VISCOSITY AND DISPERSION EFFECTS ON NATURAL CONVECTION FROM A VERTICAL CONE IN A NON-NEWTONIAN FLUID SATURATED POROUS MEDIUM

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This paper investigates the influence of double dispersion and viscosity on natural convection heat and mass transfer from vertical cone in a non-Darcy porous medium saturated with non-Newtonian fluid. The surface of the cone and the ambient medium are maintained at constant but different levels of temperature and concentration. The Ostwald–de Waele power law model is used to characterize the non-Newtonian fluid behavior. A similarity solution for the transformed governing equations is obtained. The numerical computation is carried out for various values of the non-dimensional physical parameters. The effect of non-Darcy parameter, viscosity parameter, thermal and solutal dispersion, buoyancy ratio, Lewis number and power-law index parameter on the temperature and concentration field as well as on the heat and mass transfer coefficients is analyzed.

Key words: Non-Newtonian, Natural convection, Thermal dispersion, Solutal dispersion, Variable viscosity

Nomenclature

b	Coefficient in the Forchheimer term
c_p	Specific heat at constant pressure $[\mathrm{J\,kg^{-1}K^{-1}}]$
C	Concentration
d	Pore diameter $[\mathrm{m}]$
D	Solutal diffusivity $[\mathrm{m^2s^{-1}}]$
D_e	Effective solutal diffusivity $[\mathrm{m^2s^{-1}}]$
f	Dimensionless stream function
g	Acceleration due to gravity $[\mathrm{m\,s^{-2}}]$
k	Thermal conductivity $[\mathrm{Wm^{-1}K^{-1}}]$
k_e	Effective thermal conductivity $[\mathrm{Wm^{-1}K^{-1}}]$
K	Permeability of the porous medium
K^*	Modified permeability of the porous medium of power law fluid
Gr^*	Grashof number for power law fluid $(=b[K^{*2}\rho_\infty^2\ (g\ \cos\omega\beta_T\,(T_w-T_\infty))^{2-n}/\mu^{*2}]^{1/n})$
n	Power law index
N	Buoyancy ratio $(=\beta_c(C_w-C_\infty)/\beta_T(T_w-T_\infty))$
Nu	Nusselt number $(=q_T x/k)$
q_m	Local mass flux $[\mathrm{W\,m^{-2}}]$
q_T	Local heat flux $[\mathrm{W\,m^{-2}}]$

r	Local radius of the cone $[\mathrm{m}]$
Ra_d	Pore diameter dependent Rayleigh number $(=(d/\alpha)(K^*\rho_\infty \cos\omega g \beta_T (T_w - T_\infty)/\mu^*)^{1/n})$
Ra_ξ	Solutal dispersion effect
Ra_γ	Thermal dispersion effect
Sh	Sherwood number $=(q_m x/D)$
Le	Lewis number $Le=\alpha/D$
T	Temperature $[\mathrm{K}]$
u,v	Velocity components in x and y directions $[\mathrm{m\,s^{-1}}]$
x,y	Axial and normal co-ordinates $[\mathrm{m}]$

Greek Symbols

μ^*	Fluid consistency of the inelastic non-Newtonian power-law fluid $[\mathrm{kg\,m^{-1}s^{-1}}]$
ρ	Density $[\mathrm{kg\,m^{-3}}]$
α	Thermal diffusivity $[\mathrm{m^2s^{-1}}]$
α_e	Effective thermal diffusivity $[\mathrm{m^2s^{-1}}]$
γ	Coefficient of thermal dispersion
ξ	Coefficient of solutal dispersion
ζ	Viscosity parameter
φ	Porosity of the saturated porous medium
β_T	Coefficient of thermal expansion $[\mathrm{K^{-1}}]$
β_c	Coefficient of solutal expansion $[\mathrm{K^{-1}}]$
ω	Half angle of the cone
ψ	Dimensionless stream function
η	Similarity variable
θ	Dimensionless temperature
ϕ	Dimensionless concentration

$\theta_w = T_w - T_\infty$.

