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## Unsteady MHD free convective flow through a porous medium over an infinite vertical plate

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### Abstract

In this paper we have considered the unsteady free convective flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate under the influence of uniform transverse magnetic field with time dependent permeability and oscillatory suction. The governing equations of the flow field are solved by a regular perturbation method for small amplitude of the permeability. The closed form solutions for the velocity, temperature and concentration have been derived analytically and also its behaviour is computationally discussed with reference to different flow parameters with the help of profiles. The skin friction on the boundary, the heat flux in terms of the Nusselt number and rate of mass transfer in terms of Sherwood number are also obtained and their behaviour computationally discussed.

*Key words:* Heat transfer; mass transfer; oscillatory suction; porous medium; MHD flow; vertical plates.

**Subject classification codes:** 35Q79, 80A20, 76S05, 76E06, 76R10

### 1. Introduction

In many industries and nature, various transport processes exist in which heat and mass transfer takes place simultaneously as a result of combined buoyancy effect of thermal diffusion and diffusion of chemical species. The phenomenon of heat and mass transfer is observed in buoyancy induced motions in the atmosphere, in bodies of water, quasi – solid bodies, such as earth and so on. Chen<sup>1</sup> studied combined heat and

mass transfer in MHD free convection from a vertical surface with Ohmic heating and viscous dissipation. Chamkha<sup>2</sup> analysed MHD flow of a uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Hayat and Mehmood<sup>3</sup> analyzed slip effects on MHD flow of third order fluid in a planar channel. Pal and Chatterjee<sup>4</sup> found heat and mass transfer in MHD non-Darcian flow of a micro polar fluid over a stretching sheet embedded in a porous media with non-uniform heat source and thermal radiation. Kim<sup>5</sup> studied unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. Chamkha<sup>6</sup> discussed unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption. Convective flows with simultaneous heat and mass transfer under the influence of the chemical reaction arise in many transport processes both naturally and artificially in various branches of science and engineering. This phenomenon plays an important role in the chemical industry, power and cooling industry for drying, chemical vapor deposition on surfaces, cooling of nuclear reactors, and petroleum industries. Das<sup>7</sup> studied free convective MHD flow and heat transfer in a viscous incompressible fluid confined between a long vertical wavy wall and a parallel flat wall. Soundalgekar<sup>8</sup> examined free convection effects on steady MHD flow past a vertical porous plate. Hossain *et al.*<sup>9</sup> studied the effect of radiation on free convection from a porous vertical plate. Srinivasacharya and Mendu<sup>10</sup> studied free convection in MHD micro polar fluid with radiation and chemical reaction effects. Srinivasacharya and Ram Reddy<sup>11</sup> studied natural convection heat and mass transfer in a micro polar fluid with thermal and mass stratification.

Makinde *et al.*<sup>12</sup> investigated unsteady convection with chemical reaction and radiative heat transfer past a flat porous plate moving through a binary mixture. Kandasamy *et al.*<sup>13</sup> have analyzed effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection. Das *et al.*<sup>14</sup> analyzed effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction. Anjalidevi and Kandasamy<sup>15</sup> studied effects of chemical reaction, heat and mass transfer on laminar flow along a semi-infinite horizontal plate. Seddeek *et al.*<sup>16</sup> found effects of chemical reaction and variable viscosity on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with radiation. Ibrahim *et al.*<sup>17</sup> studied effect of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Patil and Kulkarni<sup>18</sup> investigated effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Pal and Mondal<sup>19</sup> discussed effects of Soret, Dufour, chemical reaction and thermal radiation on MHD non-Darcy unsteady mixed convective heat and mass transfer over a stretching sheet. Pal and Talukdar<sup>20</sup> analyzed analytically, unsteady magneto hydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Muthucumaraswamy and Ganesan<sup>21</sup> studied first-order chemical reaction on flow past an impulsively started vertical plate with uniform heat and mass flux. Dulal Pal<sup>22</sup> studied effect of chemical reaction on the dispersion of a solute in a porous medium. Mehta and Tiwari<sup>23</sup> analyzed dispersion in the presence of slip and chemical reactions in porous wall tube flow. Hayat and Nawaz<sup>24</sup> studied Soret and Dufour effects on the mixed convection flow of a second grade fluid subject to Hall and ion-slip currents. Patil *et al.*<sup>25</sup> analyzed double diffusive mixed convection flow over a moving vertical plate in the presence of internal heat generation and a chemical reaction. Srinivasacharya and Kaladhar<sup>26</sup> studied mixed convection flow of chemically reacting couple stress fluid in a vertical channel with Soret and Dufour effects. Srinivasacharya and Upendar<sup>27</sup> studied Soret and Dufour effects on MHD free convection in a micro polar fluid. Kaladhar and Srinivasacharya<sup>28</sup> analyzed mixed convection flow

