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SORET AND DUFOUR EFFECTS ON MIXED CONVECTION FROM A VERTICAL PLATE IN POWER-LAW FLUID SATURATED POROUS MEDIUM

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Soret and Dufour effects on mixed convection from a vertical plate in power-law fluid saturated porous medium

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Abstract

Mixed convection heat and mass transfer along a vertical plate embedded in a power-law fluid saturated Darcy porous medium with Soret and Dufour effects is studied. The governing partial differential equations are transformed into ordinary differential equations using similarity transformations and then solved numerically using shooting method. The effect of Soret and Dufour parameters, power law index and mixed convection parameter on non-dimensional velocity, temperature and concentration fields are discussed. The variation of different parameters on heat and mass transfer rates is presented in tabular form.

Keywords: Mixed convection, Darcy porous medium, Power-law fluid, Soret and Dufour effects.

1 Introduction

The analysis of mixed convection boundary layer flow along a vertical surface embedded in porous media has received considerable theoretical and practical interest. The mixed convection flow occurs in several industrial and technical applications such as electronic devices cooled by fans, nuclear

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reactors cooled during an emergency shutdown, a heat exchanger placed in a low-velocity environment, solar collectors and so on. A number of studies have been reported in the literature focusing on the problem of mixed convection about different surface geometries in porous media. A review of convective heat transfer in porous medium is presented in the book by Nield and Bejan [1]. The majority of these studies dealt with the traditional Newtonian fluids. It is well known that most fluids which are encountered in chemical and allied processing applications do not satisfy the classical Newton's law and are accordingly known as non-Newtonian fluids. Due to the important applications of non-Newtonian fluids in biology,physiology, technology, and industry, considerable efforts have been directed towards the analysis and understanding of such fluids. Different mathematical models have been proposed to explain the rheological behavior of non-Newtonian fluids. Among these, a model which has been most widely used for non-Newtonian fluids, and is frequently encountered in chemical engineering processes, is the power-law model. Although this model is merely an empirical relationship between the stress and velocity gradients, it has been successfully applied to non-Newtonian fluids experimentally.

The prediction of heat or mass transfer characteristics for mixed or natural convection of non-Newtonian fluids in porous media is very important due to its practical engineering applications, such as oil recovery and food processing. Abo-Eldahab and Salem [2] studied the problem of laminar mixed convection flow of non-Newtonian power-law fluids from a constantly rotating isothermal cone or disk in the presence of a uniform magnetic field. Kumari and Nath [3] considered the conjugate mixed convection conduction heat transfer of a non-Newtonian power- law fluid on a vertical heated plate which is moving in an ambient fluid. Degan et al. [4] presented an analytical method to investigate transient free convection boundary layer flow along a vertical surface embedded in an anisotropic porous medium saturated by a non-Newtonian fluid. Chamkha and Al-Humoud [5] studied mixed convection heat and mass transfer of non-Newtonian fluids from a permeable surface embedded in a porous medium under uniform surface temperature and concentration species. Chen [6] considered the problem of magneto-hydrodynamic mixed convective flow and heat transfer of an electrically conducting, power-law fluid past a stretching surface in the presence of heat generation/absorption and thermal radiation. Elgazery and Abd Elazem [7] analyzed numerically a mathematical model to study the effects of a variable viscosity and thermal conductivity on unsteady heat and mass transfer in a non-Newtonian power-law fluid flow through a porous medium past a semi-infinite vertical plate in the presence of magnetic field and radiation. Kairi and Murthy [8] investigated the effect of double dispersion on mixed convection heat and mass transfer in a non-newtonian fluid-saturated non-Darcy porous. Chamkha et al. [9] studied the effects of melting, thermal radiation and heat generation or absorption on steady mixed convection from a vertical wall embedded in a non-Newtonian power-law fluid saturated non-Darcy porous medium for aiding and opposing external flows. Hayat et al. [10] investigated the MHD mixed convection stagnation-point flow and heat transfer of power-law fluids towards a stretching surface using the homotopy analysis method.

