Effects of Radiation and Mass Transfer on MHD Oscillatory Rivlin-Ericksen Flow in a Porous Medium Channel

S.A. Hussaini, Rafiuddin and S. Mustafa

***Abstract*— A robust analysis is carried out to investigate the impact of slip condition, radiation and chemical reaction on unsteady MHD non-Newtonian periodic flow, which involves an electrically conducting, incompressible fluid flowing through a porous medium under the influence of constant mass and heat flux. The perturbation method is employed to find the solutions to the governing equations. The final expressions for velocity, temperature, concentration, and skin friction for the rates of mass and heat transport are obtained and it is found that the rate of mass transfer increases with the rise in Re, Sc and Kr at y = 0, while the rate of heat transfer reduces with the rise in Pe, γ and N. Skin friction shoots up as Gr and N increase at y = 0 and y = 1, but Pe has the opposite effects at the plates. γ suppresses the skin friction. The effects of parameters Pe, N, γ and t are to subside the temperature field found in the plotted figures (2, 3, 4 and 15). The influence of parameters Kr, Sc, Re and t is to suppress the concentration field ascertained from the plotted graphs (5, 6, 7 and 13). The impact of Gr, N, Pe, γ and t is to increase the velocity as concluded from plotted figures (8, 9, 10, 11 and 14) and the other parameters Gc, H, Sf, Re, Sc, Kr and h have no effect on the velocity field, as observed in figure (12), these parameters are effective on viscous fluid, a deviation noted.**

***Index Terms*— Magneto hydrodynamics, Chemical reaction, Slip flow regime, Radiation, Periodic flow, Planer channel and Memory fluid.**

I. Introduction

The slip-flow regime problem has captivated the attention of many scholars due to its abundant applications in various fields. These problem's are playing a vital role in the modern era of science and technology and also in industrialization. It is a general observation in practical applications that the particles that are lying near the solid surface do not possess the surface velocity but rather some finite tangential velocity that generates slip along the surface. Its impact has to be considered. This slip of fluid characteristics at the solid surfaces is encountered in problems with nano channels or micro channels. A thin film of fragile oil is used on plates in motion or when a thick monolayer of hydrophobic special coating is applied to the surface of a mechanical device where the attachment of the lubricant thin film to the surface slips over one another or in cases where the special coating is being applied to the surfaces in order to avoid friction. The following researchers have worked on slip effects and periodic flow through planar channels. Kumar *et al.* [1] explored the time-dependent magnetic Newtonian flow in a channel. Mehmood and Ali [2] highlighted the various features of unsteady fluctuating magneto hydrodynamic Newtonian flow in a channel. Das [3] studied the velocity field of unsteady fluctuating non-Newtonain flow in a highly porous medium. Prakash *et al.* [4] probed the multiple effects of density changes and Lorentz force on the fluctuating flow of radiative Newtonian fluid with dust through a channel in a highly porous passage.

A characteristic survey is made to scan the influence of chemical reaction and heat transfer in a laminar flow by assuming different conditions. Reddy *et al.* [5] investigated the reaction effects on time-dependent magneto hydrodynamic Newtonian fluid through a highly porous medium. Reddy *et al.* [6] studied the impacts of magneto hydrodynamics on natural convection, time dependent, non-Newtonian flow past an upright porous plate. The various impacts of mass transfer and radiation on magneto hydrodynamics flow through a channel were investigated by Ibrahim *et al.* [7].

Vijayalakshmi *et al.* [8] presented the reaction effects of fluctuating radiative magnetic Newtonian fluid flow in a porous passage. Lawanya *et al.* [9] analyzed the heat generation effects on the fluctuating magnetic Newtonian fluid with mass transfer. Hema and Shanti [10] ascertained that Hartmann's number enhances induced magnetic field and magnetic Reynolds' number influences velocity in their study. Mehta *et al.* [11] investigated the fluctuation of an inclined magnetic viscous fluid subjected to heat generation. Nayak [12] investigated the time dependent magnetic fluid and found that the two memory parameters of third grade fluid reduce the velocity. Salah and Elhafian [13] obtained the solution of a heat transfer steady visco-elastic second grade flow of a stretching sheet by the SLM technique of solving highly non-linear differential equations. Opanuga *et al.* [14] discussed the effects of Hall current and ion slip on time-dependent magnetic micro channel Couette flow and found that Hall current and ion slip minimize the disorder. Reddy *et al.* [15]

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presented the magnetic effects of viscous fluid in a planar channel.

