Radiation and Mass Transfer Effects on MHD Oscillatory Memory Flow in a Channel Filled with Porous Medium in the Presence of Chemical Reaction

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Abstract — *The interaction of radiation and mass transfer in an electrically conducting memory fluid (Walter's liquid-B) through a channel filled with porous medium is studied. An attempt is made to find the combined effects of a transverse magnetic field and radiation on an unsteady mass transfer flow with chemical reaction through a channel filled with saturated porous medium and non-uniform wall temperature. The equations of continuity, linear momentum, energy and diffusion, which govern the flow field, are solved by using an analytical method. The behavior of the velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number has been discussed for variations in the governing parameters.*

Keywords — *Heat and mass transfer; Radiation; MHD; Porous medium; Chemical reaction, Walter's liquid-B.*

I. INTRODUCTION

This study deals with the convective heat and mass transfer from a solid body with different geometries embedded in a porous medium with saturated fluid. This problem is observed in many fields of science and engineering such as geothermal reservoirs, drying of porous solids, chemical catalytic reactors, thermal insulators, nuclear waste repositories, heat exchanger devices, underground energy transport etc. Bejan and Khair [1] addressed one of the most elementary cases i.e. buoyancy-induced heat and mass transfer from a vertical plate embedded in a saturated porous medium. Sammer [2] investigated the heat and mass transfer over an accelerating surface with heat source in presence of magnetic field. Bhukta *et al.* [3] studied the heat and mass transfer on magneto hydrodynamic (MHD) flow of a visco elastic fluid through porous medium over a shrinking sheet. An exact solution of the oscillatory MHD flow in a channel filled with porous medium was obtained by Singh [4].

There has been a renewed interest in research related to MHD flow and heat transfer in porous and non–porous media due to the effect of magnetic fields on the boundary layer flow associated with electrically conducting fluids. In addition, this type of flow has attracted the interest of many investigators, in the view of its applications in many engineering fields like MHD generators, plasma studies, nuclear reactors, and geothermal energy extractions. Raptis *et al.* [5] analyzed hydromagnetic free convection flow through a porous medium between two parallel plates. Abeldahab and Elbarbary [6] analyzed the Hall current effect on MHD free convection flow past a semi-infinite vertical plate with mass transfer. Chamkha and Ben-Nakhi [7] studied MHD mixed convection-radiation interaction along a permeable surface immersed in a porous medium in the presence of Soret and Dufour's effect. Hossain *et al.* [8] investigated MHD free convection flow from an isothermal plate oriented at a small angle with respect to the horizontal. Khandelwal and Jain [9] investigated the unsteady MHD flow of a stratified fluid through a porous medium over a moving plate in slip flow regime.

The thermal radiation aspect is crucial on the flow and heat transfer process in the design of many advanced high temperature energy conversion systems. The radiation effect in these systems is usually the result of emission by hot walls and the working fluid. Bakier and Gorla [10] studied the radiation effect on mixed convection from horizontal surfaces in porous media. Bala *et al.* [11] have investigated the radiation effects on MHD flow past an exponentially accelerated isothermal vertical plate with uniform mass diffusion in presence of a heat source. Baoku *et al.* [12] have analyzed the influence of thermal radiation on the transient MHD Couette flow through a porous medium. Basu *et al.* [13] have studied the radiation and mass transfer effects on transient free convection flow of dissipative fluid past semi-infinite vertical plate with uniform heat and mass flux. Singh *et al*. [14] have studied the effect of radiation and magnetic field on unsteady stretching permeable sheet under free stream condition. El-Aziz [15] investigated the radiation effect on the flow and heat transfer over an unsteady stretching sheet. Makinde and Mhone [16] studied heat transfer to MHD oscillatory flow in a channel filled with porous medium.