of chemically reacting couple stress fluid in an annulus with Soret and Dufour effects. Srinivasacharya and Kaladhar<sup>29</sup> examined Soret and Dufour effects on mixed convection flow of couple stress fluid in a non-Darcy porous medium with heat and mass fluxes. Srinivasacharya and Swamy Reddy<sup>30</sup> studied Soret and Dufour effects on mixed convection from a vertical plate in power-law fluid saturated porous medium. Hsiao<sup>31</sup> analyzed MHD mixed convection for visco-elastic fluid past a porous wedge. Hsiao<sup>32</sup> studied heat and Mass mixed convection for MHD visco-elastic fluid past a stretching Sheet with Ohmic dissipation. Recently, Krishna *et al.*<sup>35-38</sup> discussed the MHD flows of an incompressible and electrically conducting fluid in planar channel. Veera Krishna *et al.*<sup>39</sup> discussed heat and mass transfer on unsteady MHD oscillatory flow of blood through porous arteriole. The effects of radiation and Hall current on an unsteady MHD free convective flow in a vertical channel filled with a porous medium have been studied by Veera Krishna *et al.*<sup>40</sup>. The heat generation/absorption and thermo-diffusion on an unsteady free convective MHD flow of radiating and chemically reactive second grade fluid near an infinite vertical plate through a porous medium and taking the Hall current into account have been studied by Veera Krishna and Chamkha<sup>41</sup>. Veera Krishna *et al.*<sup>42</sup> discussed the heat and mass transfer on unsteady, MHD oscillatory flow of second-grade fluid through a porous medium between two vertical plates under the influence of fluctuating heat source/sink, and chemical reaction. Veera Krishna *et al.*<sup>43</sup> investigated the heat and mass transfer on MHD free convective flow over an infinite non-conducting vertical flat porous plate. Veera Krishna and Jyothi<sup>44</sup> discussed the effect of heat and mass transfer on free convective rotating flow of a visco-elastic incompressible electrically conducting fluid past a vertical porous plate with time dependent oscillatory permeability and suction in presence of a uniform transverse magnetic field and heat source. Veera Krishna and Subba Reddy [45] investigated the transient MHD flow of a reactive second grade fluid through a porous medium between two infinitely long horizontal parallel plates. Veera Krishna *et al.*<sup>46</sup> discussed heat and mass-transfer effects on an unsteady flow of a chemically reacting micropolar fluid over an infinite vertical porous plate in the presence of an inclined magnetic field, Hall current effect, and thermal radiation taken into account. Veera Krishna *et al.*<sup>47</sup> discussed Hall effects on steady hydromagnetic flow of a couple stress fluid through a composite medium in a rotating parallel plate channel with porous bed on the lower half. Veera Krishna *et al.*<sup>48</sup> discussed Hall effects on unsteady hydromagnetic natural convective rotating flow of second grade fluid past an impulsively moving vertical plate entrenched in a fluid inundated porous medium, while temperature of the plate has a temporarily ramped profile. Veera Krishna and Chamkha<sup>49</sup> discussed the MHD squeezing flow of a water-based nanofluid through a saturated porous medium between two parallel disks, taking the Hall current into account. Veera Krishna *et al.* [50] discussed Hall effects on MHD peristaltic flow of Jeffrey fluid through porous medium in a vertical stratum.

Motivated by the above studies, in this paper we have considered the unsteady free convective flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate under the influence of uniform transverse magnetic field with time dependent permeability and oscillatory suction.

## 2. Formulation and solution of the problem:

We considered the unsteady MHD free convection flow of an incompressible viscous electrically conducting fluid with simultaneous heat and mass transfer over an infinite vertical plate through porous medium with time dependent permeability and oscillatory suction under the influence of uniform transverse magnetic field of strength  $H_0$ . The  $y$ -axis is taken along the plate and  $x$ -axis perpendicular to it and  $u$  is the velocity along the  $x$ -direction.

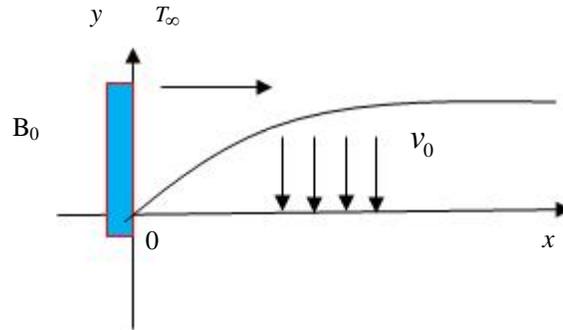


Fig. 1 Physical configuration of the problem

The basic assumptions are made as following.

1. All fluid proportions are constant.
2. The plate as well as the fluid is assumed to be at the same temperature and the concentration of species is raised or lowered.
3. The magnetic Reynolds number is small so that the induced magnetic field can be neglected in comparison to the applied magnetic field.
4. The permeability of the porous medium is assumed to be

$$K(t) = k(1 + \varepsilon e^{i\omega t}) \quad (1)$$

5. The suction velocity is assumed to be

$$v(t) = -v_0(1 + \varepsilon e^{i\omega t}) \quad (2)$$

Where,  $v_0$  represents the suction or injection velocity at the plate.

6. The pressure is assumed to be constant.
7. If the plate is extended to infinite length, then all the physical variables are functions of  $y$  and  $t$  alone.

The governing equations for the unsteady MHD free convection flow of an incompressible viscous electrically conducting fluid with simultaneous heat and mass transfer over an infinite vertical plate through porous medium under the influence of uniform transverse magnetic field with respect to the frame are given by Equation of continuity:

$$\frac{\partial u}{\partial y} = 0 \quad (3)$$

Momentum equation:

$$\frac{\partial u}{\partial t} - v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} - \frac{\sigma \mu_e^2 H_0^2}{\rho} u - \frac{v}{K(t)} u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \quad (4)$$

Equation of energy:

$$\frac{\partial T}{\partial t} - v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} - S_1(T - T_\infty) \quad (5)$$

Equation of concentration

$$\frac{\partial C}{\partial t} - v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - K_1(C - C_\infty) \quad (6)$$

The boundary conditions are

$$\begin{aligned} u(y, t) = T(y, t) = C(y, t) = f(t) & \quad \text{at } y = 0 \\ = 0 & \quad \text{at } y \rightarrow \infty \end{aligned} \quad (7)$$

Where,  $f(t) = 1 + \varepsilon e^{i\omega t}$ . With foregoing assumptions and taking usual Boussinesq's approximation into account as well as the following non-dimensional variables.

$$u^* = \frac{u}{v_0}, y = \frac{v_0 y^*}{v}, t^* = \frac{v_0^2 t}{v}, \omega^* = \frac{v \omega}{v_0^2}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, \phi = \frac{C - C_\infty}{C_w - C_\infty}$$

