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Dufour and Chemical Reaction Effect on MHD Free Convective Heat and Mass Transfer over a Vertical Surfaces in a Porous Media Considering Variable Permeability

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Abstract: In this paper we study the unsteady two-dimensional free convection and mass transfer flow of a viscous incompressible electrically conducting fluid through a porous medium with variable permeability in the presence of a radiation, a first-order homogeneous chemical reaction and magnetic filed is studied, by taking into account the diffusion -thermo (Dufour) effect. The permeability of the porous medium fluctuates in time about constant mean. The free stream velocity of the fluid vibrates about mean a constant value and the surface absorbs the fluid constant velocity. A uniform magnetic field acts perpendicular to the porous surface, which absorbs the fluid with a suction velocity varying with time. The dimensionless governing equations for this investigation are solved analytically using two-term harmonic and non-harmonic functions. Graphical results for velocity, temperature and concentration profiles of both phases based on the analytical solutions are presented and discussed.

Key words: Analytical solution · Unsteady flow · Chemical reaction · Free convection · Heat and mass transfer · Dufour effect · Variable permeability

INTRODUCTION

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and the mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries, For example, in the power industry, among the methods of generating electric power is one in which e lectrical energy is extracted directly from a moving conducting fluid. There are two types of reactions. A homogeneous reaction is one that occurs uniformly throughout a give phase. The species generation in a homogeneous reaction is analogous to internal source of heat generation. In contrast, a heterogeneous reaction takes place in a restricted region or within the boundary of a phase. It can therefore be treated as a boundary condition similar to the constant heat flux condition in heat transfer. The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Recent books by Nield and Bejan [1] present a comprehensive account of the available information in the field. Thermal diffusion, also called thermodiffusion or Soret effect [2] corresponds to species differentiation developing in an initial homogeneous mixture submitted to a thermal gradient. In many studies Dufour and Soret effect are neglected, on the basis that they are of a smaller order of magnitude than the effects described by Fourier's and Fick's laws. There are however, exceptions. Eckert and Drake [3] present several cases when the Dufour effect cannot be neglected. Benano-Melly *et al.* [4] have analyzed the problem of thermal diffusion in binary fluid mixtures, lying within a porous medium and subjected to a horizontal thermal gradient. Raptis *et al.* [5] studied the influences of the free convective flow and mass transfer on the steady of a viscous fluid through the porous medium bounded by an infinite vertical plate with constant suction. Muthucumaraswamy and Ganesan [6] studied the effect of the chemical reaction and injection on flow characteristics in an unsteady upward motion of

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an isothermal plate. Deka *et al.* [7] studied the effect of the first-order homogeneous chemical reaction on the process of an unsteady flow past an infinite vertical plate with a constant heat and mass transfer. Chamkha [8] studied the MHD flow of a numerical of uniformly stretched vertical permeable surface in the presence of heat generation / absorption and a chemical reaction. Muthucumaraswamy and Ganesan [9] analyzed the effect of a chemical reaction on the unsteady flow past an impulsively started vertical plate which is subjected to uniform mass flux and in the presence of heat transfer. Muthucumaraswamy [10] studied the effects of suction on heat and mass transfer along a moving vertical surface in the presence of a chemical reaction. Raptis and Perdikis [11] analyzed the effect of a chemical reaction of an electrically conducting viscous fluid on the flow over a non-linearly (quadratic) semiinfinite stretching sheat in the presence of a constant magnetic field which in normal to the sheet. Ibrahim *et al.* [12] studied Effect of The Chemical Reaction and Radiation Absorption on the Unsteady MHD Free Convection Flow Past a Semi Infinite Vertical Permeable Moving Plate with Heat Source and Suction. In some industrial applications, such as fixed-bed catalytic reactors, packed bed heat exchangers and drying, the value of the porosity is maximum at the wall and minimum away from the wall so the porosity of the porous medium should be taken as non-uniform. Schwartz and Smith [13], Benenati and Brosilow [14] have shown that the permeability of the porous medium varies as the porosity varies from the wall to the interior of the porous medium. This well-channeling phenomena has been reported by Vafai [15] studied forced, natural and mixed convection boundary layer flows adjacent to horizontal and vertical surfaces. They have shown that the variable porosity effect increases the temperature gradient adjacent to the wall resulting in the surface heat flux. On the other hand, Chandrasekhar and Namboodiri [16] have shown the effectiveness of variable permeability of the porous medium on velocity distribution and heat transfer. Nevertheless, the inertia effects become important in a sparsely packed porous medium and hence their effect on mixed convection problems needs to be investigated. Mohammadein and El-Shaer [17] studied mixed convective flow past a semi-infinite vertical plate embedded in a porous medium incorporating the variable permeability in Darcy's model. Singh *et al.* [18] studied a free convective flow through a porous medium with periodic permeability variation. Singh *et al.* [19] studied three dimensional fluctuating flow and heat transfer through a porous medium with venerable permeability. Hassanien and Obied [20] Allah studied the effect of permeability variation on oscillatory hydromagnetic flow through a porous medium in the presence of free convection and mass transfer flow. Elaiw *et al.* [21] studied the effect of variable permeability on vortex instability combined free and mixed convection boundary layer flow over a horizontal heated plate in a saturated porous medium. Recently, Hamad and Pop [22] presented the similarity solution of two-dimensional stagnation-point flow of an incompressible viscous fluid towards a porous stretching surface embedded in a porous medium saturated by nanofluid subject to suction/blowing with internal heat generation or absorption. Muhaimin *et al.* [23] investigated the chemical reaction effects on natural convective boundary layer flow and heat and mass transfer of a fluid with temperature-dependent fluid viscosity and thermal radiation over a vertical stretching surface in the presence of suction. Bakr [24] investigated free convection heat and mass transfer adjacent to moving vertical porous infinite plate for incompressible, micropolar fluid in a rotating frame of reference in the presence of heat generation or absorption effects, a first- order chemical reactions. However, the effect of chemical reaction and permeability variation on heat and mass transfer by free convection from vertical surfaces in porous media considering Dufour and magntic field, dose not seem to have been investigation. This motivated the present investigation. Most of the previous studies of the same problem neglected Dufour effect and chemical reaction. In the present work is to study the effect of permeability variation, Dufour on oscillatory hydro-magnetic flow through porous medium in the presence of free convection and mass transfer flow. Here we assume that a chemically reactive species is emitted from the surface and diffuses into the fluid. The reaction is assumed to take place entirely in the stream. The porous medium is bounded by vertical surface of constant temperature.