Problems involving combined heat and mass transfer with chemical reaction are of importance in many processes. These problems have received a considerable amount of attention in recent years. Heat and mass transfer occur simultaneously in processes such as drying, evaporation at the surface, energy transfer in a wet cooling tower and the flow in a desert cooler etc. A reaction is said to be of the order n, if the reaction rate is proportional to the n-power of concentration. In particular, a reaction is said to be first-order, if the rate of reaction is directly proportional to concentration itself. Uwanta *et al.* [17] studied the chemical reaction and thermal radiation effects on free convection flow through a porous medium. Sandeep *et al.* [18] have investigated the effect of radiation and chemical reaction on transient MHD free convective flow over a vertical plate through porous medium. Ibrahim *et al.* [19] studied radiation and mass transfer effects on MHD oscillatory flow in a channel filled with porous medium in the presence of chemical reaction Muthucumara swamy *et al*. [20] studied the radiation effects on unsteady flow past an accelerated isothermal vertical plate in presence of first order chemical reaction.

However, the interaction of radiation and mass transfer in an electrically conducting fluid flowing through a channel filled with porous medium has received little attention. This investigation aims to extend the work of Ibrahim *et al.* to memory fluid (Walter's liquid-B). The equations of continuity, linear momentum, energy and diffusion, which govern the flow field, are solved by using an analytical method. The variation of the velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number has been discussed for variations in the governing parameters.

II MATHEMATICAL FORMULATION

An unsteady two dimensional convective heat and mass transfer flow of a viscous, incompressible, electrically conducting, optically thin fluid in a channel filled with saturated porous medium with chemical reaction is considered. A uniform applied homogeneous magnetic field is considered in the transverse direction. It is assumed that the fluid has small electrical conductivity and the electromagnetic force produced is very small. A homogeneous first order chemical reaction between fluid and the species concentration is considered, in which the rate of chemical reaction is directly proportional to the species concentration. A Cartesian coordinate system (x, y) is assumed, where x-axis lies along the centre of the channel and y- axis in the normal direction. Then, under the usual Boussinesq's approximation, the equations governing flow field under consideration are as follows:

Momentum equation:

$$\frac{\partial u}{\partial t} = g\beta(T - T_0) + g\beta_1(C - C_0) + \vartheta\frac{\partial^2 u}{\partial y^2} - \frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{\vartheta u}{K} - \beta_1\left(\frac{\partial^3 u}{\partial t\,\partial y^2} + v\frac{\partial^3 u}{\partial y^3}\right) - \left(\frac{\sigma_e B_0^2}{\rho}\right)u \qquad (1)$$

Energy equation:

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \qquad (2)$$

Species equation:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial y^2} - K_r(C - C_0) \qquad (3)$$

The boundary conditions for the velocity, temperature and concentration fields are:

$$u = 0, T = T_w, C = C_w \text{ on } y = 1$$

$$u = 0, T = T_0, C = C_0 \quad \text{on } y = 0 \qquad (4)$$

where u- axial velocity, t- time, T- fluid temperature, P- pressure, g- gravitational force, q_r- radiative heat flux , β and β^* - coefficient of volume expansion due to temperature and concentration , c_p -specific heat at constant pressure, κ - thermal conductivity, K- porous medium permeability coefficient, $B_o = (\mu_e H_0)$ - electromagnetic induction, μ_e - magnetic permeability, H_o- intensity of magnetic field, σ_e - conductivity of the fluid, ρ - fluid density and ν - kinematic viscosity coefficient.

It is assumed that the temperature of the walls T_0 , T_w are high enough to induce radiative heat transfer. Following Cogley *et al.* [21] it is assumed that the fluid is optically thin with a relatively low density and the radiative heat flux is given by:

$$\frac{\partial q_r}{\partial y} = 4\alpha^2(T_0 - T) \qquad (5)$$

where α - is the mean radiation absorption coefficient.