$\phi_w = C_w - C_\infty$.

Subscripts

w,∞	Conditions on the wall and the ambient medium

1. Introduction

The study of convective heat and mass transfer in a porous medium from an axisymmetric body has attracted many investigators due to its wide range of applications in geophysics and energy related problems such as thermal insulation, enhanced recovery of petroleum resource, geophysical flows, polymer processing in packed beds and sensible heat storage bed. In order to design a suitable canister for nuclear waste disposal into the depth of the earth or into the sea bed demands a through understanding of the convective mechanism in a porous medium for taking care of the safety measure for all sea living beings. In this direction, one needs to study the convective heat and mass transfer from different geometries. To begin with, axisymmetric bodies such as a cone, horizontal and vertical cylinder, and sphere are used to understand convective heat and mass transfer mechanism.

In particular, a number of industrially important fluids including fossil fuels exhibit non-Newtonian fluid behavior. Non-Newtonian power law fluids are so widespread in industrial processes and in the environment that it would be no exaggeration to affirm that Newtonian shear flows are the exception rather than the rule. Shenoy [1] presented many interesting applications of non-Newtonian power law fluids with yield stress on convective heat transport in fluid saturated porous media considering geothermal and oil reservoir engineering applications. Natural convection from a vertical wall and that around a horizontal cylinder and a sphere in a non-Newtonian fluid saturated porous medium was presented by Chen and Chen in [2, 3], respectively. Nakayama and Koyama [4] analyzed the more general case of free convection over a non-isothermal body of arbitrary shape embedded in a porous medium. Non-Darcy natural, forced and mixed convection heat transfer in non-Newtonian power-law fluid saturated porous media was studied by Shenoy [5]. Coupled heat and mass transfer by free convection over a truncated cone in porous media with variable wall temperature (concentration) and variable heat (mass) flux was investigated by Yih [6]. Natural convection heat and mass transfer from a vertical truncated cone in a porous medium saturated with a non-Newtonian fluid with variable wall temperature and concentration was reported by Cheng [7].

It is known from the literature that in a non-Darcy medium where the inertia effect is substantial, thermal dispersion becomes significant (see Nield and Bejan [8]). Similarity solution for non-Darcy mixed convection over a cone in a porous medium is obtained by Murthy and Singh [9]. A detailed analysis regarding the effect of double dispersion on mixed convection heat and mass transfer in non-Darcy porous medium using similarity solution technique has been presented by Murthy [10]. It was reported that the flow, temperature and concentration fields are governed by the complex interaction among the diffusion rate, buoyancy ratio and flow deriving parameter. Double dispersion effect on natural convection heat and mass transfer in non-Darcy porous medium was investigated by El-Amin [11]. The effect of double dispersion on natural and mixed convection heat and mass transfer from vertical plate saturated with non-Newtonian fluids in non-Darcy porous medium was investigated, respectively, by Kairi et al [12] and Kairi and Murthy [13].

A lot of heat convection studies in porous media have been reported with considering constant physical properties of the ambient fluids. However, it is well known that the viscosity of liquid changes evidently with the temperature and this influences the variation of velocity through the flow. Therefore, considering constant viscosity in heat transfer problems with the large temperature difference between the surface and fluid, a significant error could occur. Lai and Kulacki [14] studied the variable viscosity effect for a mixed convection flow along a vertical plate embedded in a porous medium. The problem of variable viscosity on non-Darcy free or mixed convection flow on a vertical surface in a non-Newtonian fluid saturated porous medium was examined by Jayanthi and Kumari [15]. Flow of a generalized second grade non-Newtonian fluid with viscosity varying exponentially with temperature was studied by Massoudi and Phuoc [16].

