 FDMP, vol.9, no.3, pp.291-305, 2013

Effect of Double Stratification on Free Convection in a Power-Law Fluid Saturated Porous Medium

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Abstract: Free convection and related heat and mass transfer along a vertical plate embedded in a power-law fluid saturated Darcy porous medium with thermal and solutal stratification effects is studied. The governing partial differential equations are transformed into ordinary differential equations using similarity transformations and then solved numerically by means of a shooting method. The variations of non-dimensional velocity, temperature and concentration are presented graphically for various values of the power-law index, and of the thermal and solutal stratification parameters. In addition, the heat and mass transfer rates are tabulated for different values of the governing nondimensional numbers.

Keywords: Free convection, Power-law fluid, Vertical plate, Porous media, Thermal and solutal stratification.

1 Introduction

Natural convection in Newtonian fluids has gained much attention over the last century (see for instance, Lappa (2004, 2005, 2007a,b, 2011) and related references lists). Similarly, free convection flow, and related heat and mass transfer processes in non-Newtonian fluids, has attracted significant interest over the last three or four decades. Such interest has been driven essentially by the variety of applications that are enabled by a proper knowledge of such physical processes (among them the thermal design of industrial equipments for molten plastics, polymeric liquids, foodstuffs, or slurries). From both practical and theoretical point of views, in general, it is known that the non-linear behavior of non-Newtonian fluids in a porous matrix is quite different from that of a Newtonian fluid in a porous medium. Several investigators have tried to extend typical convection problems from the realm of Newtonian fluids to that of fluids exhibiting non-Newtonian rheology and different models have been proposed. One among these is the so-called power-law

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fluid which has gained considerable importance. Although this model is merely an empirical relationship between the stress and velocity gradients, it has been successfully applied to non-Newtonian fluids experimentally.

Free convection of non-Newtonian power law fluids with yield stress from vertical flat plate in a saturated porous media was studied by Rami and Arun (2000). Buoyant convection of a power-law fluid in an enclosure filled with heat-generating porous media was considered by Kim and Hyun (2004). The flow of natural convection heat and mass transfer of non-Newtonian power law fluids with yield stress in porous media from a vertical plate with variable wall heat and mass fluxes was considered by Cheng (2006). Free convection heat transfer from a vertical flat plate embedded in a thermally stratified non-Newtonian fluid saturated non-Darcy porous medium has been analyzed by Kairi and Murthy (2009). Pantokkratoras and Magyari (2010) investigated the steady forced- convection flow of a power-law fluid over a horizontal plate embedded in a saturated Darcy-Brinkman porous medium. Abdel-Gaied and Eid (2011) presented a numerical analysis of the free convection coupled heat and mass transfer for non-Newtonian power-law fluids with yield stress, flowing over a two-dimensional or axi-symmetric body of an arbitrary shape in a fluid-saturated porous medium.

Stratification of fluid arises due to temperature variations, concentration differences or the presence of different fluids. The analysis of natural convection in a doubly stratified medium is a fundamentally interesting and important problem because of its broad range of engineering applications. The applications include heat rejection into the environment such as lakes, rivers and the seas; thermal energy storage systems such as solar ponds and heat transfer from thermal sources such as the condensers of power plants. Although the effect of stratification of the medium on the heat removal process in a fluid is important, very little work has been reported in the literature. Jumah and Mujumdar (2000) studied the free convection heat and mass transfer of non-Newtonian power law fluids with yield stress from a vertical flat plate in saturated porous media. Murthy, Srinivasacharya, and Krishna (2004) discussed the effect of double stratification on free convection heat and mass transfer in a Darcian fluid saturated porous medium using the similarity solution technique for the case of uniform wall heat and mass flux conditions. Narayana and Murthy (2006) analyzed the free convection heat and mass transfer from a vertical flat plate in a doubly stratified non-Darcy porous medium using series solution technique. Cheng (2009) considered the combined heat and mass transfer in natural convection flow from a vertical wavy surface in a power-law fluid saturated porous medium with thermal and mass stratification. Postelnicu, Narayana, and Murthy (2009) studied the free convection heat and mass transfer in a doubly stratified porous medium saturated with a power-law fluid. More recent and relevant studies are also due to Al-Ajmi and Mosaad (2012); Hamimid, Guellal, Amroune, and Zeraibi (2012); Choukairy and Bennacer (2012); Labed, Bennamoun, and Fohr (2012); Ram and Bhandari (2012).