When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of a more intricate nature. It has been observed that an energy flux can be generated not only by temperature gradients but also by concentration gradients. The energy flux caused by a concentration gradient is termed the diffusion-thermo (Dufour) effect. On the other hand, mass fluxes can also be created by temperature gradients and this embodies the thermal-diffusion (Soret) effect. In most of the studies related to heat and mass transfer process, Soret and Dufour effects 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. But these effects are considered as second order phenomena and may become significant in areas such as hydrology, petrology, geosciences, etc. The Soret effect, for instance, has been utilized for isotope separation and in mixture between gases with very light molecular weight and of medium molecular weight. The importance of these effects in convective transport in clear fluids has been reported in the book by Eckert and Drake [11]. Although the Soret and Dufour effects of the medium on the heat and mass transfer in a viscous fluid are important, very little work has been reported in the literature. Dursunkaya and Worek [12] studied diffusion-thermo and thermal-diffusion effects in transient and steady natural convection from a vertical surface, whereas Kafoussias and Williams [13] presented the same effects on mixed convective and mass transfer steady laminar boundary layer flow over a vertical flat plate with temperature dependent viscosity. Abreu et .al [14] addressed both free and forced convection boundary layer flows with Soret and Dufour effects. Alam and Rahman [15] investigated the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction. Postelnicu [16] analyzed the simultaneous heat and mass transfer by natural convection from a vertical flat plate embedded in an electrically-conducting fluid saturated porous medium using the Darcy Boussinesq model in the presence of Dufour and Soret effects. Lakshmi Narayana and Murthy [17] reported the effect of Soret and Dufour parameters on free convection heat and mass transfer from a vertical surface in a doubly stratified Darcian porous medium. Chamkha and Nakhi [18] studied MHD mixed convection radiation interaction along a permeable surface immersed in a porous medium in the presence of Soret and Dufour effects. Mahdy [19] presented a non-similar boundary layer analysis to study the flow, heat and mass transfer characteristics of non-Darcian mixed convection of a non-Newtonian power law fluid from a vertical isothermal plate embedded in a homogeneous porous medium with the effect of Soret and Dufour and in the presence of either surface injection or suction. Tai and Char [20] studied numerically on the combined laminar free convection flow with thermal radiation and mass transfer of non-Newtonian power-law fluids along a vertical plate within a porous medium in the presence of Soret and Dufour effects.

Motivated by the works mentioned above, the objective of this work is to study the mixed convection heat and mass transfer along a vertical plate with variable wall temperature and concentration embedded in a in power-law fluid with Soret and Dufour effects. The Shooting method is employed to solve the nonlinear system of equations arising in this particular problem. The effects of Soret and Dufour parameters are examined and are displayed through graphs.

2 Mathematical formulation

Consider the Mixed convection heat and mass transfer along a vertical plate in a non-Newtonian power-law fluid saturated Darcy porous medium. Choose the coordinate system such that x-axis is along the vertical plate and y-axis normal to the plate. The plate is maintained at variable temperature and concentration, $T_w(x)$ and $C_w(x)$, respectively. The temperature and concentration of the ambient medium are T_∞ and C_∞ respectively, as shown in Fig.1. Assume that the fluid and the porous medium have constant physical properties except for the density variation required by the Boussinesq approximation. The flow is steady, laminar and two dimensional. The porous medium is isotropic and homogeneous. The fluid and the porous medium are in local thermodynamical equilibrium. In addition the Soret and Dufour effects are taken into consideration.

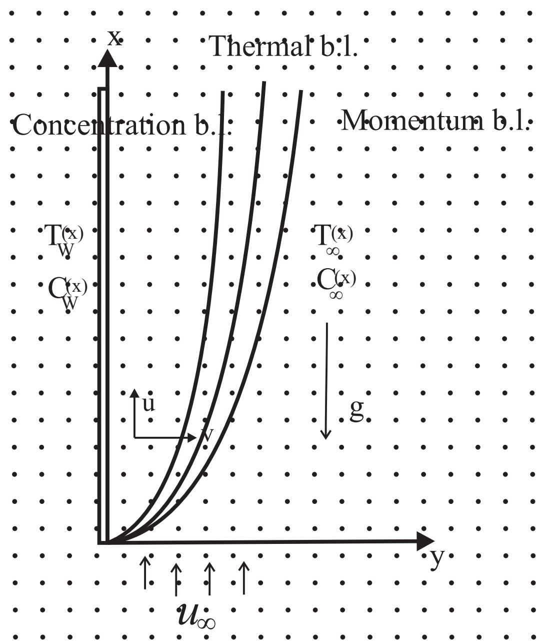


Figure 1: Flow model and physical coordinate system

Under the above conditions, the governing equations describing the fluid flow can be written as follows