MATERIALS AND METHODS

Mathematical Analysis: Consider unsteady two-dimensional flow of a laminar, viscous, electrically conducting and heat absorbing fluid past a semi-infinite vertical plate with constant suction. The flow is Considered, chemical reaction, Dufour effect, hydromagnetic free convection and mass transfer is taken into account. The fluid properties are assumed to be constant except that the influence of density variation with temperature has been considered only in the body-force term and the permeability of the porous medium is a function of the time t^*. It is also assumed that there exists a homogeneous first-order chemical reaction between the fluid and species concentration. The linear momentum equation is approximated according to the Boussinesq approximation. Due to the semi-infinite plane surface assumption, the x^*-axis is taken along the plane surface with direction opposite the direction of the gravity and the y^*-axis is taken to be normal to it the physical variables are functions of y^* and the time t^* only. Under these assumptions, the equations that describe the physical situation are given by:

$$\frac{\partial w^*}{\partial t^*} = 0, \tag{1}$$

$$\rho[\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*}] = -\frac{\partial P^*}{\partial x^*} + \mu \frac{\partial^2 u^*}{\partial y^{*2}} + \rho g - [\rho B_0^2 + \frac{\mu}{K_l^*(t^*)}]u^* \tag{2}$$

Permeability of the medium is assumed to be of the form

$$K_l^*(t^*) = K'(1 + \varepsilon e^{i\omega^* t^*}) \tag{3}$$

Where K' is the mean permeability of the medium, ω^* is the frequency of the fluctuation and ε << is a constant quantity

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k_T}{\rho c_p} \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{D_m k_T}{C_s c_p} \frac{\partial^2 C^*}{\partial y^{*2}} \tag{4}$$

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D_m \frac{\partial^2 C^*}{\partial y^{*2}} - k_l\left(C^* - C_\infty\right) \tag{5}$$

Where x^*, y^* are the dimensional distances along and perpendicular to the plate and dimensional time, respectively. u^* and v^* are the components of dimensional velocities along x^* and y^* directions, respectively, T^* is the dimensional temperature, C^* is the dimensional concentration, T_w and C_w are the temperature and concentration at the wall, T_∞ and C_∞ are the free stream dimensional temperature and concentration, ρ is the fluid density, c_p the kinematics viscosity, σ is the specific heat at constant pressure, B_0 is the electrical conductivity of the fluid, B_0 is the magnetic induction, D_m is the mass diffusivity, g is the gravitational acceleration and k_T is the thermal diffusion ratio. Integration of continuity Eq. (1) for constant suction velocity normal to the plate gives.

$$v^* = -V_o \tag{6}$$

Where V_o>0 is a constant and the negative sign indicates that the suction is towards the plate. Under these assumptions, the appropriate boundary conditions for the velocity, temperature and concentration fields are.

$$\begin{aligned} &u^* = 0, \quad T^* = T_w, \quad C^* = C_w \quad at \ y^* = 0 \\ &u^* \to U(1 + \varepsilon e^{i\omega^* t^*}), \ T^* \to T_\infty, \ C^* \to C_\infty \quad as \ y^* \to \infty \end{aligned} \tag{7}$$