However, the combined effects of mass transfer and radiation of electrically conducting fluid through saturated porous passage have been focused on by many researchers. Rafiuddin and Noushima [16] extended the above problem [15] to non-Newtonian Casson fluid flow with mass transport. Zulkifee *et al.* [17] presented the radiative heat and mass transfer flow. Mustapah and Salau [18] obtained the solution for heat and mass transfer of nano-Newtonian squeezing flow by the homotopy perturbation method. Khan *et al.* [19] employed the back propagation method to find the solution of the time-dependent Newtonian squeezing flow. Balamurugan *et al.* [20] found the solution by the Laplace technique of heat and mass transfer effects on unsteady free convection flow past a linearly accelerated isothermal inclined plate with variable temperature and mass diffusion with thermal radiation. Aghaji *et al.* [21] explored the 3- dimensional, incompressible, electrically conductive non- Newtonian fluid and found the solution by LSPM technique for flow variables. Saikia *et al.* [22] probed the fractional derivatives of Atangana-Baleanu and Caputo-Fabrizio for magnetic Newtonian fluid and deduced that Nusselt number and Sherhood number decreased due to internal friction, thermal conductivity and Lorentz force. Anncy *et al.* [23] presented Rayleigh number and corrected Rayleigh number effects on heat and mass transfer in a saturated porous medium between two horizontal parallel plates.

Now, the goal is to look into the non-Newtonian fluid that has been replaced the Newtonian fluid in reference [7]. It is decided to solve the flow field's governing equations analytically. Temperature, velocity, concentration, skin friction, Sherwood number, and Nusselt number have all been studied in relation to various governing parameters.

The constitutive equations of memory fluid given by Rivlin-Ericksen [24] are

$$t = -pI + \varphi_1 A + \varphi_2 B' + \varphi_3 A^2 \qquad (i)$$

Where *t* is stress tensor, $I = \|\delta_{ij}\|$,

$$A = d_{ij} \text{ and } d_{ij} = \frac{1}{2}\left(v_{i,j} + v_{j,i}\right),$$

$v_{i,j}$ is velocity gradient and $a_{i,j}$ is acceleration gradient.

$$B' = \|b_{ij}\|$$

$$\text{and} \qquad b_{ij} = a_{i,j} + a_{j,i} + 2v_{m,i}v_{m,j} \qquad (ii)$$

φ_1, φ_2 and φ_3 are functions of material invariants and may be taken as constants. This constitutive equation covers both elastic and inelastic fluids, and a large number of fluids, like aqueous solutions of poly-isobutylene, are well covered by this constitutive equation.

II. PROBLEM FORMULATION

Assuming the fluid be incompressible, optically thin and electrically low conductive, consider the unsteady free convective two-dimensional memory fluid through a highly porous channel subject to transverse magnetic field, first order reaction between concentration and homogenous fluid, neglecting the generated very small emf for investigating heat and mass transfer outcomes.

A Cartesian coordinate system is employed to study the problem such that the X-axis is along the mid line of the channel and the Y-axis is in the direction of the normal to the real axis. All the flow variables are functions of y and t, and for the present analysis, v = 0.

$$u = h\frac{\partial u}{\partial y}, \qquad \frac{\partial T}{\partial y} = -\frac{q}{k}, \quad \frac{\partial C}{\partial y} = -\frac{J}{D} \text{ on } y = a$$

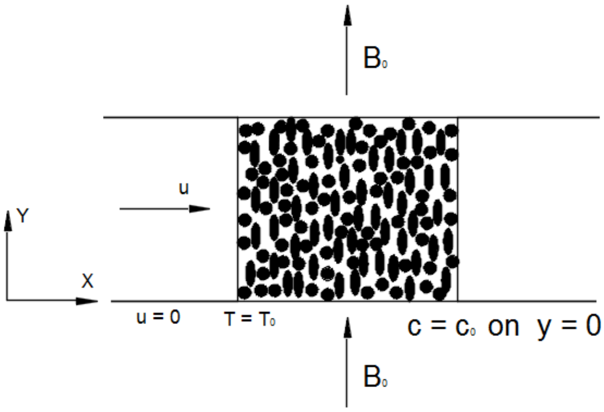

Fig-1: Geometry of the problem

Under Boussinesq's approximation and the above assumptions, the governing equations are

Momentum equation:

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

Equation for energy:

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} + \frac{Q_0(T - T_0)}{\rho C_p} \qquad (2)$$

Equation for Species:

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

Where u is velocity, t is time, g is acceleration due to gravity, β is coefficient of volumetric thermal expansion, β_1^* is coefficient of volumetric concentration expansion, T is temperature, C is concentration, υ is kinematic viscosity, ρ is density, P is pressure, K is permeability, β_1 is kinematic visco-elasticity, σ_e is electrical conductivity, B_0 is magnetic field strength, κ is thermal conductivity, C_p is specific heat at constant pressure, q_r is radiative flux, Q_0 is heat source, D is mass diffusion coefficient and Kr is dimensional reaction rate.

The boundary conditions are

$$u = h\frac{\partial u}{\partial y}, \quad \frac{\partial T}{\partial y} = -\frac{q}{k}, \quad \frac{\partial C}{\partial y} = -\frac{J}{D} \text{ on } y = a$$

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

T_0 and T_w temperature profiles at the walls, where h represents length, are sufficient to promote radiative heat transfer, according to Cogley *et al.* [25].

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

α is the coefficient of mean radiation absorption.

