Magnetohydrodynamic Convective Periodic Flow through a Porous Medium in an Inclined Channel with Thermal Radiation and Chemical Reaction

Achogo, Wisdom Hezekiah[1], Okereke, Ifeoma Chikamma[2], Ofomata, Amarachukwu I.O[2], Amadi Onyebuchi Felicia[1]
[1]Department of Mathematics/Statistics, Ignatius Ajuru University of education, P.M.B 5047 Rumuolumeni, Nigeria
[2]Department of Mathematics/Statistics, Federal Polytechnic Nekede, P.M.B 1036 Owerri, Nigeria

Abstract:- The theoretical examination of the effects of velocity, temperature, concentration parameter variations and magnetic fields on convective periodic flow was studied on an electrically conducting, viscous and incompressible fluid through a porous medium in an inclined plane. A set of coupled ordinary differential equations arising from the formulation of the problem were solved analytically by method of undetermined coefficient. The solution to the problem is obtained thereafter and with realistic parameter values the results were displayed in plots. The effects of parameter variations on velocity, concentration and temperature fields were discussed with the help of the plots. From the plots, the following results have been drawn; it is observed that increase in the Prandtl number decreases the temperature, increase in the Reynolds number decreases the temperature of the fluid, Reynolds number decreases the concentration of the fluid, increase in the Schmidt number decreases the concentration making it more significant at the centre of the flow region, increase in permeability leads to increase in the velocity and increase in the magnetic field leads to decrease in the velocity.

Keywords:- *Natural Convection, Magnetohy Drodynamic, Porous Medium, Inclined Channel, Thermal Radiation.*

I. INTRODUCTION

Porous medium is a medium that has interconnected pores where fluids can flow through. It is useful in the sense that it can be used in effective protection of some structural components of turbojet and rocket engines such as combustion chamber walls, exhaust nozzles or gas turbine blades from hot gases. Eckert and Drake(1958) and Jain and Bansal(1973) described heat transfer reduction of coutte flow of incompressible fluid injected into the flow field from a plate that is stationary vis a vis the removal of heat from a plat that is moving. It has a two dimensional issue in capsulated by uniform injection and suction applied at the porous plate. Gersten and Gross(1974) verified heat transfer along a plane wall with periodic suction velocity.

MHD meaning magneto hydrodynamic fluid is a fluid that conducts electricity in electric and magnetic fields. It incorporates fluid dynamics and electromagnetic assertions to describe concurrent effects of magnetic field on the flow and vice versa. Its concern is on gases that are ionized and liquids that are electrically conducting. Varieties of papers have evolved over the years on this concept. Take for instance; Singh and Mathew(2008) studied the effects that injection/suction has on oscillating hydrodynamic magnetic flow in a horizontal channel that is rotating. Attia and Kotb(1996) examined magneto hydrodynamic flow between parallel plates having heat transfer. Swapna et al.(2017) studied mass transfer on mixed convective periodic flow through porous medium in an inclined channel.

The concept of natural convective heat transfer occurs owing to difference in temperature in an enclosure or near a heated or cooled flat plate. Much attention has been given to natural convection on horizontal and vertical channel but a few attention has been given to inclined plates despite the frequent occurrence of this geometric configuration in engineering and natural environment. Amongst the few researchers that made research on inclined surface are Ganesan and Palani(2003) and Sparrow and Husar(1969) who studied natural convection on inclined plate. Said et al.(2005) investigated turbulent natural convection between inclined isothermal plates. Chen(2004) studied natural convection flow over an inclined surface that is permeable having variable wall temperature and concentration. Hossain et al.(1996) examined the free convection from evolving from inclined at small angle to the plate that is isothermal. The numerical solution of free convection flow past an inclined surface was studied by Anghel et al.(2001). Exact solution analysis of radiative convective flow of heat and mass transfer over inclined plate in a porous medium was examined Bhuvaneswari et al.(2010) deduced MHD flow, heat and mass transfer on an inclined stretching sheet having thermal radiation and hall effect that is permeable.

The study of thermal radiation in channels of different geometries has received attention from researchers owing to its significance in free convection which is useful in the heating of rooms and buildings by the use of radiators. Ahmed and Sarmah(2009) studied thermal radiation effect on a transient MHD flow with mass transfer past an impulsively fixed vertical plate. Alabraba et al.(1992) examined free convection interaction with thermal radiation in a hydrodynamic boundary layer taking into account the binary chemical reaction and the less attended Soret and Dufour effects. Alagoa et al.(1998) looked into the radiative and free convective effects of a MHD flow through a porous medium between infinite parallel plates with time-dependent suction. Bestman, A. R.(2005) studied free convection heat transfer to steady radiating non - Newtonian MHD flow past a vertical porous plate. Cess, R. D.(1966) studied the interaction of thermal radiation with free convection heat transfer. Ghosh et al.(2010) investigated the thermal radiation effects on unsteady hydromagnetic gas flow along an inclined plane with indirect natural convection. Israel Cookey et al.(2010) studied MHD oscillatory Coutte flow of a radiating viscous fluid in a porous medium with periodic wall temperature. Sharma et al.(2014) studied radiative and free convective effects on MHD flow through a porous medium with periodic wall temperature and heat generation or absorption.

The aim of this paper is to examine the magnetohydrodynamic convective periodic flow through a porous medium in an inclined channel with thermal radiation and chemical reaction.