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

$$u^n = u_\infty^n - \frac{K}{\mu}\left(\frac{dP}{dx} + \rho g\right) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_m \frac{\partial^2 T}{\partial y^2} + \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m \frac{\partial^2 C}{\partial y^2} + \frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where u and v are the Darcian velocity components along x and y directions, T is the temperature, C is the concentration, ν is the kinematic viscosity, K is the Darcy permeability, k_T is the thermal diffusion ratio, g is the acceleration due to gravity, α_m is the thermal diffusivity, D_m is the mass diffusivity of the medium, C_p is the specific heat capacity, C_s is the concentration susceptibility, T_m is the mean fluid temperature and n is the power-law index. When $n = 1$, the Eq. (2) represents a Newtonian fluid. Therefore, deviation of n from a unity indicates the degree of deviation from Newtonian behavior. For $n < 1$, the fluid is pseudo plastic and for $n > 1$, the fluid is dilatant.

The boundary conditions are given by

$$\begin{aligned} &v = 0, \ \ T = T_w(x), \ \ C = C_w(x) \quad at \quad y = 0 \\ &u = u_\infty, \ \ T \to T_\infty, \ \ C \to C_\infty \quad as \quad y \to \infty \end{aligned} \tag{5}$$

Outside the boundary layer, the flow of the power-law fluid remains stagnant. Thus

$$-\left(\frac{dP}{dx}\right) = \rho_\infty g \tag{6}$$

Eliminating $\frac{dP}{dx}$ from (2) and (6)

$$u^n = u_\infty^n - \frac{K}{\mu}\left(\rho_\infty - \rho\right) g \tag{7}$$

Since the pressure gradient $\frac{dP}{dx}$ is assumed as constant in the whole domain (inside and outside the boundary layer), taking into account the linear variation of temperature and concentration in the density $\rho = \rho_\infty\{1 - \beta_T(T - T_\infty) - \beta_C(C - C_\infty)\}$, the Boussinesq-approximated momentum equation is given by

$$u^n = u_\infty^n + \frac{\rho_\infty g K}{\mu}\left\{\beta_T(T - T_\infty) + \beta_C(C - C_\infty)\right\} \tag{8}$$

where β_T is the coefficient of thermal expansion and β_C is the coefficient of concentration expansion. It is noticed that the similarity transformations are possible only when the variation in the temperature and concentration of the plate are in the form $(T_w(x) - T_{\infty,0}) = Ex^{\frac{n}{3}}$ and $(C_w(x) - C_{\infty,0}) = Fx^{\frac{n}{3}}$ respectively.

3 Solution of the problem

The continuity equation (1) is satisfied by introducing the stream function ψ such that

$$u = \frac{\partial\psi}{\partial y}, \quad v = -\frac{\partial\psi}{\partial x} \tag{9}$$

In order to explore the possibility for the existence of similarity, we assume

$$\left.\begin{aligned} &\psi = Ax^a f(\eta), \;\; \eta = Byx^b, \\ &\frac{T - T_\infty}{T_w(x) - T_\infty} = \theta(\eta), \;\; T_w(x) - T_\infty = Ex^l \\ &\frac{C - C_\infty}{C_w(x) - C_\infty} = \phi(\eta), \;\; C_w(x) - C_\infty = Fx^m \end{aligned}\right\} \tag{10}$$

where A, B, E, F, a, b, l, and m are constants. Substituting (9) and (10) in (8), (3) and (4), it is found that similarity exists only if $a = \frac{2}{3}$, $b = \frac{-1}{3}$, $l = m = \frac{n}{3}$. Hence, appropriate similarity transformations are

$$\left.\begin{aligned} &\psi = Ax^{\frac{2}{3}} f(\eta), \;\; \eta = Byx^{\frac{-1}{3}}, \\ &\frac{T - T_\infty}{T_w(x) - T_\infty} = \theta(\eta), \;\; T_w(x) - T_\infty = Ex^{\frac{n}{3}} \\ &\frac{C - C_\infty}{C_w(x) - C_\infty} = \phi(\eta), \;\; C_w(x) - C_\infty = Fx^{\frac{n}{3}} \end{aligned}\right\} \tag{11}$$