The main purpose of the present investigation is to illustrate the effects of variable viscosity and double dispersion on natural convection heat and mass transfer form a vertical cone plate in a non-Newtonian fluid saturated non-Darcy porous medium, using the similarity solution technique. In particular, the viscosity is assumed to follow Reynolds viscosity model (Szeri, A. Z. and Rajagopal, K. R. [17], Massoudi and Phuoc [16]), which assumes the viscosity decreases exponential with temperature.

2. Mathematical Formulations

Consider the steady, laminar, two-dimensional natural convection boundary layer flow over a vertical cone pointing downwards embedded in a saturated porous medium. The cone is placed with its axis of symmetry along the vertical direction and the origin of the coordinate system at its the vertex, x-coordinate is taken along surface of the cone and y-coordinate is measured perpendicular to the conical surface, as shown in the Fig. 1. ω is the cone apex half angle. The porous medium is assumed to be in thermal equilibrium with the fluid. The surface of the cone is maintained at constant temperature and concentration, T_w and C_w, respectively, and the temperature and concentration in the ambient medium are $T_\infty (< T_w)$ and C_∞, respectively. The fluid flow is moderate and the permeability of the medium is assumed to be low so that the Forchheimer flow model is applicable and the boundary–drag effect is neglected. The flow is steady, laminar and two dimensional. With the usual boundary layer and linear Boussinesq approximations, the governing equations, namely the equation of continuity, the non-Darcy flow model (i.e. the model given by Shenoy [5]), the energy and concentration equations for the isotropic and homogeneous porous medium may be written as:

$$\frac{\partial (r\ u)}{\partial x} + \frac{\partial (r\ v)}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial u^n}{\partial y} + \frac{\partial}{\partial y}\left(\rho_\infty \frac{b\,K^*}{\mu(T)} u^2 \right) = \frac{\partial}{\partial y}\left(\frac{\rho_\infty\, g\, K^*}{\mu(T)} [\beta_T (T - T_\infty) + \beta_C (C - C_\infty)] \right) \qquad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(\alpha_e \frac{\partial T}{\partial y} \right) \qquad (3)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{\partial}{\partial y}\left(D_e \frac{\partial C}{\partial y} \right) \qquad (4)$$

The boundary conditions considered are

$$y = 0:\ v = 0,\ T = T_w,\ C = C_w \qquad (5)$$

$$y \to \infty:\ u \to 0,\ T \to T_\infty,\ C \to C_\infty . \qquad (6)$$

In the above equations, u and v are the average velocity components along the x and y directions, respectively, and n is the power law index ($n < 1$, $n = 1$ and $n > 1$, respectively, Pseudoplastic, Newtonian and Dilatant fluids). T and C are the temperature and concentration respectively, ρ_∞ is the reference density, g is the acceleration due to gravity, α_e and D_e are the effective thermal and solutal diffusivities respectively and these are written as $\alpha_e = \alpha + \gamma du$ and $D_e = D + \xi du$ (see Murthy [10] and El-Amin [11]), α and D are the constant thermal and molecular diffusivities respectively, γ and ξ are respectively the coefficients of the thermal and solutal dispersions. The value of these quantities lie between 1/7 and 1/3, β_T and β_C are the thermal expansion coefficient and concentration expansion coefficients, respectively, and c_p is the specific heat at constant pressure. Also, b is the empirical constant associated with the Forchheimer porous inertia term and μ is the consistency index of power law fluid. Following Christopher and Middleman [18] and Dharmadhikari and Kale [19], the modified permeability of the flow K^* of the non-Newtonian power law fluid is defined as

$$K^* = \frac{1}{2c_t}\left(\frac{n\varphi}{3n+1}\right)^n \left(\frac{50K}{3\varphi}\right)^{\frac{n+1}{2}}$$

where $K = \dfrac{\varphi^3 d^2}{150(1-\varphi)^2}$, φ is the porosity of the medium and

$$c_t = \begin{cases} \dfrac{25}{12} & \text{Christopher and Middleman [18]} \\ \dfrac{2}{3}\left(\dfrac{8n}{9n+3}\right)^n \left(\dfrac{10n-3}{6n+1}\right)\left(\dfrac{75}{16}\right)^{3(10n-3)/(10n+11)} & \text{Dharmadhikari and Kale [19]} \end{cases}$$

for $n = 1$, $c_t = \dfrac{25}{12}$.