Making use of non-dimensional variables, the governing equations reduces to (Dropping asterisks)

$$\frac{\partial u}{\partial t} - v_0(1 + \varepsilon e^{i\omega t}) \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} - \left( M^2 + \frac{1}{K(1 + \varepsilon e^{i\omega t})} \right) u + \text{Gr} \theta + \text{Gm} C \quad (8)$$

$$\text{Pr} \frac{\partial \theta}{\partial t} - v_0(1 + \varepsilon e^{i\omega t}) \text{Pr} \frac{\partial \theta}{\partial y} = \frac{\partial^2 \theta}{\partial y^2} - \text{Pr} S \theta \quad (9)$$

$$\text{Sc} \frac{\partial \phi}{\partial t} - v_0(1 + \varepsilon e^{i\omega t}) \text{Sc} \frac{\partial \phi}{\partial y} = \frac{\partial^2 \phi}{\partial y^2} - \text{KcSc} \phi, \quad (10)$$

The corresponding boundary conditions are

$$\begin{aligned} u(y, t) = \theta(y, t) = \phi(y, t) = 1 + \varepsilon e^{i\omega t} & \quad \text{at } y = 0 \\ = 0 & \quad \text{at } y \rightarrow \infty \end{aligned} \quad (11)$$

Where,  $M^2 = \frac{\sigma B_0^2 v}{\rho v_0^2}$  is the Hartmann number (Magnetic field parameter),  $K = \frac{v^2}{k v_0^2}$  is the permeability

parameter (Porosity or Darcy parameter),  $\text{Pr} = \frac{\nu}{\alpha}$  is the Prandtl number,  $\text{Sc} = \frac{\nu}{D}$  is the Schmidt number,

$\text{Kc} = \frac{K_1 \nu}{v_0^2}$  is the chemical reaction parameter,  $S = \frac{S_1 \nu}{v_0^2}$  is the Heat Source parameter,  $\text{Gr} = \frac{g \beta \nu (T_w - T_\infty)}{v_0^3}$

is the thermal Grashof number and  $\text{Gm} = \frac{g \beta^* \nu (C_w - C_\infty)}{v_0^3}$  is the mass Grashof number.

In order to solve the equations, (8) – (10) using boundary conditions (11), we assume the solutions of the following form, because the amplitude  $\varepsilon (\ll 1)$  of permeability is very small.

$$u(y,t) = u_0(y) + \varepsilon u_1(y)e^{i\omega t} \quad (12)$$

$$\theta(y,t) = \theta_0(y) + \varepsilon \theta_1(y)e^{i\omega t} \quad (13)$$

$$\phi(y,t) = \phi_0(y) + \varepsilon \phi_1(y)e^{i\omega t} \quad (14)$$

Substituting the Eqs. (12) – (14) into the Eqs. (8) – (10) respectively and equate the harmonic and non-harmonic terms to obtain the zeroth and first orders ordinary differential equations for momentum, temperature and concentration distributions.

Zeroth order:

$$\frac{\partial^2 \phi_0}{\partial y^2} + \text{Sc}v_0 \frac{\partial \phi_0}{\partial y} - \text{KcSc}\phi_0 = 0 \quad (15)$$

$$\frac{\partial^2 \theta_0}{\partial y^2} + \text{Pr}v_0 \frac{\partial \theta_0}{\partial y} - \text{Pr}S\theta_0 = 0 \quad (16)$$

$$\frac{\partial^2 u_0}{\partial y^2} + v_0 \frac{\partial u_0}{\partial y} - \left( M^2 + \frac{1}{K} \right) u_0 = -\text{Gr}\theta_0 - \text{Gm}\phi_0 \quad (17)$$

Corresponding boundary conditions are

$$\phi_0 = 1, \theta_0 = 1, u_0 = 1 \quad \text{at} \quad y = 0 \quad (18)$$

$$\phi_0 = 0, \theta_0 = 0, u_0 = 0 \quad \text{at} \quad y \rightarrow \infty \quad (19)$$

Solving the equations (15) – (17) with relevant boundary conditions (18) and (19), we obtained the zeroth order concentration, temperature and velocity.

First order:

$$\frac{\partial^2 \phi_1}{\partial y^2} + \text{Sc}v_0 \frac{\partial \phi_1}{\partial y} - \text{Sc}(\text{Kc} + i\omega)\phi_1 = -\text{Sc}v_0 \frac{\partial \phi_0}{\partial y} \quad (20)$$

$$\frac{\partial^2 \theta_1}{\partial y^2} + \text{Pr}v_0 \frac{\partial \theta_1}{\partial y} - \text{Pr}(S + i\omega)\theta_1 = -\text{Pr}v_0 \frac{\partial \theta_0}{\partial y} \quad (21)$$

$$\frac{\partial^2 u_1}{\partial y^2} + v_0 \frac{\partial u_1}{\partial y} - \left( M^2 + \frac{1}{K} + i\omega \right) u_1 = -v_0 \frac{\partial u_0}{\partial y} - \text{Gr}\theta_1 - \text{Gm}\phi_1 \quad (22)$$

Corresponding boundary conditions are

$$\phi_1 = 1, \theta_1 = 1, u_1 = 1 \quad \text{at} \quad y = 0 \quad (23)$$

$$\phi_1 = 0, \theta_1 = 0, u_1 = 0 \quad \text{at} \quad y \rightarrow \infty \quad (24)$$

Solving the equations (20) – (22) with relevant boundary conditions (23) and (24), we obtained the first order concentration, temperature and velocity.