In order to write the governing equations and the boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

$$x' = \frac{x}{a}, \quad y' = \frac{y}{a}, \quad t' = \frac{t\,U}{a}, \quad P' = \frac{aP}{\rho \vartheta U},$$
$$u' = \frac{u}{U}, \quad \vartheta = \frac{\mu}{\rho}, \quad G_r = \frac{g a^2 \beta (\mathrm{T_w} - \mathrm{T_0})}{\vartheta U},$$
$$G_c = \frac{g\beta_1(\mathrm{C_w} - \mathrm{C_0})}{\vartheta U}, \quad P_e = \frac{\mathrm{Ua\rho C_p}}{\kappa}, R_e = \frac{Ua}{\vartheta}$$
$$H^2 = \frac{a^2 \sigma_e B_0^2}{\rho \vartheta}, \quad \theta = \frac{T - T_0}{\mathrm{T_w} - \mathrm{T_0}}, \emptyset = \frac{C - C_0}{\mathrm{C_w} - \mathrm{C_0}},$$
$$K_r' = \frac{K_r a}{U}, \quad S_c = \frac{\vartheta}{D}, \quad Da = \frac{K}{a^2},$$
$$N^2 = \frac{4\alpha^2 a^2}{\kappa}, \quad \beta_1 = \frac{\beta_1 v_0^2}{\vartheta^2} \qquad (6)$$

where, U is the flow mean velocity and a being the width of the channel.

In view of the Eq. (6), the equations (1) – (3) reduce to the following dimensionless form:

$$R_e \frac{\partial u}{\partial t} = -\frac{\partial \mathrm{P}}{\partial \mathrm{x}} + \frac{\partial^2 u}{\partial y^2} + G_r \theta + G_c \emptyset - \beta_1 \left[\frac{\partial^3 u}{\partial t \partial y^2} - \frac{\partial^3 u}{\partial y^3}\right] - (S_f^2 + H^2) u \qquad (7)$$

$$P_e \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} + N^2 \theta \qquad (8)$$

$$\frac{\partial \emptyset}{\partial t} = \left(\frac{1}{S_c R_e}\right) \frac{\partial^2 \emptyset}{\partial y^2} - K_r^2 \emptyset \qquad (9)$$

The corresponding boundary conditions are:

$$u = 0, \theta = 1, \emptyset = 1 \quad on \quad y = 1$$
$$u = 0, \theta = 0, \emptyset = 0 \quad on\; y = 0 \qquad (10)$$

where *Gr*, *H*, *Gc*, *Pe*, *N*, *Re*, *Kr*, *Da*, *Sf* = (*1/Da*), *Sc* are thermal Grashoff number, Hartmann number, solutal Grashof number, Peclet number, Radiation parameter, Reynolds number, chemical reaction parameter, Darcy number, porous medium shape factor parameter and Schmidth number respectively.

III. SOLUTION OF THE PROBLEM

In order to solve Eqs. (7)- (10) for purely oscillatory flow, let

$$-\frac{\partial P}{\partial x} = \lambda e^{i\omega t}, \qquad u(y,t) = u_0(y) e^{i\omega t}$$
$$\theta(y,t) = \theta_0(y) e^{i\omega t}, \qquad \phi(y,t) = \phi_0(y) e^{i\omega t} \quad (11)$$

where λ is a constant and ω is the frequency of the oscillation.

Substituting the above expressions of Eq. (11) into Eqs. (7) -(10), we obtain,

$$u_0'' - m_3^2 u_0 = -\lambda - Gr\theta_0 - Gc\phi_0 \qquad (12)$$
$$\theta_0'' + m_1^2 \theta_0 = 0 \qquad (13)$$
$$\phi_0'' - m_2^2 \phi_0 = 0 \qquad (14)$$

The corresponding boundary conditions are:

$$u_0 = 0, \theta_0 = 1, \phi_0 = 1 \;\; on\; y = 1$$
$$u_0 = 0, \theta_0 = 0, \phi_0 = 0 \;\; on\; y = 0 \qquad (15)$$

where

$$m_1 = \sqrt{N^2 - i\omega Pe},$$
$$m_2 = \sqrt{Kr^2 ScRe + i\omega ScRe},$$
$$m_3 = \sqrt{S_f^2 + H^2 + i\omega Re}$$