The continuity equation is automatically satisfied by defining a stream function $\psi(x, y)$ such that $u = (1/r)(\partial\psi/\partial y)$ and $v = -(1/r)(\partial\psi/\partial x)$. We introduce the following transformation:

$$\eta = \frac{y}{x} Ra_x^{1/2},\ \psi(\eta) = \alpha r\ Ra_x^{1/2} f(\eta),\ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}\ ,\ \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}$$

where $r = x\sin\omega$ and $Ra_x = \dfrac{x}{\alpha}\left[\dfrac{\rho_\infty g \cos\omega K^* \beta_T (T_w - T_\infty)}{\mu^*}\right]^{1/n}$.

The fluid viscosity $\mu(\theta)$ is assumed to obey Reynolds viscosity model (Massoudi and Phuoc [16] and Szeri, A. Z. and Rajagopal, K. R. [17])

$$\mu(\theta) = \mu^* e^{-\zeta\theta} \tag{7}$$

where ζ is the non-dimensional viscosity parameter depending on the nature of the fluid and μ^* is the ambient viscosity of the fluid. This model can be applicable in many processes where pre-heating of the fuel is used as a means to enhanced heat transfer effect. In addition, for many fluids such as lubricants, polymers, and coal slurries viscous dissipation is substantial, an appropriate constitutive relation where viscosity is a function of temperature should be used.

The above transformations reduce system of partial differential equations into the following system of nonlinear ordinary differential equations:

$$\left(n\, f'^{\,n-1} + 2\,Gr^{*} f'\right) f'' = (e^{\zeta\theta}(\theta + N\,\phi))' \tag{8}$$

$$\theta'' + Ra_{\gamma}\,(f'\theta'' + f''\theta') + (3/2)\,f\,\theta' = 0 \tag{9}$$

$$(1/Le)\phi'' + Ra_{\xi}\,(f'\phi'' + f''\phi') + (3/2)\,f\,\phi' = 0 \tag{10}$$

The boundary conditions become

$$f = 0\,,\theta = 1,\ \phi = 1 \ \text{ at } \eta = 0 \tag{11}$$

$$f' \to 0\,,\theta \to 0\,,\ \phi \to 0 \text{ as } \eta \to \infty\ . \tag{12}$$

In the above equations $Ra_{\gamma} = \gamma Ra_d$ and $Ra_{\xi} = \xi Ra_d$ are solutal and thermal dispersion parameter, respectively, $Ra_d = (d/\alpha)(K^{*}\rho_{\infty}\cos\omega g\beta_T(T_w - T_{\infty})/\mu^{*})^{1/n}$ is the pore diameter dependent Rayleigh number, $Gr^{*} = b[K^{*2}\rho_{\infty}^{2}\ (g\ \cos\omega\,\beta_T\,(T_w - T_{\infty}))^{2-n}/\mu^{*2}]^{1/n}$ is the modified Grashof number, $N = \beta_c(C_w - C_{\infty})/\beta_T(T_w - T_{\infty})$ is the buoyancy ratio, $Le = \alpha/D$ is the Lewis number. The parameter $N > 0$ represents the aiding buoyancy and $N < 0$ represents the opposing buoyancy. It is noteworthy that $Gr^{*} = 0$ corresponds to the Darcian free convection, $Ra_{\gamma} = 0$ and $Ra_{\xi} = 0$ respectively are the cases where the thermal and solutal dispersion effect are neglected. The non-dimensional heat and mass transfer coefficients in terms of Nusselt and Sherwood numbers are written, respectively, as $Nu_x = (q_T\,x/k)$ and $Sh_x = (q_m\,x/D)$.