$$\phi_0 = e^{-m_1 y} \quad (25)$$

$$\theta_0 = e^{-m_3 y} \quad (26)$$

$$u_0 = A_1 e^{-m_5 y} - \frac{\text{Gr}}{A_2} e^{-m_3 y} - \frac{\text{Gm}}{A_3} e^{-m_1 y} \quad (27)$$

$$\phi_1 = \left( 1 - \frac{\text{Sc} v_0 m_1}{m_1^2 + \text{Sc} v_0 m_1 - \text{Sc}(\text{Kc} + i\omega)} \right) e^{-m_2 y} + \frac{\text{Sc} v_0 m_1 e^{-m_1 y}}{m_1^2 + \text{Sc} v_0 m_1 - \text{Sc}(\text{Kc} + i\omega)} \quad (28)$$

$$\theta_1 = \left( 1 - \frac{\text{Pr} v_0 m_3}{m_3^2 + \text{Pr} v_0 m_3 - \text{Pr}(S + i\omega)} \right) e^{-m_4 y} + \frac{\text{Pr} v_0 m_3 e^{-m_3 y}}{m_3^2 + \text{Pr} v_0 m_3 - \text{Pr}(S + i\omega)} \quad (29)$$

$$u_1 = (1 - B_1 + \text{Gr}B_2 + \text{Gm}B_3) e^{-m_6 y} + \frac{A_8}{A_{11}} e^{-m_5 y} + \frac{A_9}{A_{12}} e^{-m_3 y} + \frac{A_{10}}{A_{13}} e^{-m_1 y} \\ - \text{Gr} \left( \frac{A_4}{A_{14}} e^{-m_4 y} + \frac{A_5}{A_{12}} e^{-m_3 y} \right) - \text{Gm} \left( \frac{A_6}{A_{15}} e^{-m_2 y} + \frac{A_7}{A_{13}} e^{-m_1 y} \right) \quad (30)$$

The skin friction at the plate in terms of amplitude and phase is given by

$$\tau = \left( \frac{\partial u}{\partial y} \right)_{y=0} = \left( \frac{\partial u_0}{\partial y} \right)_{y=0} + \varepsilon \left( \frac{\partial u_1}{\partial y} \right)_{y=0} = F_1 + \varepsilon |F_2| \cos(\omega t + \psi)$$

$$\text{Where, } F_1 = \left( \frac{\partial u_0}{\partial y} \right)_{y=0}; F_2 = \left( \frac{\partial u_1}{\partial y} \right)_{y=0} \text{ and } \tan(\psi) = \frac{\text{Re}[F_2]}{\text{Im}[F_2]}.$$

The Nusselt number at the plate in terms of amplitude and phase is given by

$$\text{Nu} = - \left( \frac{\partial \theta}{\partial y} \right)_{y=0} = \left( \frac{\partial \theta_0}{\partial y} \right)_{y=0} + \varepsilon \left( \frac{\partial \theta_1}{\partial y} \right)_{y=0} = F_3 + \varepsilon |F_4| \cos(\omega t + \gamma)$$

$$\text{Where, } F_3 = \left( \frac{\partial \theta_0}{\partial y} \right)_{y=0}; F_4 = \left( \frac{\partial \theta_1}{\partial y} \right)_{y=0} \text{ and } \tan(\gamma) = \frac{\text{Re}[F_4]}{\text{Im}[F_4]}.$$

The Sherwood number at the plate in terms of amplitude and phase is given by

$$Sh = -\left(\frac{\partial\phi}{\partial y}\right)_{y=0} = \left(\frac{\partial\phi_0}{\partial y}\right)_{y=0} + \varepsilon \left(\frac{\partial\phi_1}{\partial y}\right)_{y=0} = F_5 + \varepsilon |F_6| \cos(\omega t + \zeta)$$

$$\text{Where, } F_5 = \left(\frac{\partial\phi_0}{\partial y}\right)_{y=0}; F_6 = \left(\frac{\partial\phi_1}{\partial y}\right)_{y=0} \text{ and } \tan(\zeta) = \frac{\text{Re}[F_6]}{\text{Im}[F_6]}.$$

### 3. Results and Discussion

We have considered the unsteady free convective flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate under the influence of uniform transverse magnetic field with time dependent permeability and oscillatory suction. The governing equations of the flow field are solved by a regular perturbation method for small amplitude of the permeability. The closed form solutions for the velocity, temperature and concentration have been derived analytically and also its behavior is computationally discussed with reference to different flow parameters like  $M$  Hartmann number,  $K$  porosity parameter,  $Pr$  is the Prandtl number,  $Sc$  is the Schmidt number,  $Kc$  is the chemical reaction parameter,  $S$  is the Heat Source parameter,  $Gr$  is the thermal Grashof number,  $Gm$  is the mass Grashof number,  $v_0$  is the suction velocity and the frequency of oscillation  $\omega$ . Figures (2-3) represent velocity, Figures (4) and Figures (5) represent the temperature and concentration distributions respectively. The stresses, Nusselt number and Sherwood number at the plate are evaluated numerically and discussed with governing parameters and are tabulated in the tables (1-3). Fixing the parameters  $M=2$ ,  $K=1$ ,  $Pr=0.71$ ,  $S=1$ ,  $Sc=0.22$ ,  $Kc=1$ ,  $Gr=5$ ,  $Gm=10$ ,  $v_0=0.2$  and  $\omega = \pi / 6$ , we draw the profiles varying for each parameter while the other parameters being fixed.

From the Figures 2(a-f), we noticed that the magnitude of the velocity component  $u$  reduces with increasing the intensity of the magnetic field  $M$ , Prandtl number  $Pr$  and Heat source parameter  $S$ . Whereas the velocity component  $u$  enhance with increasing permeability parameter  $K$ , thermal Grashof number  $Gr$  or mass Grashof number  $Gm$  throughout the fluid region. Lower the permeability of the porous medium lesser the fluid speed in the entire region. The Figures (3) depict the velocity component  $u$  experiences retardation in the flow field with increasing the chemical reaction parameter  $Kc$ , Schmidt number  $Sc$ , the suction velocity  $v_0$  or the frequency of oscillation entire the fluid region.