In the free stream, from equation (2), we get

$$-\frac{\partial P^*}{\partial x^*} = \rho \frac{dU^*}{dt^*} + \rho_\infty g + [\sigma B_0^2 + \frac{\mu}{K_l^*(t^*)}]U^* \tag{8}$$

Upon substituting the expressions in (8) into equation (1), we have

$$\begin{aligned} &\rho\left(\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*}\right) = \rho \frac{dU^*}{\partial t^*} + \mu \frac{\partial^2 u^*}{\partial y^{*2}} + g(\rho_\infty - \rho) \\ &+[\sigma B_0^2 + \frac{\mu}{K_l^*(t^*)}](U^* - u^*) \end{aligned} \tag{9}$$

by making use of the equation of state [20]

$$\rho_\infty - \rho = \rho\beta(T^* - T_\infty) + \rho\beta^*(C^* - C_\infty) \tag{10}$$

Where β and β^* are the thermal and concentration volumetric coefficients, respectively.

On the introducing the dimensionless quantities:

$$\begin{aligned} &y = \frac{y^* V_0}{\upsilon}, u = \frac{u^*}{U}, t = \frac{t^* V_0^2}{\upsilon}, \omega = \frac{\omega^* \upsilon}{V_0^2}, \\ &U^+ = \frac{U^*}{U}, \theta = \frac{T^* - T_\infty}{T_w - T_\infty}, C = \frac{C^* - C_\infty}{C_w - C_\infty} \end{aligned} \tag{11}$$

In view of the above non-dimensional variables, the basic field Eqs. (4), (5) and (9) can be expressed in non dimensional form as

$$\begin{aligned} &\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial U^+}{\partial t} + Gr\theta + GmC + \frac{\partial^2 u}{\partial y^2} \\ &+(\frac{1}{K(1 + \varepsilon e^{i\omega t})} + M)(U^+ - u) \end{aligned} \tag{12}$$

$$\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2}+D_f\frac{\partial^2 C}{\partial y^2} \quad (13)$$

$$\frac{\partial C}{\partial t}-\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-\gamma C \quad (14)$$

The boundary condition can be written in non-dimensional forms as:

$$\begin{aligned} &u=0, \quad \theta=1, \quad \phi=1 \quad at \quad y=0\\ &u\to(1+\varepsilon e^{i\omega t}), \quad \theta=0, \quad \phi=0 \quad as \quad y\to\infty \end{aligned} \quad (15)$$

Where Gr is the Grashof number, Gm is the solutal Grashof number, Pr is the Prandtl number, M is the magnetic field parameter, K is the permeability parameter, γ is the Chemical reaction parameter, Sc is the Schmidt number, D_f is the Dufour parameter.

$$Sc=\frac{\nu}{D}, \Pr=\frac{\nu\rho c_p}{k}, Gr=\frac{\nu g B(T_w^*-T_\infty^*)}{UV_0^2}, Gm=\frac{\nu g B^*(C_w^*-C_\infty^*)}{UV_0^2},$$
$$M=\frac{\sigma B_0^2\nu}{V_0^2\rho}, \gamma=\frac{K_l\upsilon}{V_0^2}, D_f=\frac{D_m K_T(C_w-C_\infty)}{\upsilon C_s c_p(T_w-T_\infty)}, K=\frac{V_0^2k^*}{\nu^2}$$

The mathematical statement of the problem is now complete and embodies the solution of Equations (12)-(14) subject to boundary conditions (15).

Method of Solution: In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we may represent the liner velocity, temperature and concentration as.

$$\left.\begin{aligned} u(y,t)&=u_0(y)+\varepsilon e^{iwt}u_1(y),+O(\varepsilon^2)\\ \theta(y,t)&=\theta_0(y)+\varepsilon e^{iwt}\theta_1(y)+O(\varepsilon^2),\\ C(y,t)&=C_0(y)+\varepsilon e^{iwt}C_1(y)+O(\varepsilon^2),\end{aligned}\right\} \quad (16)$$

By substituting the above Eq. (16) into Eqs. (12-15), equating the harmonic and non-harmonic terms and neglecting the higher order of $O(\varepsilon^2)$ and simplifying we obtains the following pairs of equations for u_0, θ_0, C_0 and u_1,θ_1,C_1

For O(0), we get

$$u_0''+u_0'-(M+K^{-1})u_0=-(M+K^{-1})-GrT_0-GmC_0 \quad (17)$$

$$\theta_0''+\Pr\theta_0'=-\Pr D_f C_0'' \quad (18)$$

$$C_0''+ScC_0'-Sc\gamma C_0=0 \quad (19)$$

Subject to the boundary conditions:

$$\begin{aligned} &u_0=0, \quad \theta_0=1, \quad C_0=1 \quad at\ y=0\\ &u_0\to 1, \quad \theta_0\to 0, \quad C_0\to 0 \quad as\ y\to\infty \end{aligned} \quad (20)$$