The following transformations convert the above equations into dimensionless form:

$$h' = \frac{h}{a}, \quad x' = \frac{x}{a}, \quad y' = \frac{y}{a}, \quad t' = \frac{tU}{a}, \quad P' = \frac{aP}{\rho\vartheta U},$$

$$u' = \frac{u}{U}, \quad \vartheta = \frac{\mu}{\rho}, \quad Gr = \frac{ga^2\beta(T_w - T_0)}{\vartheta U}, Sc = \frac{\vartheta}{D},$$

$$Gc = \frac{g\beta_1 a(C_w - C_0)}{\vartheta U}, \quad N^2 = \frac{4\alpha^2 a^2}{\kappa}, \quad \beta_1 = \frac{\beta_1 v_0^2}{\vartheta^2},$$

$$Pe = \frac{Ua\rho C_p}{\kappa}, \quad Re = \frac{Ua}{\vartheta}, \quad Da = \frac{K}{a^2},$$

$$Kr' = \frac{aKr}{U}, \quad \gamma = \frac{Q_0 a^2}{\kappa}, \quad H^2 = \frac{a^2\sigma_e B_0^2}{\rho\vartheta},$$

$$\theta = \frac{(T - T_0)\kappa}{aq}, \quad \emptyset = \frac{(C - C_0)D}{aJ} \qquad (6)$$

U denotes average velocity and ‘a’ is the width of the channel, Gr is Greshoff number, Gc is Solutal Greshoff number, Re is Reynolds number, Pe is Peclet number, Kr is chemical reaction rate parameter, N is radiation parameter, Sc is Schmidt number, β_1 is visco-elastic parameter, Sf is shape factor, γ is heat generation parameter, u, θ and $\emptyset$ are non-dimensional velocity, temperature and concentration.

Making use of (6) into equations (1, 2 and 3) then the transformed equations in the dimensionless form are

$$Re\frac{\partial u}{\partial t} = -\frac{\partial P}{\partial x} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\emptyset - \beta_1\left[\frac{\partial^3 u}{\partial t\partial y^2}\right] - \{(Sf)^2 + H^2\}u \qquad (7)$$

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

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

The boundary conditions in dimensionless form are

$$u = h\frac{\partial u}{\partial y}, \quad \frac{\partial \theta}{\partial y} = -1, \quad \frac{\partial \emptyset}{\partial y} = -1 \text{ on } y = 1$$

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

III. METHOD OF SOLUTION

Assuming the flow to be purely oscillatory

$$-\frac{\partial P}{\partial x} = \lambda e^{i\omega t}, \quad u(y,t) = u_0(y)e^{i\omega t},$$

$$\theta(y,t) = \theta_0(y)e^{i\omega t}, \quad \phi(y,t) = \phi_0(y)e^{i\omega t} \qquad (11)$$

Here λ is a constant and ω is frequency, the differential equations (7, 8, and 9) under (11), become

$$u_0'' - m_3^2 u_0 = (-\lambda - Gr\theta_0 - Gc\phi_0)/(1 - i\beta_1 w) \qquad (12)$$

$$\theta_0'' + m_1^2\theta_0 = 0 \qquad (13)$$

$$\phi_0'' - m_2^2\phi_0 = 0 \qquad (14)$$

Oscillatory flow boundary conditions take the form

$$u_0 = h\frac{\partial u_0}{\partial y}, \quad \frac{\partial \theta_0}{\partial y} = -1, \frac{\partial \phi_0}{\partial y} = -1 \ \ ony = 1$$

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

In above, h is rare fraction parameter

$$m_1 = \sqrt{N^2 + \gamma - i\omega Pe}, m_2 = \sqrt{Kr^2 ScRe + i\omega ScRe},$$

$$m_3 = \sqrt{Sf^2 + H^2 + i\omega Re)/(1 - i\beta_1\omega)}$$

Solving the equations (12, 13, and 14) under (15), gives rise to the expressions for fluid temperature, concentration and velocity which are:

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

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

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

where

$$u_0(y,t) = \Bigg[\beta_5 Gr\left\{h - \frac{\tan(m_1)}{m_1}\right\}\sinh(m_3 y) - \beta_4 Gc\left\{h - \frac{\tan h(m_2)}{m_2}\right\}\sinh(m_3 y) - \beta_3\lambda\{e^{-m_3}(hm_3 + 1) - 1\}\sinh(m_3 y)\Bigg]\frac{1}{hm_3 coshm_3 - sinhm_3} + \beta_3\lambda(1 - e^{-m_3 y}) + \beta_4 Gc\left(\frac{\sinh(m_2 y)}{m_2 cosh m_2}\right) - \beta_5 Gr\left(\frac{sinm_1 y}{m_1 cosm_1}\right)$$

The parameters Nusselt number, skin-friction and Sherwood number are important physical quantities for boundary layer flows. The values of dimensionless skin-friction for the channel plates are calculated with the help of known values of velocity field.

$$\tau = -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0,1} = \left[\beta_4 Gc\left[m_3\frac{\cos h(m_3 y)}{\sinh m_3} - m_2\frac{\cos h(m_2 y)}{\sinh m_2}\right] + \beta_5 Gr\left[m_1\frac{\cos(m_1 y)}{\sin m_1} - m_3\frac{\cosh(m_3 y)}{\sinh m_3}\right] + \beta_3\lambda\left\{\left(\frac{coshm_3 - 1}{\sinh m_3}\right)(m_3\cosh(m_3 y)) - m_3 sinh(m_3 y)\right\}\right]e^{i\omega t} \quad (19)$$

