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Chemical reaction effects on hydromagnetic flow of a radiating and dissipative fluid past a tilted stretching sheet

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Abstract

This paper probes into the chemical reaction effects on steady hydromagnetic flow of an incompressible viscous electrically conducting, radiating and dissipative fluid past a tilted stretching sheet in the presence of heat source. The governing boundary layer equations are first transformed into a non-dimensional form using suitable similarity variables and the resulting system of ordinary differential equations are then solved numerically using midpoint method with Richardson extrapolation (MMRE). The effects of The Soret-Dufour and other governing parameters on the flow variables are discussed quantitatively with the help of graphs for the velocity, temperature and concentration fields.

1. Introduction

The study of boundary layer behaviour on stretching or continuously moving sheet or surface, received much attention in recent years. This is owing to its relevance in engineering processes(see, for example, Chen and Char [1] and literature cited therein). Vajravelu [2] was particularly interested in areas, such as the aerodynamic extrusion of plastic sheets, cooling of an infinite metallic plate in a cooling bath, and the boundary layer along a liquid film in condensation

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processes. He carried out the transient and steady convective heat transfer near a continuously moving vertical plate.

Extensive work is available for the boundary layer flow generated by: a linearly stretching sheet or surface (oriented in horizontal direction [3, 4] and in vertical direction [5]), as well as exponentially stretching sheet or surface (horizontally oriented [6, 7, 8] and vertically oriented [9]) for different thermal boundary conditions. In all these studies, [5] and [9] worked on the flow and heat transfer processes caused by buoyancy effect of thermal diffusion only.

However, free convection flow is not often caused entirely by the effect of temperature gradients but also by differences in concentration of dissimilar chemical species. Convection flows driven by buoyancy mechanisms arising from both thermal and species diffusion have been studied in the past and various extensions of the problems have been reported in the literature. Researches on hydromagnetic buoyancy-induced flow and mass transfer over or past a stretching, continuously moving sheet or surface include that of Shit and Halder [10] and Hossain and Samand [11]. They reported that hydromagnetic power generators, flight hydromagnetic as well as in the field of planetary magnetosphere, aeronautics and chemical engineering are its numerous applications. The thermal radiation effect is important in the context of space technology and processes involving high temperature. The inclusion of heat generation or absorption effects in moving fluid is also important in view of several physical problems such as fluids undergoing exothermic or endothermic chemical reactions.

Accordingly, the heat and mass transfer effects on MHD boundary layer flow of a radiating fluid over an exponentially stretching sheet was studied by Renukadevi *et al.* [12]. Renukadevi *et al.* [13] discussed the slip flow of electrically conducting and radiating fluid with temperature dependent viscosity and heat source or sink due to linearly stretching sheet. Kristaiah *et al.* [14] have considered the influence of variable viscosity, dissipation and Hall current on convective heat and mass transfer flow past a stretching sheet in the presence of heat generation or absorption.

In many practical situations such as drying, condensation, evaporation at the surface of a water body, energy transfer in a wet cooling tower, the flow in a desert cooler and chemical reactions, the heat transfer process is always accompanied by the mass transfer process. Hence, necessitate the study of combined heat and mass transfer problems with chemical reaction. Other vital applications of simultaneous diffusion of thermal energy and of chemical species problems with chemical reaction are found in many industries. For instance, in the power industry, among the methods of generating electric power is one in which electrical energy is extracted directly from a moving conducting fluid (see [14, 15]).

In most of the previous papers involving the combined buoyancy effects arising from the simultaneous diffusion of thermal energy and of chemical species, the

Soret and Dufour effects are neglected. This is restricted to a situation of low species concentration levels. However, Dufour and Soret effects are relevant in a situation of isotope separation, when density differences exist in the flow regime, and in interaction between gases with very light molecular weight (H_2, H_e) and for medium molecular weight (N_2, air). Thus, Soret and Dufour effects has applications in many areas such as petrology, geosciences, hydrology, and so on (see, for example,([16, 17]). The Lie-group analysis of Soret, Dufour and chemical reaction effects on convective heat and mass transfer flow over a stretching sheet with heat generating sources was investigated by Sulochana and Tayappa [18]. They have shown that, for fluids with medium molecular weight (H_2,air), Dufour and Soret effects should not be ignored.

The applications of hydromagnetic free convective heat and mass transfer flow past or over a horizontal or a vertical linearly or exponentially stretching, continuously moving sheet or surface cited above, cannot be enough to understand the flow and energy transport characters. The main reason for this is that the cited above geometry may be tilted because in this case due to earth's gravitation, there will be external body force on the flow. Tilted geometry has enormous applications in the heat transfer technology like solar collector. Problems with tilted geometry are close to realistic practical situations and much attention has not been given to handle them except the work of Alam *et al.* [19] and a recent study by Alam [20]. Alam concluded, among other things that: the fluid velocity inside the boundary layer decreases with the increasing values of the angle of inclination, and that Dufour and Soret parameters have significant effects on the heat and mass transfer flow of hydrogen-air mixture fluid.