For O(1), we get

$$u_1''+u_1'-(M+K^{-1}+i\omega)u_1=-(M+K^{-1})-Gr\theta_1-GmC_1 \quad (21)$$

$$\theta_1''+\Pr\theta_1'-i\omega\Pr\theta_1=-D_f\Pr C_1'' \quad (22)$$

$$C_1''+ScC_1'-Sc(i\omega+\gamma)C_1=0 \quad (23)$$

With the boundary conditions:

$$\begin{aligned} &u_1=0, \quad \theta_1=0, \quad C_1=0 \quad at\ y=0\\ &u_1\to 1, \quad \theta_1\to 0, \quad C_1\to 0 \quad as\ y\to\infty \end{aligned} \quad (24)$$

The prime denotes differentiation with respect to y.

Without going into detail, the solutions of Equations (17)-(19) and (21)-(23) subject to Equations (20), (24) can be shown to be.

$$\begin{aligned} u(y,t)&=(L_1+L_2-1)e^{R_1y}-L_1e^{-\Pr y}-L_2e^{m_1y}+1\\ &+\varepsilon e^{i\omega t}(1+A_6e^{R_1y}+A_7e^{-\Pr y}+A_8e^{m_1y}+A_9+A_{10}e^{R_3y}) \end{aligned} \quad (25)$$

$$\theta(y,t)=A_1e^{m_1y}+A_2e^{-\Pr y} \quad (26)$$

$$C(y,t)=A_1e^{m_1y} \quad (27)$$

The exponential indices and the coefficients appearing in the Eqs. (25 - 27) are given in the Appendix. The physical quantities of interest are the wall shear stress τ_w defined by.

$$\begin{aligned}\tau_w=\frac{\tau_w^*}{\rho UV_0}\left(\frac{\partial u}{\partial y}\right)_{y=0}&=R_1(L_1+L_2-1)+\Pr L_1+m_1L_2+\varepsilon e^{i\omega t}\\ &(A_6R_1-\Pr A_7+m1A_8+R_1A_{10})\end{aligned} \quad (28)$$

In addition, the rate of heat transfer at the surface of wall in terms of Nusselt number, Nu, can be written as:

$$Nu = -x\frac{\left(\partial T^* / \partial y^*\right)_{y=0}}{\left(T_w - T_\infty\right)} \Rightarrow Nu\,\mathrm{Re}_x^{-1} = -\theta'(0) = m_1 A_1 - A_2\,\mathrm{Pr} \quad (29)$$

The local Sherwood number is given by;

$$Sh = -x\frac{\left(\partial C^* / \partial y^*\right)_{y=0}}{\left(C_w - C_\infty\right)} \Rightarrow Sh\,\mathrm{Re}_x^{-1} = -C'(0) = -m_1 \quad (30)$$

Where $\mathrm{Re}_x = \frac{V_0 x}{\upsilon}$ is the local Reynolds number

RESULTS AND DISCUSSION

In order to get a clear insight of the physical problem, numerical results are displayed with the help of graphical illustrations. We consider a homogeneous first-order chemical reaction. The diffusing species either can be destroyed or generated in the homogeneous reaction. The chemical reaction parameter can be adjusted to meet these circumstances if one takes (i) $K > 0$ for a destructive reaction, (ii) $K < 0$ for a generative reaction and (iii) $K = > 0$ for no reaction. Numerical evaluation of the analytical results reported in the previous section was performed and a representative set of results is reported graphically in Figures 1-12. These results are obtained to illustrate the influence of the chemical reaction parameter γ, Dufour number D_f, the Schmidt number Sc, the magnetic field parameter M and permeability parameter K on the velocity, temperature and the concentration profiles, while the values of the physical parameters are fixed at real constants, A=0.5, ε = 0.01, the frequency of oscillations ω = 0.2, Grashof number $Gr = 10$, solutal Grashof number $Gm=2$, Prandtl number $Pr=0.71$ and $t = 1.0$.

Figures 1-3 displays results for the velocity, temperature and concentration distributions, respectively. It is seen, that the velocity, temperature and concentration increases with decreasing the chemical reaction parameter γ, Also, we observe that the magnitude of the stream wise velocity increases and the inflection point for the velocity distribution moves further away from the surface. The time required to reach the steady state increases with increasing Schmidt number and chemical reaction parameter. This shows that the contribution of mass diffusion to the buoyancy force increases the maximum velocity significantly. For the case of $\gamma > 0$, i.e., for a destructive reaction, increasing values of γ leads to a fall in velocity profiles or a generative reaction, $\gamma < 0$ a fall in velocity is also observed for increasing γ. This is due to the fact that as $\gamma < 0$, the last term in the concentration equation becomes positive and plays a crucial role.