Solving the Eqs. (12)- (14) subject to the boundary conditions (15), the fluid velocity, temperature and concentration are obtained as follows:

$$\theta(y,t) = \frac{\sin(m_1 y)}{\mathrm{sinm_1}} e^{i\omega t} \qquad (16)$$

$$\phi(y,t) = \frac{\sinh(m_2 y)}{\mathrm{sinhm_2}} e^{i\omega t} \qquad (17)$$

$$u(y,t) = u_0(y,t) e^{i\omega t} \qquad (18)$$

Where

$$u_0(y,t) = \beta_4 Gc \left[\frac{\sinh(m_3 y)}{\mathrm{sinhm_3}} - \frac{\sinh(m_2 y)}{\mathrm{sinhm_2}}\right] + \beta_5 Gr \left[\frac{\sin(m_1 y)}{\mathrm{sinm_1}} - \frac{\sinh(m_3 y)}{\mathrm{sinhm_3}}\right] + \beta_3 \lambda \left[(coshm_3 - 1)\left(\frac{\sinh(m_3 y)}{\mathrm{sinhm_3}}\right) + (1 - coshm_3 y)\right]$$

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. As the velocity field is known, the skin-friction at both the walls of the channel can be obtained, which in non-dimensional form is given by:

$$\tau = -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0,1}$$
$$= -\left[\beta_4 Gc\left[m_3\frac{\cos h(m_3 y)}{\sinh m_3} - m_2\frac{\cos h(m_2 y)}{\sinh m_2}\right]\right.$$
$$+ \beta_5 Gr\left[m_1\frac{\cos(m_1 y)}{\sin m_1} - m_3\frac{\cosh(m_3 y)}{\sinh m_3}\right]$$
$$+ \beta_3\lambda\left\{\left(\frac{cosh m_3 - 1}{\sinh m_3}\right)(m_3\cosh(m_3 y))\right.$$
$$\left.\left. - m_3 sinh(m_3 y)\right\}\right] e^{i\omega t} \quad (19)$$

Knowing the temperature field, the rate of heat transfer coefficient at both walls of the channel can be obtained, which in the terms of the Nusselt number, is given by:

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0,1} = -\left(m_1\frac{\cos(m_1 y)}{\sin m_1}\right)e^{i\omega t} \quad (20)$$

For a given concentration field, the rate of mass transfer coefficient at both walls of the channel can be obtained, which in the terms of the Sherwood number, is given by:

$$Sh = -\left(\frac{\partial\phi}{\partial y}\right)_{y=0,1} = -\left(m_2\frac{\cosh(m_2 y)}{\sinh m_2}\right)e^{i\omega t} \quad (21)$$

IV. RESULTS AND DISCUSSION

The analytical results thus obtained are represented by a set of graphical results. These results are obtained to illustrate the influence of various parameters on the velocity, temperature and concentration. For numerical validation of the analytical results, the real part of the results has been considered. The velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number are evaluated for different sets of governing parameters viz., thermal Grashof number *Gr*, solutal Grashof number *Gc*, Hartmann number *H*, radiation parameter *N*, Peclet number *Pe*, Reynolds number *Re*, porous medium shape factor parameter S_f,, Schmidt number *Sc* and chemical reaction parameter *Kr*. In the present study we adopted the following default parametric values: *Gr* = 1.0, *Pe = 0.71, Gc = 0.5, Kr = 0.5, H = 1.0,* S_f, *= 1.0, N = 1.0, Sc = 0.6, Re = 1.0, t = 0.0,* ω*= 1.0,* λ *= 1.0 and* $\beta_1 = 0.5$. All the graphs therefore correspond to these values unless specifically indicated on the appropriate graph.

It can be observed that the fluid velocity profile is parabolic with maximum magnitude along the channel centre-line and minimum at the walls. Here θ correspond to the profiles of the non-dimensional temperature which is either positive or negative. It is observed that in general the temperature θ is continuously positive for variations of the governing parameters. Thus the temperature in the flow field is always higher than the temperature on the plate *y* = 0, and less than the temperature on the plate *y* =1. For any given set of parameters, the profiles indicate that the temperature gradually enhances from its lowest value on the boundary *y* = 0 to attain its highest prescribed value on the boundary *y* =1.

Here ϕ corresponds to the profiles of the non-dimensional concentration which is either positive or negative. It is observed that in general the concentration ϕ is continuously positive for variations of the governing parameters. Thus the concentration in the flow field is always higher than the concentration on the plate *y* = 0, and less than the concentration on the plate *y* =1. For any given set of parameters, the profiles indicate that the concentration gradually enhances from its lowest value on the boundary y = 0 to attain its highest prescribed value on the boundary y =1.