II. FORMULATION OF THE PROBLEM.

We consider the periodic flow of an electrically conducting, viscous and incompressible fluid through an inclined medium. The two plates are at a distance d apart. The coordinate system is chosen such that x – axis lies along the centerline and the y – axis along the magnetic field. The fluid is injected through the lower stationary porous plate and sucked through the upper porous plate in oscillatory motion in its own plane. The injection and suction velocity is V'. The magnetic field is applied perpendicular to the parallel plates. The temperature difference of the plates is assumed high enough to induce radiation. All the physical parameters are independent of x for this problem of fully developed flows that is laminar. The flow is governed by the following equations:

$$\frac{\partial V'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y^{I}} = -\frac{1}{\rho}\frac{\partial P'}{\partial x'} + \vartheta\frac{\partial^2 u'}{\partial y'^2} - \frac{\vartheta}{K'}u' - \frac{\sigma B_0^2}{\rho}u' + g B_T T'\sin\propto + g B_C C'\sin\propto \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p}\frac{\partial q'}{\partial y'} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - K_r' C' \tag{4}$$

The boundary conditions expedient to this problem are

$$u' = 0,\ v' = V, T' = 0, C' = 0 \text{ at } y = -\frac{d}{2} \tag{5}$$

$$u' = U\cos\omega' t',\ v^{I} = V,\ T' = T_0\cos\omega' t',\ C' = C_0\cos\omega' t' \text{ at } y = \frac{d}{2} \tag{6}$$

where $u'(y', t')$ axial velocity, t' is the time, ν' is the kinematic viscosity, σ is electrical conductivity, k is the thermal conductivity, C_p is the specific heat at constant pressure, ρ is the fluid density, ω is the frequency of oscillation, T' is the temperature of the fluid, C' is the concentration of the fluid, B_0 is the magnetic field, T_0 and C_0 are reference temperature and concentration respectively, D is mass diffusivity, P' is the pressure, V is the oscillating velocity, g is the acceleration due to gravity, K_r' is the chemical reaction term, q' is the radiation flux, K' is the permeability of the porous medium, B_T and B_C are coefficient of thermal and concentration constant.

We assumed that the fluid is optically thin having a relatively low density. Hence the heat flux according to Cogley et al.(1968) is expressed as;

$$\frac{\partial q'}{\partial y'} = 4\alpha^2 T' \tag{7}$$

where α is the mean absorption coefficient.

Going by the internal flow of the oscillation in the channel; the pressure gradient variations is assumed as

$$-\frac{1}{\rho}\frac{\partial p'}{\partial x'} = P\cos\omega' t' \tag{8}$$

Substituting equation (7) into equation (3); we get

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{4\alpha^2}{\rho C_p}T'$$

Equation (1) integrates to v' = V on the assumption that there is constant injection and suction velocity V at the upper and lower plates.

Introducing the following dimensionless variables:

$x = \frac{x'}{d}$, $y = \frac{y'}{d}$, $u = \frac{u'}{U}$, $T = \frac{T'}{T_0}$, $v' = V$, $C = \frac{C'}{C_0}$, $Sc = \frac{\vartheta}{D}$, $P = \frac{P'}{\rho U V}$, $\omega = \frac{\omega' d^2}{\vartheta}$, $t = \omega' t'$, $Re = \frac{Vd}{\vartheta}$,

$P_r = \frac{\mu C_p}{K\vartheta} = \frac{\rho C_p}{K}$, K = $\frac{K'}{d^2}$, Gr = $\frac{gB_T d^2 T_0}{\vartheta V}$, M = $B_0 d\sqrt{\frac{\sigma}{\mu}}$, Gm = $\frac{gB_c d^2 C_0}{\vartheta V}$, N = $2\propto \frac{d}{\sqrt{K}}$, $K_r = \frac{K_r' d^2}{\vartheta}$,
$\rho = \frac{\mu}{v}$ (10) into equations (2), (4)

and (9), we obtain

$$\frac{\omega}{Re}\frac{\partial u}{\partial y} + \frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{1}{Re}\frac{\partial^2 u}{\partial y^2} - \frac{M^2}{Re}u - \frac{1}{kRe}u + \frac{Gr}{Re}\sin\propto T + \frac{Gm}{Re}\sin\propto C \quad (11)$$

$$\frac{\omega}{Re}\frac{\partial T}{\partial t} + \frac{\partial T}{\partial y} = \frac{1}{RePr}\frac{\partial^2 T}{\partial y^2} - \frac{N^2}{RePr}T \quad (12)$$

$$\frac{\omega}{Re}\frac{\partial C}{\partial t} + \frac{\partial C}{\partial y} = \frac{1}{ScRe}\frac{\partial^2 C}{\partial y^2} - \frac{K_r}{Re}C \quad (13)$$

Where u is the dimensionless velocity, y is the dimensionless co-ordinate axis normal to the plates, t is the dimensionless time, T is the dimensionless temperature, C is the dimensionless concentration, Gr is the thermal Grashof number, Gm is the concentration Grashof number, Pr is the Prandt number, M is the magnetic parameter, Sc is the Schmidt number, K porosity and Kr chemical reaction.

The corresponding boundary conditions are non - dimensioned to;

u = 0, T = 0, C = 0 at y = $-\frac{1}{2}$

u = 1, T = I, C = 1 at y = $\frac{1}{2}$ (14)

III. METHOD OF SOLUTION

Equations (10) – (13) are second order coupled partial differential equations, we therefore assumed the solution of the form;

$$u(y) = u_0(y)e^{it} \quad (15)$$

$$T(y,t) = \theta_0(y)e^{it} \quad (16)$$

$$C(y,t) = \varphi_0(y)e^{it} \quad (17)$$

$$-\frac{\partial P}{\partial x} = Pe^{it} \quad (18)$$

Applying (14 –17) into the relevant equations in (10 - 13), we obtain

$$\frac{d^2u_0}{dy^2} - Re\frac{du_0}{dy} - (M^2 + \frac{I}{K} + i\omega)u_0 = -ReP - Gr\sin\propto \theta_0 - Gm\sin\propto \varphi_0 \quad (19)$$

$$\frac{d^2\theta_0}{dy^2} - ReP_r\frac{d\theta_0}{dy} - (N^2 + i\omega Pr)\theta_0 = 0 \quad (20)$$

$$\frac{d^2\varphi_0}{dy^2} - ReS_c\frac{d\varphi_0}{dy} - (ReScK_r + i\omega S_c)\varphi_0 = 0 \quad (21)$$

