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ORIGINAL ARTICLE

Chemical reaction and radiation effects on mixed convection heat and mass transfer over 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 chemical reaction and radiation effects is studied. The governing partial differential equations are transformed into ordinary differential equations using similarity transformations and then solved numerically using shooting method. A parametric study of the physical parameters involved in the problem is conducted and a representative set of numerical results is illustrated graphically.

2010 MATHEMATICS SUBJECT CLASSIFICATION: 76A05; 76E06; 80A20

1. Introduction

The analysis of mixed convection boundary layer flow along a vertical surface embedded in porous medium has received considerable theoretical and practical interest. 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]. 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 toward the analysis and understanding of such fluids. A number of 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

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Nomenclature

A, B	dimensional constants	R	radiation parameter
a, b	constants	σ	Stefan–Boltzman constant
l	temperature variation index at wall	Le	Lewis number
T	temperature	N	buoyancy ratio
C	concentration	n	power-law index
g	gravitational acceleration	β_T	coefficient of thermal expansion
T_∞	ambient temperature	β_C	coefficient of concentration expansion
K	Darcy permeability	Nu_x	Nusselt number
k_1	rate of chemical reaction	Sh_x	Sherwood number
k	thermal conductivity	v	kinematic viscosity
q_y^r	radiative heat flux	ϕ	dimensionless concentration
$q_w(x)$	heat flux	θ	dimensionless temperature
$q_m(x)$	mass flux	u, v	Darcian velocity components in x and y directions
C_p	specific heat at constant pressure	x, y	co-ordinates along and normal to the plate
C_s	concentration susceptibility	η	similarity variable
α_m	thermal diffusivity	ψ	stream function
D_m	mass diffusivity		
γ	chemical reaction parameter		

applications. 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 magnetohydrodynamic 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 with variable surface temperature in the presence of magnetic field and radiation. Effect of double dispersion on mixed convection heat and mass transfer in a non-Newtonian fluid-saturated non-Darcy porous medium has been investigated by Kairi and Murthy [8]. 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 Magnetohydrodynamic (MHD) mixed convection stagnation-point flow and heat transfer of power-law fluids toward a stretching surface using the homotopy analysis method.

Radiative convective flows are very important in many industrial and environment processes that are operating at high temperature. Since the solution for convection and radiation equation is very complicated, there are few studies about simultaneous effect of convection and radiation for internal flows. Salem [11] considered the coupled heat and mass transfer in Darcy–Forchheimer mixed convection from a vertical flat plate embedded in a fluid saturated porous medium under the effects of radiation and viscous dissipation. Damseh [12] studied magnetohydrodynamics-mixed convection from radiate vertical isothermal surface embedded in a saturated porous media. The radiation effect on MHD mixed convection flow about a permeable vertical plate was studied by Orhan Aydn [13]. Hayat et al. [14] analyzed the effects of radiation and magnetic field on the mixed convection stagnation point flow over a vertical stretching sheet in a porous medium.

On the other hand, chemical reaction effects on heat and mass transfer are of considerable importance in hydrometallurgical industries and chemical technology. Several investigators have examined the effect of chemical reaction on the flow, heat and mass transfer past a vertical plate. Further, chemical reaction effects on heat and mass transfer with radiation are of considerable importance in hydrometallurgical industries and chemical technology such as polymer production and food processing. Chamkha et al. [15] studied MHD mixed convection radiation interaction along a permeable surface immersed in a porous medium in the presence of Soret and Dufour effects. Prabhu et al. [16] considered the effects of chemical reaction, heat and mass transfer on MHD flow over a vertical stretching surface with heat source and thermal stratification effects. Postelnicu [17] studied the influence of chemical reaction on heat and mass transfer by natural convection from vertical surfaces in porous media by considering Soret and Dufour effects. Ibrahim et al. [18] analyzed the effects of chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi infinite vertical permeable moving plate with heat source and suction. Unsteady natural convective power-law fluid flow past a vertical plate embedded in a non-Darcian porous medium in the presence of a homogeneous chemical reaction was studied by Chamkha [19]. Recently Pal and Mondal [20] studied the influence of chemical reaction and thermal radiation on mixed convection heat and mass transfer over a stretching sheet in Darcy porous medium with Soret and Dufour effects.