Motivated by the investigations mentioned above herein, we undertake the investigation of the thermal and solutal stratification effects on free-convection along a vertical plate in Darcy porous media saturated with a power-law fluid with variable surface temperature and concentration conditions.

2 Physical model

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 $T_\infty(x)$ and $C_\infty(x)$ respectively is shown in Fig. 1.

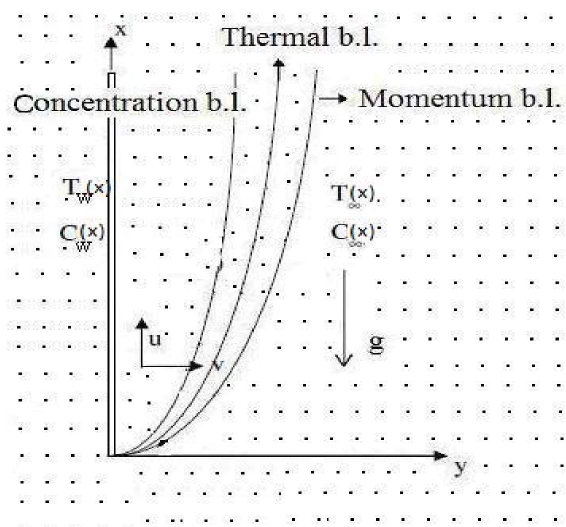

Figure 1: Physical model and coordinate system.

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, two dimensional. The porous medium is isotropic and homogeneous. The fluid and the porous medium are in local thermo dynamical equilibrium. In addition the thermal and solutal stratification effects are taken in to consideration. The ambient medium is assumed to be vertically non-linearly stratified with respect to both temperature and concentration in the form $T_\infty(x) =$

$T_{\infty,0} + Gx^l$ and $C_\infty(x) = C_{\infty,0} + Hx^m$ respectively, where G and H are constants and varied to alter the intensity of stratification in the medium.

3 Mathematical formulation

Using the Boussinesq and boundary layer approximations, the governing equations for the power-law fluid are given by

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

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

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_m \frac{\partial^2 T}{\partial y^2} \tag{3}$$

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

where u and v are the Darcian velocity components along x and y directions, T is the temperature, C is the concentration, v is the kinematic viscosity, K is the permeability, g is the acceleration due to gravity, β_T is the coefficient of thermal expansion, β_C is the coefficient of concentration expansion, α_m is the thermal diffusivity, D_m is the mass diffusivity of the porous medium, 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

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

$$u \to 0, T \to T_\infty(x), C \to C_\infty(x) \text{ as } y \to \infty \tag{5b}$$

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 dp/dx from (2) and (6)

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

Since the pressure gradient dp/dx is assumed 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

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

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 $(T_w(x)-T_{\infty,0}) = Ex^{n/3}$ and $(C_w(x)-C_{\infty,0}) = Fx^{n/3}$ respectively and the temperature and concentration stratifications are in the form $T_\infty(x) = T_{\infty,0}+Gx^l$ and $C_\infty(x) = C_{\infty,0}+Hx^m$ respectively.

In view of the continuity eq. (1), we introduce the stream function ψ by

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

Substituting eq. (9) in (8), (3) and (4) and then using the following similarity transformations

$$\left.\begin{array}{l} \eta = Byx^{-1/3}, \psi = Ax^{2/3}f(\eta) \\ \frac{T-T_\infty(x)}{T_w(x)-T_{\infty,0}} = \theta(\eta), T_w(x)-T_{\infty,0} = Ex^{n/3} \\ \frac{C-C_\infty(x)}{c_w(x)-C_{\infty,0}} = \phi(\eta), T_{C_w}(x)-C_{\infty,0} = Fx^{n/3} \end{array}\right\} \tag{10}$$

we get the following nonlinear system of differential equations.

$$(f^{'})^n = (\theta+N\phi) \tag{11}$$

$$\theta^{''} = \frac{1}{3}(nf^{'}\theta-2f\theta^{'}+\varepsilon_1 f^{'}) \tag{12}$$

$$\phi^{''} = \frac{Le}{3}(nf^{'}\phi-2f\phi^{'}+\varepsilon_2 f^{'}) \tag{13}$$

where primes denote differentiation with respect to η alone $\varepsilon_1 = \frac{nG}{E}$ is the thermal stratification parameter, $\varepsilon_2 = \frac{nH}{F}$ is the solutal stratification parameter, $N = \frac{\beta_C F}{\beta_T E}$ is the buoyancy ratio, $Le = \frac{\alpha_m}{D_m}$ is the Lewis number, $A = \left(\frac{EgK\beta_T d_m^n}{v}\right)^{1/2n}$ and $B = \left(\frac{EgK\beta_T}{v\alpha_m^n}\right)^{1/2n}$.