Making use of the similarity transformations (11) in (8), (3) and (4) we get the following nonlinear system of differential equations.

$$(f')^n = [1 + \theta + N\phi] \tag{12}$$

$$\theta'' = \frac{1}{3}[nf'\theta - 2f\theta' - 3D_f\phi''] \tag{13}$$

$$\phi'' = \frac{Le}{3}[nf'\phi - 2f\phi' - 3S_r\theta''] \tag{14}$$

where prime denotes differentiation with respect to η alone. $S_r = \dfrac{D_m k_T E}{\alpha_m T_m F}$ is the Soret number, $D_f = \dfrac{D_m k_T F}{\alpha_m C_s C_p E}$ is the Dufour number, $N = \dfrac{\beta_C F}{\beta_T E}$ is the buoyancy parameter, $Le = \dfrac{\alpha_m}{D_m}$ is the Lewis number, $A = \left[\frac{Egk\beta_T\alpha_m^n}{\nu}\right]^{\frac{1}{2n}}$ and $B = \left[\frac{Egk\beta_T}{\nu\alpha_m^n}\right]^{\frac{1}{2n}}$.

Boundary conditions (5) in terms of f, θ and ϕ become

$$f = 0, \quad \theta = 1, \quad \phi = 1 \quad \text{at} \quad \eta = 0 \tag{15a}$$

$$f' = 1, \quad \theta = 0, \quad \phi = 0 \quad \text{as} \quad \eta \to \infty \tag{15b}$$

The parameters of engineering interest for the present problem are the Nusselt and Sherwood numbers Nu_x and Sh_x respectively and these are given by

$$\frac{Nu_x}{Bx^{\frac{2}{3}}} = -\theta'(0), \quad \frac{Sh_x}{Bx^{\frac{2}{3}}} = -\phi'(0) \tag{16}$$

4 Results and discussion

The flow equation (12) coupled with the energy and concentration equations (13) and (14) constitute a set of nonlinear non-homogeneous differential equation for which closed-form solution cannot be obtained and hence the problem has to be solved numerically. The boundary value problem given by equations (12)-(14) along with the boundary conditions (15) are solved using the Shooting method by giving appropriate initial guess values for $f'(0), \theta'(0)$and $\phi'(0)$ to match the values with the corresponding boundary conditions at $f'(\infty), \theta(\infty)$and $\phi(\infty)$ respectively. In the present study, the boundary conditions for η at ∞ vary with parameter values and it has been suitably chosen at each time such that the velocity approaches one and temperature and concentration profiles approach zero at the outer edge of the boundary layer.

In the present model we are concerned primarily with elucidating the influence of Soret, Dufour parameters and power-law index n on the velocity, temperature and concentration fields. In order to get clear insight into the physical problem, a comprehensive numerical parametric study is conducted and the results are reported in terms of graphs (Figs.2-5). Throughout the calculations, we have fixed the values of N and Le as 1 and 0.5, respectively, unless otherwise indicated.

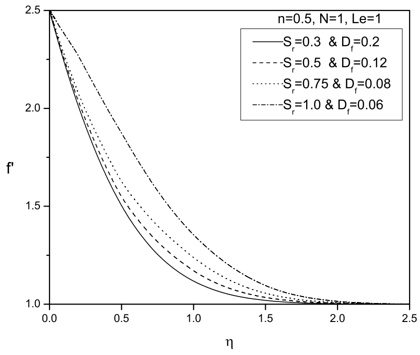
The set of figures, (2) to (4), is for $N = 1, Le = 1$, and refer to the variation of the non-dimensional velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ across the boundary layer with Soret and Dufour parameters. Figures 2(a)-2(c) are for pseudo-plastic fluids with $n = 0.5$. Figures 3(a)-3(c) are for Newtonian fluids ($n = 1.0$), while Figs.4(a)-4(c) are for dilatant fluids with $n = 2.0$. The effect of varying Dufour and Soret numbers is seen to be qualitatively the same for the hydrodynamic, thermal and concentration boundary layers in the comparison between these three categories of fluids. It is observed from Fig.2(a), 3(a) and 4(a) that increasing Soret parameter (or simultaneously decreasing Dufour parameter) leads to increase in the velocity. Soret number is the ratio of temperature difference to the concentration. Hence, the bigger Soret number stands for a larger temperature difference and precipitous gradient. Thus the fluid velocity rises due to greater thermal diffusion factor. It is found from Fig.2(b), 3(b) and 4(b) that the temperature of the fluid increases with increasing value of the Soret parameter (or decreasing values of Dufour parameter). It is seen from Fig.2(c), 3(c) and 4(c) that the fluid concentration decreases with increasing values of the Soret parameter. The Dufour number denotes the contribution of the concentration gradients to the thermal energy flux in the flow. Hence, increase in the Dufour number causes a drop in the temperature and a rise in the concentration.