Subject to:

$u_0 = \theta_0 = \varphi_0 = 0$ at y = $-\frac{1}{2}$

$u_0 = \theta_0 = \varphi_0 = 1$ at y = $\frac{1}{2}$ (22)

Equations (18) – (20) are ordinary second order coupled differential equations and solved under the boundary conditions (21) through a straight forward analytical method, we obtain u(y), $\theta_0(y)$ and $\varphi_0(y)$ as

$$u_0 = -\frac{1}{\left(1-e^{-\frac{\propto_5}{2}}\right)e^{\frac{\propto_6}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}e^{\frac{-\propto_6}{2}} + D_{12}\right]e^{\frac{\propto_5 y}{2}} + \frac{1}{\left(1-e^{-\frac{\propto_5}{2}}\right)e^{\frac{\propto_6}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}\right]e^{\frac{\propto_6 y}{2}} + D_7 + D_8e^{\propto_1 y - \frac{\propto_2}{2}} - D_9e^{\propto_2 y - \frac{\propto_1}{2}} + D_{10}e^{\propto_3 y - \frac{\propto_4}{2}} - D_{11}e^{\propto_4 y - \frac{\propto_3}{2}} \quad (23)$$

$$\theta_0 = \frac{e^{\propto_2 y - \frac{\propto_1}{2}} - e^{\propto_1 y - \frac{\propto_2}{2}}}{e^{\frac{\propto_2 - \propto_1}{2}} - e^{\frac{\propto_1 - \propto_2}{2}}} \quad (24)$$

$$\varphi_0 = \frac{e^{\propto_4 y - \frac{\propto_3}{2}} - e^{\propto_3 y - \frac{\propto_4}{2}}}{e^{\frac{\propto_4 - \propto_3}{2}} - e^{\frac{\propto_3 - \propto_4}{2}}} \quad (25)$$

The final expressions of u(y,t), T(y,t) and C(y,t) are given by

$$U(y,t) = \Bigg(-\frac{1}{\left(1-e^{-\frac{\propto_5}{2}}\right)e^{\frac{\propto_6}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}e^{\frac{-\propto_6}{2}} + D_{12}\right]e^{\frac{\propto_5 y}{2}} + \frac{1}{\left(1-e^{-\frac{\propto_5}{2}}\right)e^{\frac{\propto_6}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}\right]e^{\frac{\propto_6 y}{2}} + D_7 + D_8e^{\propto_1 y - \frac{\propto_2}{2}} - D_9e^{\propto_2 y - \frac{\propto_1}{2}} + D_{10}e^{\propto_3 y - \frac{\propto_4}{2}} - D_{11}e^{\propto_4 y - \frac{\propto_3}{2}}\Bigg)e^{it} \quad (26)$$

$$T(y,t) = \left[\frac{e^{\propto_2 y - \frac{\propto_1}{2}} - e^{\propto_1 y - \frac{\propto_2}{2}}}{e^{\frac{\propto_2 - \propto_1}{2}} - e^{\frac{\propto_1 - \propto_2}{2}}}\right]e^{it} \quad (27)$$

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$$C(y,t) = \left[\frac{e^{\propto_4 y-\frac{\propto_3}{2}} - e^{\propto_3 y-\frac{\propto_4}{2}}}{e^{\frac{\propto_4-\propto_3}{2}} - e^{\frac{\propto_3-\propto_4}{2}}}\right] e^{it} \quad (28)$$

The values for D1 to D12 are given and clearly stated in the appendix.

The physical point of expression for the shear stress, Nusselt number and the Sherwood number on the walls are given below

$$\tau = \left(\frac{\partial u_0}{\partial y}\right)_{y=0} \quad (29)$$

$$Nu = -\left(\frac{\partial \theta_0}{\partial y}\right)_{y=0} \quad (30)$$

$$Sh = -\left(\frac{\partial \varphi_0}{\partial y}\right)_{y=0} \quad (31)$$

IV. RESULTS AND DISCUSSION

The effect of the Prandtl number on the temperature is shown in figure 1. It is observed that increase in the Prandtl number decreases the temperature. This is possible physically because increasing the Prandtl number decreases the thermal conductivity of the fluid. Figure 2 shows the effect of the Reynolds number on the temperature, where it is shown that increase in the Reynolds number decreases the temperature of the fluid. The effect is more pronounced at the centre of the flow region. This is because the viscous forces exerts more influence on the inertial forces at the centre such that heat transfer performance is reduced. The influence of radiation on the temperature is indicated in figure 3. Increase in the radiation parameter has the tendency of reducing the temperature. Physically, radiating heat at higher values results in cooling the fluid. The effect of the frequency of oscillation on temperature is shown in figure 4, wherein it is observed that as the frequency of oscillation increases, the temperature reduces. Figure 5 shows the effect of the Reynolds number on the concentration profile. It can be seen clearly that the Reynolds number decreases the concentration of the fluid.