Motivated by the investigations and applications mentioned above, the aim of this investigation was to consider the effects of radiation and chemical reaction on the mixed convection heat and mass transfer along a vertical plate embedded in a power-law fluid saturated porous medium. Majority of the studies, reported in literature, on convective heat and mass transfer in power-law fluid saturated porous medium deal with local similarity solutions and non-similarity solutions. But, in the present analysis, an attempt is made to obtain similarity solutions for mixed convection heat and mass transfer along a vertical plate embedded in a power-law fluid saturated porous medium. It is established that similarity solutions are possible only when variation in the temperature and concentration flux are linear functions of the distance from the leading edge measured along the plate. Using these similarity transformations, the governing system of partial differential equations is transformed into a system of nonlinear ordinary differential equations and then solved numerically using shooting method along with fourth order Runge–Kutta integration.

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 surface heat flux $q_w(x)$ and mass flux $q_m(x)$. The temperature and concentration of the ambient medium are T_∞ and C_∞ respectively. 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 thermodynamical equilibrium. The fluid is considered to be a gray, absorbing emitting radiation but non-scattering medium and the Rosseland approximation [21] is used to describe the radiative heat flux in the energy equation. The radiative heat flux in the x-direction is considered negligible in comparison with the y-direction. Also, it is assumed that there exists a homogenous chemical reaction of first-order with rate constant k_1 between the diffusing species and the fluid (see Fig. 1).

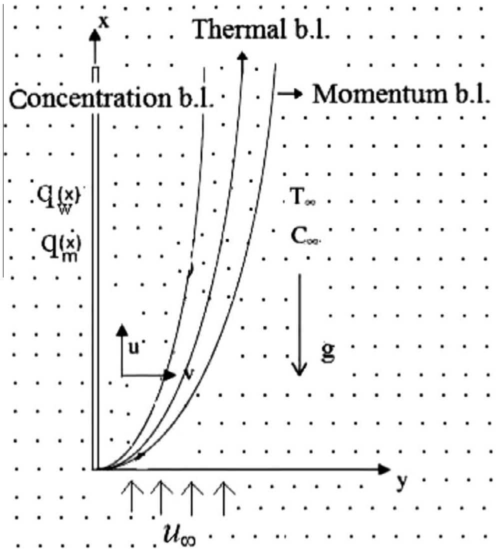


Figure 1 Flow model and physical coordinate system.

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

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

$$u^n = u_\infty^n + \frac{gK}{\nu}\{\beta_T(T - T_\infty) + \beta_C(C - C_\infty)\} \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left\{\alpha_m\frac{\partial T}{\partial y} - \frac{1}{\rho C_p}q_y^r\right\} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} - k_1(C - C_\infty) \tag{4}$$

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

$$v = 0,\ -k\frac{\partial T}{\partial y} = q_w(x),\ -D_m\frac{\partial C}{\partial y} = q_m(x)\ at\ y = 0 \tag{5a}$$

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

Using Rosseland approximation in the last term (for the radiative heat flux q_r) of Eq. (3) [9], we obtain

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_m\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^* T_\infty^3}{3\rho C_p k^*}\frac{\partial^2 T}{\partial y^2} \tag{6}$$

where σ^* and k^* are the Stefan–Boltzmann constant and the mean absorption coefficient respectively.