For different values of the Dufour number D_f, the velocity and temperature profiles are plotted in Figures 4 and 5. It is obvious that an increase in the Dufour number D_f results increasing in the velocity and temperature profiles within the boundary layer, as well as increasing in the momentum and thermal thickness. This is because the large D_f-values correspond to increased dominance of conduction over absorption radiation there by increasing buoyancy force (thus, vertical velocity) and thickness of the thermal and momentum boundary layers.

Figures 6-8 display the effects of the Schmidt number Sc on the velocity, temperature and concentration profiles, respectively. As the Schmidt number increases, the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reductions in the velocity, temperature and concentration profiles are accompanied by simultaneous reductions in the momentum and concentration boundary layer thickens. These behaviors are clearly shown in Figures 6, 7 and 8. Also, the beak velocity and temperature increases as increases Schmidt number Sc. Figure 9 illustrate the variation of velocity distribution across the boundary layer for various values of the permeability parameter K. The velocity increases with decrease in permeability parameter K.

The local skin-friction profiles for different chemical reaction parameters and Dufour number D_f are plotted in Fig. 10. It is noted that the local shear stress increases with increasing values of the chemical reaction parameter and decreasing values of the Dufour number D_f. The local Nusselt number for different γ and D_f are presented in Figure 11. It is observed that the rate of heat transfer increases with decreasing values of γ and D_f.

The average skin friction and Nusselt number are shown in Figures 12-13 respectively, for various parameters. Figure 12 shows that the shear stress increases with increasing values of Sc. Initially, higher values of the average Nusselt numbers are observed and then they Schmidt numbers. The local Sherwood numbers for different values of Sc and γ are shown in Figure 14 higher

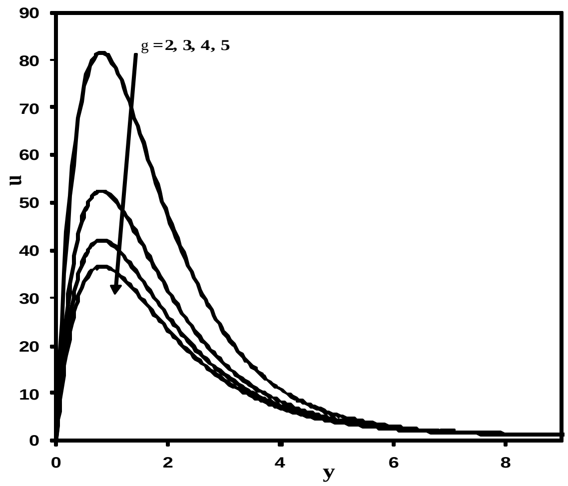

Fig. 1: Velocity profile against spanwise coordinate y for different values of (g) with $Gm = 2,\ Gr = 10, Sc = 0.6,\ K = 3,\ \ M = 0.2$ and $Df = 6$

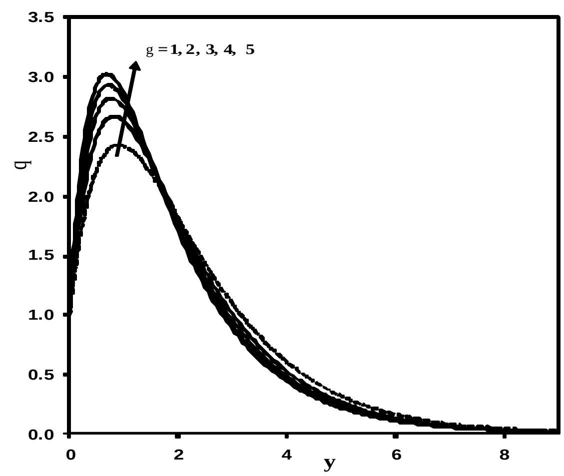

Fig. 2: Temperature profile against spanwise coordinate y for different values of (g) with $Gm = 2,\ Gr = 10, Sc = 0.6,\ K = 3,\ \ M = 0.2$ and $Df = 6$

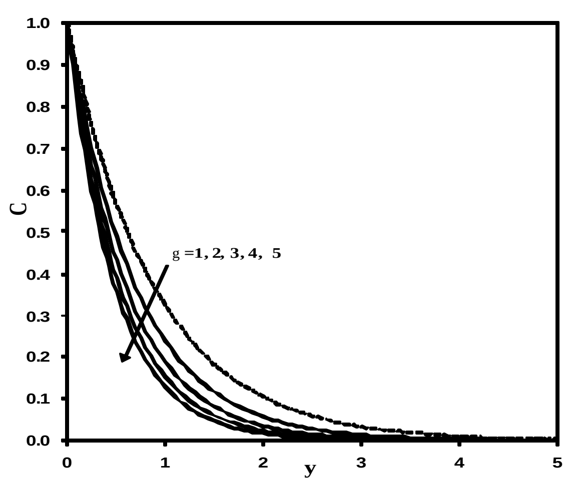

Fig. 3: Concentration profiles against spanwise coordinate y for different values of (g) with $Gm = 2,\ Gr = 10, Sc = 0.6,\ K = 3,\ \ M = 0.2$ and $Df = 6$