Figures 4(a-d) showed the effect of Heat source parameter  $S$ , the Prandtl number  $Pr$ , suction velocity  $v_0$  and the frequency of oscillation  $\omega$  on the temperature of the flow field. We noted that the temperature of the flow field diminishes as the Prandtl number increases. This is consistent with the fact that the thermal boundary layer thickness decreases with increasing Prandtl number. With increasing heat source parameter reduces the temperature of the flow field. This may happen due the elastic property of the fluid. It is observed that temperature of the flow field diminishes as the suction parameter or the frequency of oscillation increases.

Figures 5(a-d) depict the effect of the Schmidt number  $Sc$  and the frequency of oscillation  $\omega$  on concentration distribution. The concentration distribution decreases at all points of the flow field with the increase in the Schmidt number  $Sc$  or chemical reaction parameter  $Kc$ . This shows that the heavier diffusing species have a greater retarding effect on the concentration distribution of the flow field. Also, it is observed that presence of the frequency of oscillation  $\omega$  or increasing the suction velocity reduces the concentration distribution.

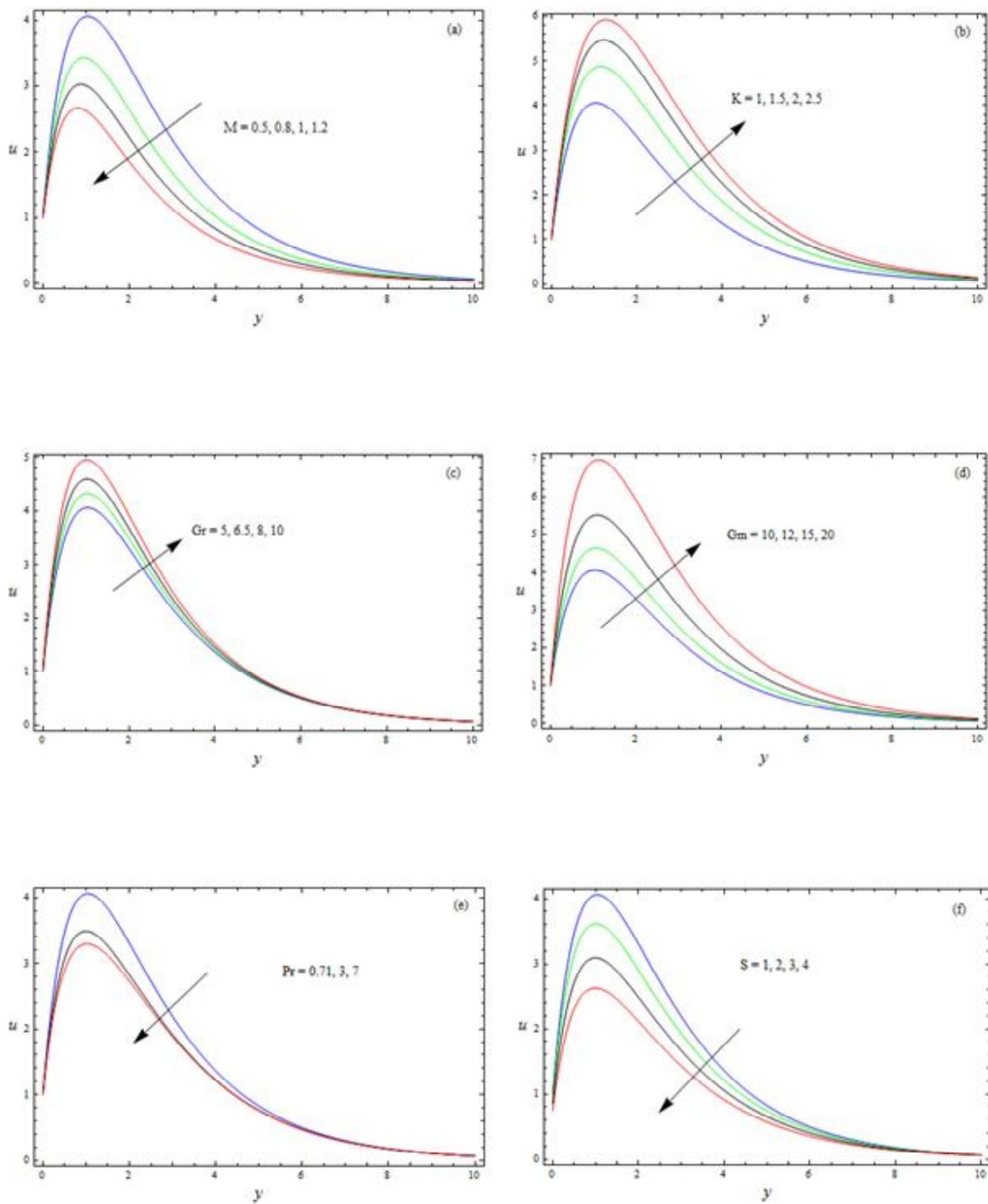


Fig 2(a-f): The velocity Profiles against  $M, K, Gr, Gm, Pr$  and  $S$  with  $\varepsilon = 0.001, t = 1$