Another most recent paper is that of Hassan *et al.* [21]. They considered the heat and mass transfer of an electrically conducting viscous incompressible, radiating and dissipative fluid occurring on an isothermal stretching permeable inclined sheet embedded in a porous medium; using Darcy-Forchhemier model, with heat generation or absorption. Alam [20] and Hassan *et al.* [21] solved numerically the resulting similarity equations by applying a sixth-order Runge-Kutta method with Nachetsheim-Swigert shooting iteration technique. Therefore, in the present investigation, a major emphasis is to extend Hassan *et al.* [21] work to include Soret, Dufour and chemical reaction on hydromagnetic free convective heat and mass transfer flow using midpoint method with Richardson extrapolation method implemented on Maple.

2. Mathematical Analysis

We consider a steady two-dimensional laminar flow of an incompressible electrically conducting viscous fluid past an isothermal non-conducting stretching permeable tilted sheet with an angle α in a porous medium with heat source and the following assumptions;

i all the fluid properties except the density in the buoyancy force term are constants.

ii a magnetic field of uniform strength B_0 is applied transversely to the tilted sheet.

iii the magnetic Reynolds number of the flow is assumed to be very small enough to neglect the induced magnetic field.

iv there exists a first order homogeneous reaction takes place entirely in the stream with a constant rate K^* between the diffusing species and the fluid.

v the concentration of the diffusing species in the binary mixture is assumed to be of considerable magnitude in comparison with the other chemical species and hence, the Soret and Dufour effects cannot be ignored.

vi the x-axis is taken along the tilted stretching sheet and points in the direction of motion and the y-axis normal to it.

vii the sheet temperature and concentration are initially raised to T_w and C_w respectively which are thereafter maintained constant. The ambient temperature of the flow is T_w and the concentration of the uniform flow is C_w.

Under the above assumptions, employing the Boussinesq and boundary layer approximation and taken into account the Darcy-Forchheimier model, the governing equations for this problem can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)cos\alpha+g\beta^*(C-C_\infty)cos\alpha-\frac{\sigma_e B_0^2}{\rho}u-\frac{\nu}{K^1}u-\frac{b}{K^1}u^2 \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{K}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q}{\rho C_p}(T-T_\infty)+\frac{\nu}{C_p}\left(\frac{\partial u}{\partial y}\right)^2-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y}+\frac{\lambda K_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\lambda\frac{\partial^2 C}{\partial y^2}-K^*(C-C_\infty)+\frac{\lambda K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where u and v are the velocity components in the x-direction and y-direction respectively, ν is the kinematic viscosity, g is the acceleration due to gravity, β is the volumetric coefficient of thermal expansion, β^* is the volumetric coefficient of mass expansion, α is the angle of inclination, K^1 is the Darcy permeability constant, T and T_∞ are the fluid temperature within the boundary layer and in the free stream respectively while C is the concentration of the fluid within the boundary layer, σ_e is the electric conductivity, B_0 is the uniform magnetic field strength (magnetic induction), ρ is the density of the fluid, K is thermal conductivity of the fluid, C_p is the specific heat at constant pressure, the amount

of heat source or sink per unit volume is $Q(T - T_\infty)$, Q being a constant, which may be taken either positive or negative, the source term represents the heat generation when $Q > 0$ and heat absorption when $Q < 0$. λ is the chemical molecular diffusivity, K_T is the thermal diffusion ratio, C_s is the concentration susceptibility, and T_m is the mean fluid temperature.
The boundary conditions are:

$$u = dx, \quad v = v_w(x), \quad T = T_w, \quad C = C_w \quad \text{at} \quad y = 0 \tag{5}$$

$$u \to 0, \quad T \to T_\infty, \quad C \to C_\infty \quad \text{at} \quad y \to \infty \tag{6}$$

where $d > 0$ being stretching rate of the sheet, is a constant, $v_w(x)$ is a velocity component at the wall having positive value to indicate suction, T_w is the uniform sheet temperature and C_w is the concentration of the fluid at the sheet. The boundary conditions on velocity in (5) and (6) are the non-slip condition at the surface $y = 0$ while the boundary conditions on velocity at $y \longrightarrow \infty$ follow from the fact that there is no flow far away from the stretching surface.
The fluid is gray, absorbing-emitting but non-scattering medium and the Roseland approximation for radiative heat flux which leads to

$$q_r = -\frac{4\sigma_1}{3K_1}\frac{\partial T^4}{\partial y} \tag{7}$$

in y direction is taken, where σ_1 is the stefan-Boltzman constant and K_1 is the mean absorption coefficient. It is assumed that the temperature difference within the flow are sufficiently small such that T^4 may be expressed as a linear function of temperature, thus