Nusselt number in terms of temperature gradients is

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

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=1} = -e^{i\omega t} \quad (21)$$

Sherwood number in terms of concentration gradients is

$$Sh = -\left(\frac{\partial\phi}{\partial y}\right)_{y=0} = -\left(\frac{e^{i\omega t}}{\cosh m_2}\right) \quad (22)$$

$$Sh = -\left(\frac{\partial\phi}{\partial y}\right)_{y=1} = -e^{i\omega t} \quad (23)$$

IV. RESULTS AND DISCUSSION

Computations for the final expressions in the problem are carried out numerically and the set of numerical results thus obtained are shown graphically. A detailed analysis is presented to examine the impact of different parameters on the temperature, concentration and velocity. For the sake of validation of the analytical findings, the imaginary part of the final outcome is neglected. The behavior of flow variables and their gradients is found numerically by changing the values of parameters governing the equations viz., Gr, Gc, H, N, Pe, Re, Sf,, Sc, γ and Kr. The invariant values different used for the parameters used are Pe = 0.71, Gr= 1, H = 1, Gc = 0.5, Sc = 0.6, N = 1, Re = 1, Sf = 1, Kr = 0.5, t = 0, ω= 1, λ= 1, $\gamma = 0$ and $\beta_1 = 0.5$. These specific values are used to represent all the graphs unless they are mentioned on the graph.

It can be observed from the graphs of the extended article that velocity profile is parabolic in nature and reaches its zenith value at the central line of the channel, whereas its nadir is at the lower plate of the channel. If flow field temperature θ, is higher than temperature at the lower plate y=0 then θ will be positive and if θ is less than lower plate temperature then it will be negative. For assigned values of parameters, the obtained results depict that the temperature gradually rises from its lowest value on the lower plate y = 0 and reaches its zenith on the upper plate y = 1.

The non-dimensional concentration ϕ may be positive or negative depending upon the concentration in the flow field. It may be more or less than the concentration on the boundary, but for optically thin and relatively low-density flow, it is always negative. It is also found that for varying values of the governing parameters, the concentration is repeatedly negative. The concentration on the lower plate is greater than the concentration on the upper plate. For assigned values, the concentration profiles slowly dip from their zenith value on the lower plate y = 0 to their nadir value on upper plate y =1.

As shown in Fig.2, temperature profiles decrease as N increases. The product of Sc and Re is Pe. Pe decreases the temperature field shown in Fig.3. Heat generation parameter γ reduces the temperature as shown in Fig.4. The effect of N, Pe and γ is to reduce the temperature.