Figure 6 indicates the effect of the Schmidt number on the concentration of the fluid. The plot reveals that increase in the Schmidt number decreases the concentration making it more significant at the centre of the flow region. The influence of the Reynolds number on the skin friction is shown in figure 7. There is no significant change in the skin friction for the values of Reynolds number considered even if the radiation parameter is increased. A slight decrease is noted in the skin friction as the Schmidt number and radiation parameter are simultaneously increased as shown in figure 8. Figure 9 shows that the skin friction is reduced as the Schmidt number and the Reynolds number are increased simultaneously. The heat transfer effect is shown in figure 10. The heat transfer rate increases as a result of increase in radiation and Reynolds parameter. The effect of the Reynolds number on the mass transfer rate is shown in figure 11. It is noted that there is no significant change in the mass transfer rate for simultaneous increases in the value of the Reynolds number and radiation parameters. The effect of the permeability of the medium is shown in figure 12. It is observed that increase in permeability leads to increase in the velocity. This is true because permeability is a property of the porous medium and its increase shows the ability of the formation to transmit more fluid. Figure 13 shows the effect of the magnetic field on the velocity. The profile reveals that increase in the magnetic field leads to decrease in the velocity. This is as a result of the Lorentz force in the magnetic field. The influence of thermal radiation in the velocity is depicted in figure 14. Take notice that increase in the thermal radiation decrease the velocity. This is because increase in the thermal radiation leads to decrease in the momentum boundary layer. Figure 15 shows the effect of the Grashoff number on the velocity. It is observed that increase in the Grashoff number increases the velocity of the fluid. Physically, this is possible because thermal buoyancy increases the boundary layer which leads to increase in velocity.

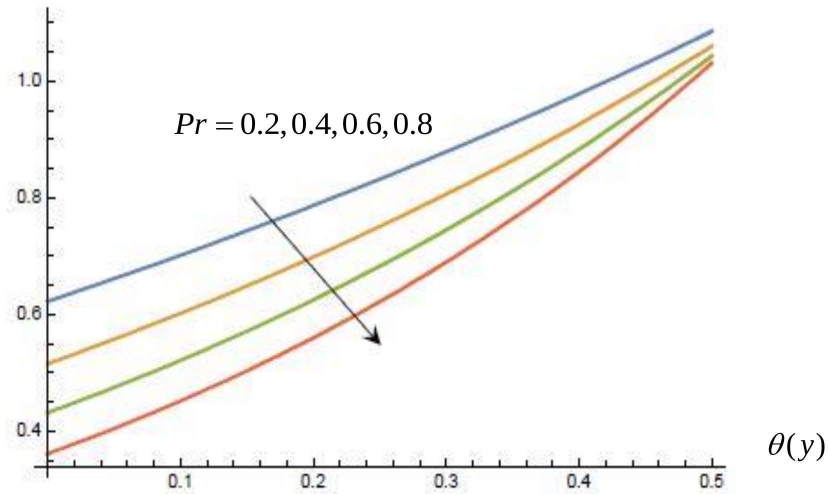

Fig 1:- Effect of Prandtl number on temperature for $\omega = 1, t = 0, Re = 0.5, N = 0.5$

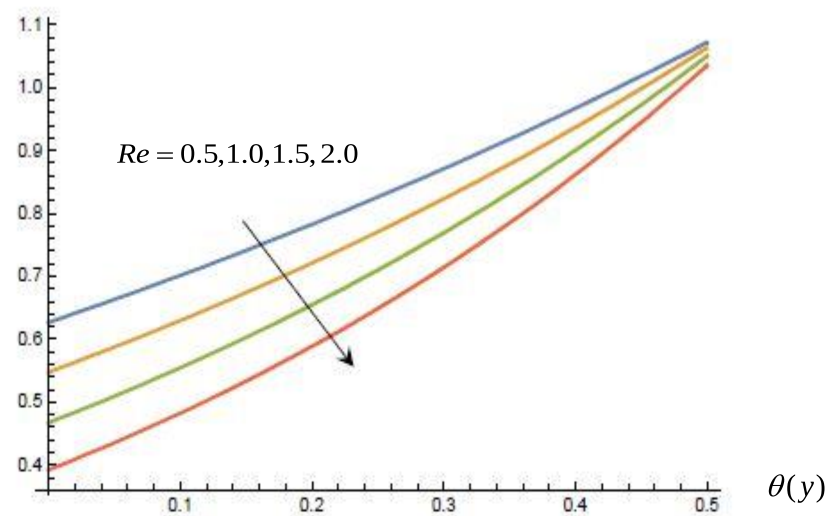

Fig 2:- Effect of Reynolds number on temperature for $\omega = 1, t = 0, Pr = 0.71, N = 0.5$

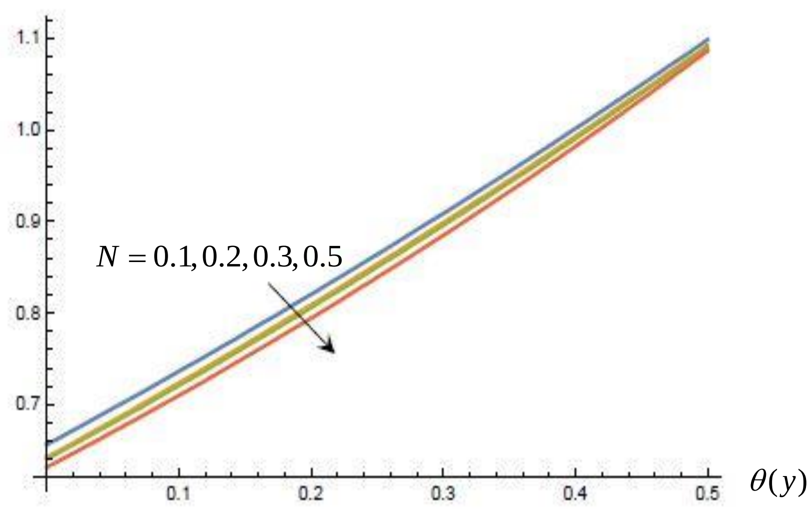

Fig 3:- Effect of Radiation parameter on temperature for $\omega = 1, Pr = 0.71, t = 0, Re = 0.5$

