Available online at www.elixirpublishers.com (Elixir International Journal)

Applied Mathematics

Elixir Appl. Math. 101 (2016) 43845-43853

ISSN: 2229-712X

# Unsteady Chemically Reactive MHD Flow Over a Horizontal Surface in a Porous Medium in the Presence of Heat Source, Soret and Dufour Effects

B.R.Sharma and Debozani Borgohain

Department of Mathematics, Dibrugarh University, Dibrugarh-786004, Assam, India.

ARTICLE INFO

Article history:

Received: 10 October 2016;

Received in revised form: 19 November 2016;

Accepted: 2 December 2016;

Keywords

Heat and Mass transfer,
MHD,
Porous Medium,
Dufour and Soret effects,
Chemical reaction.

ABSTRACT

Soret and Dufour effects on unsteady heat and mass transfer of an incompressible chemically reacting, electrically conducting memory fluid over a continuously moving horizontal non-conducting surface embedded in a porous medium in the presence of transverse magnetic field and volumetric rate of heat generation/ absorption are investigated. The governing non linear partial differential equations are transformed into coupled non dimensional non linear ordinary differential equations by using separation of variables and series expansion methods and are solved numerically by using MATLAB's built in solver bvp4c. The influence of the Dufour number, Soret number, porosity parameter, heat source parameter and dimensionless chemical reaction parameter on temperature and concentration profiles as well as on local Nusselt number and Sherwood number are illustrated graphically. It is concluded that the Soret number, Dufour number and the chemical reaction parameter play a crucial role on the heat and mass transfer.



## 1.Introduction

Heat and mass transfer has many applications in reservoir engineering, chemical industries, extending theory of separation processes, hydro-metallurgical industries and other processes due to which it has received great amount of interest of the researchers over decades. . Many researchers such as Nield and Bejan[1], Vafai[2] and Ingham and Pop[3, 4] have made comprehensive reviews on free convection heat and mass transfer through porous media due to their important applications in the field of large storage systems of agricultural products, petroleum extraction, control of pollutant spread in groundwater, solar power collectors, heat recovery from geothermal systems and porous material regenerative heat exchangers. The binary mixture in MHD through porous medium has many applications in nuclear reactors, problems dealing with liquid metals, geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors and underground energy transport, the study of the stellar and solar structures, interstellar matter, radio propagation through the ionosphere, MHD pumps, MHD bearings, existence of geomagnetic field, hydromagnetic flow and heat transfer in the earth's liquid core and others [5, 6]. Chemical reactions in combined heat and mass transfer problems play a significant role. Chemical reaction between a foreign mass and the fluid occurs in many industrial applications such as polymer production, the manufacturing of ceramics or glassware, formation and dispersion of fog, damage of crops due to freezing, distribution of temperature and moisture over groves of fruit trees and so on.

## II. Related Work

Researchers such as Sparrow and Cess [7], Riley [8], Raptis and Kafoussias [9], Raptis and Singh [10], Raptis [11], Hossain [12], Kafoussias [13], Takhar and Ram [14], Chamkha [15] have investigated magnetohydrodynamic flow and heat transfer in porous and non-porous geometries.

The magnetohydrodynamic unsteady flow of non-Newtonian fluid past an infinite porous plate was discussed by Ezzat Madgy [16]. Chowdhury and Islam [17] have studied the MHD free convection flow of visco-elastic fluid past an infinite vertical porous plate. Vinay Kumar et al. [18] have investigated the heat transfer in MHD free convection flow over an infinite vertical plate through porous medium with time dependent suction. Unsteady MHD memory flow with oscillating suction, variable free stream and heat source was studied by Mustafa et. al.[19]. The unsteady oscillatory MHD flow of a visco-elastic fluid past a porous vertical plate with periodic suction was examined by Rita and Kamal [20]. The effects of heat transfer on MHD free convective flow through porous medium with viscous dissipation were discussed by Hemant Poonia and Chaudhary [21].

Soret effect is the tendency of a convection-free fluid mixture to separate under a temperature gradient. Soret effect also plays a crucial role in the hydrodynamic instability of mixtures, mineral migrations and mass transport in living matters. The influence of chemical reaction, heat source, Soret and Dufour effects on separation of a binary fluid mixture in MHD natural convection flow in porous media were studied by Sharma et al.[22]. Sharma et al. [23] have analyzed the influence of the order of chemical reaction and Soret effect on mass transfer of a binary fluid mixture over a stretching tube embedded in a porous media. Influence of chemical reaction, Soret and Dufour effects on heat and mass transfer of a binary fluid mixture in porous medium over a rotating disk were investigated by Sharma and Borgohain [24]. The Soret and Dufour effects on chemically reacting MHD mixed convection flow from a rotating vertical cone in a porous medium were studied by Sharma and Borgohain [25]. Effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction were analyzed by Deka et al. [26].

Tele:
E-mail address: bishwaramsharma@yahoo.com

Muthucumaraswamy and Ganesan [27] have discussed the effect of the chemical reaction and injection on flow characteristics in an unsteady upward motion of an isothermal plate. The effects of thermal radiation and viscous dissipation on MHD heat and mass diffusion flow past an oscillating vertical plate embedded in a porous medium with variable surface conditions were studied by Kishore et al. [28]. Sandeep et al. [29] have investigated the effect of radiation and chemical reaction on transient MHD free convective flow over a vertical plate through porous media. Sreelatha et. al.[30] have discussed the chemical reaction and ohmic dissipation effects on MHD flow through porous medium.