3. Solution of the problem

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

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

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

$$\psi = Ax^a f(\eta),\ \eta = Byx^b,\quad T = T_\infty + \frac{q_w(x)}{k}\theta(\eta),\ \frac{q_w(x)}{k} = Ex^l,\quad C = C_\infty + \frac{q_m(x)}{D}\phi(\eta),\ \frac{q_m(x)}{D} = Fx^m \tag{8}$$

where A, B, E, F, a, b, l, and m are constants. Substituting (7) and (8) in (2), (4) and (6), it is found that similarity exists only if $a = 1$, $b = 0$, $l = m = n$. Hence, appropriate similarity transformations are

$$\psi = Axf(\eta),\ \eta = By,\quad T = T_\infty + \frac{q_w(x)}{k}\theta(\eta),\ \frac{q_w(x)}{k} = Ex^n,\quad C = C_\infty + \frac{q_m(x)}{D}\phi(\eta),\ \frac{q_m(x)}{D} = Fx^n \tag{9}$$

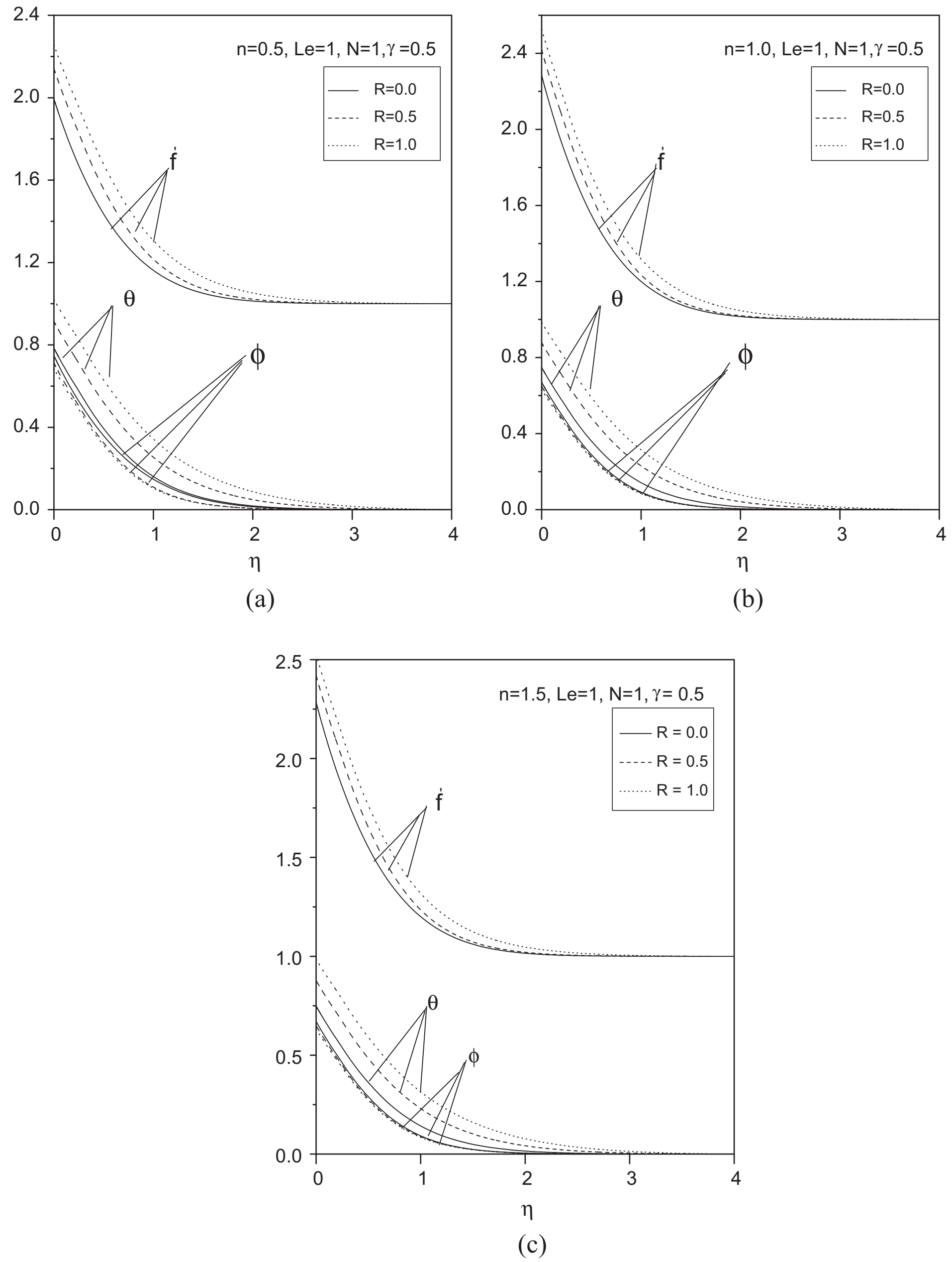


