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Effects of Chemical Reaction on MHD Slip Flow of A Power-Law Fluid Over Flat Plate

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ABSTRACT

This paper reports the effects of chemical reaction with Soret and Dufour effects on MHD boundary layer flow of a power-law fluid over a flat plate with slip boundary conditions. With the aid of implicit finite difference scheme, the transformed differential equations are solved numerically. Effects of pertinent parameters with appropriate boundary conditions on flow, thermal and concentration fields are studied with graphical illustrations. Also, the effects of slip parameters, Soret and Dufour number on skin friction, Nusselt number and Sherwood number are studied. Results show that the increase in Soret number leads to decrease in temperature distribution while increase in concentration fields. The effect of Chemical reaction parameter is to decrease the concentration of the fluid.

Keywords: Power-law Fluid, Chemical reaction parameter, Soret and Dufour number, slip boundary conditions, finite difference method, Prandtl number.

INTRODUCTION

The layer of the fluid that flows directly adjacent to its bounding surface is called the boundary layer. The boundary layer is an extremely important concept in fluid mechanics and has been studied extensively for decades. Fluid motion in the boundary layer is influenced by a number of factors namely fluid viscosity, external forces, bounding surface characteristics and so on. Sakiadas[1] was the first among the others to consider the boundary layer flow at a continuous solid surface with constant speed. Crane[2] extended the work of Sakiadas[1] to the flow caused by an elastic sheet moving in its own plane with a velocity varying linearly with the distance from a fixed point. Ali[3] discussed the problem of coupled heat and mass transfer by natural convection from a vertical impermeable semi-finite flat plate embedded in a non-uniform non-metallic porous medium n the presence of thermal dispersion effects.

The theory of non-Newtonian fluids offers mathematicians, engineers and numerical specialists varied challenges in developing analytical and numerical solutions for highly non-linear equations. However, due to the practical significance of these non-Newtonian fluids, many authors have presented various non-Newtonian models like Elabassbeshy *et al*.[4], Nadeem *et al*.[5] and Kishan and Shashidar[6]. The surface velocity on the boundary, the study of boundary layer MHD flow towards a shrinking/stretching sheet has gained considerable attention of many researchers because of its frequent occurrence in industrial technology, geothermal application and high temperature plasmas applicable to nuclear fusion energy conversion and MHD power generation systems. Muhamin and Khamis[7] studied effects of heat and mass transfer on the non-linear MHD viscous fluid flow over a shrinking sheet in the presence of suction. Mostafa A. A. Mahmaud[8] studied the non-uniform heat generation effect on heat transfer of a non-Newtonian power-law fluid over a non-linear stretching sheet. MHD mixed convection stagnation-point flow of a power-law non-Newtonian nanofluid towards a stretching surface with radiation and heat source/sink was analyzed by Madhu and Kishan[9]. Heat and mass transfer with hydrodynamic slip over a moving plate in porous media was investigated by Hamad *et al*.[10] via Runge-Kutta-Fehlberg fourth-fifth order method. Over the years, considerable amount of literature has addressed the problem of fluid flow and heat transfer past a flat plate, especially in Newtonian fluids and to a limited extent in power-law fluids. Kishan and Shashidar[11] studied MHD effects on non-Newtonian power-law fluid past a continuously moving porous flat plate.

In the above investigations Soret and Dufour's effect were neglected. However, when heat and mass transfer occurs simultaneously in a moving fluid the relation between the fluxes and driving potentials are of a more intricate nature. It has been found that an energy flux can be generated not only by temperature gradient but also by a concentration gradient. The Soret effect, for instance, has been utilized for isotope separation and in mixtures between gases with very light molecular weight (H_2, He). For medium molecular weight (N_2, air) the Dufour effect was found to be of a considerable magnitude such that it cannot be neglected. Postelnicu[12] used an implicit finite difference scheme to investigate the influence of magnetic field on heat and mass transfer by natural convection from vertical surfaces in a porous media considering Soret and Dufour effects. Rashidi *et al*.[13] discussed Heat and mass transfer for MHD viscoelastic fluid flow over a vertical stretching sheet with considering Soret and Dufour effects. Soret and Dufour effects on MHD convective heat and mass transfer of a power-law fluid over an inclined plate with variable thermal conductivity in a porous medium were studied by Pal and Chatterjee[14]. Ibrahim and Shanker[15] investigated MHD boundary layer flow and heat transfer of a nanofluid past a permeable stretching sheet with velocity, thermal and solutal slip boundary conditions. Hirschhorn *et al*.[16] studied MDH boundary layer slip flow and heat transfer of power-law fluid over a flat plate.