The local heat and mass fluxes from the wall are given by

$$q_T = -k_e \left.\frac{\partial T}{\partial y}\right|_{y=0} = -[k + \gamma u d]\left.\frac{\partial T}{\partial y}\right|_{y=0} \tag{13}$$

$$q_m = -D_e \left.\frac{\partial C}{\partial y}\right|_{y=0} = -[D + \xi u d]\left.\frac{\partial C}{\partial y}\right|_{y=0}\ . \tag{14}$$

The primary objective of this study is to estimate the Nusselt and Sherwood numbers as

$$Nu_x / Ra_x^{1/2} = -[1 + Ra_{\gamma}\ f'(0)]\ \theta'(0)\ , \tag{15}$$

$$Sh_x / Ra_x^{1/2} = -[1 + Ra_{\xi}\,f'(0)]\ \phi'(0)\,. \tag{16}$$

Effect of the viscosity, power-law index, thermal and solutal dispersion parameters on these coefficients is discussed in the following section.

3. Results and Discussion

The coupled non-linear differential equations (8-10) along with the boundary conditions (11-12) are solved using 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 given boundary conditions at $f'(\infty)$, $\theta(\infty)$ and $\phi(\infty)$ respectively, these obtained values for $f'(\infty)$, $\theta(\infty)$ and $\phi(\infty)$ are matched with the specified boundary conditions by making use of Newton-Raphson method. The integration length η_∞ varies with the parameter values and it has been suitably chosen each time such that the boundary conditions at the outer edge of the boundary layer are satisfied. In order to assess the accuracy of the solution, the present results for the heat and mass transfer coefficients are compared (Table 1) with those obtained Yih [6] in case of Newtonian fluid of constant viscosity in absence of thermal and solutal dispersions, which indicates that the present numerical results are in good agreement. The following values are considered for the parameters: $0.5 \le n \le 1.5$, $0 \le \zeta \le 0.5$, $0 \le Ra_\gamma \le 1$, $0 \le Ra_\xi \le 1$ and $0.01 \le Gr^* \le 0.30$. The variation of heat and mass transfer coefficients (given by equs.(15-16)) are shown for some selected values of the parameters through figs. (2-7b).

Figure 2 shows the variation of the non-dimensional temperature profile θ across the boundary layer for various values of power law index n and Ra_γ for fixed values of other parameters. With an increase in the values of thermal dispersion parameter, a rise in temperature distribution in the boundary layer is seen for both pseudoplastic and dilatant fluids. The variation of non-dimensional concentration distribution ϕ against the similarity variable η is shown in fig. 3 for different values of n and Ra_ξ. A rise in concentration distribution is also observed for both pseudoplastic and dilatant fluids with increasing values of solutal dispersion parameter.

In figs. 4a and 4b variation of the Nusselt number as a function of viscosity parameter ζ is shown, respectively, for $n = 0.5$ and $n = 1.5$ with two different values of N and Ra_γ for fixed value of other parameter values. From these figures it is evident that the heat transfer coefficient increases with an increase in the values of ζ, N and Ra_γ for both pseudoplastic and dilatant fluids. This is because of the increases in thermal boundary layer thicknesses with increasing values of ζ, N and Ra_γ for all values of n. Also the effect of thermal dispersion is becoming more effective for higher values of ζ and N for all types of power law fluids. Figures 5a and 5b, respectively, for $n = 0.5$ and $n = 1.5$ illustrate the variation of Sherwood number against ζ for two different values of N and Ra_ξ with fixed value of other parameters. It is noted that Sherwood number increases with an increases in the values of ζ, N and Ra_ξ. The reason is that, concentration boundary layer thicknesses increases with the increasing values of ζ, N and Ra_ξ for all values of n. Similar to thermal dispersion, the effect of solutal dispersion is significant for higher values of ζ and N for both pseudoplastic and dilatant fluids.