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \tag{8}$$

and equation (3) becomes;

$$u\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{Q}{\rho c_p}(T - T_\infty) + \frac{\nu}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{16\sigma_1 T_\infty^3}{3\rho C_p K_1}\frac{\partial^2 y}{\partial y^2} + \frac{\lambda K_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \tag{9}$$

To transform the above equations into dimensionless form, the following relations and suitable similarity dimensionless variables are introduced:

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x} \quad \eta = y\sqrt{\frac{d}{\nu}}, \quad \psi = \sqrt{d\nu x}f(\eta) \tag{10}$$

$$\text{and} \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \tag{11}$$

where ψ is the stream function satisfying the continuity equation, $f(\eta)$ is the dimensionless stream function, η is the pseudo-similarity variable normal to the sheet, $\theta(\eta)$ is the dimensionless temperature of the fluid in the boundary layer region, $\phi(\eta)$ is the dimensionless concentration.

substituting equations(10) and (11) into equations (2), (4) and (9), we obtain the ordinary differential equations:

$$(12)\quad f''' + ff'' + G_r\theta cos\alpha + G_m\phi cos\alpha - \left(M + \frac{1}{A\cdot R_e}\right)f' - \left(1 + \frac{F_s}{A}\right)(f')^2 = 0$$

$$(13)\qquad \theta'' + \frac{3NP_r}{4+3N}f\theta' + \frac{3NP_rS}{4+3N}\theta + \frac{3NP_rE_c}{4+3N}(f'')^2 + \frac{3NP_rD_f}{4+3N}\phi'' = 0$$

$$(14)\qquad \phi'' + S_cf\phi' + S_cS_r\theta'' - S_c\delta_c\phi = 0$$

where $G_r = \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}$ is the thermal Grashof number, $G_m = \frac{g\beta^*(C_w - C_\infty)x^3}{\nu^2}$ is the mass Grashof number, $M = \frac{\sigma_e B_0^2}{\rho d}$ is the magnetic field parameter, $N = \frac{KK_1}{4\sigma_1 T_\infty^3}$ is the radiation parameter, $A = \frac{K^1}{x^2}$ is the local Darcy number, $Re = \frac{x^2 d}{\nu}$ is the Reynold's number,$F_s = \frac{b}{x}$ is the Forchhemier number, $P_r = \frac{\mu c_p}{K}$ is the Prandtl number, $S = \frac{Q}{\rho c_p d}$ is heat source ($S > 0$) or sink($S < 0$) parameter, $E_c = \frac{d^2x^2}{C_p(T_w - T_\infty)}$ is the Eckert number, $S_c = \frac{\nu}{\lambda}$ is the Schmidt number, $D_f = \frac{\lambda K_T(C_w - C_\infty)}{C_sC_p\nu(T_w - T_\infty)}$ is the Dufour number, $S_r = \frac{\lambda K_T(T_w - T_\infty)}{T_m\nu(C_w - C_\infty)}$ is the Soret number, $\delta_c = \frac{K^*}{d}$ is the chemical reaction rate parameter.
The transformed boundary conditions become

$$(15)\quad f'(0) = 1, f(0) = f_w, \theta(0) = 1, \phi(0) = 1, f'(\infty) = 0, \theta(\infty) = 0, \quad \phi(\infty) = 0$$

where $f_0 = -\frac{v_w}{\sqrt{d\nu}}$ is the suction parameter for $f_0 > 0$.

3. Results and Discussion

Equations (12)-(14) with boundary conditions (15) were numerically solved with Richardson Extrapolation implemented on Maple 17 software in order to reveal the effects of some parameters on the dimensional quantities; velocity, temperature and concentration distributions, demonstrated in graphs.

During the numerical computation, the value of Prandtl number P_r is equal to 0.71, corresponds physically to the air at 20^oC. Due to free convection problem local Grashof number for heat transfer takes value 5, and local modifying Grashof number takes value 10 (correspond to heating of the fluid or cooling of the sheet). To be realistic, the value of the Schmidt number S_c (=0.22-Hydrogen gas) chosen to represent the presence of diffusing chemical species of most common interest in air. The geometric parameter characterizing the inclination of the sheet α is varied. Here we took typical angle of inclination (α=0^o, 30^o, 45^o, 60^o). In the absence of heat source, we have $S = 0$ while $S = 0.5$ correspond to source and $S = -0.5$ corresponds to sink. Dufour number takes value 0.03, 0.06, 0.12, 0.24. Soret number takes the values 2.0, 1.0, 0.5, 0.25. The chemical reaction parameter δ_c takes the ±0.5, ±1.5, ±2.5 and ±3.5. The values of other parameters are chosen arbitrarily. The default parameter values used through out the numerical computations, unless otherwise stated are: $\alpha = 30^o$, $M = 0.5$, $A = 0.20$, $R_e = 100$, $F_s = 0.1$, $N = 0.5$, $S = 0.75$, $E_c = 0.1$, $D_f = 0.03$, $S_c = 0.22$, $S_r = 2.0$, δ_c=1.5 and $f_0 = 0.1$.