Srinivasa chary and swamy[17] studied the effect of chemical reaction and radiation on mixed convection heat and mass transfer over a vertical plate in power-law fluid saturated porous medium. Kabeir *et al*.[18] investigated the effects of radiation, chemical reaction, soret and dufour on heat and mass transfer by MHD stagnation point flow of a power-law fluid towards a stretching surface. Effect of chemical reaction, Soret and Dufour on heat and mass transfer of non-Newtonian power-law fluid past a porous flat plate is studied by Shashidar and Saritha[19].

Recently, Saritha *et al*.[20] studied combined effects of Soret and Dufour on MHD flow of a power-law fluid over flat plate in slip flow rigime. This paper extends earlier works by examining chemical reaction effects on on MHD boundary layer heat and mass transfer of power-law fluid over a flat plate with velocity, thermal and solutal slip boundary conditions.

MATHEMATICAL FORMULATION

Consider a steady, laminar two-dimensional heat and mass transfer flow of an incompressible electrically conducting, viscous fluid obeying power-law model over a flat plate in the presence of transverse magnetic field B. x-axis is taken along the direction of the flow and y-axis normal to it. The thermo-physical properties of the sheet and the fluid are assumed to be constant except for the viscosity of the power-law fluid which depends on the shear rate. We assume that the Dufour effect may be described by a second-order concentration derivative with respect to the transverse coordinate in the energy equation whereas Soret effect is described by second-order temperature derivative in the mass-diffusion equation. With these assumptions and invoking the boundary layer approximations, the governing equations for the boundary layer flow, heat and mass transfer are

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial}{\partial y}\left(\left|\frac{\partial u}{\partial y}\right|^{n-1}\frac{\partial u}{\partial y}\right)-\frac{\sigma B^2}{\rho}(u-U_\infty), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2}, \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2}-K_1(C-C_\infty), \tag{4}$$

Subject to the boundary conditions

$$u=L_1\left(\frac{\partial u}{\partial y}\right),\ \ v=0,\ \ T=T_w+D_1\left(\frac{\partial T}{\partial y}\right),\ \ C=C_w+P_1\left(\frac{\partial C}{\partial y}\right) at\ y=0; \tag{5a}$$

$$u\to U_\infty,\ \ T\to T_\infty,\ C\to C_\infty\ \ as\ \ y\to\infty, \tag{5b}$$

Where u and v are the velocity components in the directions of x and y axes respectively, ρ is the fluid density, σ is the constant electrical conductivity of the fluid, B is the magnetic field strength, $\nu=\frac{K}{\rho}$ is the kinematic viscosity, K is the consistency coefficient, U_∞ is the free stream velocity, T is temperature, $\alpha=\frac{k}{\rho c_p}$ is the thermal diffusivity, k is the thermal conductivity, c_p is the specific heat capacity of the fluid, c_s is the concentration susceptibility, k_T is the thermal diffusion ratio, D_m is the coefficient of mass diffusivity, K_1 is dimensional chemical reaction parameter.

Also $L_1 = L\sqrt{Re_x}$ is the velocity slip factor with L being the initial value at the leading edge, $D_1 = D\sqrt{Re_x}$ is the thermal slip factor with D being the initial value at the leading edge and $P_1 = P\sqrt{Re_x}$ is the concentration slip factor with P being the initial value at the leading edge. Here, T_w and C_w are the temperature and concentration of the flat plate, T_∞ and C_∞ are the free stream temperature and concentration, and $Re_x = \frac{U_\infty^{2-n} x^n \rho}{K}$ is the local Reynolds number.

The momentum, energy and mass equations can be transformed to a non-linear boundary value problem involving a system of coupled ordinary differential equations. In particular, we introduce the dimensionless similarity variables used by Reddy *et al.*[21] and defined as

$$\Psi = bU_\infty \left(\frac{\frac{x}{b}}{Re}\right)^{\frac{1}{n+1}} f(\eta), \tag{6a}$$

$$\eta = \left(\frac{Re}{\frac{x}{b}}\right)^{\frac{1}{n+1}} \frac{y}{b}, \tag{6b}$$

$$T = T_\infty + (T_w - T_\infty)\theta(\eta), \tag{6c}$$

$$C = C_\infty + (C_w - T_\infty)\emptyset(\eta), \tag{6d}$$

Where η is the similarity variable, Ψ is the stream function, $f, \theta\ and\ \emptyset$ are the dimensionless similarity function, temperature and concentration respectively. Here b is the characteristic length.