The thermal Grashof number Gr signifies the ratio of thermal buoyancy force to viscous hydrodynamic force. The rise in velocity is due to increase in thermal buoyancy force as shown in Fig. 1. The solutal Grashof number Gc defines the ratio of species buoyancy force to viscous hydrodynamic force. The increase in velocity is attributed to species buoyancy force enhancement which is reflected in Fig. 2. The magnetic Hartmann number H is the ratio of magnetic force to viscous force, magnetic force gives rise to Lorentz force, which suppresses the flow so velocity reduces as Hartmann number increases as shown in Fig. 3.

The porous medium shape factor S_f, has no effect on memory flow which is a deviation from viscous case referred in Fig. 4. The radiation parameter N is the ratio of heat transfer to thermal radiation transfer, so the velocity and temperature profiles goes up as radiation parameter N rises refer Fig. 5. (a) & (b).

The Peclet number Pe is the product of Reynolds number and Scmidth number. Peclet number embodies the ratio of heat transfer by the motion of the fluid to the heat transfer by thermal conduction, so the velocity and temperature increases as Peclet number decreases as shown in Fig. 6. (a) & (b). The Reynolds number Re is the ratio of inertial forces to viscous forces, velocity increases as Re increases, which is a deviation from viscous case whereas Re has opposite effect on concentration as observed in Fig. 7.(a) & (b).

The effect of the Schmidt number *Sc* on the velocity and concentration profiles is plotted. The Schmidt number embodies the ratio of the momentum to the mass diffusivity. It quantifies the relative effectiveness of momentum and mass transport by diffusion in the hydrodynamic (velocity) and concentration (species) boundary layers. As the Schmidt number increases the concentration decreases. This causes the concentration buoyancy effects to decrease, yielding a reduction in the fluid velocity. This behaviour is evident from Fig. 8. (a) &(b). The chemical reaction parameter Kr has adverse effect on velocity and concentration refer Fig. 9. (a) & (b).

The effects of various governing parameters on the wall shear stress τ, Nusselt number *Nu* and Sherwood number *Sh* at lower wall *y* = 0 and upper wall *y* = 1 of the channel are shown in Tables 1, 2 and 3. From Table 1, it is observed that Gr and Gc decrease shear stress at the lower wall y = 0 and increase shear stress at the upper wall y = 1. Hartmann number H have opposite effects as compare to Gr and Gc. From Table 2, it is noted that Pe influences shear stress and Nusselt number at the lower wall y = 0. N increases shear stress at the walls y = 0 and y = 1 where as N decreases Nusselt number at y = 0 and increases at y = 1. Pe increases Nusselt number at y = 0 and decreases at y = 1. From Table 3, it is observed that Sc influences shear stress and Sherwood number at y = 0 and reduces both the numbers at y = 1. Kr reduces shear stress at the walls i.e. y = 0 and y = 1 and have opposite effects on Sherwood number as y = 0 and y = 1. Kr enhances shearing stress and Sherwood number at the lower plate y = 0 where as it subsides the same on upper plate at y = 1. Furthermore, the negative values of the wall shear stress, Nusselt number and Sherwood number, for all values of the parameters, are indicative of the physical fact that the heat flows from the sheet surface to the ambient fluid.