$$f = 0, \theta = 1-\varepsilon_1/n, \phi = 1-\varepsilon_2/n \text{ at } \eta = 0 \tag{14a}$$

$$f^{'} = 1, \theta = 0, \phi = 0 \text{ as } \eta \to \infty \tag{14b}$$

The parameters of engineering interest for the present problem are the Nusselt and Sherwood numbers, which are given by the expressions

$$\frac{Nu_x}{Bx^{2/3}} = -\theta^{'}(0) \text{ and } \frac{Sh_x}{Bx^{2/3}} = -\phi^{'}(0) \tag{15}$$

4 Numerical procedure and validation

The flow Eq. (11) coupled with the energy and concentration Eqs. (12) and (13) constitute a set of nonlinear non-homogeneous differential equations for which closed-form solution cannot be obtained. Hence the problem is solved numerically using shooting technique along with fourth order Runge-Kutta integration. The non-linear differential equations (11)-(13) are converted into a system of first order linear differential equations and then integrated using the 4th order Runge - Kutta method by giving appropriate initial guess values for $f^{'}(0)$, $\theta^{'}(0)$ and $\phi^{'}(0)$ to match the values with the corresponding boundary conditions $f^{'}(\infty)$, $\theta^{'}(\infty)$ and $\phi^{'}(\infty)$ respectively.

In order to see the effects of step size ($\Delta\eta$) we ran the code for our model with three different step sizes as $\Delta\eta = 0.01, 0.001, 0.005$ and for the parameter values $N = 1$, $n = 1.5$, $\varepsilon_1 = 0.5$ and $Le = 0.5$. In each case we found very good agreement between them. A step size of $\Delta\eta = 0.01$ is selected to be satisfactory for the convergence criterion of 10^{-6} in all cases. In the present study, the boundary conditions for η at ∞ vary with parameter values and it is suitably chosen at each time such that the velocity, temperature and concentration approach zero at the outer edge of the boundary layer. Extensive calculations are performed to obtain the velocity, temperature and concentration fields for a wide range of parameters.

Table 1: Comparison of $-\theta^{l}(0)$ and $-\phi^{l}(0)$ various values of N and Le calculated by the present method and that of Yih (1999) for $\varepsilon_1 = \varepsilon_2 = 0$ and $n = 1$

		$-\theta^{l}(0)$		$-\phi^{l}(0)$	
N	Le	Yih (1999) with $\lambda = 1/3$	Present Result	Yih (1999) with $\lambda = 1/3$	Present Result
1	1	0.9583	0.9583	0.9583	0.9583
1	10	0.8053	0.8053	3.339	3.3394
1	100	0.7233	0.7233	10.8298	10.8298
4	1	1.5153	1.5153	1.5153	1.5153
4	10	1.0668	1.0668	5.0070	5.0070
4	100	0.8126	0.8126	16.0127	16.0127

To validate the accuracy of the present numerical scheme, a comparison of the heat and mass transfer coefficients for the case of Newtonian fluid flow ($n = 1$) in the absence of thermal and solutal stratification parameters is made with the previously published results of Yih (1999). The comparison is listed in Table (1) and our results are found to be in good agreement with those of Yih (1999).

5 Results and discussion

In the present model we are concerned primarily with elucidating the influence of the three dimensionless parameters: thermal stratification parameter ε_1, solutal stratification parameter ε_2 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. 2-8). Numerical calculations have been carried out for different values of ε_1, ε_2 and n. Throughout the calculations, we have fixed the values of N and Le as 1 and 0.5, respectively, unless otherwise indicated.