The velocity components u and v in terms of stream function $\Psi(x, y)$ are given by

$$u = \frac{\partial \Psi}{\partial y}, v = -\frac{\partial \Psi}{\partial x}, \tag{7}$$

The generalized Reynolds number Re is defined by $Re = \frac{\rho U_\infty^{2-n} b^n}{K}$. (8)

Introducing the similarity transformations (6) and (7), the continuity equation is satisfied whereas the momentum, energy and mass equation given by (2), (3) and (4) are transformed into the coupled non-linear ordinary differential equations of the form

$$n|f''|^{n-1} f''' + \frac{1}{n+1} f f'' - M(f' - 1) = 0 \tag{9}$$

$$\theta'' + \frac{1}{n+1} Prf\theta' + Du.\emptyset'' = 0 \tag{10}$$

$$\frac{1}{Le}\emptyset'' + \frac{1}{n+1} Prf\emptyset' + Sr.\theta'' - \gamma\emptyset = 0 \tag{11}$$

Here primes denote the differentiation with respect to η.

And where $M = \frac{\sigma B^2 x}{\rho U_\infty}$ is the Magnetic parameter,

$Pr = \frac{Ux}{\alpha} Re_x^{\frac{-2}{n+1}}$ is the Prandtl number,

$Le = \frac{\alpha}{D_m}$ is the Lewis number,

$\gamma = \frac{K_1 x^2}{\alpha} Re_x^{-\frac{2}{n+1}}$ is the Chemical reaction parameter

$Du = \frac{D_m k_T}{c_s c_p} \cdot \frac{(C_w - C_\infty)}{(T_w - T_\infty)\alpha}$ is the Dufour number,

$Sr = \frac{D_m k_T}{T_{m\alpha}} \cdot \frac{(T_w - T_\infty)}{(C_w - C_\infty)}$ is the Soret number.

Boundary conditions (5a) and (5b) are transformed into

$$f(\eta) = 0, \quad f'(\eta) = A_1 f''(\eta), \quad \theta(\eta) = 1 + B_1\theta'(\eta), \quad \emptyset(\eta) = 1 + C_1\emptyset'(\eta) \quad at \quad \eta = 0, \quad (12a)$$

$$f'(\eta) \to 1, \quad \theta(\eta) \to 0, \quad \emptyset(\eta) \to 0 \quad as \quad \eta \to \infty, \quad (12b)$$

Where A_1, B_1 and C_1 are respectively the velocity, temperature and concentration slip parameters, which are further defined as

$$A_1 = L\frac{U_\infty \rho}{K}, \quad (13a)$$

$$B_1 = D\frac{U_\infty \rho}{K}, \quad (13b)$$

$$C_1 = P\frac{U_\infty \rho}{K} \quad (13c)$$

In practical applications, the physical quantities of principal interest are the skin-friction coefficient C_f, local Nusselt number Nu_x and local Sherwood number Sh_x which indicate the physical wall shear stress, rate of heat transfer and the rate of mass transfer respectively. These physical quantities are defined respectively as

$$C_f = \frac{2\tau_w}{\rho U_\infty^2} = 2[f''(0)]^n Re_x^{1/n+1}, \qquad Nu_x = \frac{q_w x}{k(T_w - T_\infty)} = -\theta'(0) Re_x^{1/n+1}$$

and $$Sh_x = \frac{J_w x}{D_m(C_w - C_\infty)} = -\emptyset'(0) Re_x^{1/n+1}$$

Where the wall shear stress τ_w, the heat flux at the wall q_w and the mass flux at the wall J_w are defined as

$$\tau_w = \mu_0\left[\frac{\partial u}{\partial y}\right]_{y=0}, \; q_w = -k\left[\frac{\partial T}{\partial y}\right]_{y=0} \qquad \text{and} \qquad J_w = -D_m\left[\frac{\partial C}{\partial y}\right]_{y=0}$$