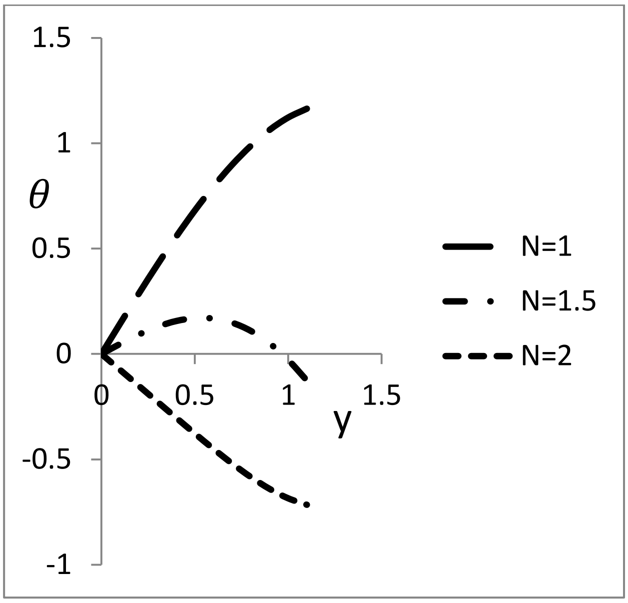

Fig.2: Temperature profiles for different values of N

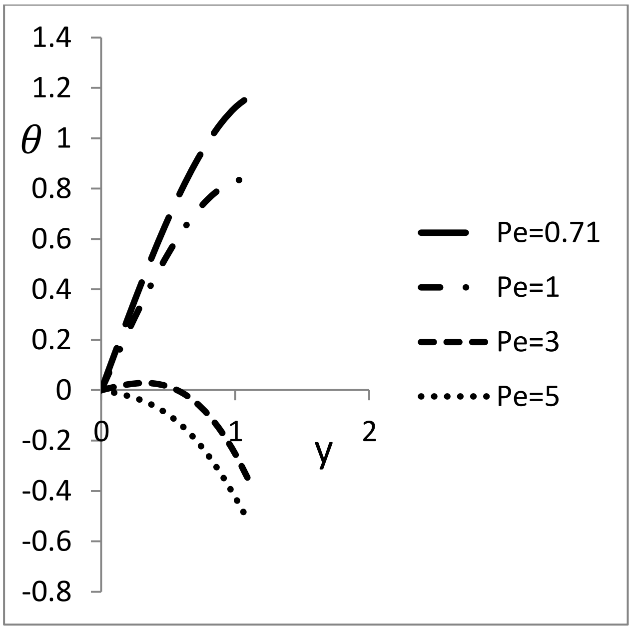

Fig.3: Temperature profiles for different values of Pe

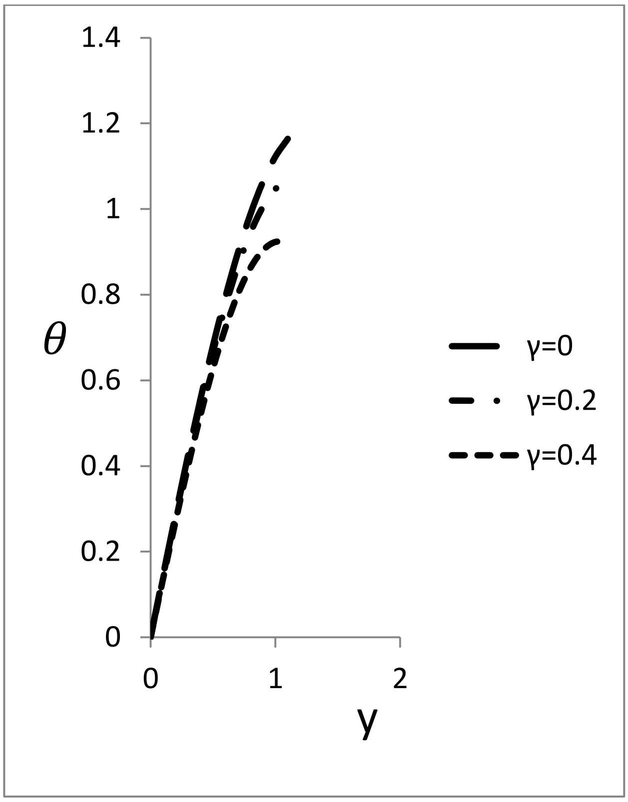

Fig.4: Temperature profiles for different values of γ

The concentration decreases as Re increases, which is observed in Fig.5. As Sc shoots up, the concentration as shown reduces in Fig.6. As Kr goes up, the concentration dips as shown in Fig.7. The effect of Re, Sc and Kr is to suppress the concentration profiles.