The present paper deals with the two dimensional unsteady mixed convection flow over a continuously moving horizontal non-conducting surface embedded in a porous medium in the presence of heat generation or absorption, first order chemical reaction and transverse magnetic field. The aim of this paper is to study the influence of Soret effect, Dufour effect, porosity parameter and dimensionless chemical reaction parameter. The effects of material parameters on temperature and concentration are investigated mathematically.

## III. Mathematical Formulation

Consider the unsteady laminar incompressible boundary layer flow of a viscous, chemically reacting, electrically conducting and heat generating/ absorbing memory fluid over a continuously moving horizontal non-conducting surface embedded in a porous medium in the presence of a transverse magnetic field $B_0$. The x-axis is taken along the surface i.e. in the direction of the flow and y-axis normal to the surface. Figure 1 shows the physical model of the problem. The fluid properties are assumed to be constant. The induced magnetic field is considered to be very small in comparison to the applied magnetic field and hence is neglected.

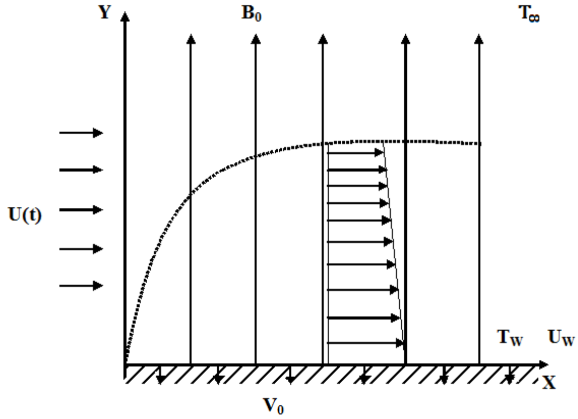



**Figure 1. Physical model.**

Under these assumptions as well as the Boussinesq approximation, the governing equations of continuity, momentum, energy and diffusion are given by

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

$$\rho\left(\frac{\partial u^*}{\partial t^*}+v^*\frac{\partial u^*}{\partial y^*}\right)=\rho\frac{\partial U^*(t)}{\partial t^*}+\mu\frac{\partial^2 u^*}{\partial y^{*2}}+\rho g\beta_T(T-T_\infty)+\rho g\beta_C(C-C_\infty)-B_1\left(\frac{\partial^3 u^*}{\partial t^*\partial y^{*2}}+v^*\frac{\partial^3 u^*}{\partial y^{*3}}\right)-\left(\sigma B_0^2+\frac{\rho\nu}{\kappa}\right)\left(u^*-U^*(t^*)\right) \tag{2}$$

$$\frac{\partial T}{\partial t^*}+v^*\frac{\partial T}{\partial y^*}=\alpha_m\frac{\partial^2 T}{\partial y^{*2}}+\frac{\nu}{c_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2+\frac{\sigma B_0^2}{\rho c_p}\left(u^*-U^*(t^*)\right)^2+Q_0(T-T_\infty)+\frac{D_m K_T}{c_s c_p}\frac{\partial^2 C}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial C}{\partial t^*}+v^*\frac{\partial C}{\partial y^*}=D_m\frac{\partial^2 C}{\partial y^{*2}}+\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^{*2}}-K_1(C-C_\infty) \tag{4}$$

where $u^*$ and $v^*$ are the fluid velocity components along x-axis and y-axis respectively, $t^*$ is time, T is temperature, C is concentration, $\nu$ is the kinematic viscosity, $\sigma$ is the electrical conductivity, $B_0$ is the applied magnetic field, $B_1$ is the kinematic viscoelasticity, $\rho$ is the fluid density, $\beta_T$ is the thermal expansion coefficient, $\beta_C$ is compositional expansion coefficient, $\alpha_m$ is the thermal diffusivity, g is the acceleration due to gravity, $K_1$ is the dimensional chemical reaction parameter, $c_p$ is the specific heat of the fluid, $D_m$ is the mass diffusion coefficient, $Q_0$ is the heat generation/ absorption coefficient, $K_T$ is the thermal diffusion ratio, $c_s$ is the concentration susceptibility , $T_m$ is the mean fluid temperature, $\kappa$ is the permeability of porous medium and $U^*(t^*)$ is the uniform free stream.

The boundary conditions are:

$$\left.\begin{array}{lll} u^*=U_W,\ T=T_W,\ C=C_W+\varepsilon(C_W-C_\infty)e^{i\omega^* t^*} & \text{at} & y^*=0 \\ u^*\to U^*(t^*),\ T\to T_\infty,\ C\to C_\infty & \text{as} & y^*\to\infty \end{array}\right\} \tag{5}$$

where $U_W$ is the surface velocity, $T_W$ is the surface temperature, $C_W$ is the surface concentration, $T_\infty$ is the free stream temperature, $C_\infty$ is the free stream concentration and $\omega^*$ is the frequency.

Taking in view equation (1) we assume the suction velocity of the form

$$v^*=-v_0\left(1+\varepsilon e^{i\omega^* t^*}\right) \tag{6}$$

where $v_0$ is the cross flow velocity.