NUMERICAL PROCEDURE

The combined effects of various physical parameters will have large impact on heat and mass transfer characteristics. The non-linearity of the basic equations and additional mathematical difficulties associated with the solution part has led us to use the numerical method. In this section, an efficient implicit finite difference scheme along with Quasi-linearization technique has been employed to analyze the flow model for the above coupled ordinary differential equations (9), (10)and (11) along with the boundary conditions (12) for different values of the governing parameters. The transformed non-linear differential equation (9) is first linearized by Quasi-linearization technique discussed by Bellman and Kalaba[22]. Now by applying implicit finite difference scheme, these equations are transformed to system of linear equations. To carry out the computational procedure, first the momentum equation is solved which gives the values of *f* necessary for obtaining the solution of coupled energy and concentration equations under the boundary conditions (12) by Gauss Seidal iteration procedure. The numerical solutions of *f* are considered as $(n+1)^{th}$ order iterative solutions and F are the n^{th} order iterative solutions. To prove convergence of finite difference scheme, the computation is carried out for slightly changed value of h by running same program. No significant change was observed in the value. At every position, the iteration process continues until the convergence criterion for all the variables, 10^{-5} is achieved.

RESULTS AND DISCUSSIONS

Numerical computations are carried out for several sets of values of the governing parameters, namely, velocity slip parameter A_1, temperature slip parameter B_1, concentration slip parameter C_1, Soret number Sr and Dufour number Du. In order to get clear insight of the physical problem, numerical results are displayed with the help of graphical illustrations. Numerical Graphical illustration of the results is very useful and practical to discuss the effect of different parameters.

To validate our results, the numerical computations of skin friction coefficients, Nusselt number and Sherwood number which are respectively proportional to $f''(0), -\theta'(0)\ and - \emptyset'(0)$ are presented in the tabular form. Tables 1 and 2 show the effect of power-law index n, Soret number Sr and Dufour number Du on coefficient of skin friction $f''(0)$, Nusselt number $-\theta'(0)$ and Sherwood number $-\emptyset'(0)$ respectively. It can be seen that the effect of power-law index n is to decrease skin friction coefficient, Nusselt number and Sherwood number. It is evident from the tables that increase in Soret number (or decrease in the Dufour number) decreases the Nusselt number but increases Sherwood number.

Table 1: Numerical results of Nusslet number $-\boldsymbol{\theta}'(\mathbf{0})$ for different values of Soret and Dufour number with M = 0.2, Pr = 0.7, Le = 1.0, A_1 = 0, B_1=0, C1 =0.

	Values of $-\theta'(0)$		
Sr, Du	n = 0.5	n = 1.0	n = 1.5
0.08,0.01	0.330075	0.269637	0.255924
0.04, 0.02	0.307352	0.258658	0.247737
0.02, 0.04	0.261925	0.236719	0.231336
0.01, 0.08	0.171099	0.192867	0.198493

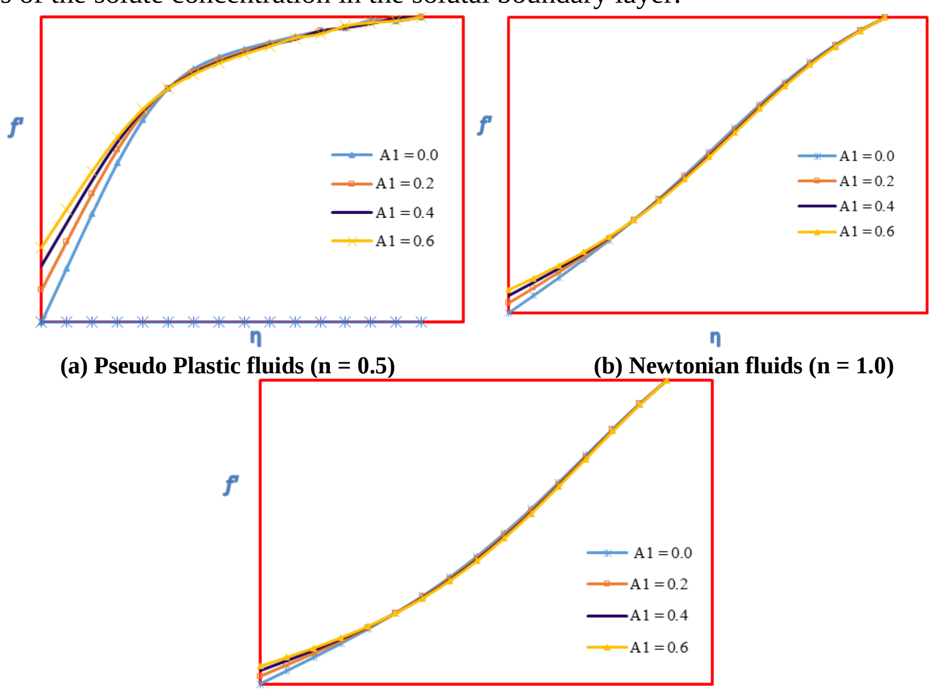
Table 2: Numerical results of Sherwood number $-\emptyset'(\mathbf{0})$ for different values of Soret and Dufour number with M = 0.2, Pr = 0.7, Le = 1.0, A_1 = 0, B_1=0, C1 =0.