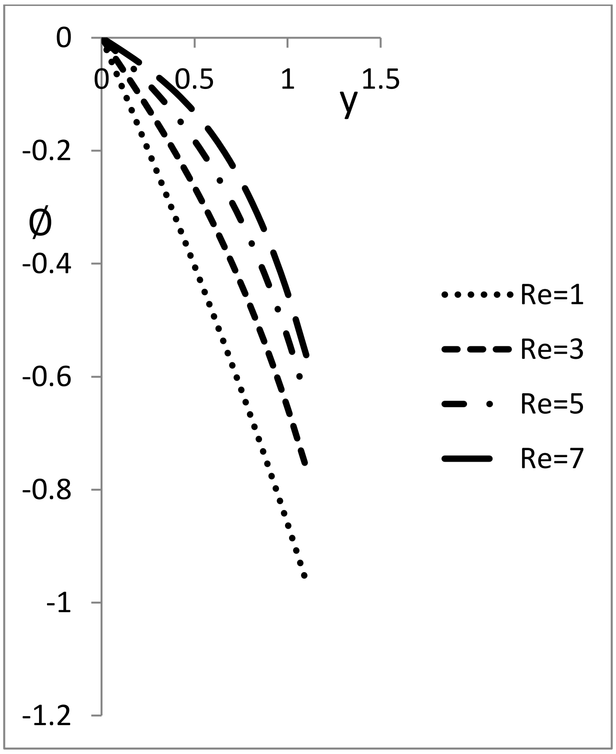

Fig.5: Concentration profiles for different values of Re

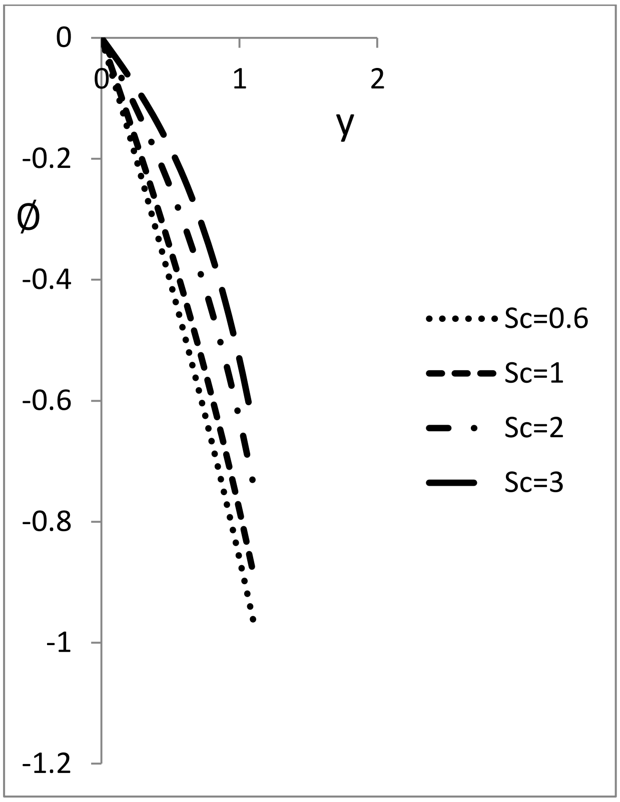

Fig.6: Concentration profiles for different values of Sc

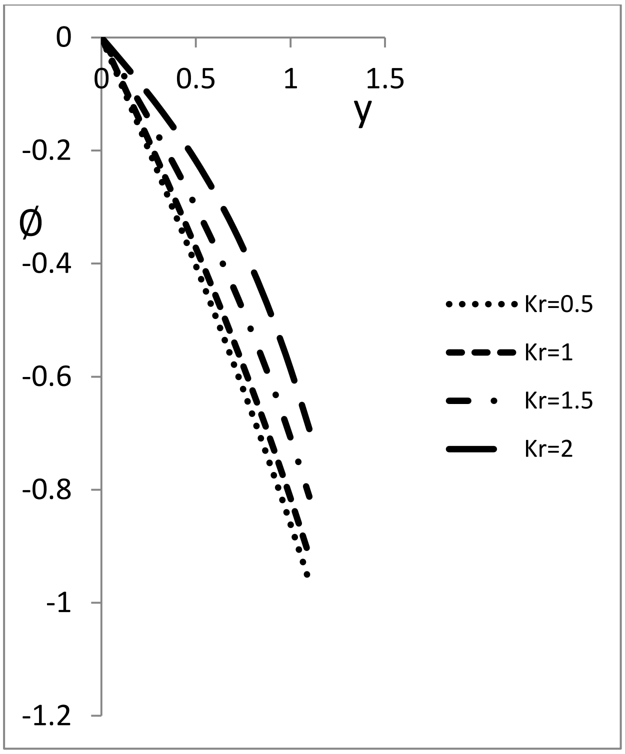

Fig.7: Concentration profiles for different values of Kr

The effect of Gr, N and Pe is to increase the velocity rapidly, then a downward trend is observed for greater values of parameters and gradually for smaller values of the same as observed in Figs. 8, 9 and 10. The trend of Gr, N and Pe is reversed from the middle of the channel. The effect of heat generation parameter is to enhance the velocity shown in Fig. 11.