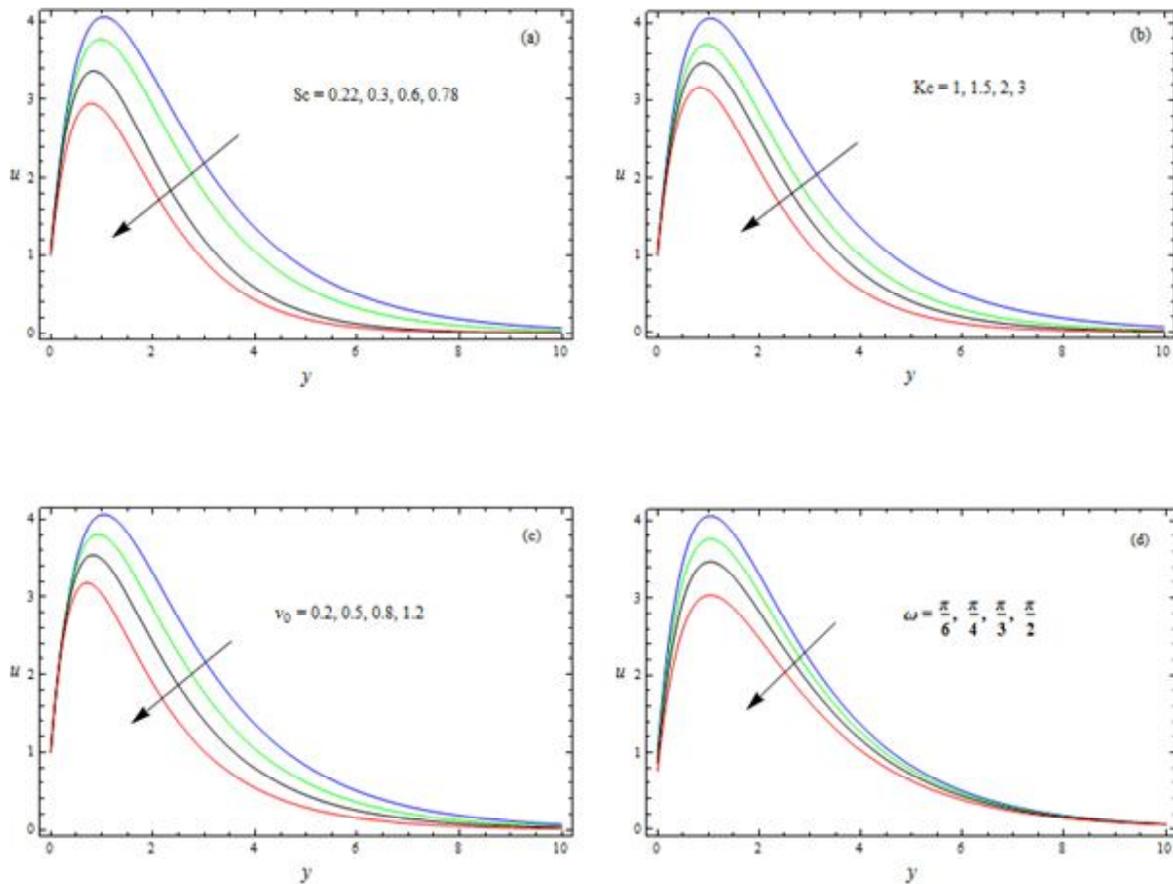


Fig 3(a-d): The velocity Profiles against  $Sc$ ,  $Kc$ ,  $v_0$  and  $\omega$  with  $\varepsilon = 0.001$ ,  $t = 1$

The skin friction is significant phenomenon which characterizes the frictional drag force at the solid surface. From Table 1, it is observed that the skin friction increases with the increase in permeability parameter  $K$ , thermal Grashof number  $Gr$ , Mass Grashof number  $Gm$  and suction velocity  $v_0$ , but it is interesting to note that the skin friction decreases with the increase in Hartmann number  $M$ , Prandtl number  $Pr$ , Schmidt number  $Sc$ , chemical reaction parameter  $Kc$ , Heat source parameter  $S$  and the frequency of oscillation. Similarly the amplitude augments with increase  $K$ ,  $Sc$ ,  $Kc$ ,  $Gr$ ,  $Gm$  and  $v_0$  retards with increase  $M$ ,  $Pr$ ,  $S$  and  $\omega$ . The magnitude of the phase angle increase with  $Pr$ ,  $S$  and  $Gm$  and reduces with  $K$ ,  $Sc$ ,  $Kc$ ,  $Gr$  and  $\omega$ . From Table 2, it is to note that all the entries are positive. It is seen that Heat source parameter  $S$ , the Prandtl number  $Pr$  and the suction velocity increase amplitude and the rate of heat transfer (Nusselt number  $Nu$ ) at the surface of the plate. Reduce the phase angle and increase the amplitude and Nusselt number with increase the frequency of oscillations  $\omega$ . From Table 3 it is to note that all the entries are positive. It is observed that Schmidt number  $Sc$ , chemical reaction parameter  $Kc$  and the suction velocity increase amplitude and the rate of mass transfer at the surface of the plate. Increase the frequency of oscillations  $\omega$ , enhance the amplitude, the rate of mass transfer decrease the phase angle. Table 4 represents comparison of the results. Results are very good agreement with the results of Ashraf<sup>34</sup> when  $Sc=0$ .