Figure 2 Velocity, temperature and concentration profiles for various values of R for (a) pseudo-plastic fluids, (b) Newtonian fluids and (c) dilatant fluids.

Making use of the similarity transformations (9) in (2), (4) and (6) we get the following nonlinear system of differential equations.

$$(f')^n = [1 + \theta + N\phi] \tag{10}$$

$$\theta'' = \frac{1}{\left[1 + \frac{4}{3}R\right]}[nf'\theta - f\theta'] \tag{11}$$

$$\phi'' = Le[nf'\phi - f\phi' + \gamma\phi] \tag{12}$$

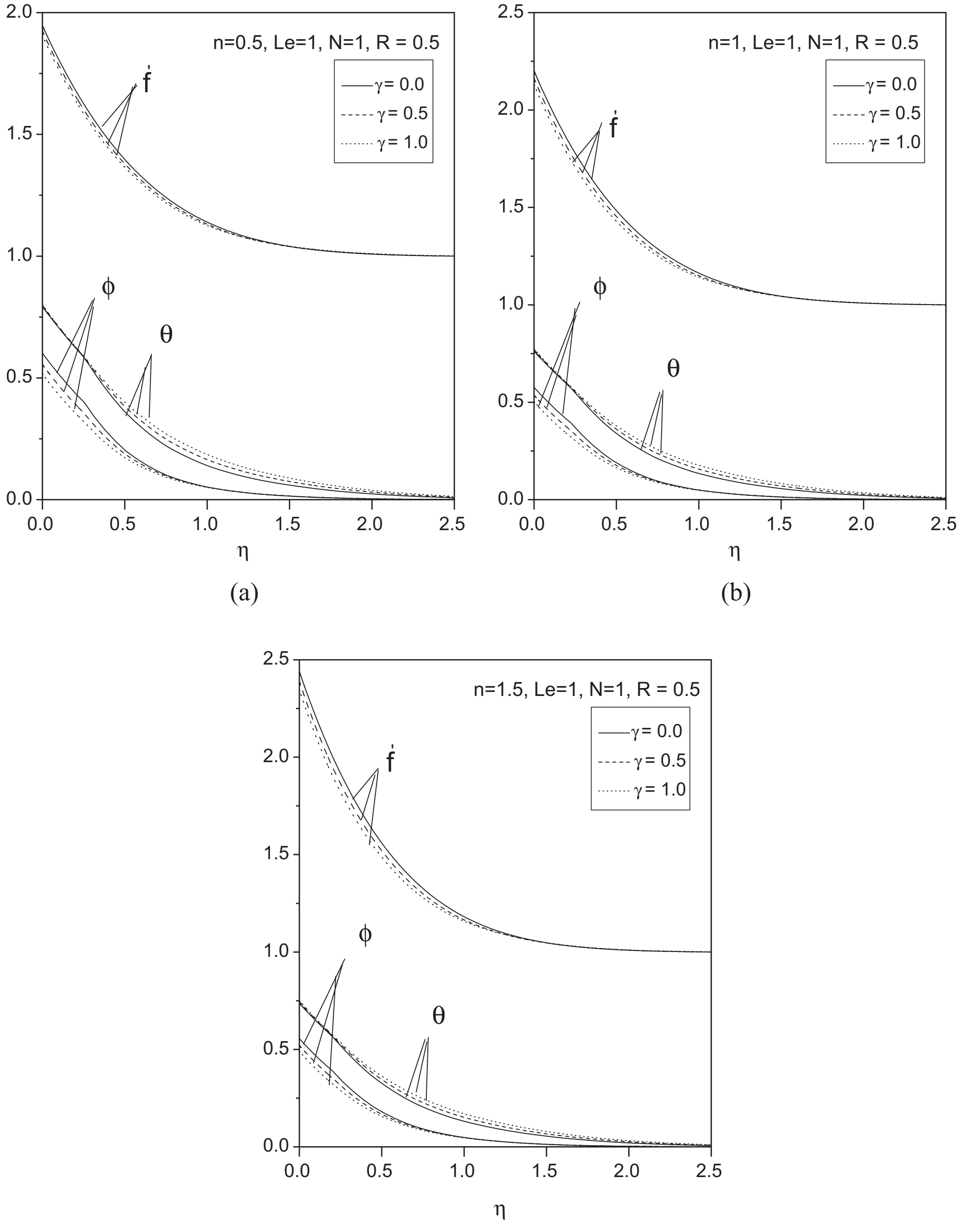
where the prime denotes differentiation with respect to η alone. $N = \frac{\beta_C F}{\beta_T E}$ is the buoyancy parameter, $\gamma = \frac{k_1}{B^2\alpha_m}$ is the chemical reaction parameter, $R = \frac{4\sigma^* T_\infty^3}{k^* k}$ is the conduction radiation parameter, $Le = \frac{\alpha_m}{D_m}$ 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