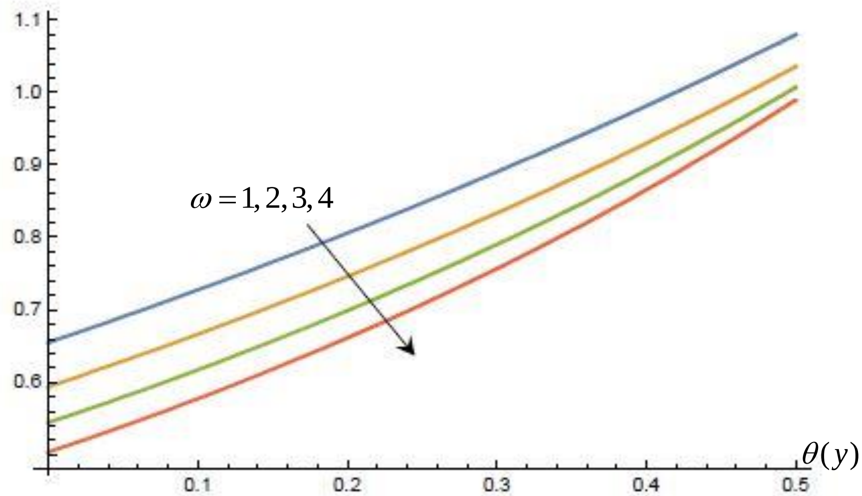

Fig 4:- Effect of frequency of oscillatory on temperature for $Re = 0.5, t = 0, Pr = 0.71, N = 0.5$

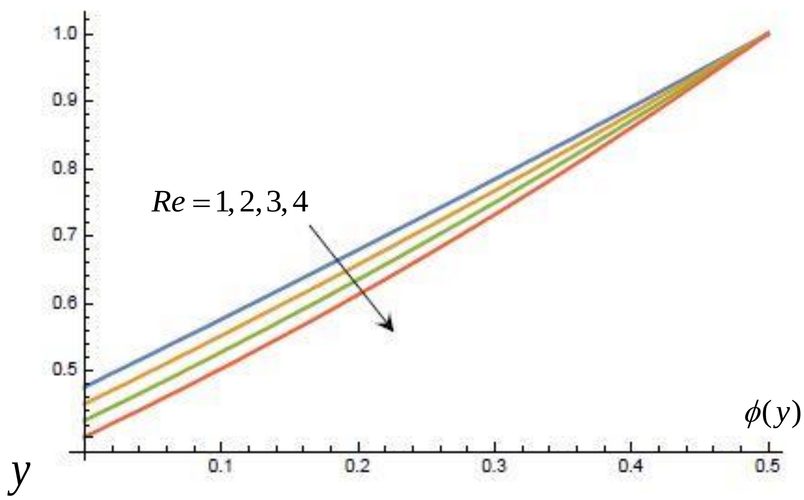

Fig 5:- Effect of Reynolds number on concentration for $\omega = 0.5, t = 0, Sc = 0.2$

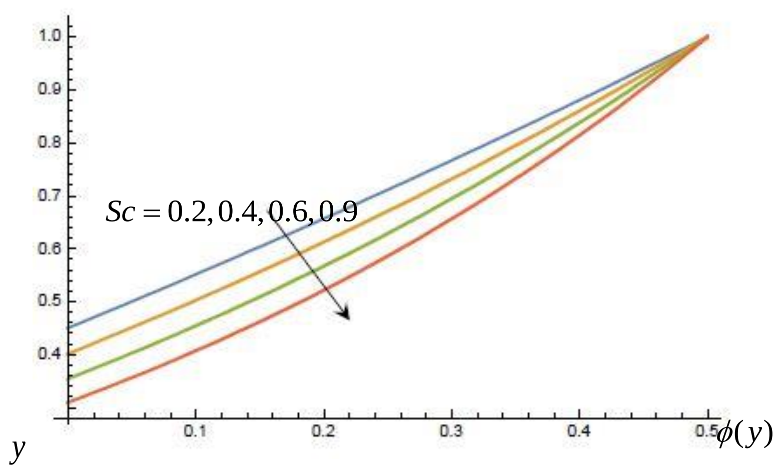

Fig 6:- Effect of Schmidt number on concentration for $\omega = 0.5, t = 0, Re = 0.5$

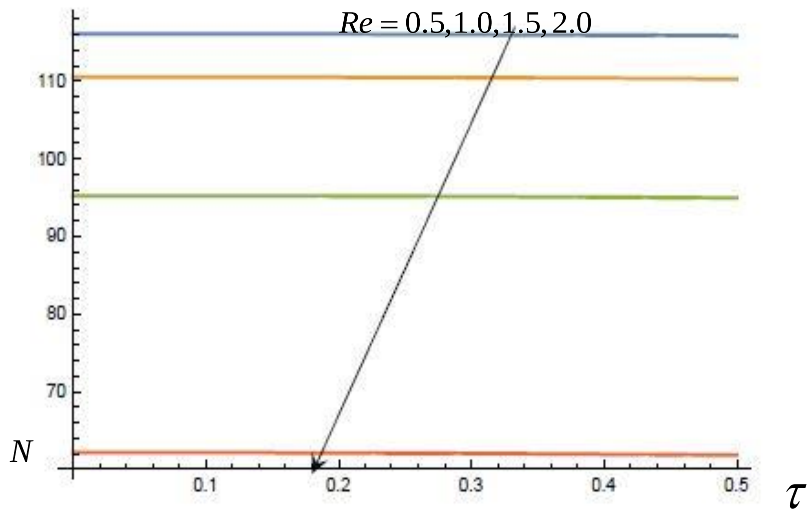

Fig 7:- Effect of Reynolds number on the skin friction for $\omega = 0.5, t = 0, Sc = 0.2, Pr = 0.71$