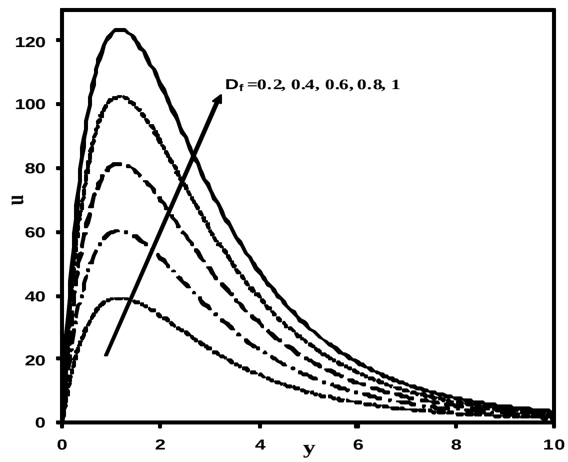

Fig. 4: Velocity profile against spanwise coordinate y for different values of (the chemical reaction parameter g) with. $Gm=2, Gr=10, Sc=0.16, K=3, M=0.2$ and $g = 1$.

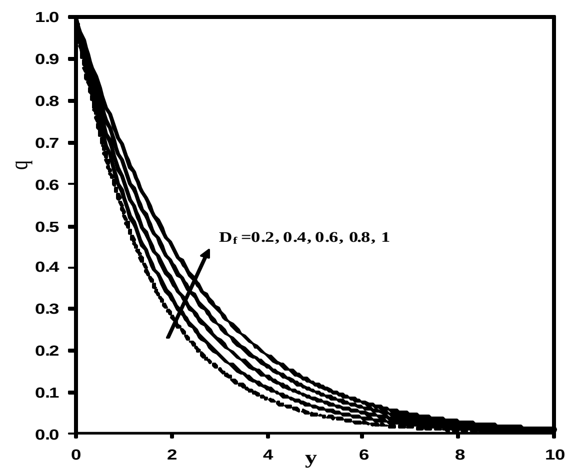

Fig. 5: Temperature profile against spanwise coordinate y for different values of (the chemical reaction parameter g) with. $Gm=2, Gr=10, Sc=0.16, K=3, M=0.2$ and $g = 1$.

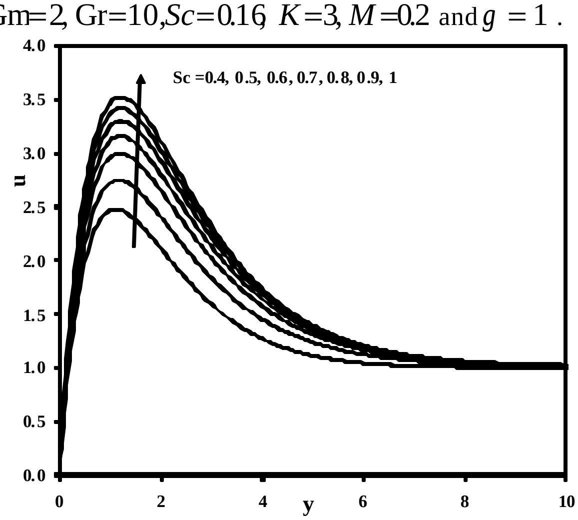

Fig. 6: Velocity profile against spanwise coordinate y for different values of (the Schmidt number Sc) with $Gm = 4, \ Gr = 10, \ K = 3, g = 0.2 \ \ M = 0.2$ and $Df = 5$

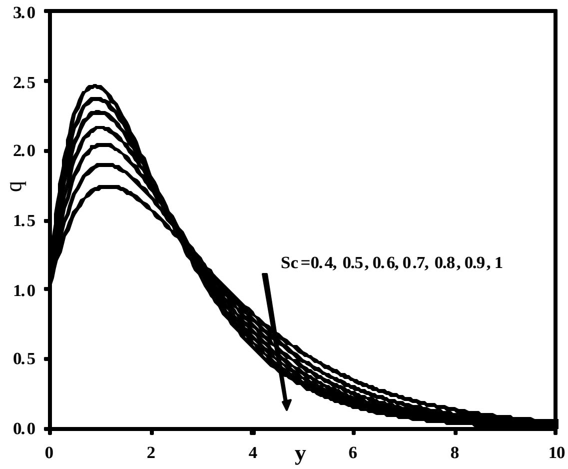

Fig. 7: Temperature profile against spanwise coordinate y for different values of (the Schmidt number Sc) with $\mathrm{Gm} = 4,\ \mathrm{Gr} = 10,\ K = 3, g = 0.1\ \ M = 0.2$ and $Df = 6$