$$\begin{aligned} &f(0) = 0, \quad \theta'(0) = -1, \quad \phi'(0) = -1, \\ &f'(\infty) = 1, \quad \theta(\infty) = 0, \quad \phi(\infty) = 0. \end{aligned} \tag{13}$$

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

$$\frac{Nu_x}{Bx} = \frac{1}{\theta(0)}, \frac{Sh_x}{Bx} = \frac{1}{\phi(0)} \tag{14}$$



(a)

(b)

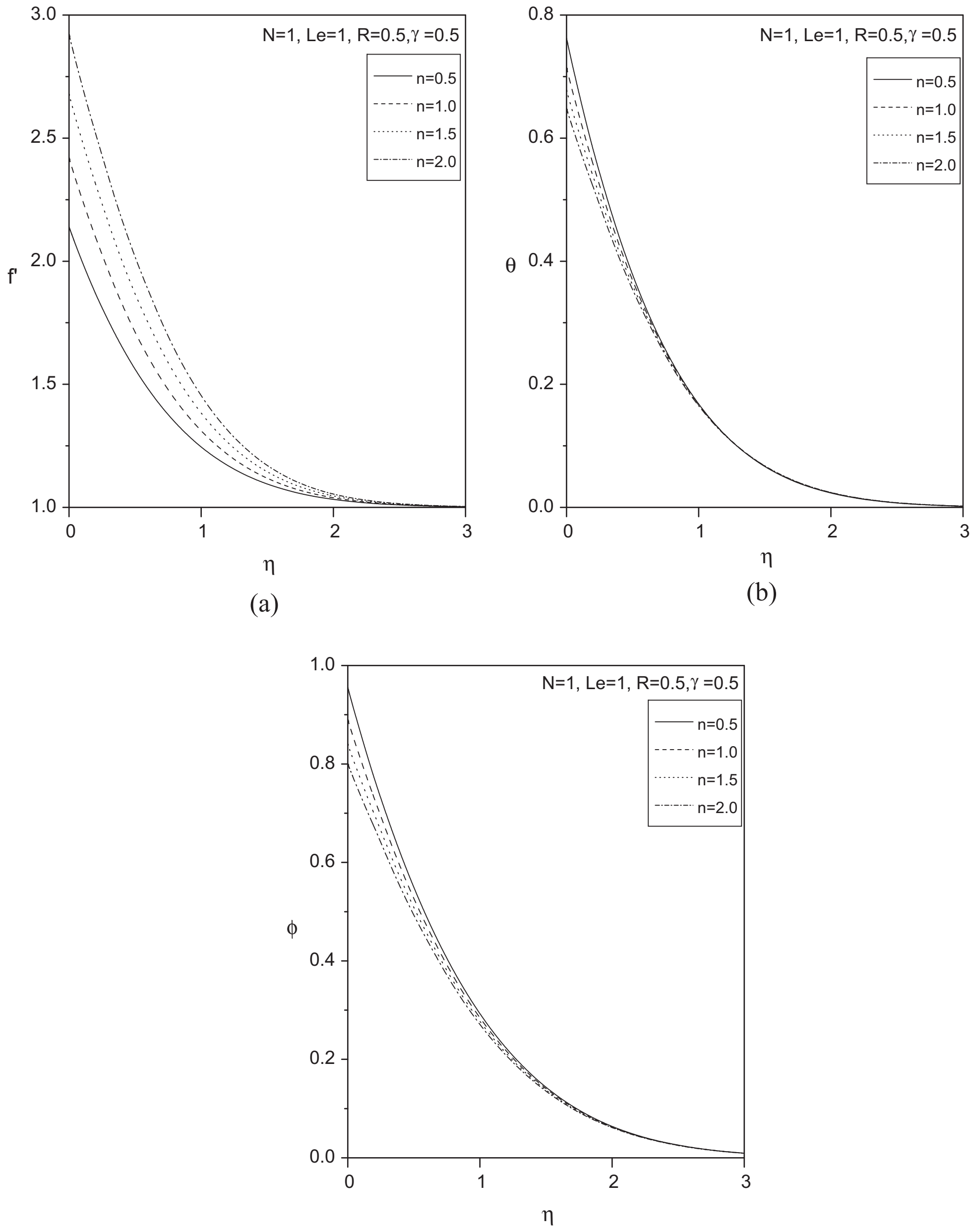
(c)