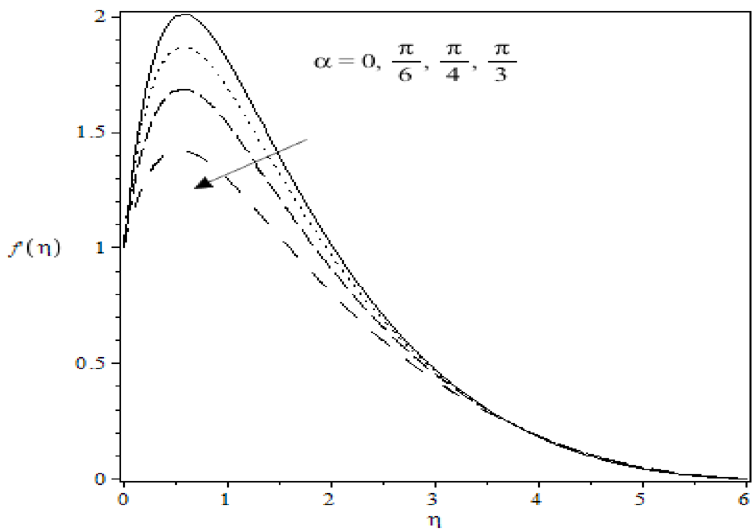

Figure 1: Profile of velocity for different values of α

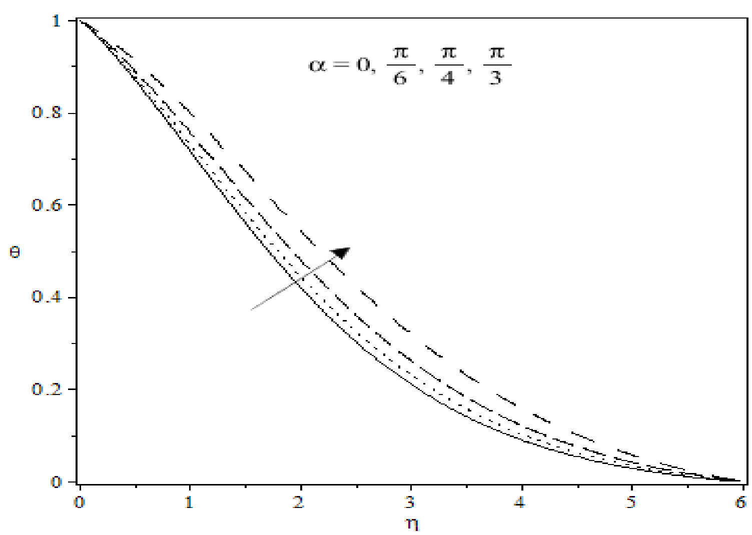

Figure 2: Profile of temperature for different values of α

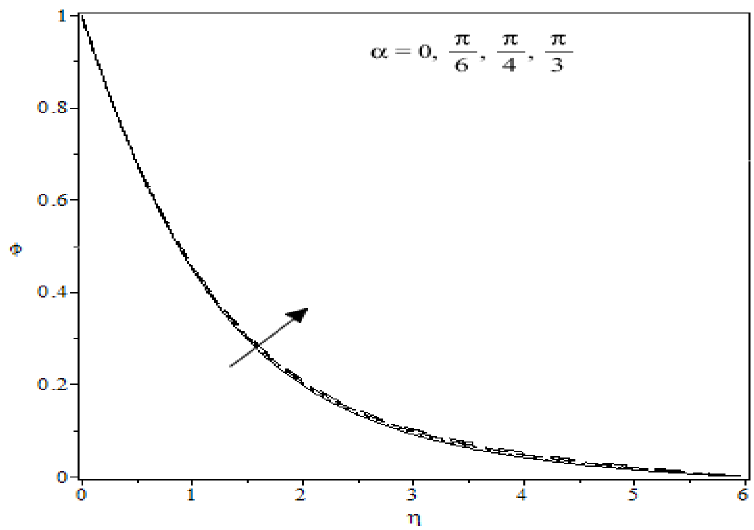

Figure 3: Profile of concentration for different values of phi_alpha

The effect of the angle of inclination α of the sheet on the velocity field is illustrated in Figure 1. The increase in α contributes to the fall in the velocity field, considerably away from the sheet. Figure 2 depicts that the increase in the angle of inclination α has the tendency to raise the temperature distribution significantly as well as the concentration in Figure 3.