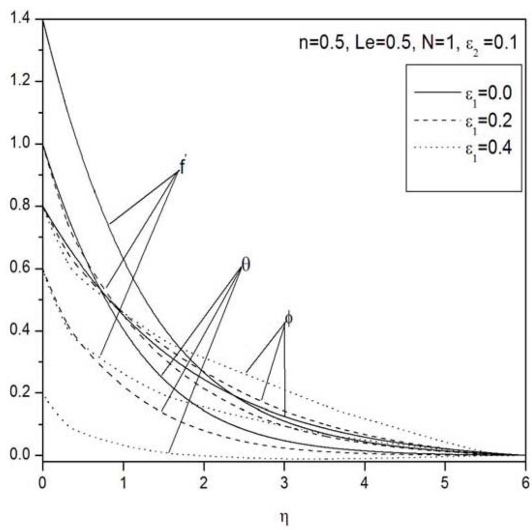

Figure 2: Velocity, Temperature and Concentration profiles for various values of ε_1 for pseudo-plastic fluids.

5.1 Effect of the thermal stratification parameter

Figures. (2)-(4) are for pseudo-plastic fluids with $n = 0.5$, Newtonian fluids with $n = 1.0$, and dilatant fluids with $n = 1.5$. These figures demonstrate that the velocity of the fluid in all cases decreases with increase in the value of thermal stratification

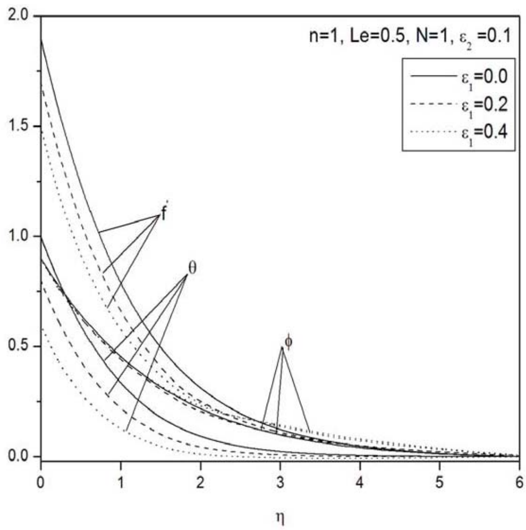

Figure 3: Velocity, Temperature and Concentration profiles for various values of ε_1 for Newtonian fluid.

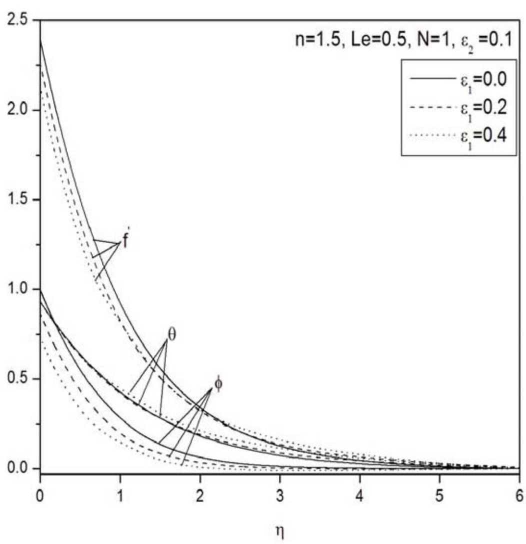

Figure 4: Velocity, Temperature and Concentration profiles for various values of ε_1 for dilatant fluids.

parameter (ε_1). The parameter ε_1 appears only in the energy Eq. (12) and the thermal boundary conditions (14a) i.e. as ε_1, $f^{'}$ in Eq. (12) and featuring in $\theta = 1 - \varepsilon_1/n$

in Eq. (14a). As such the effect of 1 is experienced indirectly in the velocity field (momentum) via the coupling of the momentum Eq. (11) to the energy Eq. (12) in the buoyancy-assisting term in Eq. (11). Increase in thermal stratification parameter reduces the effective convective potential between the heated plate and the ambient fluid in the medium. This factor causes a decrease in the buoyancy force, which decelerates the velocity of the flow. The non-dimensional temperature of the fluid lessens with the raise in thermal stratification parameter. When the thermal stratification effect is taken into consideration, the effective temperature difference between the plate and the ambient fluid will diminish; in view of this, the thermal boundary layer is thickened and the temperature is reduced. It is observed that the concentration of the fluid declines near the plate and then shows an escalating trend away from the plate with enhance in the value of the thermal stratification parameter.