The non-dimensional velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ for $N = 1, Le = 1, S_r = 0.2, D_f = 0.3$ with a variation in power law index parameter is plotted in Figs.5(a)-5(c). It is observed from Fig.5(a) that the fluid velocity increases with increasing values of the power law index parameter. The effect of the power law index n is to increase the hydrodynamic boundary layer thickness. That is, the thickness is much smaller for shear thinning (pseudo plastic; $n < 1$) fluids than that of shear thickening (dilatants; $n > 1$) fluids. In case of the shear thinning fluid ($n < 1$), the shear rate near the walls is higher than those for a Newtonian fluid. It is seen from Fig.5(b) that increasing of power law index leads to increase the thermal boundary layer thickness. It is found from Fig.5(c) that the concentration of the fluid increases with increasing values of the power law index parameter. It is interesting to note that the velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ for Newtonian fluids is more than that of Pseudo plastic fluids and less than that of dilatants fluids.

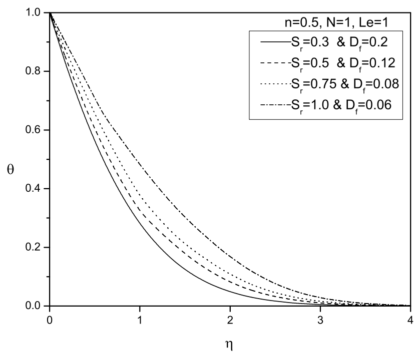
Table 1 shows the effects of n, Le, S_r, D_f and N on the non-dimensional heat and mass transfer coefficients. It is seen from this table that both the heat and mass transfer rates increase with increasing values of power law index n. For increasing value of Le, the heat transfer rate is decreasing where as the mass transfer rate is increasing. The Lewis number (diffusion ratio) is the ratio of Schmidt number (ν/D_m) and Prandtl number (ν/α_m). The Schmidt number quantifies the relative effectiveness of momentum and mass transport by diffusion in the hydrodynamic (velocity) and concentration (species) boundary layers. Hence the rate of mass transfer is increased with the increase in Schmidt number or Lewis number. Similarly, decrease in Prandtl number i.e. increase in Lewis number is equivalent to increasing the thermal conductivities, and therefore heat diffuses away from the heated plate more rapidly. Hence the rate of heat transfer is reduced. The heat transfer rate is decreasing for increasing values of Soret parameter(or simultaneously decreasing of Dufour parameter) but the mass transfer rate is increasing. There is decrease in both the heat and mass transfer rates with increase in the buoyancy ratio.

Table 1: Variation of non-dimensional heat and mass transfer coefficients for various values of n, Le, N, S_r and D_f.