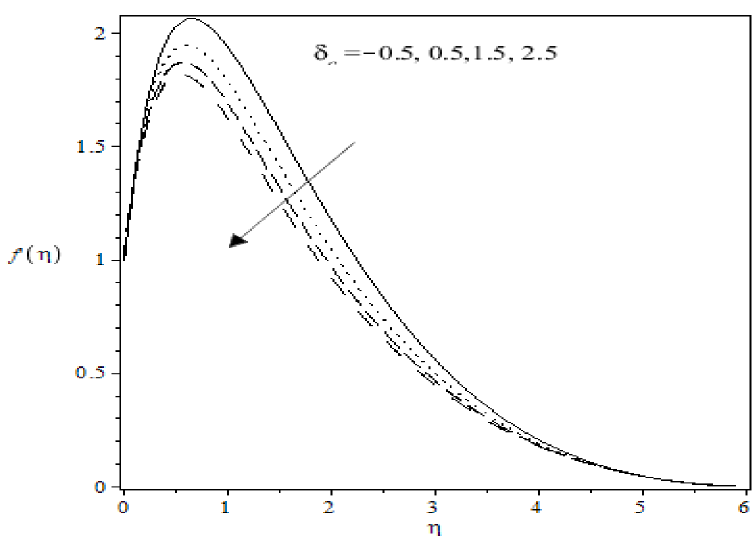

Figure 4: Profile of velocity for different values of δ_c

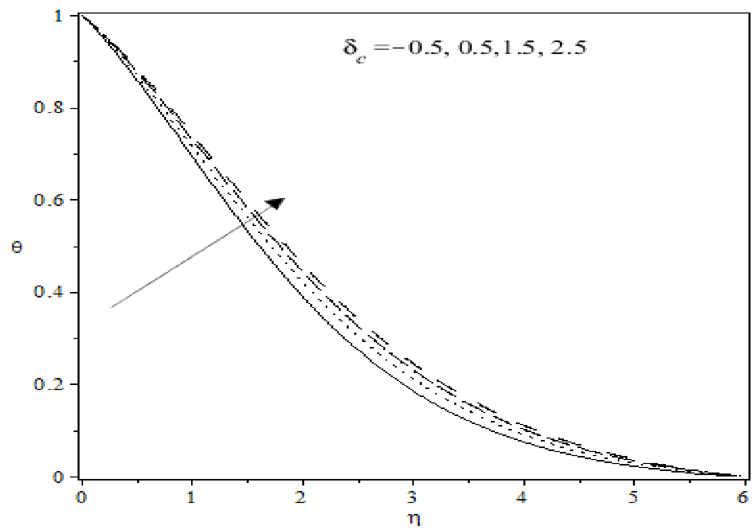

Figure 5: Profile of temperature for different values of δ_c

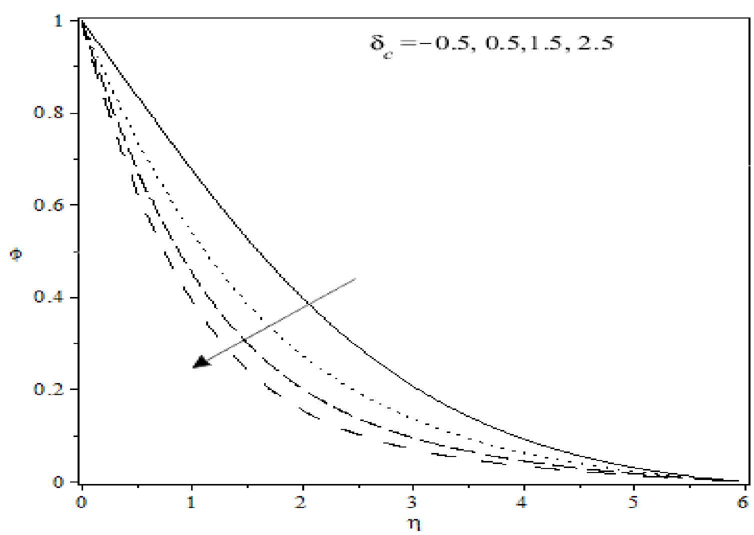

Figure 6: Profile of concentration for different values of δ_c

Figure 4-6 exhibit the influence of the chemical reaction rate δ_c on the velocity temperature and concentration profiles. It is clearly observed that the velocity profiles decrease with the increase in chemical reaction rate. Arise in δ_c from -0.5 through 0.5, 1.5 to very high order 2.5 as seen in Figure 5 significantly enhances θ values and diminishes ϕ values (see Figure 6) through out the boundary layer.