The effect of diffusivity ratio Le on the Nusselt number for $n = 0.5$ and $n = 1.5$ is plotted in fig. 6a and fig. 6b, respectively, varying Ra_γ and ζ with fixed value of other parameters. It is observed that heat transfer coefficient increases with the viscosity and thermal dispersion parameter while it decreases with Le. Also the effect of ζ and Ra_γ on Nusselt number is diminished by increasing Le. More over the effect of ζ and Ra_{γ} on the heat transfer coefficient is noteworthy for pseudoplastics with compared to dilatants. Figures 7a and 7b illustrate the variation of the Sherwood number for $n = 0.5$ and $n = 1.5$ against Le for different values of Ra_{ξ} and ζ, respectively with fixed value of other parameters. It is observed that Sherwood number increases with ζ and Le. It is also noted that the Sherwood number increases marginally with Ra_{ξ} for smaller values of Le, while a reduction in its value is observed for large Le. Also it is found that the amount of fall in the Sherwood number due to increase in the value of Ra_{ξ} is more in case of pseudoplastics when compared to the dilatants in the medium. On the other hand the impact of viscosity on the mass transfer coefficient is reduced by introducing solutal dispersion effect in the porous medium.

4. Conclusions

In this study the effects of variable viscosity and double dispersion on natural convection heat and mass transfer form a vertical cone in a non-Darcy porous medium saturated with non-Newtonian fluid is investigated. The heat and mass transfer coefficients are obtained for various values of flow influencing parameters. The results are analyzed thoroughly for different cases of Le<1, Le=1 and Le>1. The effect of thermal and solutal dispersion on heat and mass transfer coefficients is becoming significant for higher values of ζ and N for both pseudoplastic and dilatant fluids. As Le increases the effect of viscosity and dispersion on heat transfer coefficient is diminished. Moreover, the impact of viscosity on the mass transfer coefficient is reduced by introducing solutal dispersion effect in the medium.

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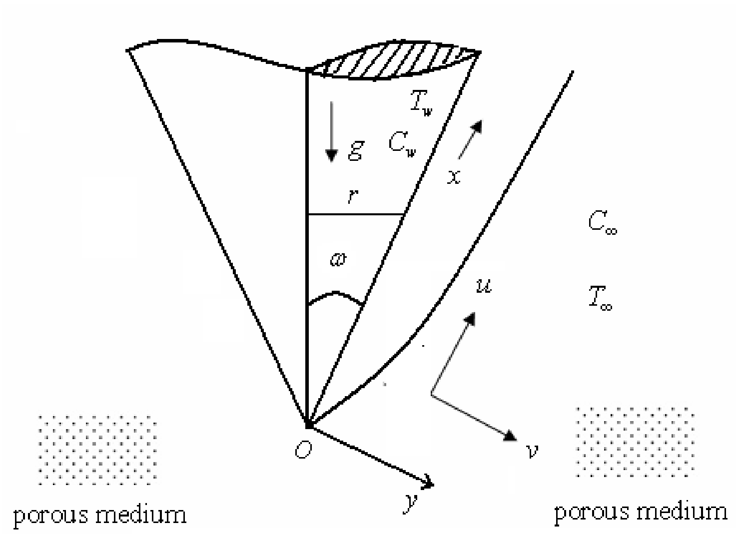