	Values of $-\emptyset'(0)$		
Sr, Du	n = 0.5	n = 1.0	n = 1.5
0.08,0.01	0.171099	0.192867	0.198493
0.04, 0.02	0.261925	0.236719	0.231336
0.02, 0.04	0.307352	0.258658	0.247737
0.01, 0.08	0.330075	0.269637	0.255924

Figure 1 display the distinction of velocity profile with respect to variation in velocity slip parameter. On observing these figures, the velocity graph increases with the increase in the values of velocity slip parameter A_1. The effect of thermal slip parameter B_1 on the temperature profiles in shown in figure 2. It is noticed from the profiles that the wall temperature $\theta(0)$ and the thermal boundary layer thickness decreases with the increase in the thermal slip parameter. Figure 3 demonstrates the variation of concentration profiles in response to the change in the concentration slip parameter C_1. It can be noticed from the graphs that by increasing C_1, wall concentration $\phi(0)$ and concentration profiles decreases and hence concentration boundary layer thickness decreases.

The variation of Soret and Dufour number on the temperature and concentration fields are displayed respectively in figures 4 and 5. The mass flux due to temperature gradient is defined as Soret effect whereas enthalpy flux due to concentration gradient Dufour effect. These graphs reveal that the decrease in Soret number (or increase in Dufour number) enhances the temperature profiles and reduces the concentration profiles. It is due to the fact that, an increase in Soret number cools down the fluid and hence the temperature reduces.

The effect of Chemical reaction parameter on the concentration field is shown in figure (6). It can be noticed from the graphical presentation that the rise in the chemical reaction parameter will suppress the concentration of the species in the boundary layer, whereas the velocity and temperature of the fluid are not significant with increase of chemical reaction parameter. This is due to the fact that chemical reaction in this system results in consumption of the chemical and hence results in decrease of concentration profile. The most important effect is that the first-order chemical reaction has a tendency to diminish the overshoot in the profiles of the solute concentration in the solutal boundary layer.

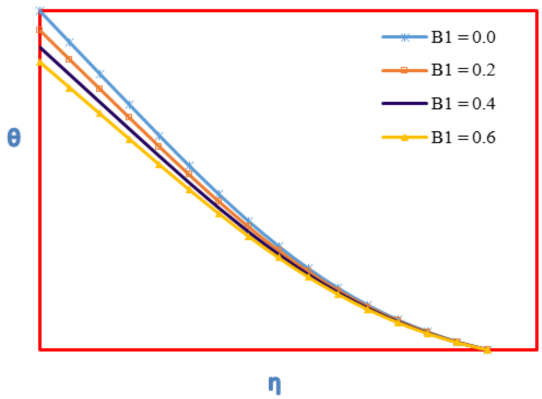


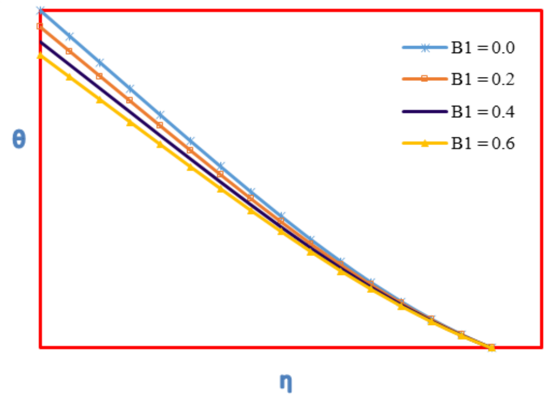
(a) Pseudo Plastic fluids (n = 0.5)