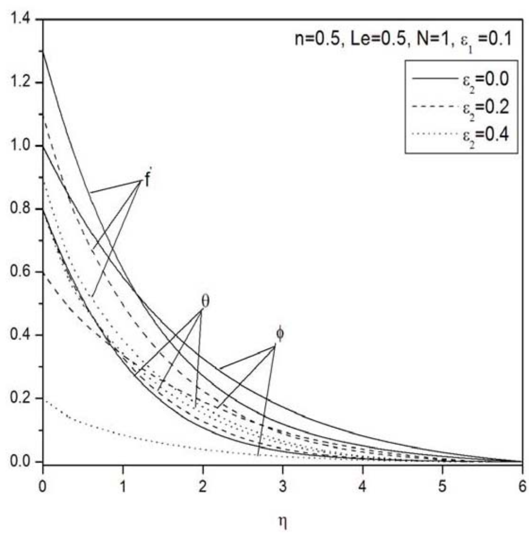

Figure 5: Velocity, Temperature and Concentration profiles for various values of ε_2 for pseudo-plastic fluids.

5.2 Effect of the solutal stratification parameter

The effect of solutal stratification parameter on $f^1(\eta)$, $\theta(\eta)$ and $\phi(\eta)$ for pseudo plastic fluids, Newtonian fluids and dilatant fluids presented in Figs. (5)-(7) respectively with $N = 1$, $Le = 0.5$, $\varepsilon_1 = 0.5$. It is observed from these figures that the velocity and concentration of the fluid in all cases have reduced with an enhance

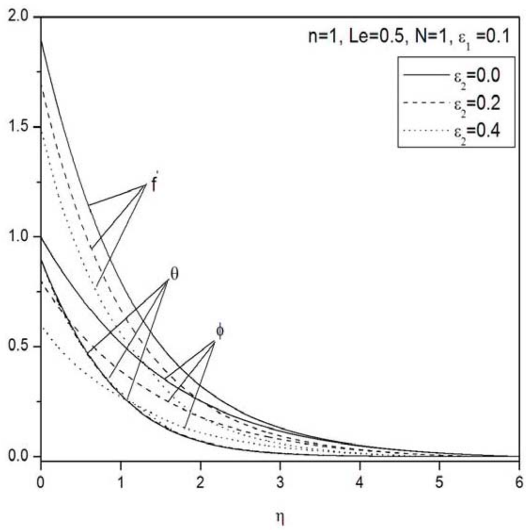

Figure 6: Velocity, Temperature and Concentration profiles for various values of ε_2 for Newtonian fluid.

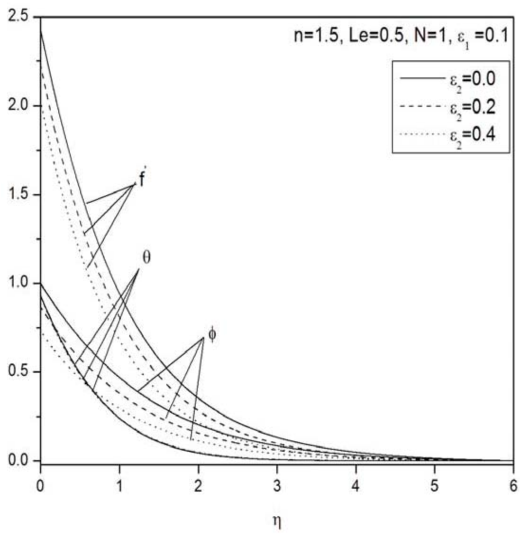

Figure 7: Velocity, Temperature and Concentration profiles for various values of ε_2 for dilatant fluids.

in the value of solutal stratification parameter. Raise in mass stratification parameter lessens the concentration gradient between the ambient and the surface. This declines the buoyancy force, which decelerates the velocity of the flow. The temperature of the fluid in all cases is seen to have an increasing trend away from the plate with an increase in the value of solutal stratification parameter.

5.3 Effect of power-law index

The non-dimensional velocity $f^1(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ for $N = 1$, $Le = 0.5$, $\varepsilon_1 = 0.5$, $\varepsilon_2 = 0.5$ with a variation in power law index parameter is plotted in Fig. (8). It is found from the figure that the fluid velocity is enhanced with raise in the value of the power law index parameter. The effect of the increasing values of the power law index n is to increase the horizontal 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 the case of a shear thinning fluid ($n < 1$) the shear rates near the walls are higher than those for a Newtonian fluid. The temperature and concentration of the fluid are lessened with increase in the value of the power law index parameter. Increasing the values of the power law index (n) tends to accelerate the flow and increase the thermal and solutal boundary layer thickness.