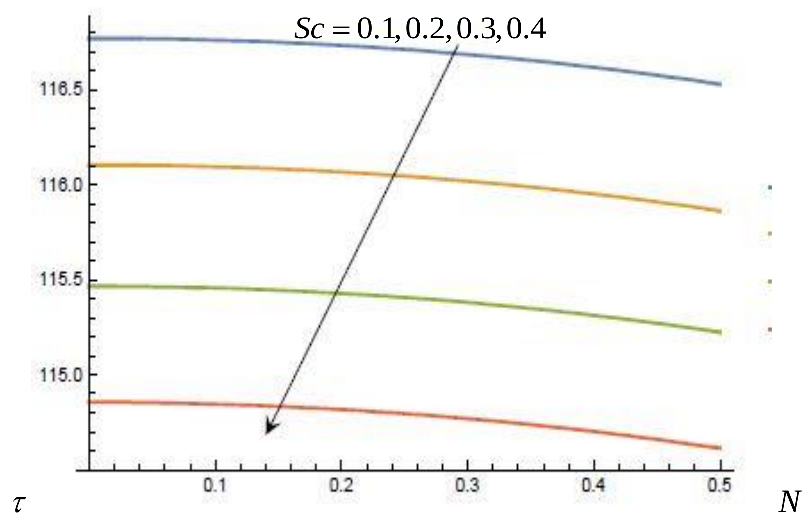

Fig 8:- Effect of Scmidt number on the skin friction for $\omega = 0.5, t = 0, Re = 0.5, Pr = 0.71$

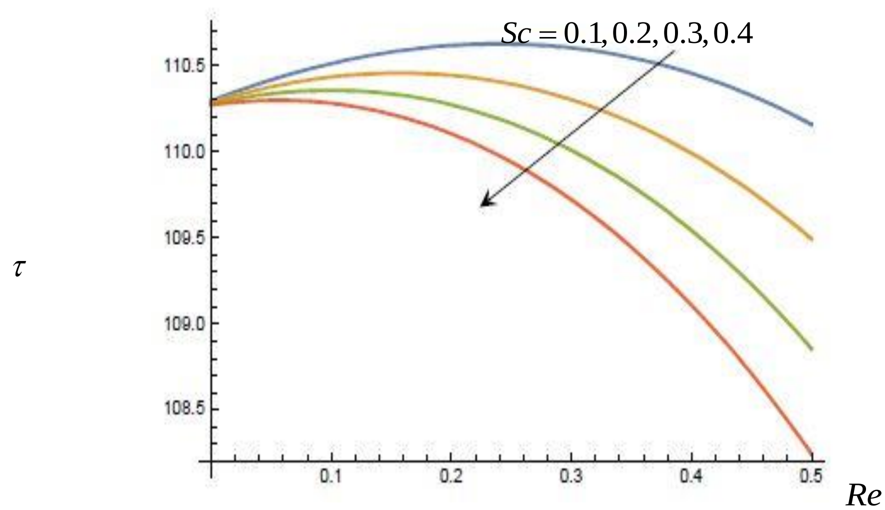

Fig 9:- Effect of Schmidt number on the skin friction for $\omega = 0.5, t = 0, Re = 0.5, Pr = 0.71$

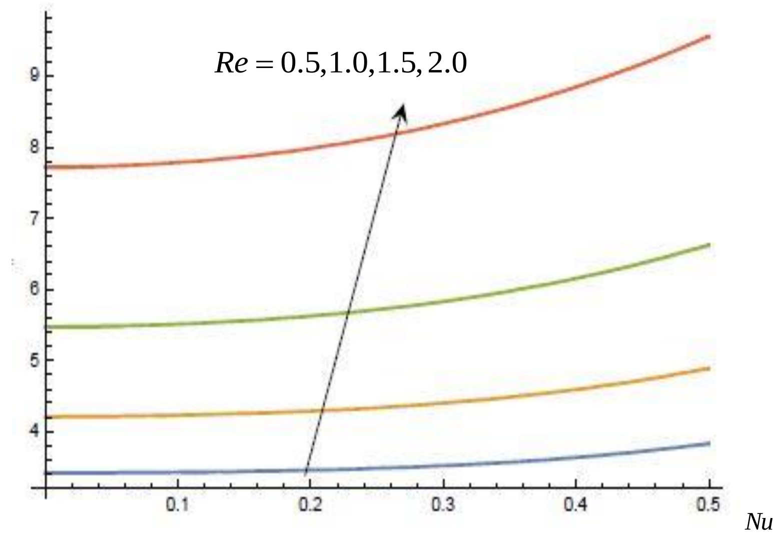

Fig 10:- Effect of Reynolds number on heat transfer for $t = 0, Pr = 0.71, \omega = 0.5$