Introduce the following non-dimensional quantities:

$$y=\frac{y^{*}v_0}{\nu}, t=\frac{t^{*}v_0^2}{4\nu}, u=\frac{u^{*}}{U}, U(t)=\frac{U^{*}(t^{*})}{U}, \omega=\frac{\omega^{*}4\nu}{v_0^2}, \theta=\frac{(T-T_\infty)}{(T_W-T_\infty)}, \phi=\frac{(C-C_\infty)}{(C_W-C_\infty)}, U=\frac{U_W}{\beta_T}, R_m=\frac{B_1 v_0^2}{\rho\nu^2}, M=\frac{\nu\sigma B_0^2}{\rho v_0^2}, Sc=\frac{\nu}{D_m}, \gamma=\frac{K_1\nu}{v_0^2}, G_T=\frac{\nu g\beta_T(T_W-T_\infty)}{Uv_0^2}, G_C=\frac{\nu g\beta_C(C_W-C_\infty)}{Uv_0^2}, Da=\frac{\kappa v_0^2}{\nu^2}, Pr=\frac{\nu}{\alpha_m}, \delta=\frac{Q_0\nu^2}{\alpha_m v_0^2}, Ec=\frac{U^2}{c_p(T_W-T_\infty)}, D_f=\frac{D_mK_T}{c_sc_p\alpha_m}\frac{(C_W-C_\infty)}{(T_W-T_\infty)}, Sr=\frac{D_mK_T}{T_m\alpha_m}\frac{(T_W-T_\infty)}{(C_W-C_\infty)} \quad (7)$$

Introducing the relation (6)-(7) into the equations (2)-(4), the following non dimensional equations are obtained:

$$\frac{1}{4}\frac{\partial u}{\partial t}-\left(1+\varepsilon e^{i\omega t}\right)\frac{\partial u}{\partial y}=\frac{1}{4}\frac{\partial U}{\partial t}+\frac{\partial^2 u}{\partial y^2}+G_T\theta+G_C\phi-\frac{1}{4}R_m\frac{\partial^3 u}{\partial t\partial y^2}+R_m\left(1+\varepsilon e^{i\omega t}\right)\frac{\partial^3 u}{\partial y^3}-\left(M+\frac{1}{Da}\right)\left(u-U(t)\right) \quad (8)$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t}-\left(1+\varepsilon e^{i\omega t}\right)\frac{\partial \theta}{\partial y}=\frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2}+Ec\left(\frac{\partial u}{\partial y}\right)^2+M.Ec\left(u-U(t)\right)^2+\frac{\delta}{Pr}\theta+\frac{D_f}{Pr}\frac{\partial^2 \phi}{\partial y^2} \quad (9)$$

$$\frac{1}{4}\frac{\partial \phi}{\partial t}-\left(1+\varepsilon e^{i\omega t}\right)\frac{\partial \phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2}+\frac{Sr}{Pr}\frac{\partial^2 \theta}{\partial y^2}-\gamma\phi \quad (10)$$

where $G_T$ is the thermal Grashof number, $G_C$ is the solutal Grashof number, $R_m$ is the Magnetic Reynolds number, M is the Hartmann Number i.e magnetic field parameter, Da is the permeability parameter, Pr is the Prandtl number, Ec is the Eckert number, $\delta$ is the heat source parameter, $D_f$ is the Dufour number, $Sc$ is the Schimdt number, $Sr$ is the Soret number and $\gamma$ is the dimensionless chemical reaction parameter.

The boundary conditions (5) in terms of dimensionless quantities reduce to

$$\left.\begin{array}{lll} u=\beta_T, u'=0, \theta=1, \phi=1+\varepsilon e^{i\omega t} & \text{at} & y=0 \\ u\to U(t), \theta\to 0, \phi\to 0 & \text{as} & y\to\infty \end{array}\right\} \quad (11)$$

## IV. Solution of the Problem

Equations (8) – (10) are coupled, non-linear partial differential equations and so cannot be solved in closed form. However, these equations can be reduced to a set of ordinary differential equations by using series expansion method. This can be done by representing the velocity, temperature and concentration of the fluid as

$$u(y,t)=u_0(y)+\varepsilon e^{i\omega t}u_1(y)+o(\varepsilon^2)+\cdots \quad (12)$$

$$\theta(y,t)=\theta_0(y)+\varepsilon e^{i\omega t}\theta_1(y)+o(\varepsilon^2)+\cdots \quad (13)$$

$$\phi(y,t)=\phi_0(y)+\varepsilon e^{i\omega t}\phi_1(y)+o(\varepsilon^2)+\cdots \quad (14)$$

And for free stream velocity

$$U(t)=1+\varepsilon e^{i\omega t} \quad (15)$$

Substituting equations (12)-(15) into equations (8)-(10) and equating the harmonic and non-harmonic terms after neglecting the terms of $o(\varepsilon^2)$ and higher than that, the following pairs of equations for $(u_0,\theta_0,\phi_0)$ and $(u_1,\theta_1,\phi_1)$ are obtained:

$$R_m u_0'''+u_0''+u_0'-\left(M+\frac{1}{Da}\right)u_0+G_T\theta_0+G_C\phi_0+\left(M+\frac{1}{Da}\right)=0 \quad (16)$$

$$R_m u_1'''+R_m u_0'''+\left(1-\frac{1}{4}R_m i\omega\right)u_1''+u_0'+u_1'-\left(M+\frac{1}{Da}-\frac{1}{4}i\omega\right)u_1+G_T\theta_1+G_C\phi_1+\left(M+\frac{1}{Da}+\frac{1}{4}i\omega\right)=0 \quad (17)$$

$$\frac{1}{Pr}\theta_0''+\frac{D_f}{Pr}\phi_0''+Ec(u_0')^2+\frac{\delta}{Pr}\theta_0+\theta_0'+M.Ec(u_0^2+1-u_0)=0 \quad (18)$$

$$\frac{1}{Pr}\theta_1''+\frac{D_f}{Pr}\phi_1''+2Ec.u_0'u_1'+\left(\frac{\delta}{Pr}-\frac{1}{4}i\omega\right)\theta_1+\theta_0'+\theta_1'+2M.Ec(u_0u_1-u_1+1-u_0)=0 \quad (19)$$

$$\frac{1}{Sc}\phi_0''+\frac{Sr}{Pr}\theta_0''+\phi_0'-\gamma\phi_0=0 \quad (20)$$

$$\frac{1}{Sc}\phi_1''+\frac{Sr}{Pr}\theta_1''-\left(\gamma+\frac{1}{4}i\omega\right)\phi_1+\phi_0'+\phi_1'=0 \quad (21)$$

where the prime denotes differentiation with respect to y.