Fig. 1 Physical model and coordinates

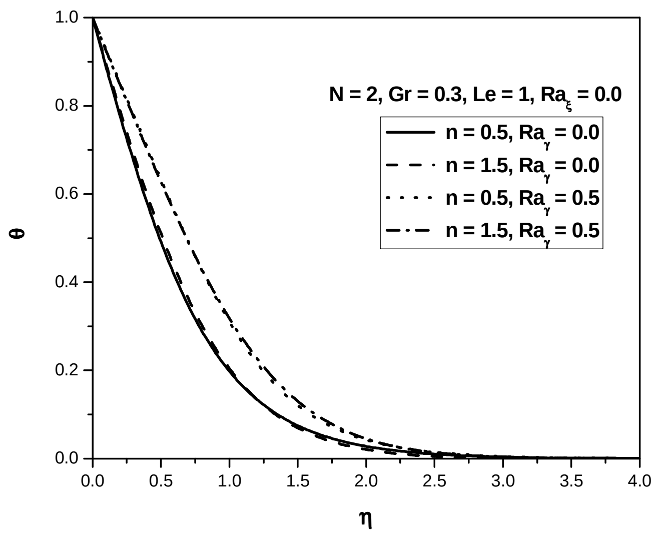

Fig. 2 Variation of temperature distribution with η for $\zeta = 0.0$

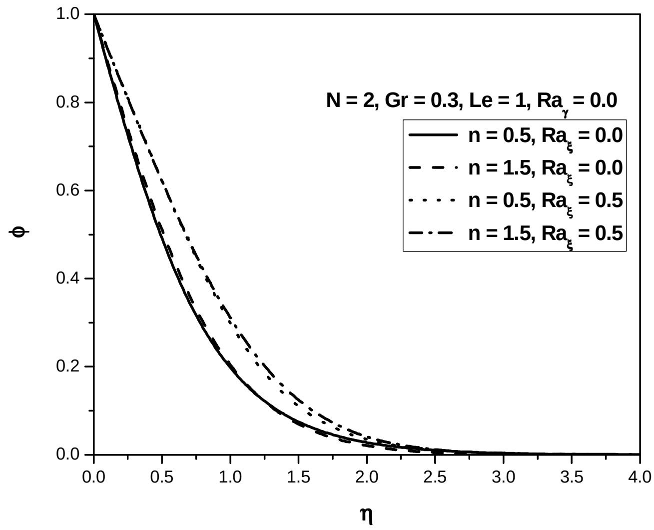

Fig. 3 Variation of concentration distribution with η for $\zeta = 0.0$

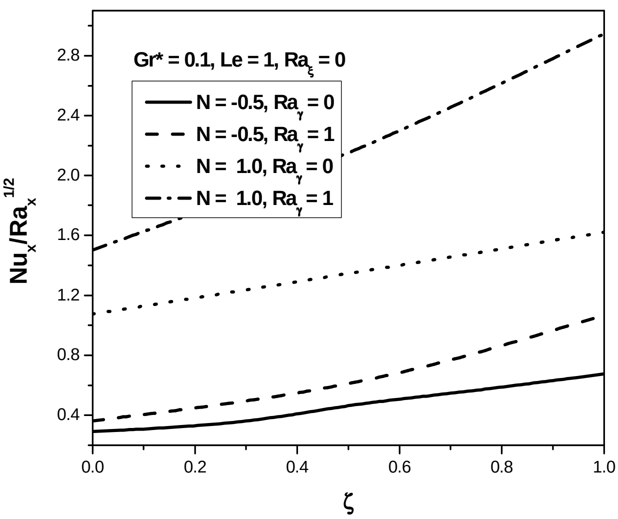

Fig. 4a: Variation of heat transfer coefficient with ζ for $n = 0.5$

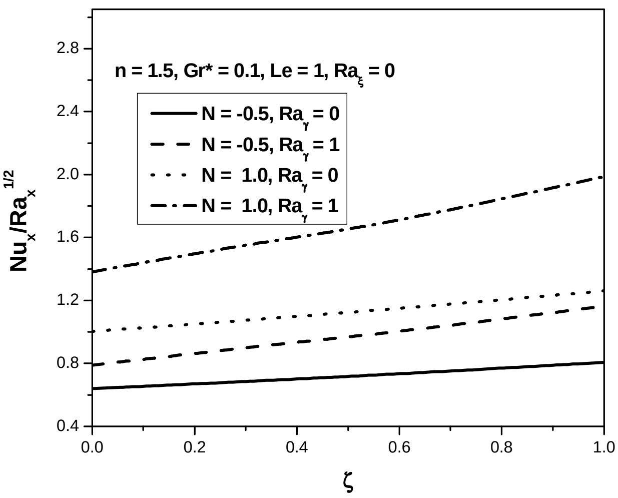