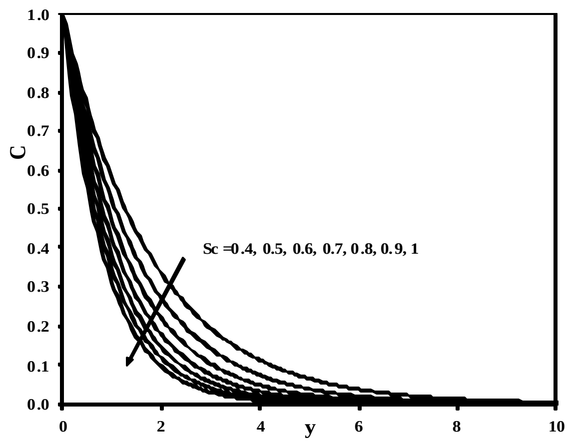

Fig. 8: Concentration profile against spanwise coordinate y for different values of (the Schmidt number Sc) with $\mathrm{Gm} = 4,\ \mathrm{Gr} = 10,\ K = 3, g = 0.2\ \ M = 0.2$ and $Df = 5$

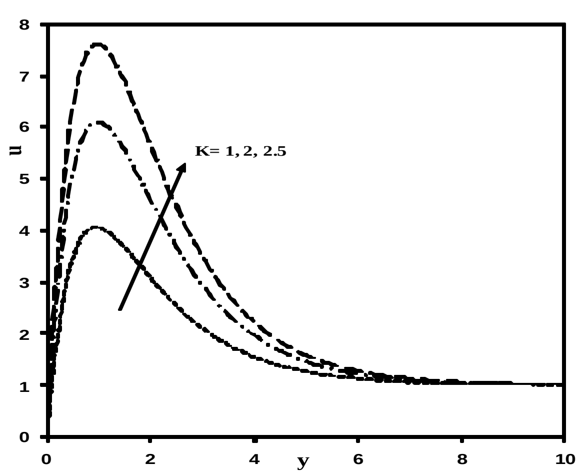

Fig. 9: Velocity profile against spanwise coordinate y for different values of (permeability parameter K) with $\mathrm{Gm} = 2,\ \mathrm{Gr} = 10,\ M = 0.2, g = 0.5,\ Sc = 0.6$ and $Df = 0.03$

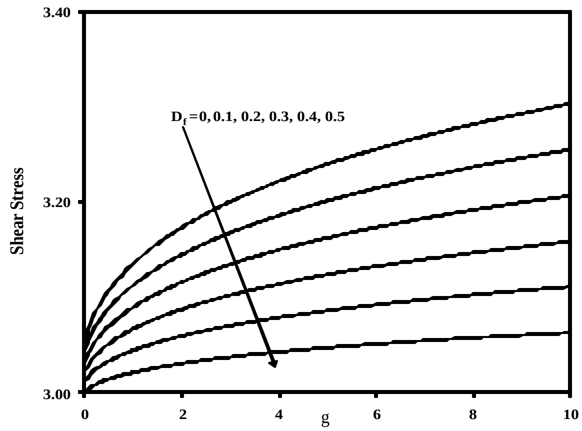

Fig. 10: Dependence the shear stress on the material parameter g for different values of (Dufour number D_f) with $\mathrm{Gm} = 4,\ \mathrm{Gr} = 10,\ K = 20,\ M = 20$ and $Sc = 0.3$

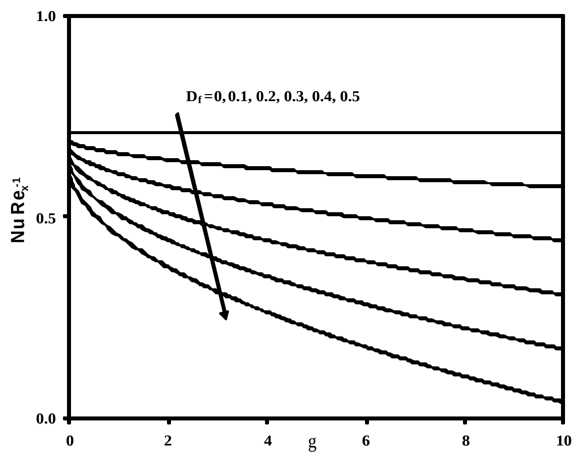

Fig. 11: Nuselt number on the material parameter g for different values of (Dufour number D_f) with $\mathrm{Gm} = 4,\ \mathrm{Gr} = 10,\ K = 20,\ M = 20$ and $Sc = 0.3$