The corresponding boundary conditions reduce to

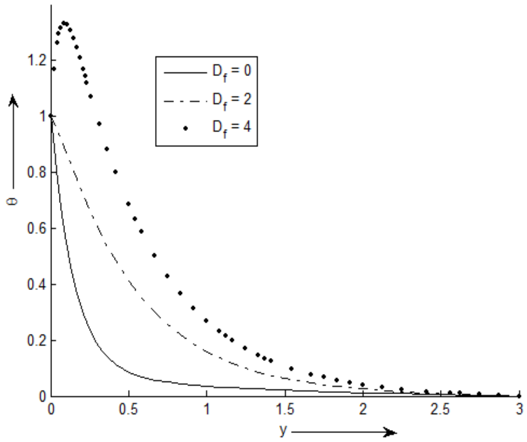
$$\left.\begin{array}{lll} u_0=\beta_T, u_1=0, u_0'=0, u_1'=0, \theta_0=1, \theta_1=0, \phi_0=1, \phi_1=1 & \text{at} & y=0 \\ u_0=1, u_1=1, \theta_0=0, \theta_1=0, \phi_0=0, \phi_1=0 & \text{as} & y\to\infty \end{array}\right\} \quad (22)$$

## V. Results and Discussion

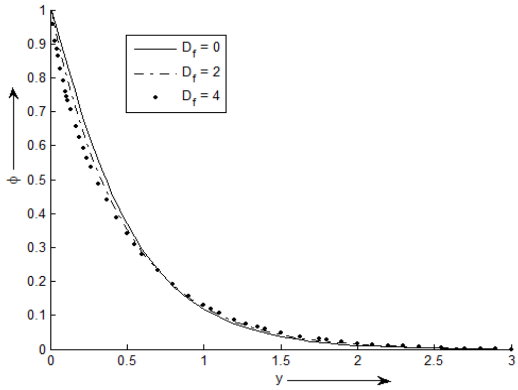
The set of equations (16) to (21) under the boundary conditions (22) are non-linear and highly coupled ordinary differential equations and so cannot be obtained in closed form. Therefore these equations are solved numerically with MATLAB's built-in solver bvp4c.

Numerical calculations have been carried out for concentration of the rarer component and temperature of the memory fluid for various values of the parameters $D_f$, Sr, $\gamma$, $\delta$, M, $Da^{-1}$ and Pr and are plotted against *y* in Figures 2-8. The value of Schmidt number (*Sc*) is chosen for ethanol diffused in air (Sc = 1.6). The values of Prandtl number is chosen to be *Pr* = (4, 5, 7) which represent water at temperature 44°C, 34°C, 20°C respectively. Also the buoyancy parameters are chosen as thermal Grashof number $G_T$ =1 > 0 (which corresponds to the cooling problem) and solutal Grashof number $G_c$ =1 > 0 (which indicates that the chemical species concentration in the free stream region is less than the concentration at the boundary surface).

Figures 2 (a)-(b) exhibit temperature and concentration profiles for various values of $D_f = (0, 2, 4)$ by taking $Sr = 0.6$, $\gamma = 1$, $\delta = 2$, $M = 1$, $Da^{-1} = 0.01$, $Pr = 7$, $R_m = 0.5$, $G_T = 1$, $G_C = 1$, $\omega = 0.1$, $\omega t = \frac{\pi}{3}$, $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.01$. It is observed that the temperature increases near the surface and attains its maximum value at about $y = 0.1 - 0.2$ and then decreases exponentially to the minimum value at the end of the boundary layer. It is also noticed that concentration decreases exponentially from the maximum value at the surface to the minimum value at the end of the boundary layer. It is also observed that with an increase in the values of Dufour number $D_f$, the temperature increases sharply while the concentration of the fluid decreases near the surface and the effect gets reversed after $y = 0.7$. Thus it is evident that the Dufour number favours the temperature of the memory fluid whereas the species separation can be enhanced by decreasing the Dufour number in the region $y < 0.7$ and increasing Dufour number in the region $y > 0.7$. At y = 0.7 the species separation is not affected by the change in the values of Dufour number.



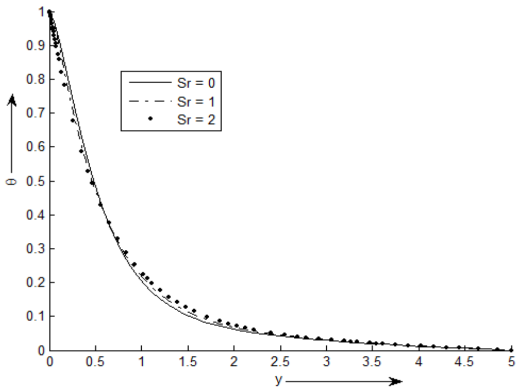
(a)



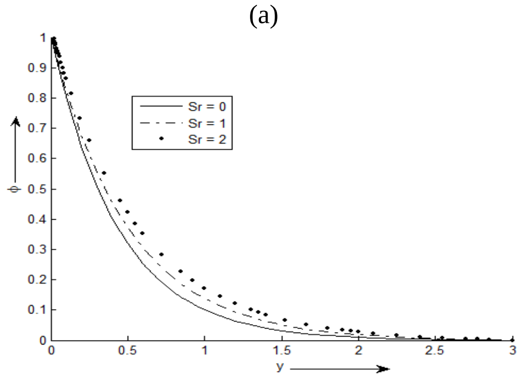
(b)