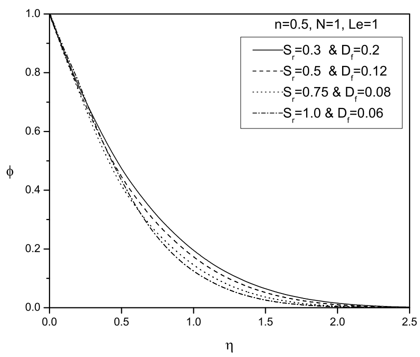
n	Le	S_r	D_f	N	$-\theta'(0)$	$-\phi'(0)$
0.0	1	0.3	0.2	1	0.948601	1.010641
0.5	1	0.3	0.2	1	1.034388	1.103721
1.0	1	0.3	0.2	1	1.113342	1.189344
1.5	1	0.3	0.2	1	1.186892	1.269066
2.0	1	0.3	0.2	1	1.256029	1.343975
2.5	1	0.3	0.2	1	1.321471	1.414857
1.5	0.0	0.3	0.2	1	1.499493	0.125000
1.5	0.5	0.3	0.2	1	1.304682	0.880668
1.5	1.0	0.3	0.2	1	1.186892	1.269066
1.5	1.5	0.3	0.2	1	1.090750	1.580181
1.5	2.0	0.3	0.2	1	1.005768	1.854397
1.5	2.5	0.3	0.2	1	0.927396	2.107590
1.5	1	0.3	0.2	1	1.186892	1.269066
1.5	1	0.4	0.15	1	1.105605	1.311094
1.5	1	0.5	0.12	1	1.025310	1.337831
1.5	1	0.6	0.1	1	0.945402	1.356935
1.5	1	0.8	0.075	1	0.785864	1.383680
1.5	1	1.0	0.06	1	0.626093	1.402756
1.5	1	0.3	0.2	0.5	1.723452	1.858859
1.5	1	0.3	0.2	0.6	1.497377	1.610498
1.5	1	0.3	0.2	0.7	1.364862	1.464944
1.5	1	0.3	0.2	0.8	1.280899	1.372654
1.5	1	0.3	0.2	0.9	1.225076	1.311203
1.5	1	0.3	0.2	1.0	1.186892	1.269066



(a) Velocity profiles.

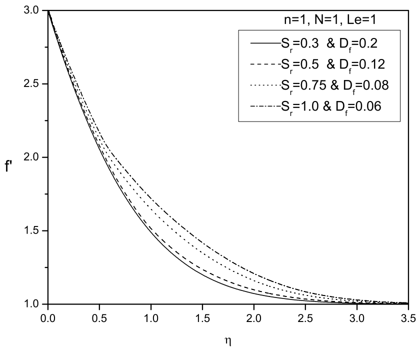


(b) Temperature profiles.

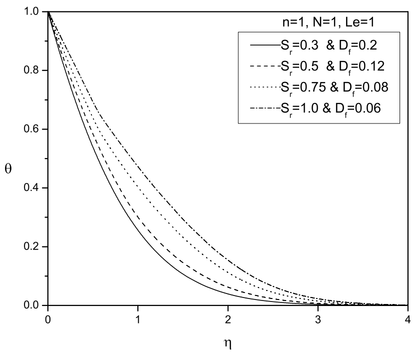


(c) Concentration profiles .

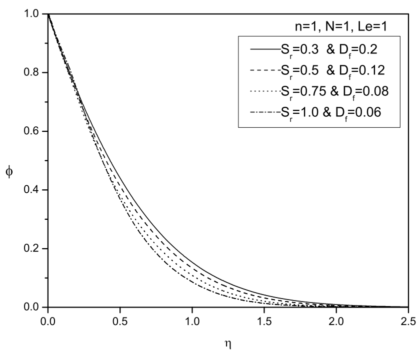
Figure 2: Velocity, temperature and concentration profiles for various values of S_r and D_f for pseudo-plastic fluid.



(a) Velocity profiles.

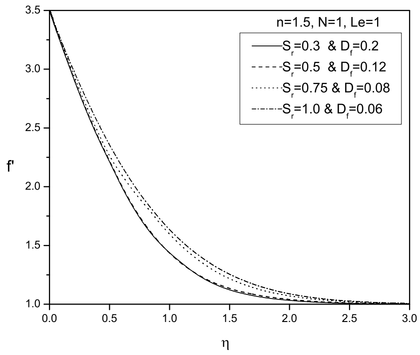


(b) Temperature profiles.

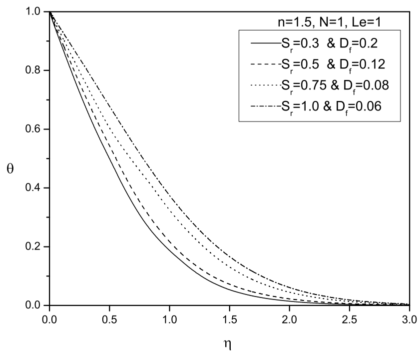


(c) Concentration profiles .