Figure 3 Velocity, temperature and concentration profiles for various values of γ for (a) pseudo-plastic fluids, (b) Newtonian fluids and (c) dilatant fluids.

The flow Eq. (10) coupled with the energy and concentration Eqs. (11) and (12) constitute a set of nonlinear non-homogeneous differential equations for which closed-form solution cannot be obtained. Hence the problem is solved numerically using a shooting technique along with fourth order Runge–Kutta integration.

4. Results and discussion

The effect of radiation parameter on the non-dimensional velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ for pseudo-plastic fluids with $n = 0.5$, Newtonian fluids with $n = 1.0$, and dilatant fluids with $n = 1.5$ is presented in Fig. 2 for $N = 1,\ Le = 1,\ \gamma = 0.5$. It is demonstrated from this figure that an increase in the value of radiation parameter enhances the velocity of the fluid in all cases. It is noticed that the temperature of the fluid increases with the increase in the value of the radiation parameter. It is clear from Fig. 2 that the concentration of the fluid decreases with the rise in the value of the radiation parameter. These results can be explained by the fact that an increase in the radiation parameter $R = \frac{4\sigma^* T_\infty^3}{k^* k}$ for given k and T_∞ means a decrease in the Rosseland radiation absorptivity k^*. Hence, the divergence of radiative heat flux q_r increases as k^* decreases. Therefore, the rate of radiative heat



(a) (b) (c)

Figure 4 (a) Velocity, (b) temperature and (c) concentration profiles for various values of power-law index (n).

transferred to the fluid increases and consequently the fluid temperature and simultaneously the velocity of the fluid also increases.

The non-dimensional velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ are plotted for pseudo-plastic fluids with $n = 0.5$, Newtonian fluids with $n = 1.0$, and dilatant fluids with $n = 1.5$ with $N = 1,\ Le = 1,\ R = 0.5$ in Fig. 3 with varying chemical reaction parameter. It is observed from this figure that the velocity of the fluid decreases with the increase in the value of chemical reaction parameter. It is found that the temperature of the fluid increases with increase in the value of the chemical reaction parameter. An increase in chemical reaction parameter will suppress the concentration of the fluid. Higher values of γ amount to a fall in the chemical molecular diffusivity, i.e., less diffusion. Therefore, they are obtained by species transfer. An increase in γ will suppress species concentration. The concentration distribution decreases at all points of the flow field with the increase in the reaction parameter.