**Figure 2. Effects of Dufour number $D_f$ on (a) temperature profiles and (b) concentration profiles.**

Figures 3 (a)-(b) depict temperature and concentration profiles for various values of $Sr = (0, 1, 2)$ by taking $D_f = 2$, $\gamma = 1$, $\delta = 2$, $M = 1$, $Da^{-1} = 0.01$, $Pr = 7$, $R_m = 0.5$, $G_T = 1$, $G_C = 1$, $\omega = 0.1$, $\omega t = \frac{\pi}{3}$, $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.01$ It is observed that there is an exponential decrease in temperature and concentration of the fluid from the maximum value at the surface to the minimum value at the end of the boundary layer. It is also noticed that with an increase in the values of Soret number Sr, the concentration increases sharply while the temperature of the fluid decreases near the surface and the effect gets reversed after $y = 0.5$. It is seen that at $y = 0.5$, the temperature is not affected by the change in the values of Soret number. Thus it can be established that the species separation can be enhanced by increasing the Soret number while the temperature of the memory fluid rises by decreasing the Soret number in the region $y < 0.5$ and increasing Soret number in the region $y > 0.5$.



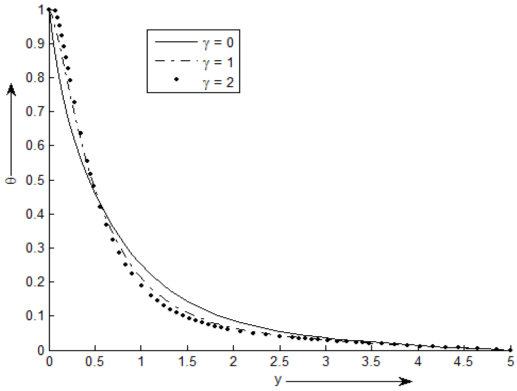
(a)



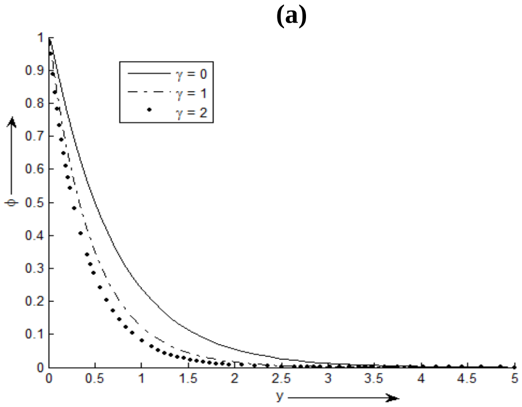
**(b)**

**Figure 3. Effects of Soret number Sr on (a) temperature profiles and (b) concentration profiles.**

The temperature and concentration profiles for various values of $\gamma = (0,1,2)$ by considering $D_f = 2$, $Sr = 0.6$, , $\delta = 2$, $M = 1$, $Da^{-1} = 0.01$, $Pr = 7$, $R_m = 0.5$, $G_T = 1$, $G_C = 1$, $\omega = 0.1$, $\omega t = \frac{\pi}{3}$, $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.01$ are shown in figures 4 (a) - (b). It is noticed that the temperature and concentration of the fluid decrease exponentially from their maximum value at the surface to their minimum value at the end of the boundary layer. It is also observed that with an increase in the values of dimensionless chemical reaction parameter $\gamma$, the concentration decreases sharply while the temperature of the fluid increases near the surface and the effect gets reversed after $y = 0.5$. It is seen that at $y = 0.5$, the temperature is not affected by the change in the values of dimensionless chemical reaction parameter.



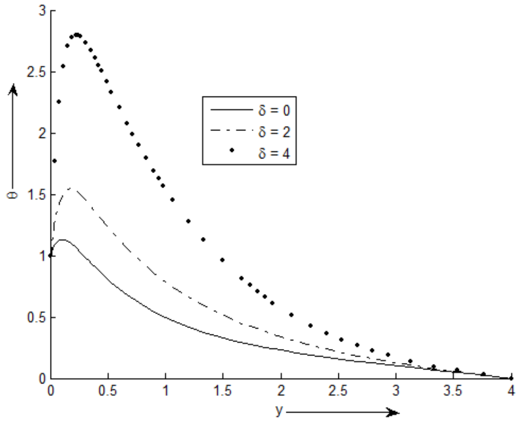

**(a)**



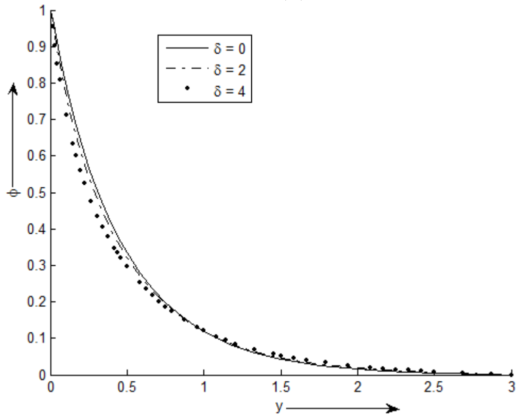

**(b)**

**Figure 4. Effects of dimensionless chemical reaction parameter $\gamma$ on (a) temperature profiles and (b) concentration profiles.**

Figures 5 (a)-(b) exhibit temperature and concentration profiles for various values of $\delta = (0,2,4)$ by taking $D_f = 2$, $Sr = 0.6$, $\gamma = 1$, , $M = 1$, $Da^{-1} = 0.01$, $Pr = 7$, $R_m = 0.5$, $G_T = 1$, $G_C = 1$, $\omega = 0.1$, $\omega t = \frac{\pi}{3}$, $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.1$. It is noticed that the temperature increases near the surface and attains its maximum value at about $y = 0.2$ and then decreases exponentially to the minimum value at the end of the boundary layer. It is also observed that concentration decreases exponentially from the maximum value at the surface to the minimum value at the end of the boundary layer. It is also noticed that with an increase in the values of heat source parameter $\delta$, the temperature increases sharply while the concentration of the fluid decreases near the surface and the effect gets reversed after $y = 0.9$.