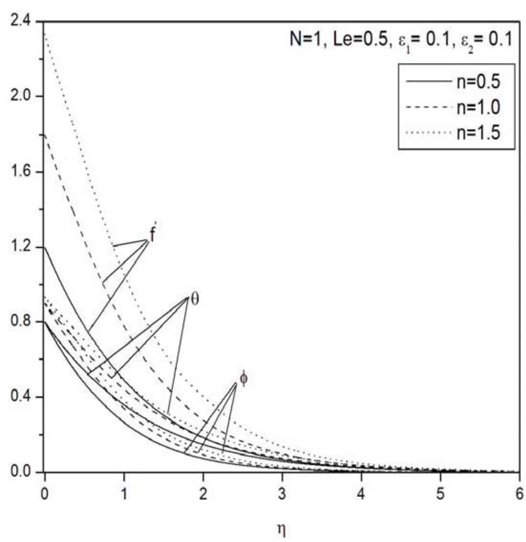

Figure 8: Velocity, Temperature and Concentration profiles for various values of power-law $index(n)$.

Table 2: Variation of non-dimensional heat and mass transfer coefficients for various values of n, Le, N, ε_1 and ε_2

n	Le	N	ε_1	ε_2	$-\theta'(0)$	$-\phi'(0)$
0.5	1	1	0.1	0.1	0.620074	0.620074
1.0	1	1	0.1	0.1	0.849859	0.849859
1.5	1	1	0.1	0.1	1.001968	1.001968
2.0	1	1	0.1	0.1	1.126374	1.126374
2.5	1	1	0.1	0.1	1.235412	1.235412
0.5	0.0	1	0.1	0.1	0.668106	0.133333
0.5	0.5	1	0.1	0.1	0.638568	0.413083
0.5	1.0	1	0.1	0.1	0.620074	0.620074
0.5	1.5	1	0.1	0.1	0.607566	0.787620
0.5	2.0	1	0.1	0.1	0.598520	0.930689
0.5	1	0.5	0.1	0.1	0.514931	0.514931
0.5	1	0.6	0.1	0.1	0.537437	0.537437
0.5	1	0.7	0.1	0.1	0.559361	0.559361
0.5	1	0.8	0.1	0.1	0.580424	0.580424
0.5	1	0.9	0.1	0.1	0.600647	0.600647
0.5	1	1.0	0.1	0.1	0.620074	0.620074
0.5	1	1	0.0	0.1	0.800289	0.674316
0.5	1	1	0.1	0.1	0.620074	0.620074
0.5	1	1	0.2	0.1	0.455355	0.561196
0.5	1	1	0.3	0.1	0.307586	0.496486
0.5	1	1	0.4	0.1	0.178637	0.424267
0.5	1	1	0.1	0.0	0.647714	0.768931
0.5	1	1	0.1	0.1	0.620074	0.620074
0.5	1	1	0.1	0.2	0.591280	0.480109
0.5	1	1	0.1	0.3	0.561196	0.349514
0.5	1	1	0.1	0.4	0.529661	0.228831

5.4 Nusselt and Sherwood numbers

Table (2) shows the effects of n, Le, N, ε_1, ε_2 on the non-dimensional heat and mass transfer rates. It is seen from this table that both the heat and mass transfer rates enhance with an increase in the power law index n. The Lewis number (diffusion ratio) is the ratio of Schmidt number (v/D_m) and Prandtl number (v/α_m). As the Lewis number increases i.e. Schmidt number raises (or Prandtl number lessens) Nusselt number is decreasing while the Sherwood number is increasing.

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 enhanced with the raise in Schmidt number or Lewis number. Similarly, a reduction in Prandtl number i.e. an increase in Lewis number is equivalent to increasing the thermal conductivity, and therefore heat is able to diffuse away from the heated plate more rapidly. Hence the rate of heat transfer is reduced. There is increase in both the heat and mass transfer rates with increase in the buoyancy ratio. The heat transfer rate and mass transfer rate are decreasing for an increase in the value of thermal stratification parameter, same is the case with increase in solutal stratification parameter.

6 Conclusions

In this paper, free convection heat and mass transfer along a vertical plate embedded in a power-law fluid saturated Darcy porous medium in the presence of thermal and solutal stratification parameters has been considered. The following conclusions can be drawn:

Higher values of thermal and solutal stratification parameter result in lower velocity. An increase in the thermal stratification parameter, decreases temperature but increases the concentration distribution. The reverse trend is observed for temperature and concentration distributions in case of solutal stratification parameter increase. Also, increase in the power-law index parameter results in higher velocity, temperature and concentration distributions within the boundary layer.

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