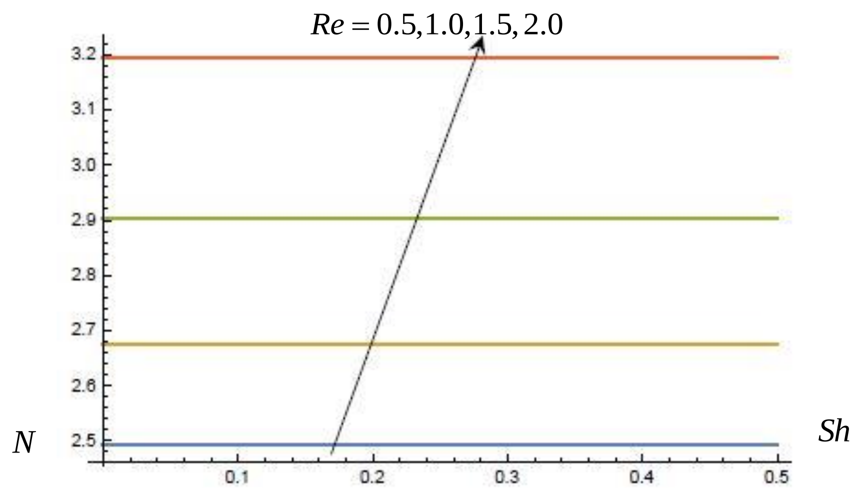

Fig 11:- Effect of Reynolds number on mass transfer for $\omega = 0.5, t = 0, Sc = 0.2$

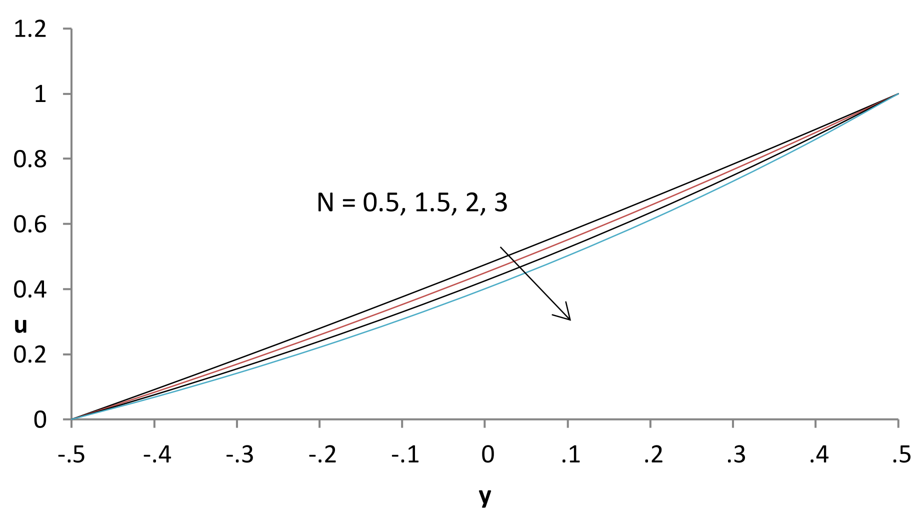

Fig 12:- Effect of thermal radiation on the velocity for $Re = 1, Pr = 0.71, M = 0.5, Gr = 5, Gm = 5, Sc = 0.5, K = 0.1, t = 0, P = 1, \alpha = 45, \omega = 1$

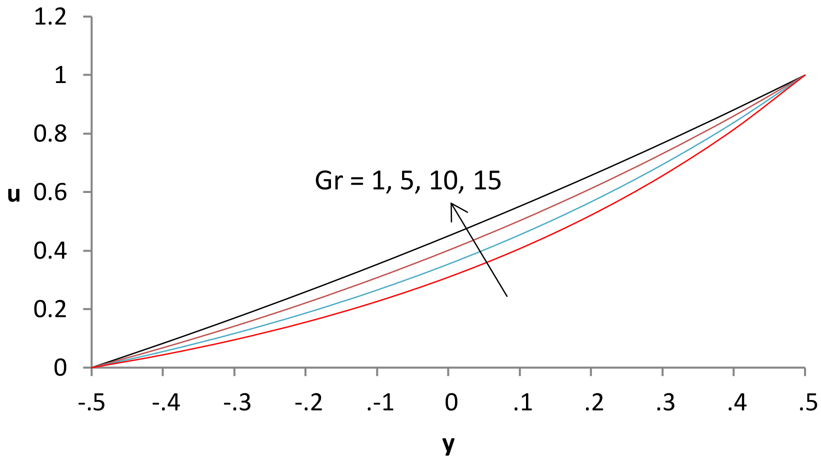

Fig 13:- Effect of Grashof number on the velocity for $Re = 1, Pr = 0.71, N = 0.5,\ M = 0.5, Gm = 5, Sc = 0.5, K = 0.1, t = 0, P = 1, \alpha = 45, \omega = 1$

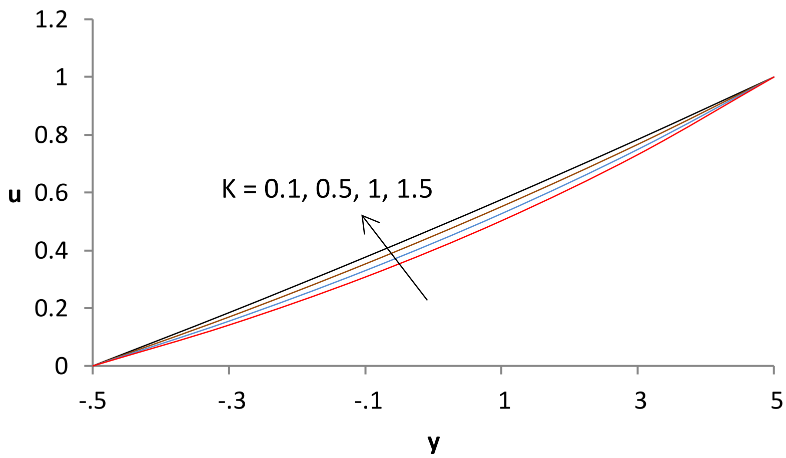

Fig 14:- Effect of permeability on the velocity for $Re = 1, Pr = 0.71, N = 0.5, Gr = 5, Gm = 5, Sc = 0.5, M = 0.5, t = 0, P = 1, \alpha = 45, \omega = 1$