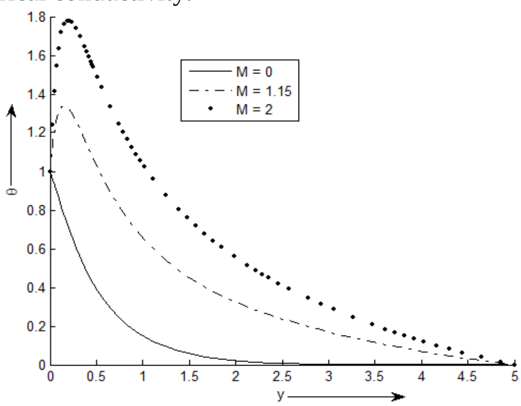

**(a)**



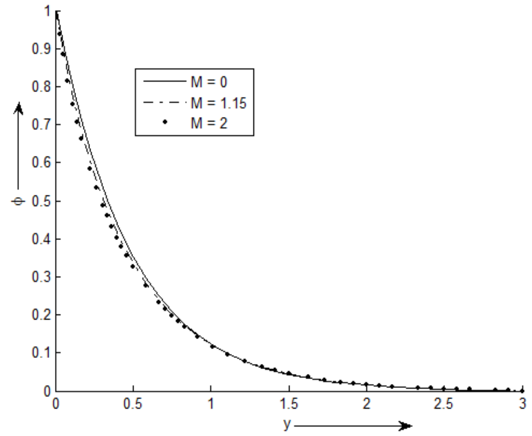

**(b)**

**Figure 5. Effects of heat source parameter $\delta$ on (a) temperature profiles and (b) concentration profiles.**

Figures 6 (a)-(b) depict temperature and concentration profiles for various values of $M = (0, 1.15, 2)$ by taking $D_f = 2$, $Sr = 0.6$, $\gamma = 1$, $\delta = 2$, , $Da^{-1} = 0.01$, $Pr = 7$, $R_m = 0.5$, $G_T = 1$, $G_C = 1$, $\omega = 0.1$, $\omega t = \frac{\pi}{3}$, $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.05$. It is observed that the temperature increases near the surface, attains the maximum value and then decreases exponentially to the minimum value at the end of the boundary layer. It is also noticed that there is an exponential decrease in concentration of the fluid from the maximum value at the surface to the minimum value at the end of the boundary layer. It is also observed that with an increase in the values of Hartmann number M, the temperature increases sharply while the concentration of the fluid decreases. Hence it is established that the temperature of the memory fluid rises while species separation is reduced by enhancing the magnetic field strength and electrical conductivity.



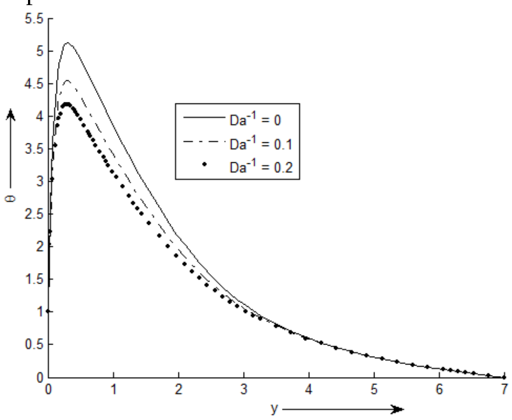

**(a)**



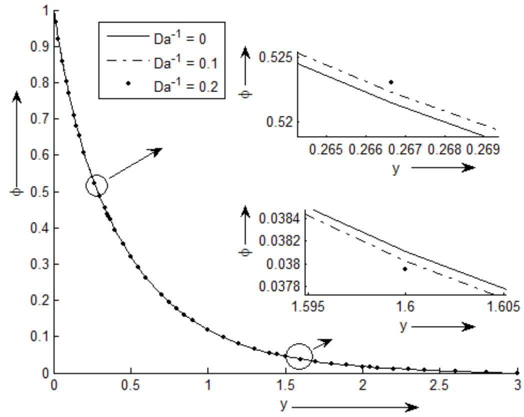

**(b)**

**Figure 6. Effects of Hartmann number M on (a) temperature profiles and (b) concentration profiles.**

The temperature and concentration profiles for various values of $Da^{-1} = (0, 0.1, 0.2)$ are shown in figures 7 (a) - (b). The values of other parameters are taken as $D_f = 2$, $Sr = 0.6$, $\gamma = 1$, $\delta = 2$, $M = 1$, , $Pr = 7$, $R_m = 0.5$, $G_T = 1$ , $G_C = 1$ , $\omega = 0.1$, $\omega t = \frac{\pi}{3}$ , $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.1$ It is noticed that the temperature increases near the surface, attains the maximum value at about $y = 0.3$ and then decreases exponentially to the minimum value at the end of the boundary layer. It is also observed that concentration decreases exponentially from the maximum value at the surface to the minimum value at the end of the boundary layer. It is also noticed that with an increase in the values of porosity parameter $Da^{-1}$, the temperature decreases sharply while the concentration of the fluid increases very slightly near the surface with reverse effect after $y = 1.4$. Hence it is evident that the porosity of the medium has adverse effect on the temperature of the fluid i.e. more the porosity less is the temperature. Also the species separation can be enhanced by strengthening the porosity of the medium in the region y $<$ 1.4 and reducing the porosity in the region y $>$ 1.4. At y = 1.4 the change in porosity does not affect the species separation.