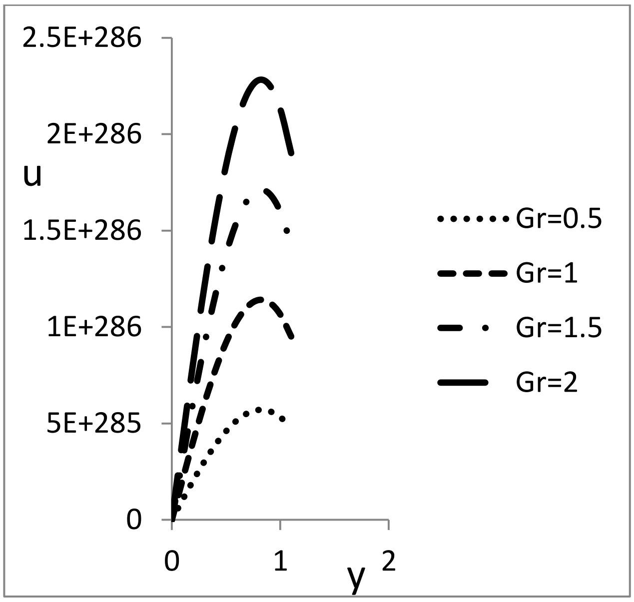

Fig.8: Velocity profiles for different values of Gr

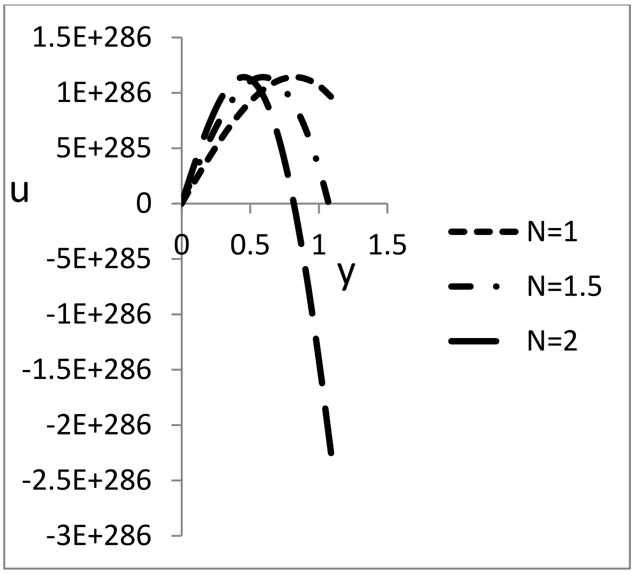

Fig.9: Velocity profiles for different values of N

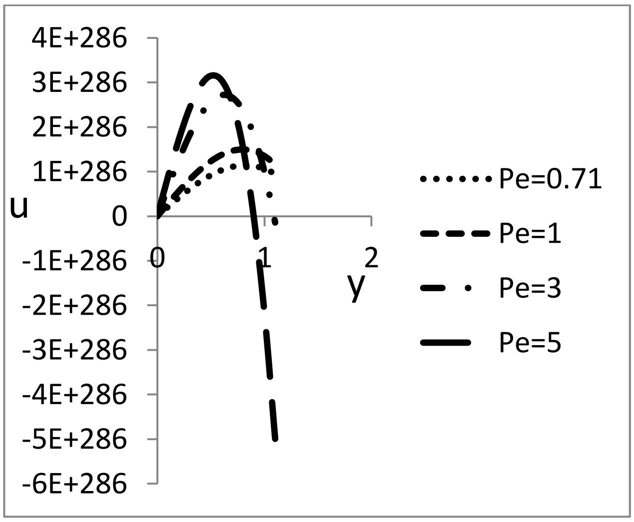

Fig.10: Velocity profiles for different values of Pe

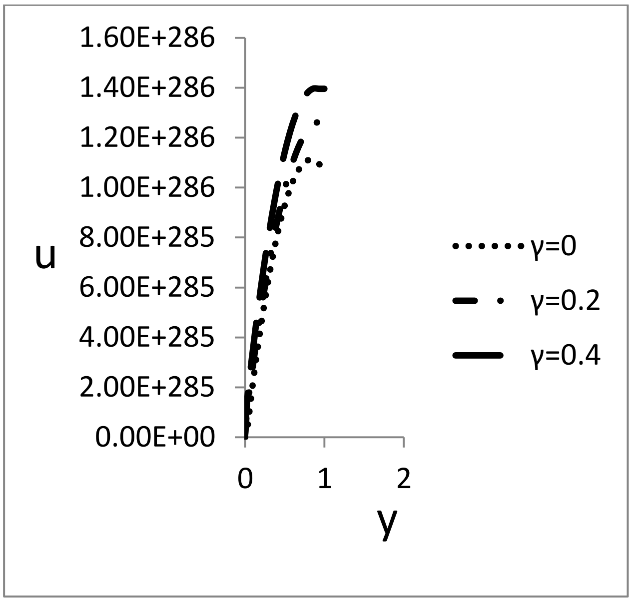

Fig.11: Velocity profiles for different values of γ

The other parameters such as Gc, H, Sf, Re, Sc, Kr and h do not have any effect on the velocity in the Rivlin-Ericksen fluid shown in Fig. 12, which is a total deviation from the behavior of viscous fluid presented in reference (7).

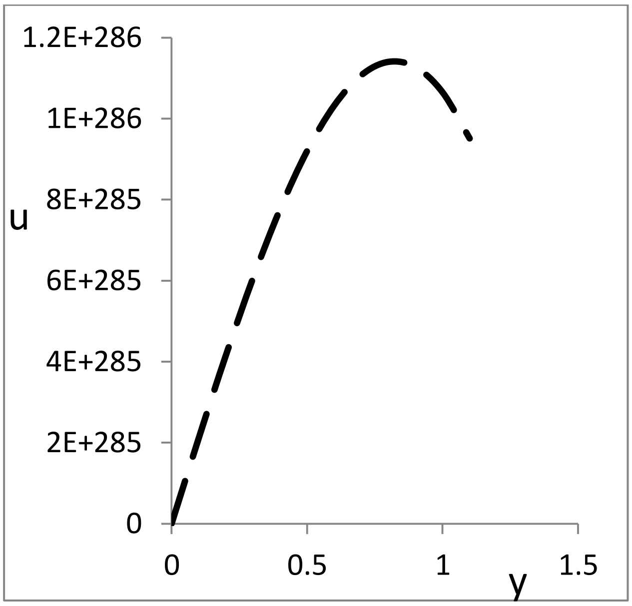

Fig.12: Velocity profiles for all other parameters

It is observed that concentration and velocity diminish with the passage of time, t observed in Figs. 13 and 14. But the reverse trend is noted in the temperature profiles shown in Fig. 15.