(b) Newtonian fluids (n = 1.0)

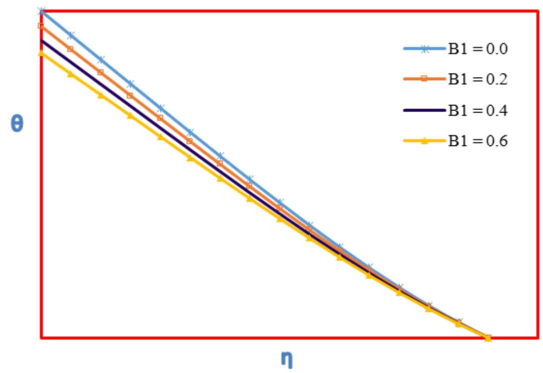
(c) Dilatant fluids (n =1.5)

Figure 1. Variation of Velocity profiles for various values of Velocity Slip parameter A_1 with Pr = 0.7, Le = 1.0, Sr = 0, Du = 0, M = 0, B_1 = 0, C_1 = 0.



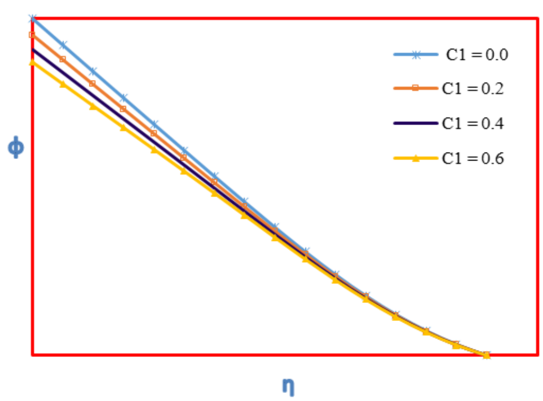


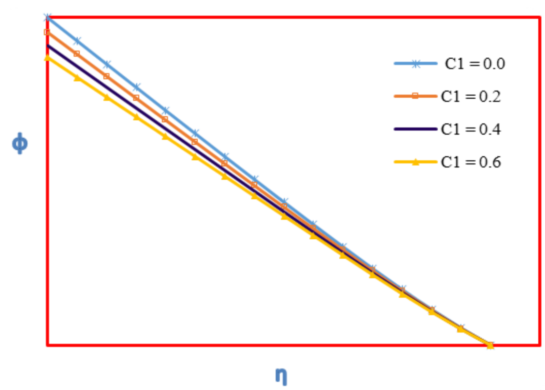
(a) Pseudo Plastic fluids (n = 0.5) **(b) Dilatant fluids (n = 1.0)**



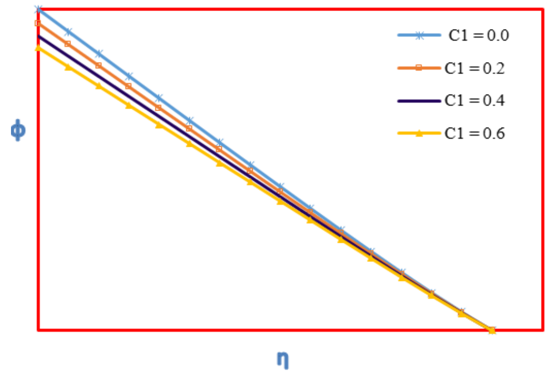
(c) Dilatant fluids (n = 1.5)

Figure 2. Variation of Temperature profiles for various values of Temperature Slip parameter B_1 with M = 0.2, Pr = 0.7, Le = 1.0, Sr = 0.04, Du = 0.02, A_1 = 0, C_1 = 0.