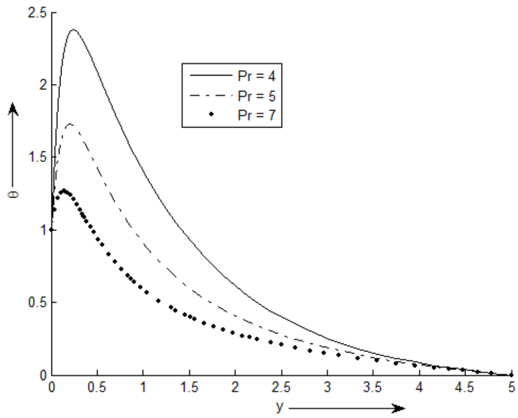

**(a)**



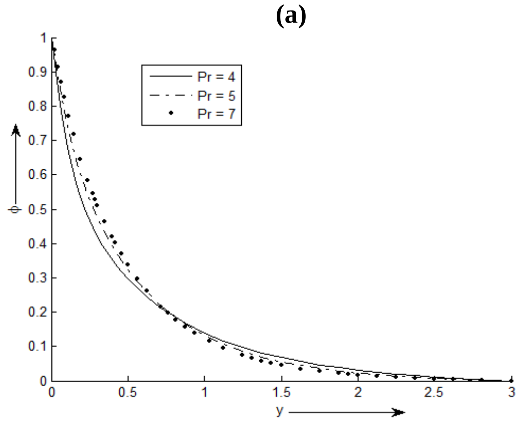

**(b)**

**Figure 7. Effects of porosity parameter $Da^{-1}$ on (a) temperature profiles and (b) concentration profiles.**

Figures 8 (a) – (b) exhibit the temperature and concentration profiles for various values of $Pr = (4, 5, 7)$ by considering $D_f = 2$, $Sr = 0.6$, $\gamma = 1$, $\delta = 2$, $M = 1$, $Da^{-1} = 0.01$, , $R_m = 0.5$, $G_T = 1$ , $G_C = 1$ , $\omega = 0.1$, $\omega t = \frac{\pi}{3}$ , $\varepsilon = 0.03$, $Sc = 1.6$, $Ec = 0.05$. It is noticed that the temperature increases near the surface, attains its maximum value at about $y = 0.2$ and then decreases exponentially to the minimum value at the end of the boundary layer. The concentration of the fluid is seen to decrease exponentially from its maximum value at the surface to its minimum value at the end of the boundary layer. It is also observed that the temperature decreases sharply while concentration increases near the surface and then decreases after $y = 0.7$ with the increase in the values of Prandtl number Pr.




**(a)**

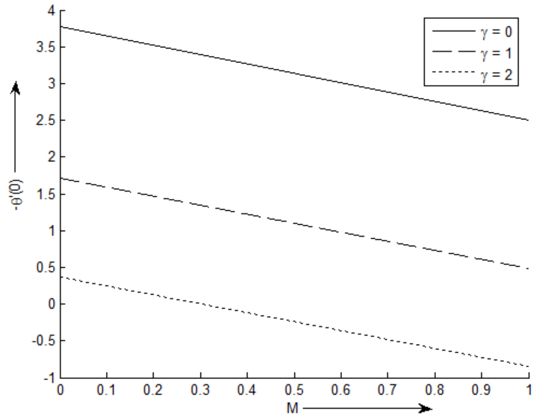



**(b)**

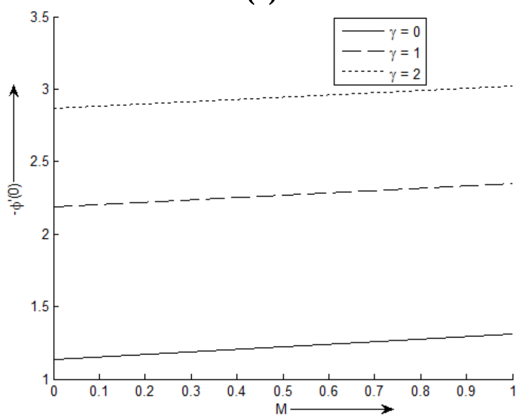
**Figure 8. Effects of Prandtl number Pr on (a) temperature profiles and (b) concentration profiles.**

Finally, with the help of the figures 9, 10 and 11, the behaviour of the local reduced Nusselt and Sherwood numbers $\left(-\theta'(0), -\phi'(0)\right)$ are observed.

Figure 9 show the effects of Hartmann number M and dimensionless chemical reaction parameter $\gamma$ on the local reduced Nusselt and Sherwood numbers $\left(-\theta'(0), -\phi'(0)\right)$. It is noticed that the local reduced Sherwood number $\left(-\phi'(0)\right)$ increase with increasing values of either the Hartmann number M or the dimensionless chemical reaction parameter $\gamma$. But the local reduced Nusselt number $\left(-\theta'(0)\right)$ decreases with increasing values of Hartmann number and decreasing chemical reaction parameter.



