnetic field leads to growth in the Nusselt number, while increase in the Grashof number for heat transfer, Grashof number for mass transfer, Eckert number or permeability parameter results in an decrease in the Nusselt number. It is also observed that Sherwood number at the plate increases due to increase in the Schmidt number or chemical reaction parameter while it is unaltered from other physical parameter.

V. CONCLUSIONS

Influence of different physical parameters on unsteady free convective flow, heat and mass transfer past a semi vertical porous plate immersed through porous medium with viscous dissipation effect and in the presence of inclined magnetic field is carried out and skin friction coefficient, Nusselt number and Sherwood number at the plate are discussed numerically and the following conclusions are made:

(i). The increase in Grashof number for heat transfer, Grashof number for mass transfer or permeability parameter leads to the increase in velocity distributions.

(ii). The fluid velocity and temperature decrease with the increase of radiation parameter or Prandtl number.

(iii). The fluid velocity decreases with an increase of angle of inclination of magnetic field, while it increases with an increase of viscous dissipation effect.

(iv). The fluid concentration increases with the increase of chemical reaction parameter or Schmidt number while fluid velocity decreases.

(v). For the unsteady flow, the skin friction increases with the increase of magnetic field parameter or angle of inclination of magnetic field.

(vi). The Nusselt number decreases with the increase of permeability parameter or Grashof number for heat transfer.

(vii). An increase in Schmidt number or chemical reaction parameter leads to increase in the Sherwood number.

REFERENCES

[1] Sparrow, E.M. and Cess, R.D., (1961). The effect of a magnetic field on free convention heat transfer. Int. J. of Heat Mass Transfer, Vol. 3(4), pp. 267-274.

[2] Raptis, A. and Perdikis, C., (1999). Radiation and free convection flow past a moving plate. Int. j. of Applied Mechanics and Engineering, Vol. 4, pp. 817-821.

[3] Kim, Y.J., (2000). Unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. Int. J. of Engineering and Sciences, Vol. 38, pp. 833-845.

[4] Singh, C.B., (2000). Unsteady flow of liquid through a channel with pressure gradient changing exponentially under the influence of inclined magnetic field. Int. J. of Biochemiphysic., Vol. 10, pp. 37-40.

[5] Chamka, A. J., (2003). MHD flow of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Int. Communication Heat Mass Transfer, Vol. 30, pp. 413-422.

[6] Ogulu, A. and J. Prakash, (2006). Heat transfer to unsteady MHD flow past an infinite moving vertical plate with variable suction. Phys. Scr., Vol. 74, pp. 232-239.

[7] Sharma, P. R. and Sharma, Kalpna, (2007). Effect of oscillatory suction and heat source on heat and mass transfer in MHD flow along a vertical moving porous plate bounded by porous medium. Model. Meas. & Control 'B', AMSE J., France, Vol. 76, pp. 34-60.

[8] Hayat, T. and Abbas, Z., (2008). Radiation effect on MHD flow in a porous space. Int. J. Heat Mass Transfer, Vol. 51, pp. 1024-1033.

[9] Sharma, P. R. and Singh, G., (2008). Unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation. Int. J. Appl. Math. and Mech., Vol. 4, pp. 01-08.

[10] Sharma, P. R.; Kumar, N. and Sharma, Pooja, (2009). Radiation effects on unsteady MHD free convective flow with hall current and mass transfer through viscous incompressible fluid past a vertical porous plate immersed in porous medium with heat source/sink. J. Int. Acad. Phys. Sciences, Vol. 13, pp. 231-252.

[11] Sharma, P. R. and Mehta, Ruchika, (2009). Radiative and free convective effects on MHD flow through porous medium between infinite porous plates with periodic cross flow velocity. J. National Academy of Mathematics, Vol. 23, pp. 83-100.

[12] Sharma, P. R.; Kumar, N. and Sharma, Pooja, (2010). Unsteady MHD convective flow and heat transfer between heated inclined plates with magnetic field in the presence of radiation effects. J. Int. Acad. Physical Sciences, Vol. 14, pp. 181-193.

[13] Turkyilmazoglu, M. and Pop, I., (2012). Soret and heat source effects on the unsteady radiation MHD free convection flow from an impulsively started infinite vertical plate. Int. J. of Heat Mass Transfer, Vol. 55, pp. 7635-7644.

[14] Sandeep, N. and Sugunamma, V., (2013). Effect of inclined magnetic field on unsteady free convective flow of dissipative fluid past a vertical plate. World Applied Sciences J., Vol. 22(7), pp. 975-984.

[15] Sugunamma, V.; Sandeep, N.; Mohan Krishna, P. and Ramanabahunadam, (2013). Inclined magnetic field and chemical reaction effects on Flow over a semi infinite vertical porous plate through porous medium. Communications in Applied Sciences, Vol. 1(1), pp. 1-24.