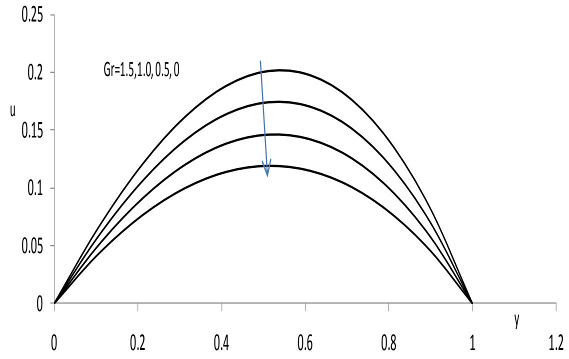

Fig. 1.Velocity profiles for different values of *Gr*

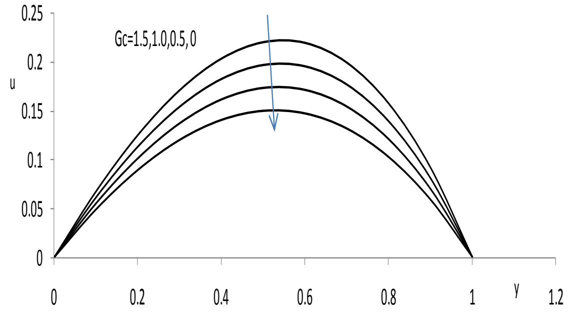

Fig. 2. Velocity profiles for different values of *Gc*

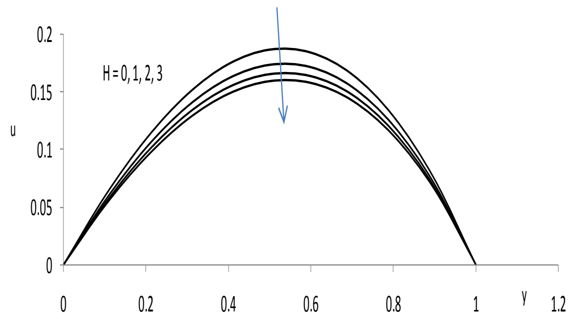

Fig. 3. Velocity profiles for different values of *H*

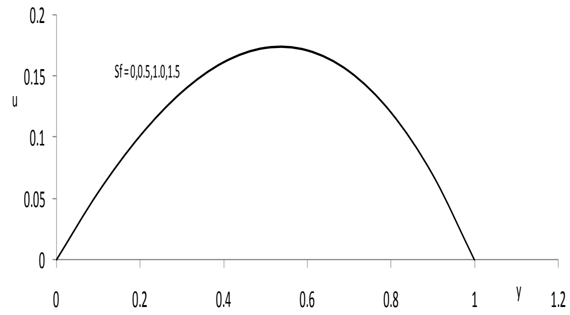

Fig. 4. Velocity profiles for different values of *Sf*

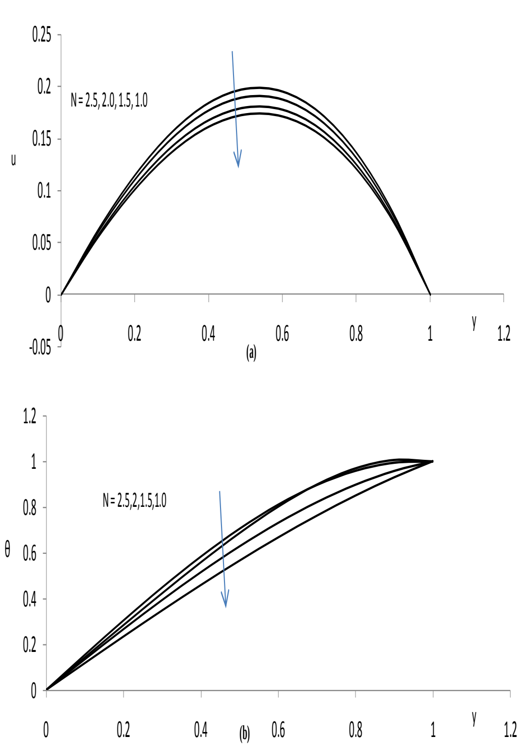

Fig.5. (a) Velocity profiles for different values of *N*; (b) Temperature profiles for different values of *N*