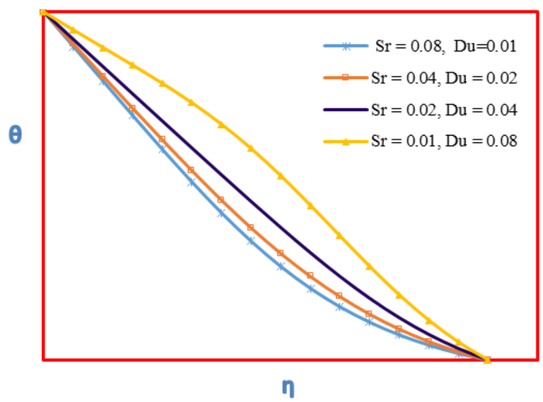


(a) Pseudo Plastic fluids (n = 0.5) **(b) Newtonian fluids (n = 1.0)**

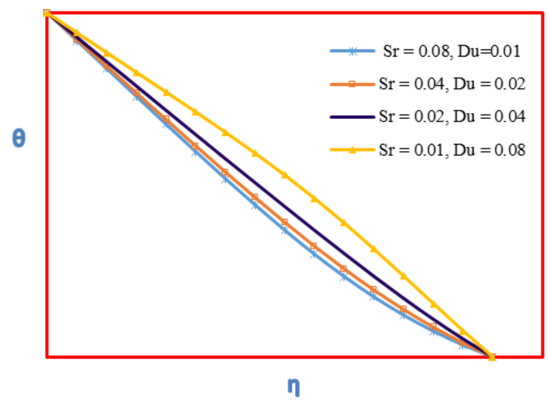


(c) Dilatant fluids (n = 1.5)

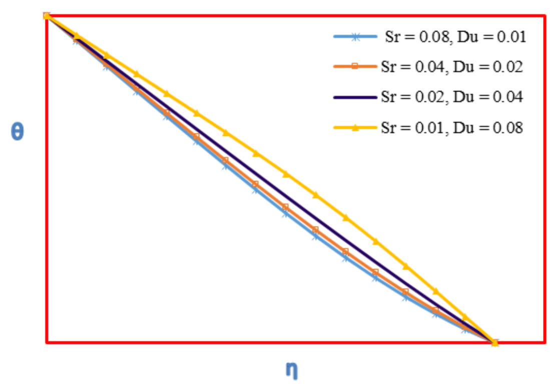
Figure 3. Variation of Concentration profiles for various values of Concentration Slip parameter C_1 with $M = 0.2$, $Pr = 0.7$, $Le = 1.0$, $Sr = 0.04$, $Du = 0.02$, $A = 0$, $B = 0$



(a) Pseudo Plastic fluids (n = 0.5)

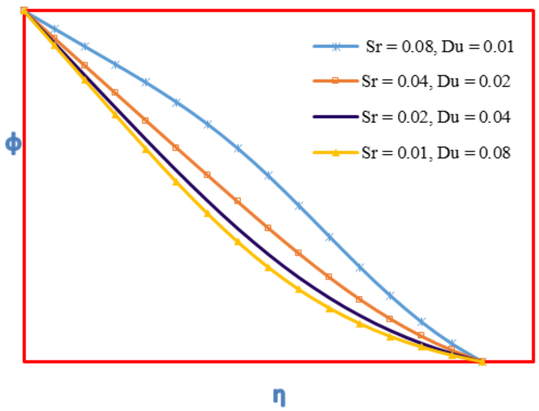


(b) Newtonian fluids (n = 1.0)

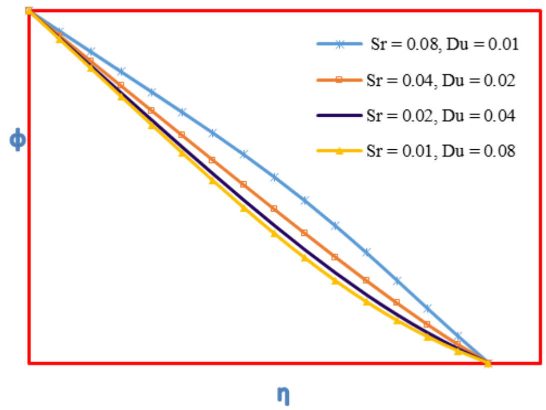


(c) Dilatant fluids (n = 1.5)

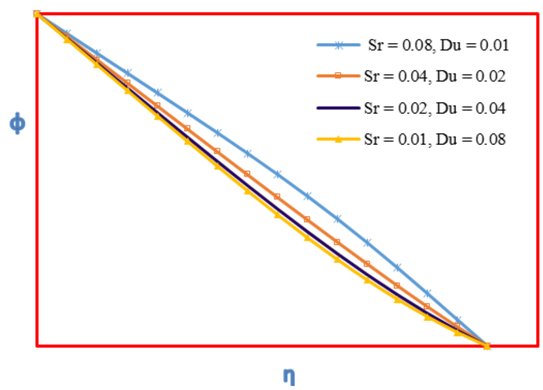
Figure 4. Variation of Temperature profiles for various values of Soret number and Dufour number with $M = 0.2$, $Pr = 0.7$, $Le = 1.0$, $A_1 = 0$, $B_1 = 0$, $C_1 = 0$.