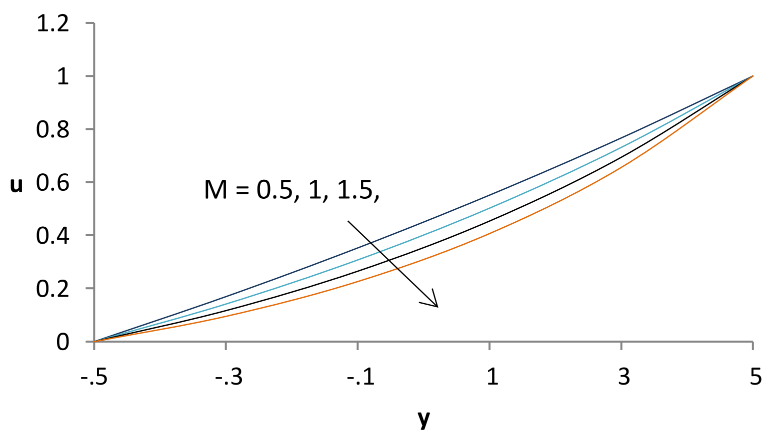

Figure15: Effect of magnetic field on the velocity for $Re = 1, Pr = 0.71, N = 0.5, Gr = 5, Gm = 5, Sc = 0.5, K = 0.1, t = 0, P = 1, \alpha = 45, \omega = 1$

V. CONCLUSIONS

In this paper, we have analyzed the MHD convective periodic flow through a porous medium in an inclined channel with thermal radiation and chemical reaction. The governing equations are solved analytically. The solutions for velocity, temperature and concentration fields are obtained in terms of exponential and complimentary functions. From this investigation, the following observations have been drawn.

1. It is observed that increase in the Prandtl number decreases the temperature.
2. It can be seen clearly that the Reynolds number decreases the concentration of the fluid.
3. The heat transfer rate increases as a result of increase in radiation and Reynolds parameter.
4. It is observed that increase in permeability leads to increase in the velocity.
5. It is noted that increase in the magnetic field leads to decrease in the velocity.
6. It is observed that increase in the Grashoff number increases the velocity of the fluid.

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APPENDIX

$$D_7 = \frac{ReP}{A_1},\ D_8 = \frac{G_r sin\propto A_1}{\propto_1^2 - Re\propto_1 - A1},\ D_9 = \frac{G_r sin\propto A_2}{\propto_2^2 - Re\propto_2 - A1},\ D_{10} = \frac{Gm sin\propto A_3}{\propto_3^2 - Re\propto_3 - A1},\ D_{11} = \frac{Gm sin\propto A_3}{\propto_4^2 - Re\propto_4 - A1}$$

$$D_5 = -\frac{1}{e^{\frac{\propto_6}{2}} - e^{\frac{-\propto_6}{2}.\frac{\propto_5}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}e^{\frac{-\propto_6}{2}} - D_{12}\right],\ D_6 = -\frac{1}{e^{\frac{\propto_6}{2}} - e^{\frac{-\propto_6}{2}.\frac{\propto_5}{2}}}\left[1 + D_{12}e^{\frac{\propto_5}{2}} - D_{12}\right]$$

$$D_{12} = D_{11}e^{\frac{-(\propto_4+\propto_3)}{2}} - D_8 e^{\frac{-(\propto_1+\propto_2)}{2}} + D_9 e^{\frac{-(\propto_2+\propto_1)}{2}} - D_{10}e^{\frac{-(\propto_3+\propto_4)}{2}},\ \propto_1 = \frac{RePr + \sqrt{Re^2Pr^2 + 4(N^2 + i\omega P_r)}}{2},$$

$$\propto_2 = \frac{RePr - \sqrt{Re^2Pr^2 + 4(N^2 + i\omega P_r)}}{2},\ D_1 = \frac{-e^{-\frac{\propto_2}{2}}}{e^{\frac{\propto_2-\propto_1}{2}} - e^{\frac{\propto_1-\propto_2}{2}}},\ D_2 = \frac{e^{-\frac{\propto_1}{2}}}{e^{\frac{\propto_2-\propto_1}{2}} - e^{\frac{\propto_1-\propto_2}{2}}}$$

$$\propto_3 = \frac{ReSc + \sqrt{Re^2Sc^2 + 4(R_eS_cK_r + i\omega S_c)}}{2}$$

$$\propto_4 = \frac{R_eS_c - \sqrt{Re^2Sc^2 + 4(R_eS_cK_r + i\omega S_c)}}{2} D_3 = \frac{-e^{-\frac{\propto_4}{2}}}{e^{\frac{\propto_4-\propto_3}{2}} - e^{\frac{\propto_3-\propto_4}{2}}},\ D_4 = \frac{e^{-\frac{\propto_3}{2}}}{e^{\frac{\propto_4-\propto_3}{2}} - e^{\frac{\propto_3-\propto_4}{2}}},\ A_1 = M^2 + \frac{I}{K} + i\omega$$

$$\propto_5 = \frac{Re + \sqrt{Re^2 + 4A_1}}{2},\ \propto_6 = \frac{Re - \sqrt{Re^2 + 4A_1}}{2},\ A_2 = \frac{1}{e^{\frac{\propto_2-\propto_1}{2}} - e^{\frac{\propto_1-\propto_2}{2}}},\ A_3 = \frac{1}{e^{\frac{\propto_4-\propto_3}{2}} - e^{\frac{\propto_3-\propto_4}{2}}}$$