The non-dimensional velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ for $N = 1,\ Le = 1,\ \gamma = 0.5,\ R = 0.5$ with a variation in power law index parameter are plotted in Fig. 4(a)–(c). It is found from Fig. 4(a) that the fluid velocity is increased with increase 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

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

n	Le	R	γ	N	$\frac{Nu_x}{Bx} = \frac{1}{\theta(0)}$	$\frac{Sh_x}{Bx} = \frac{1}{\phi(0)}$
0.0	1	0.5	0.5	1	1.203637	1.308354
0.5	1	0.5	0.5	1	1.275188	1.407180
1.0	1	0.5	0.5	1	1.336053	1.491417
1.5	1	0.5	0.5	1	1.389624	1.565670
2.0	1	0.5	0.5	1	1.437824	1.632557
1.5	0.0	0.5	0.5	1	2.562919	0.250000
1.5	0.5	0.5	0.5	1	1.475744	1.190670
1.5	1.0	0.5	0.5	1	1.389624	1.565670
1.5	1.5	0.5	0.5	1	1.351302	1.828655
1.5	2.0	0.5	0.5	1	1.328912	2.034016
1.5	1	0.0	0.5	1	1.789068	1.511297
1.5	1	0.5	0.5	1	1.389624	1.565670
1.5	1	1.0	0.5	1	1.180034	1.609968
1.5	1	1.5	0.5	1	1.046726	1.647639
1.5	1	2.0	0.5	1	0.952871	1.680499
1.5	1	0.5	0.0	1	1.356426	1.799538
1.5	1	0.5	0.5	1	1.342871	1.922622
1.5	1	0.5	1.0	1	1.331584	2.040250
1.5	1	0.5	1.5	1	1.322055	2.152829
1.5	1	0.5	2.0	1	1.313910	2.260801
1.5	1	0.5	0.5	0.5	1.564433	1.822021
1.5	1	0.5	0.5	0.6	1.490721	1.714583
1.5	1	0.5	0.5	0.7	1.444612	1.647438
1.5	1	0.5	0.5	0.8	1.415873	1.605352
1.5	1	0.5	0.5	0.9	1.398716	1.579803
1.5	1	0.5	0.5	1.0	1.389624	1.565670

($n < 1$), the shear rates near the walls are higher than those for a Newtonian fluid. It can be seen from Fig. 4(b) and (c) the temperature and concentration in the fluid are decreased with increase in the value of the power law index parameter. Increase in the values of the power law index n tends to accelerate the flow and decrease the thermal and solutal boundary layer thickness.

Table 1 shows the effects of $n,\ Le,\ R,\ \gamma$ 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 power law index n. For increasing value of Le, the heat transfer rate is decreasing whereas the mass transfer rate is increasing. The Lewis number (diffusion ratio) is the ratio of Schmidt number (v/D_m) and Prandtl number (v/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 radiation parameter but the mass transfer rate is increasing. The chemical reaction parameter decreases the heat transfer coefficient but increases the mass transfer rate. Increase in the values of γ implies more interaction of species concentration with the momentum boundary layer and less interaction with thermal boundary layer. Hence, chemical reaction parameter has more significant effect on Sherwood number than it does on Nusselt number. There is increase in both the heat and mass transfer rates with increase in the buoyancy ratio.

5. Conclusions

In the present study focuses on the effects of thermal radiation and chemical reaction on free convection heat and mass transfer along a vertical plate in a Darcy porous medium saturated with power-law fluid. The following conclusions can be summarized:

- The higher values of the radiation parameter R result in higher velocity, temperature distributions and non-dimensional mass transfer rate but lower concentration distribution and non-dimensional heat transfer rate.
- An increase in chemical reaction parameter, decrease in the velocity, concentration and heat transfer rate accompanied by an increase in temperature and mass transfer rate.
- An increase in power-law index parameter, increase in the velocity, but decrease in the temperature, heat and mass transfer rates within the boundary layer.

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