(a) Pseudo Plastic fluids (n = 0.5)

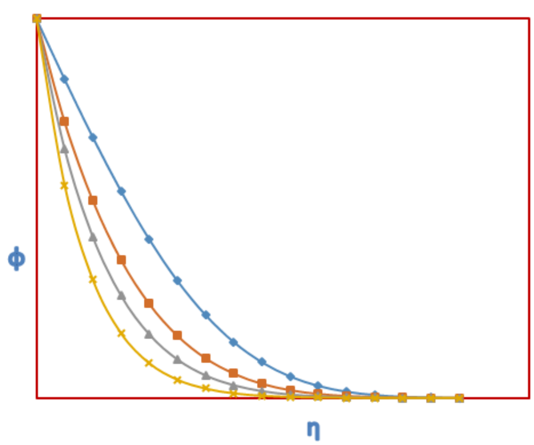


(b) Newtonian fluids (n = 1.0)

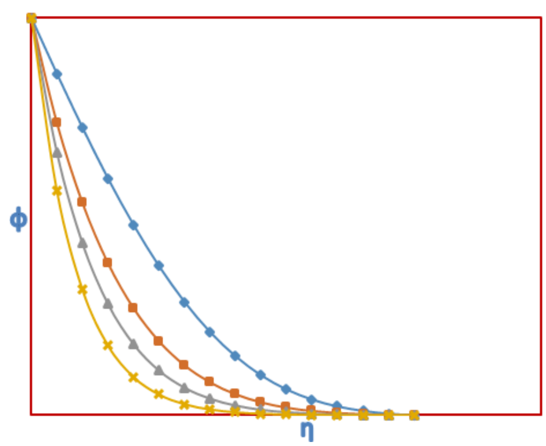


(c) Dilatant fluids (n = 1.5)

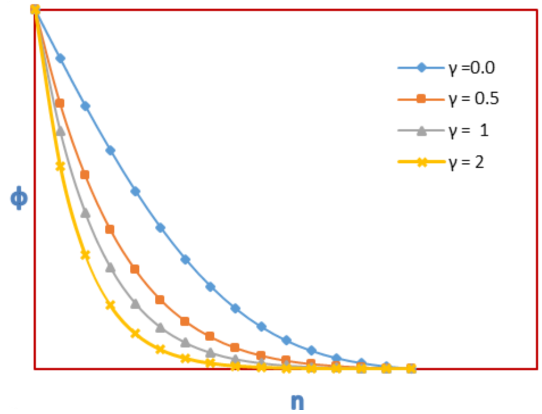
Figure 5. Variation of Concentration profiles for various values of Soret number and Dufour number with M = 0.2, Pr = 0.7, Le = 1.0, A_1 = 0, B_1 = 0, C_1 =0.



(a) Pseudo Plastic fluids (n = 0.5)



(b) Newtonian fluids (n = 1.0)



(c)Dilatant fluids (n=1.5)

Figure 6: Concentration profiles for various values of Chemical reaction parameter with M=0.1,Pr=1.0, Le=1.0, f_w=0.0, Sr = 0.0, Du = 0.1.

CONCLUSIONS

In summary the present study describes the heat and mass transfer of a power-law fluid flow over a flat plate in the presence of a transverse magnetic field by taking into account Soret and Dufour effects. From the above investigation, the following conclusions may be drawn:

1. The higher the velocity, temperature and concentration slip parameters, the lower the coefficient of skin friction, Nusselt number and Sherwood number respectively.
2. A high thermal diffusion (Soret number) effect enhances the rate of heat transfer and reduces the rate of mass transfer.
3. Velocity at the surface of the plate decreases with the increase in the velocity slip parameter.
4. Thickness of the boundary layer decreases with the increase in the temperature slip parameter.
5. Concentration boundary layer thickness decreases with the increase in the concentration slip parameter.
6. The effect of Soret number is to reduces the temperature and enhance the concentration.

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