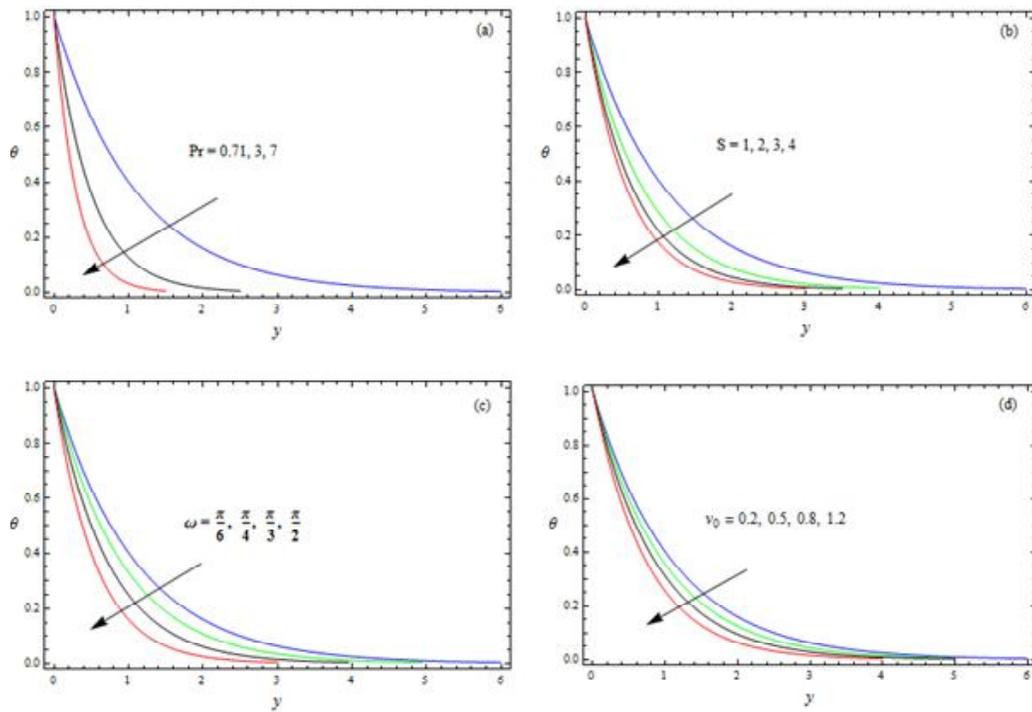


Fig 4(a-d): The temperature profiles against Pr, S,  $\omega$  and  $\nu_0$  with

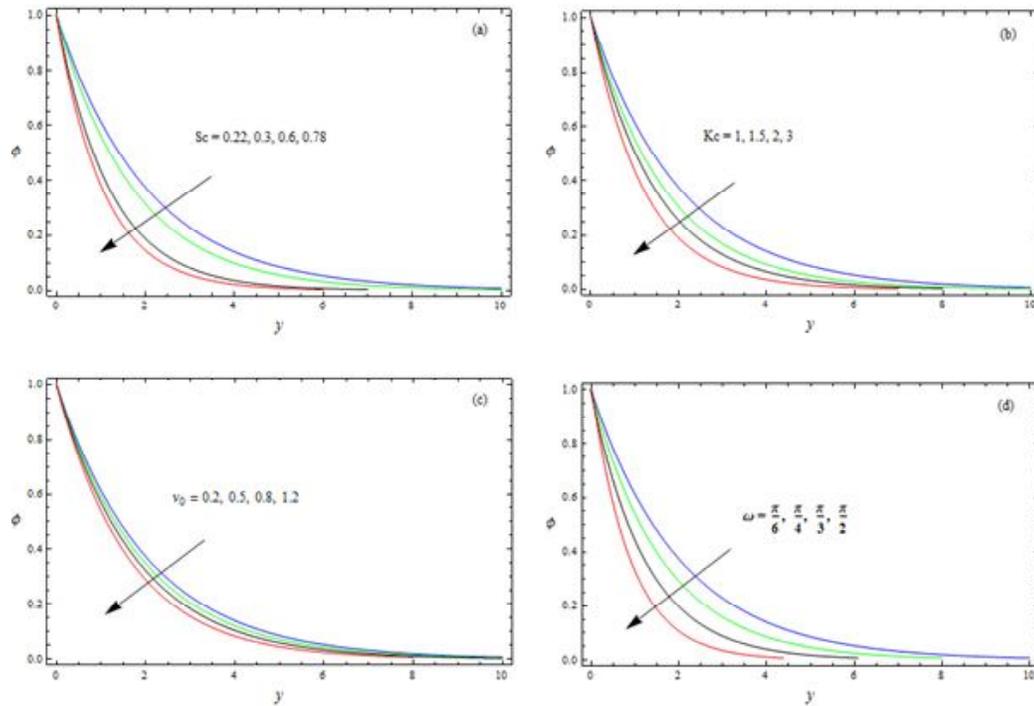


Fig 5(a-d): The Concentration profiles against Sc, Kc,  $\nu_0$  and  $\omega$  with  $\varepsilon = 0.001$ ,  $t = 0.2$

Table 1. Shear stresses with  $\varepsilon = 0.001$ ,  $t = 0.2$ 

M	K	Pr	Sc	Kc	S	Gr	Gn	$\nu_0$	$\omega$	Amplitude $ F_2 $	Phase Angle ( $\psi$ )	$\tau$
0.5	2	0.71	0.22	1	1	5	10	0.2	$\pi/6$	11.6485	-1.08662	9.91165
2	2	0.71	0.22	1	1	5	10	0.2	$\pi/6$	4.27658	-1.55299	3.45314
3	2	0.71	0.22	1	1	5	10	0.2	$\pi/6$	1.29628	-1.41396	0.97579
2	3	0.71	0.22	1	1	5	10	0.2	$\pi/6$	12.9525	-1.00391	10.8957
2	4	0.71	0.22	1	1	5	10	0.2	$\pi/6$	13.1681	-0.92668	11.5053
2	2	3	0.22	1	1	5	10	0.2	$\pi/6$	10.9926	-1.28004	8.71502
2	2	7	0.22	1	1	5	10	0.2	$\pi/6$	10.8139	-1.30829	8.13573
2	2	0.71	0.3	1	1	5	10	0.2	$\pi/6$	13.2281	-1.01306	9.40431
2	2	0.71	0.6	1	1	5	10	0.2	$\pi/6$	13.5472	-0.09769	8.21942
2	2	0.71	0.22	1.5	1	5	10	0.2	$\pi/6$	13.0636	-0.99636	9.30427
2	2	0.71	0.22	2	1	5	10	0.2	$\pi/6$	14.0976	-0.85477	8.86116
2	2	0.71	0.22	1	2	5	10	0.2	$\pi/6$	11.6012	-1.13883	9.61323
2	2	0.71	0.22	1	3	5	10	0.2	$\pi/6$	11.3064	-1.18272	9.40427
2	2	0.71	0.22	1	1	8	10	0.2	$\pi/6$	12.8687	-0.98211	11.6903
2	2	0.71	0.22	1	1	10	10	0.2	$\pi/6$	13.7484	-0.92315	12.8765
2	2	0.71	0.22	1	1	5	15	0.2	$\pi/6$	16.7650	-1.17909	13.8706
2	2	0.71	0.22	1	1	5	20	0.2	$\pi/6$	21.9576	-1.22812	17.8302
2	2	0.71	0.22	1	1	5	10	0.5	$\pi/6$	23.0389	-0.608754	10.3117
2	2	0.71	0.22	1	1	5	10	0.8	$\pi/6$	33.0972	-0.020482	10.5091
2	2	0.71	0.22	1	1	5	10	0.2	$\pi/4$	8.03813	-0.886265	9.91118
2	2	0.71	0.22	1	1	5	10	0.2	$\pi/3$	6.43892	-0.631840	9.91105
2	2	0.71	0.22	1	1	5	10	0.2	$\pi/2$	5.48819	-0.273832	9.91067