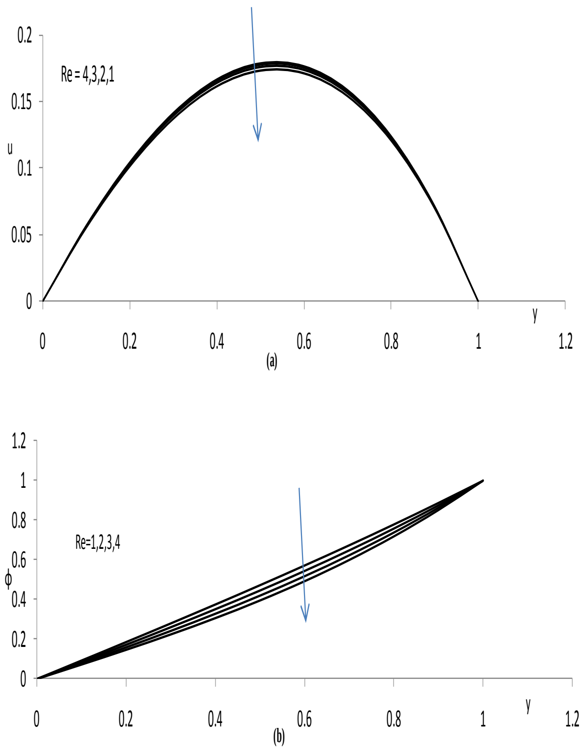

Fig.7. (a) Velocity profiles for different values of *Re*; (b) Concentration profiles for different values of *Re*

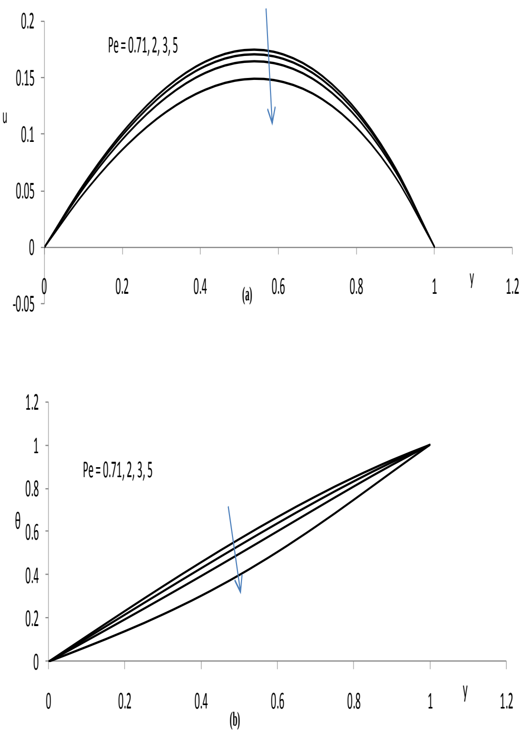

Fig.6. (a) Velocity profiles for different values of *Pe*; (b) Temperature profiles for different values of *Pe*

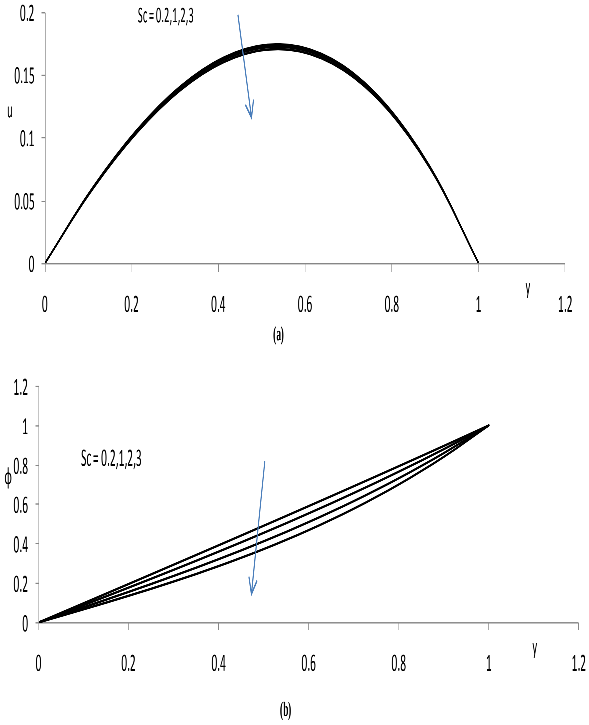

Fig.8. (a) Velocity profiles for different values of *Sc*; (b) Concentration profiles for different values of *Sc*