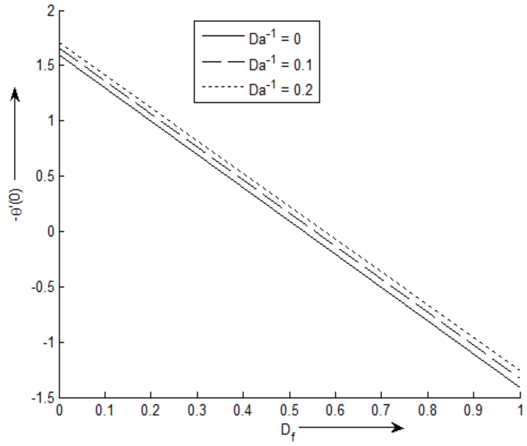

**(a)**



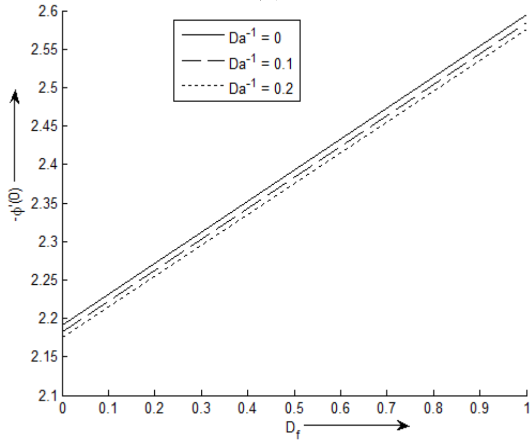

**(b)**

**Figure 9. Effects of Hartmann number M and dimensionless chemical reaction parameter $\gamma$ on (a) local reduced Nusselt number $-\theta'(0)$ and (b) local reduced Sherwood number $-\phi'(0)$.**

The effects of Dufour number $D_f$ and porosity parameter $Da^{-1}$ on the local reduced Nusselt and Sherwood numbers $\left(-\theta'(0), -\phi'(0)\right)$ are depicted in figure 10. It is noticed that the local reduced Sherwood number $\left(-\phi'(0)\right)$ increase with increasing values of the Dufour number $D_f$ and decreasing values of porosity parameter $Da^{-1}$. But the local reduced Nusselt number $\left(-\theta'(0)\right)$ decreases with increasing values of either the Dufour number $D_f$ or porosity parameter $Da^{-1}$.



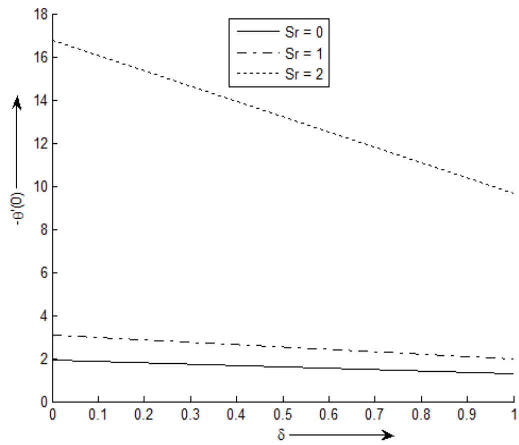

**(a)**



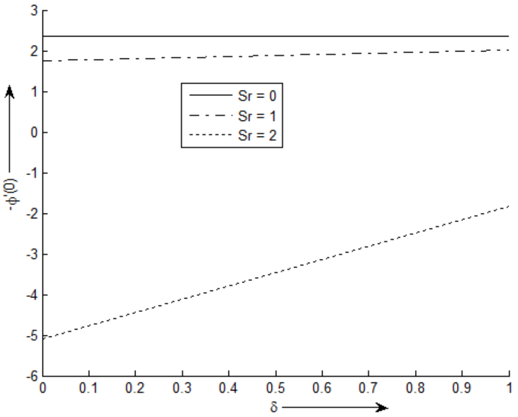

**(b)**

**Figure 10.Effects of Dufour number $D_f$ and porosity parameter $Da^{-1}$ on (a) local reduced Nusselt number $-\theta'(0)$ and (b) local reduced Sherwood number $-\phi'(0)$.**

Figure 11 exhibit the effects of Soret number Sr and heat source parameter $\delta$ on the local reduced Nusselt and Sherwood numbers $\left(-\theta'(0), -\phi'(0)\right)$. It is noticed that the local reduced Nusselt number $\left(-\theta'(0)\right)$ decreases with increasing values of either the Soret number Sr or the heat source parameter $\delta$ but the local reduced Sherwood number $\left(-\phi'(0)\right)$ increase with increasing values of the heat source parameter $\delta$ and decreasing values of the Soret number.




**(a)**




**(b)**

**Figure 11. Effects of Soret number Sr and heat source parameter $\delta$ on (a) local reduced Nusselt number $-\theta'(0)$ and (b) local reduced Sherwood number $-\phi'(0)$.**

## VI. Conclusion

- Enhancement in the Soret number and porosity parameter result in the enhancement of concentration of the rarer and lighter components while the rates of heat and mass transfer (Nusselt number and Sherwood number) decrease but the results get reversed with the enhancement of the dimensionless chemical reaction parameter.
- The temperature and the rate of mass transfer of the memory fluid increase with the enhancement of Dufour number but the result is opposite for the Nusselt number.
- Soret effect and porosity of the medium restrict the species separation and the rates of heat and mass transfer.
- Dufour effect favours the temperature of the memory fluid and rate of mass transfer but opposes the rate of heat transfer.
- Chemical reaction enhances the species separation and the rates of heat and mass transfer.
- Application of transverse magnetic field, electrical conductivity and heat source give a rise in temperature and favour the rate of mass transfer and species separation but oppose the rate of heat transfer.

The results of the work can be used by the researchers in the field of chemical engineering, petroleum engineering, medicines and ceramics. It will has its application in the production of petroleum, natural gases from porous earth, flow of blood through biological membranes and electro-osmosis, manufacturing of ceramic products and filtration of gases and liquids, chromatography and gel permeation. It is hoped that the present work will serve as a motivation for future experimental work which seems to be lacking at the present time.

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