Table 2. Nusselt number (Nu) with  $\varepsilon = 0.001$ ,  $t = 0.2$ 

Pr	S	$\nu_0$	$\omega$	Amplitude $ F_4 $	Phase Angle $\gamma$	Nu
0.71	1	0.2	$\pi/6$	1.00365	1.39869	0.91666
3	1	0.2	$\pi/6$	2.20629	1.44928	2.05788
7	1	0.2	$\pi/6$	3.60564	1.47239	3.43676
0.71	2	0.2	$\pi/6$	1.31588	1.48355	1.26473
0.71	3	0.2	$\pi/6$	1.56988	1.51423	1.53210
0.71	1	0.5	$\pi/6$	1.10256	1.46078	1.03861
0.71	1	0.8	$\pi/6$	1.21656	1.48335	1.17317
0.71	1	0.2	$\pi/4$	1.06122	1.31218	0.91670
0.71	1	0.2	$\pi/3$	1.12272	1.24229	0.91673

#### 4. Conclusions

The unsteady free convective flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate under the influence of uniform transverse magnetic field with time dependent permeability and oscillatory suction. has been discussed. The conclusions are made as the following.

1. The velocity reduces with increasing the intensity of the magnetic field or Prandtl number  $Pr$  or Heat source parameter  $S$ .
2. The velocity enhance with increasing thermal Grashof number  $Gr$  or mass Grashof number.
3. The resultant velocity enhances with increasing the permeability parameter  $K$  throughout the fluid region. Lower the permeability of the porous medium lesser the fluid speed in the entire region.
4. The reversal behaviour is observed with increasing Schmidt number  $Sc$ , chemical reaction parameter  $Kc$ , suction parameter  $v_0$  or the frequency of oscillation  $\omega$ .
5. The magnitude of the temperature of the flow field diminishes as the Prandtl number, Heat source parameter  $S$  or suction parameter  $v_0$  or the frequency of oscillation.
6. The concentration reduces at all points of the flow field with the increase in the Schmidt number  $Sc$ , chemical reaction parameter  $Kc$ , suction parameter  $v_0$  and presence of the frequency of oscillation  $\omega$ .
7. The skin friction increases with the increase in  $K$ ,  $Gr$ ,  $Gm$  and  $v_0$  and decreases with the increase in  $M$ ,  $Pr$ ,  $Sc$ ,  $Kc$ ,  $S$  and  $\omega$ .
8. Nusselt number ( $Nu$ ) at the surface of the plate and amplitude increase with increase  $S$ ,  $Pr$  and  $v_0$ . Also enhance the amplitude, the rate of heat transfer decrease the phase angle with increase the frequency of oscillations  $\omega$ .
9. Schmidt number  $Sc$ , chemical reaction parameter  $Kc$ , the frequency of oscillations  $\omega$  and suction parameter  $v_0$  increase the amplitude, the phase angle the rate of mass transfer at the surface of the plate.
10. Increase the frequency of oscillations  $\omega$ , enhance the amplitude, the rate of mass transfer decrease the phase angle.

Table3. Sherwood number ( $Sh$ ) with  $\varepsilon = 0.001$ ,  $t = 0.2$

$Sc$	$Kc$	$v_0$	$\omega$	Amplitude $ F_6 $	Phase Angle ( $\zeta$ )	$Sh$
0.22	1	0.2	$\pi / 6$	0.536249	1.365880	0.491611
0.3	1	0.2	$\pi / 6$	0.632410	1.373015	0.578602
0.6	1	0.2	$\pi / 6$	0.916662	1.393062	0.836984
0.22	1.5	0.2	$\pi / 6$	0.629483	1.429490	0.596922
0.22	2	0.2	$\pi / 6$	0.712364	1.464392	0.685691
0.22	1	0.5	$\pi / 6$	0.574058	1.422405	0.527289
0.22	1	0.8	$\pi / 6$	0.603609	1.454160	0.565233
0.22	1	0.2	$\pi / 4$	0.566008	1.276890	0.491634
0.22	1	0.2	$\pi / 3$	0.599008	1.206869	0.491650

Table 4. Comparison of Results

Sc	$v_0$	$\omega$	Sh	
			Ashraf <i>et al.</i> <sup>34</sup>	Present work [Kc=0]
0.22	0.2	$\pi / 6$	0.045262	0.044020
0.3	0.2	$\pi / 6$	0.061854	0.060238
0.6	0.2	$\pi / 6$	0.120552	0.120325
0.22	0.5	$\pi / 6$	0.115245	0.110179
0.22	0.8	$\pi / 6$	0.176334	0.176133
0.22	0.2	$\pi / 4$	0.046625	0.044236
0.22	0.2	$\pi / 3$	0.046246	0.044253

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