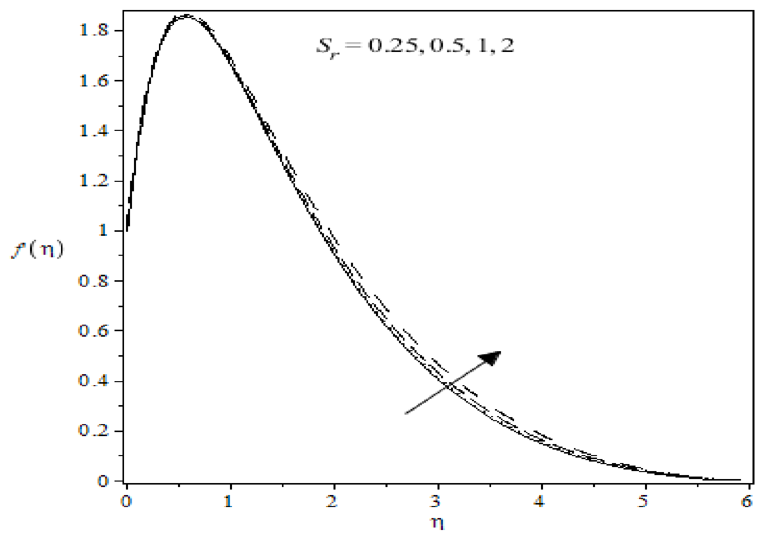

Figure 7: Profile of velocity for different values of Sr

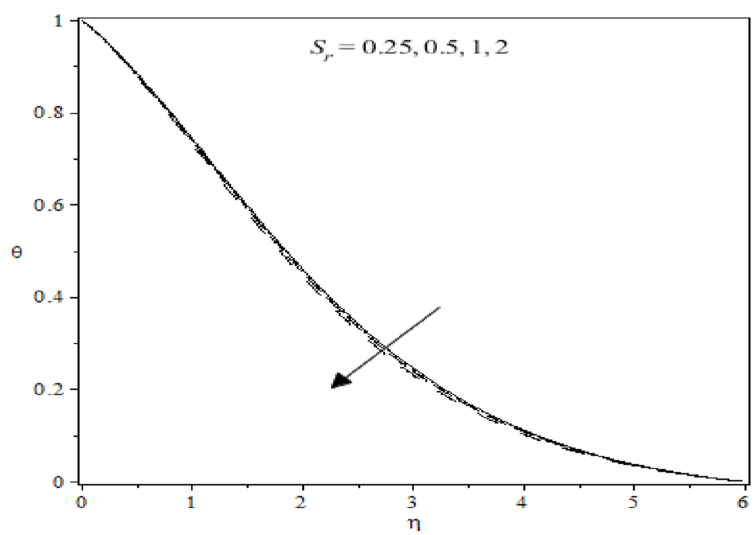

Figure 8: Profile of temperature for different values of Sr

The variation of f, θ and ϕ with Soret number S_r is displayed in Figure 7-9. It was found from Figure 7 that increase in S_r enhances the velocity profiles. From Figure 8 we find that the temperature profile depreciates with increase in S_r. Also from Figure 9, we find that an increase in S_r enhances the concentration profiles.