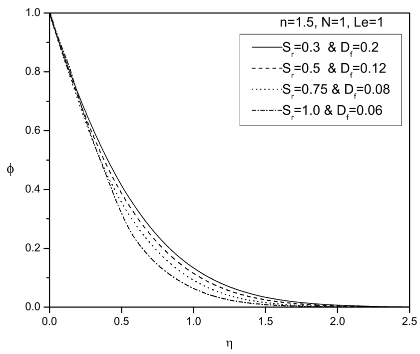
Figure 3: Velocity, temperature and concentration profiles for various values of S_r and D_f for Newtonian fluid.



(a) Velocity profiles.

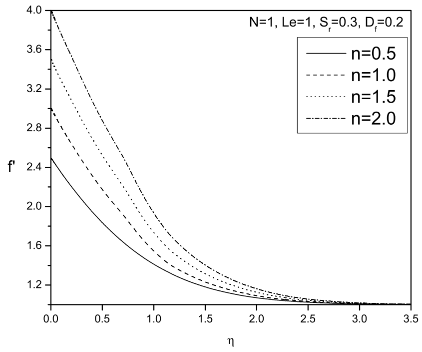


(b) Temperature profiles.

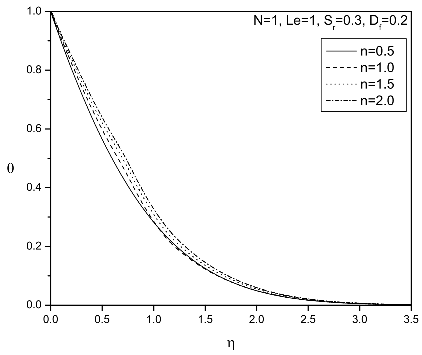


(c) Concentration profiles .

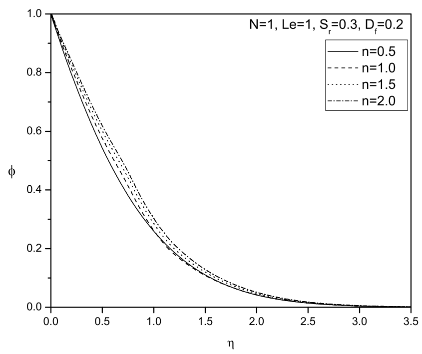
Figure 4: Velocity, temperature and concentration profiles for various values of S_r and D_f for dilatant fluids.



(a) Velocity profiles.



(b) Temperature profiles.



(c) Concentration profiles .

Figure 5: Velocity, temperature and concentration profiles for various values of Power-law index (n).

Concluding remarks

In this paper, a boundary layer analysis for mixed convection heat and mass transfer along a vertical plate in a Darcy porous medium saturated with power-law fluid with variable temperature and concentration $T_w(x)$ and $C_w(x)$, respectively in presence of the Soret and Dufour effects has been made. We found that

- The higher values of the Soret parameter (or lower values of Dufour parameter) result in higher velocity and temperature distributions but lower concentration distribution for all cases i.e., pseudo-plastic, dilatant and Newtonian fluid.
- The higher values of the power-law index parameter result in higher velocity, temperature and concentration distributions within the boundary layer.

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Uticaj Soret-a i Dufour-a na mešovitu konvekciju iz vertikalne porozne ploče i zasićene fluidom stepenog reda

Proučena je mešovita konvekcija toplote i mase duž vertikalne Darsijeve porozne ploče potopljene i zasićene sa tečnošću (stepenog reda) sa prisutnim Soret-ovim i Dufour-ovim efektom. Vladajuće parcijalne diferencijalne jednačine su preobražene u obične diferencijalne jednačine pomoću transformacije sličnosti i onda rešene numeričkim metodom gadjanja. Uticaj parametara Soret-a i Dufour-a, indeksa stepenog reda i parametra mešovite konvekcije na bezdimenzionalnu brzinu, temperaturu i koncentraciju polja se razmatra. Varijacija različitih parametara na toplotne i masene brzine prenosa je predstavljena u obliku tabele.

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