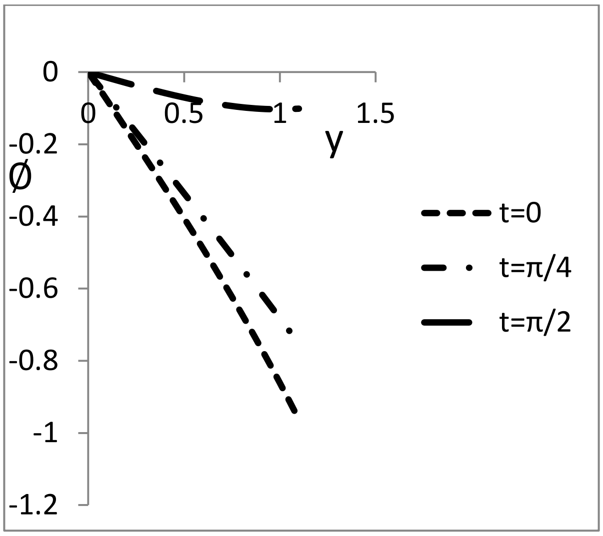

Fig.13: Effects of t on concentration profiles

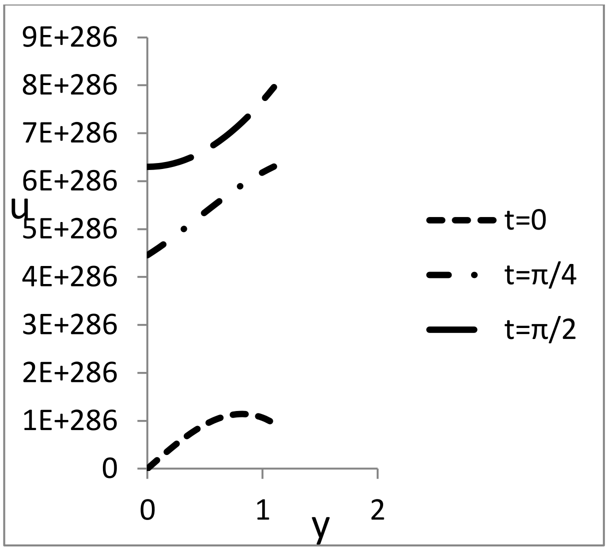

Fig.14: Effects of t on velocity profiles

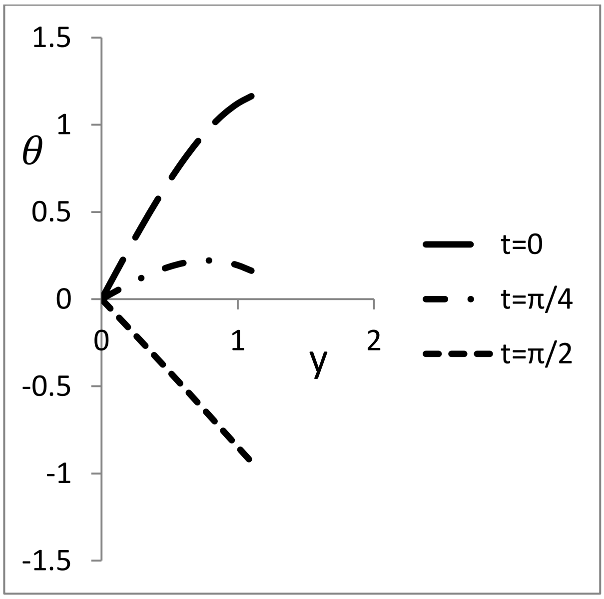

Fig.15: Effects of t on temperature distribution

The effect of Grashoff number, radiation parameter, Peclet number and heat generation parameter are shown in TABLE I

TABLE I

Behaviour of the channel shear stress for Gc = 0.5, $\lambda = 1$, H =1, *Sf = 1, t =0, Re = 1, Kr = 0.5, ω = 1 and Sc = 0.6.*

Gr	N	Pe	γ	$\tau(0)$	$\tau(1)$
1	**1**	**0.71**	**0**	**2.1193 x e^{286}**	**-5.1625 x e^{286}**
2	**1**	**0.71**	**0**	**4.2387 x e^{286}**	**-1.0325 x e^{287}**
1	**2**	**0.71**	**0**	**3.8572 x e^{286}**	**-1.2807 x e^{286}**
1	**1**	**5**	**0**	**9.0175 x e^{286}**	**-9.8056 x e^{286}**
1	**1**	**0.71**	**0.4**	**1.2534 x e^{286}**	**-7.1451 x e^{286}**

The effect of the Peclet number, radiation parameter and heat generation parameter is to suppress the Nusselt number at y = 0 and y = 1 shown in TABLE II.

TABLE II

Behaviour of heat transfer rate i.e. Nusselt number of the channel for Kr *= 0.5, λ = 1, Gr = 1.0, Gc = 0.5, t = 0, Sf = 1, Re = 1, ω = 1, H = 1, and Sc =0.6.*

Pe	N	γ	Nu(0)	Nu(1)
0.71	**1**	**0**	**3.26644**	**0.506804**
5	**1**	**0**	**-0.00491**	**-0.923976**
0.71	**2**	**0**	**-0.34300**	**-0.383232**
0.71	**1**	**0.4**	**3.04322**	**0.086245**

Behaviour of Reynold's number, Scmidth's number and chemical reaction parameters is to enhance the Sherwood number at y = 0 shown in TABLE III.

TABLE III

Behavior of mass transfer rate i.e. Sherwood number of the channel for *Gc = 0.5, t = 1, H =1, Gr = 1, λ = 1,* $\gamma = 0$, *Sf = 1, ω = 1, and N = 1*

Re	Sc	Kr	Sh(0)	Sh(1)
1	**0.6**	**0.5**	**-0.79133**	**-1**
7	**0.6**	**0.5**	**-0.29076**	**-1**
1	**3**	**0.5**	**-0.31411**	**-1**
1	**0.6**	**2**	**-0.39009**	**-1**

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