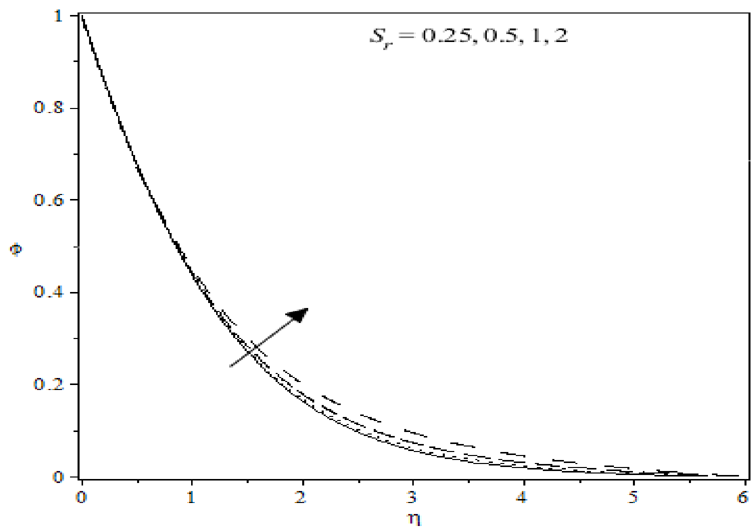

Figure 9: Profile of concentration for different values of Sr

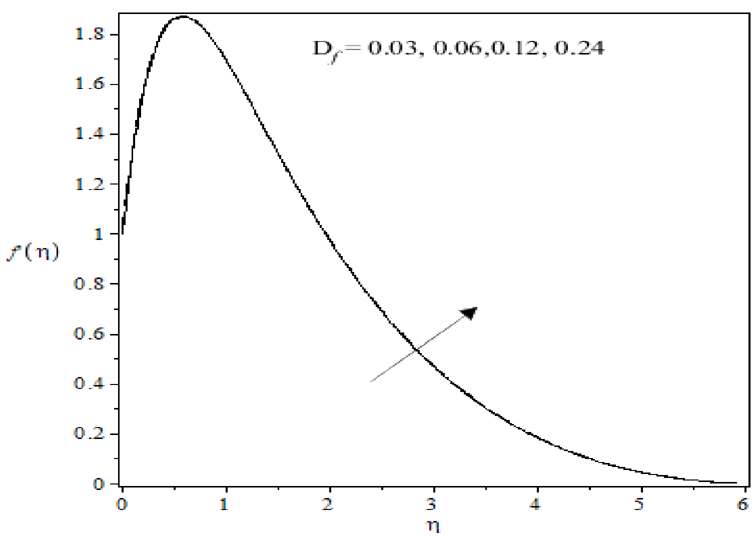

Figure 10: Profile of velocity for different values of Df

Figure 10-12 illustrate the variation of f', θ and ϕ with increase in Dufour number D_f (or decrease in Soret number S_r). It is clearly observed that the velocity and temperature profiles enhances while concentration reduces with increase in Dufour number (or decrease in Soret number).

With an increase in S from -0.5 (heat sink) through 0.0 to 0.75(heat source), there is a clear increase in the velocity i.e the flow is accelerated when heat is

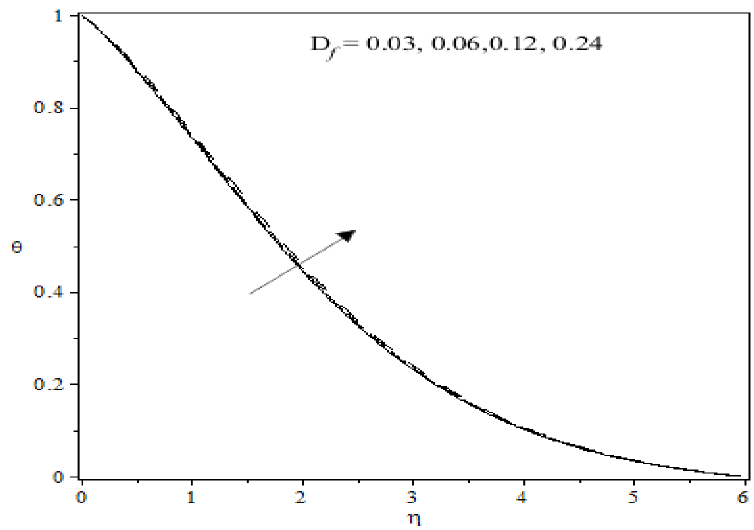

Figure 11: Profile of temperature for different values of Df

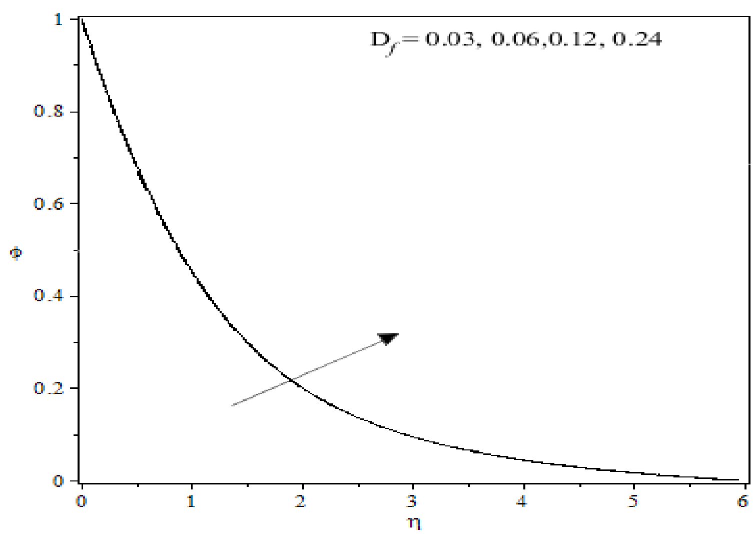

Figure 12: Profiles of concentration for different values of D_f

absorbed, the buoyancy force decreases, which retards the flow rate and thereby giving rise to the decrease in the velocity profiles in Figure 13. The temperature profiles are depicted in Figure 14 for different values of heat source or sink parameter S. It is seen that the fluid temperature is noticeably enhanced with increase in S. However, there is decrease in concentration as heat source parameter increases as shown in Figure15.