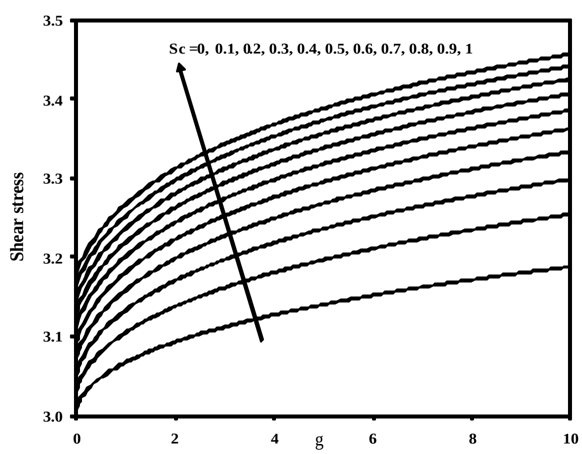

Fig. 12: Dependence the shear stress on the material parameter g for different values of Sc with $\mathrm{Gm} = 4,\ \mathrm{Gr} = 10,\ K = 20,\ M = 20$ and $Df = 0.01$

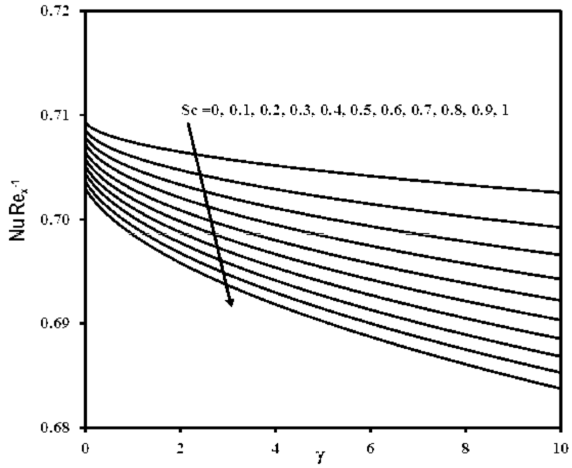

Fig. 13: Nuselt number on the material parameter γ for different values of Sc with Gm = 4, Gr = 10, K = 20, M = 20 and $Df = 0.01$

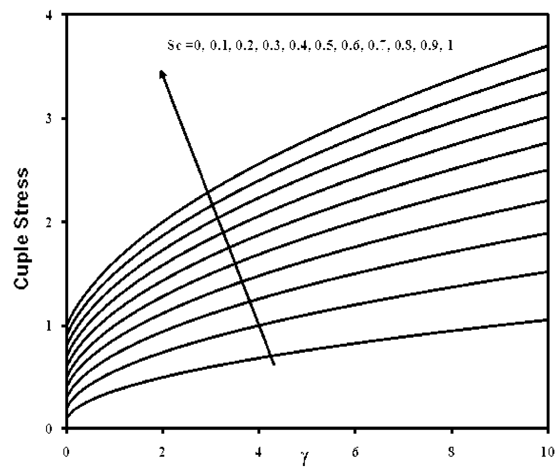

Fig. 14: The couple stress on the material parameter γ for different values of Sc with Gm = 4, Gr = 10, K = 20, M = 20 and $Df = 0.01$

values of the average Sherwood number is observed and then they increase chemical reaction parameter and Schmidt numbers. This is due to the fact that for a generative reaction the rate of mass transfer increases as Sc and the reaction parameter increase but the opposite effect has been observed for a destructive reaction.

APPENDIX

$$m_1 = \frac{-1}{2}\left(Sc + \sqrt{(Sc)^2 + 4\gamma Sc}\right) \quad R_3 = \frac{-1}{2}\left(1 + \sqrt{1 + 4(M + i\omega + 1/K}\right) \quad L_1 = \frac{Gr\, A_2}{(Pr + R_1)(Pr + R_2)} \quad R_4 = \frac{1}{2}\left(-1 + \sqrt{1 + 4(M + i\omega + 1/K}\right)$$

$$m_2 = \frac{1}{2}\left(-Sc + \sqrt{(Sc)^2 + 4\gamma Sc}\right) \quad R_3 = \frac{1}{2}\left(-1 + \sqrt{1 + 4(M + i\omega + 1/K}\right) \quad L_2 = \frac{Gr\, A_2}{(m_1 - R_1)(m_2 - R_2)} \quad A_5 = \frac{L_1}{Pr^2 + Pr - (M + i\omega + 1/K)}$$

$$R_1 = \frac{-1}{2}\left(1 + \sqrt{1 + 4(M + 1/K}\right) \quad A_1 = \frac{-Pr\, D_f\, m_1^2}{m_1(Pr + m_1)} \quad A_3 = L_1 + L_2 - 1 \quad A_6 = \frac{L_2}{m_1^2 + m_1 - (M + i\omega + 1/K)}$$

$$R_2 = \frac{1}{2}\left(-1 + \sqrt{1 + 4(M + 1/K}\right) \quad A_4 = \frac{-A_3}{R_1^2 + R_1 - (M + i\omega + 1/K)} \quad A_2 = 1 - A_1 \quad A_{10} = -(1 + A_4 + A_5 + A_6)$$

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