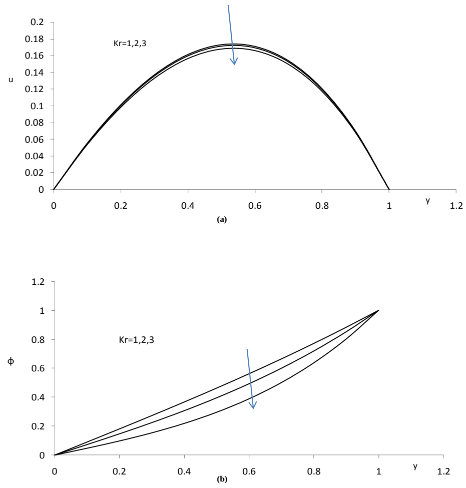

Fig. 9. (a) Velocity profiles for different values of *Kr;* (b) Concentration profiles for different values of *Kr*

Table 1 Numerical *values* of the shear stress of the channel for *Pe = 0.71, N = 1.0, λ = 1.0, t =0.0, s = 1.0, Re = 1.0, w = 1.0, Kr = 0.5, Sc = 0.6*

Gr	Gc	H	$\tau(0)$	$\tau(1)$
1.0	0.5	1.0	-0.929329	-0.183625
2.0	0.5	1.0	-1.412190	-0.027466
1.0	1.0	1.0	-0.990551	-0.056458
1.0	0.5	2.0	-0.705165	-0.317096

Table 2 Numerical values of the shear stress and the rate of heat transfer i.e. Nusselt number of the channel for *Gr = 1.0, Gc = 0.5 = 1.0, H = 1.0, λ = 1.0, t = 0.0, s = 1.0, Re = 1.0, w = 1.0, Sc =0.6, Kr = 0.5*

Pe	N	$\tau(0)$	$\tau(1)$	Nu(0)	Nu(1)
0.71	1	-0.929329	-0.183625	-1.17482	-0.657171
1	1	-0.805383	-0.288767	-1.16164	-0.671829
0.71	2	-0.075823	-0.165465	-1.54289	0.108455

Table 3 Numerical values of the shear stress and the rate of mass transfer i.e. Sherwood number of the channel for *Gr = 1.0, Gc = 0.5 = 1.0, H =1.0, λ = 1.0, t = 1.0, s = 1.0, Re = 1.0, w = 1.0, Pe= 0.71, N = 1.0*

Sc	Kr	$\tau(0)$	$\tau(1)$	Sh(0)	Sh(1)
0.6	0.5	-0.929329	-0.183625	-0.927427	-1.14545
1	0.5	-0.927912	-0.185216	-0.87989	-1.24154
0.6	1	-0.928545	-0.184505	-0.900783	-1.19919

NOMENCLATURE

B_0	magnetic flux density
C	dimensionless concentration
Cf	skin friction coefficient
Cp	specific heat at constant pressure
D	mass diffusion coefficient
Da	Darcy number
U_∞	scale of free stream velocity
Gc	solutal Grashof number
Gr	Grashof number
g	acceleration due to gravity
H	Hartmann number
Kr	chemical reaction parameter.
k	thermal conductivity
β *c*	coefficient of volumetric concentration expansion of the working fluid
N	Radiation parameter
Nu	Nusselt number
β *f*	coefficient of volumetric thermal expansion of the working fluid
n	scalar constant
Pe	Peclet number
ε	scalar constant (<<1)
p	pressure
θ	dimensionless temperature
Q	heat generation parameter
R	Radiation parameter
Rex	local Reynolds number
λ	constant
Sc	Schmidt number
σ	electrical conductivity.
Sh	Sherwood number
S_f	porous medium shape factor parameter
T	temperature
t	time
u,v	components of velocities along and perpendicular to the plate
U_p	plate moving velocity
V_0	scale of suction velocity
x.y	distances of along and perpendicular to the plate
α	fluid thermal diffusivity
μ	fluid dynamic viscosity
ρ	fluid density
υ	fluid kinematic viscosity
τ	friction coefficient
ω	frequency of the oscillation

Superscripts

w wall condition

∞ free stream condition

Subscripts

( ) differentiation with respect to *y*

* dimensional properties

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