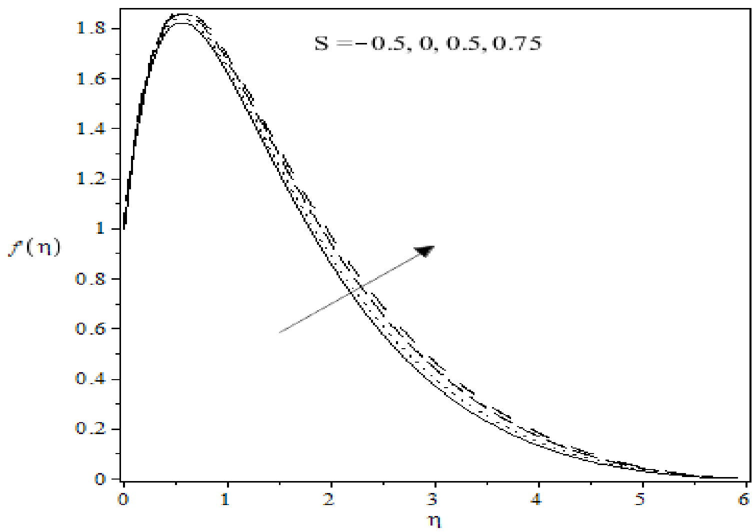

Figure 13: Profile of velocity for different values of S

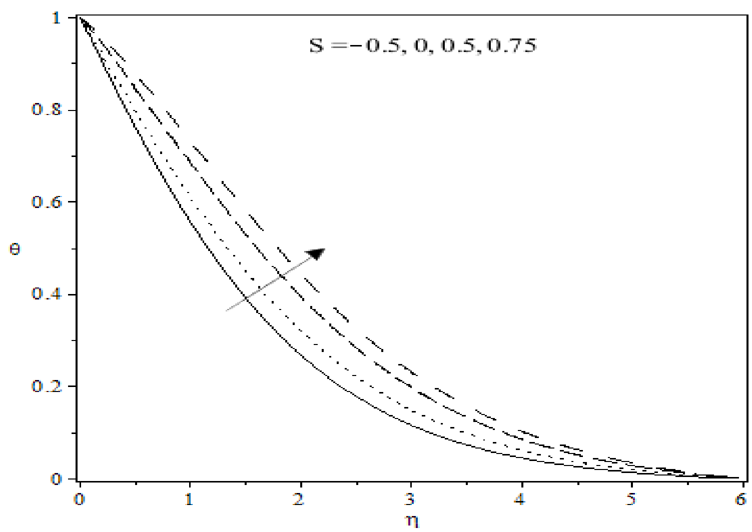

Figure 14: Profile of temperature for different values of S

4. Conclusions

In conclusion, we found that:

i Increase in Dufour number and heat source parameter enhances both velocity and temperature,

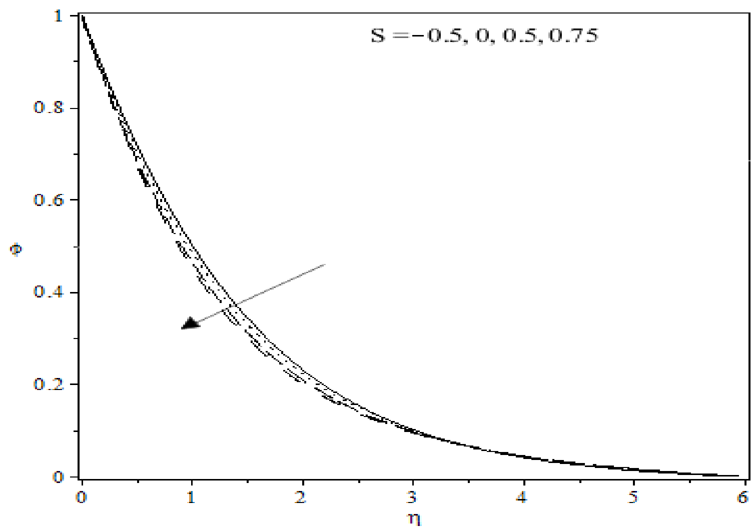

Figure 15: Profile of concentration for different values of S

ii Temperature increase with increase in angle of inclination, chemical reaction, Dufour number and heat source parameter but decreases with rise in Soret number.

iii Velocity decrease as angle of inclination and chemical reaction increase but increase with increase in Soret number, Dufour number and heat source parameter.

iv Cocentration increase with increase in angle of inclination, Soret number, Dufour number and heat source parameter while it decreases with rise in chemical reaction.

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