Fig. 4b: Variation of heat transfer coefficient with ζ **for** $n = 1.5$

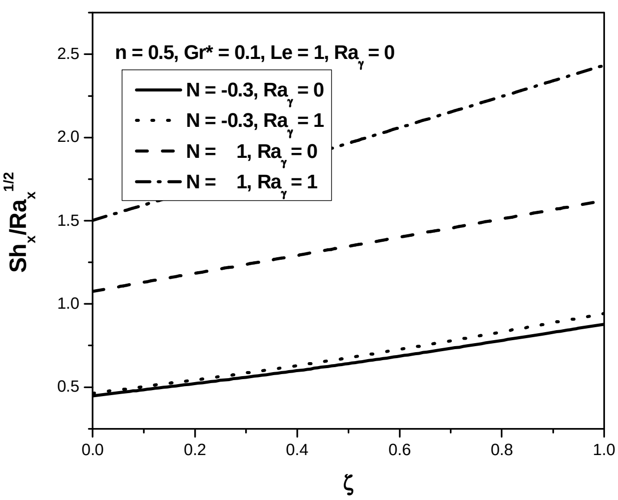

Fig. 5a: Variation of mass transfer coefficient with ζ **for** $n = 0.5$

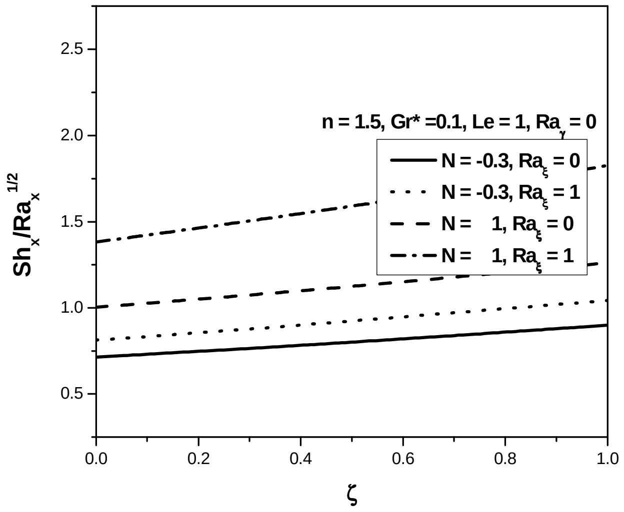

Fig. 5b: Variation of mass transfer coefficient with ζ for $n = 1.5$

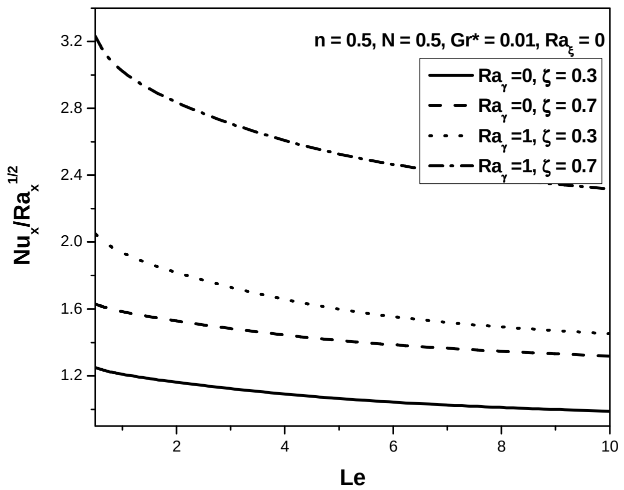

Fig. 6a: Variation of heat transfer coefficient with *Le* for $n = 0.5$

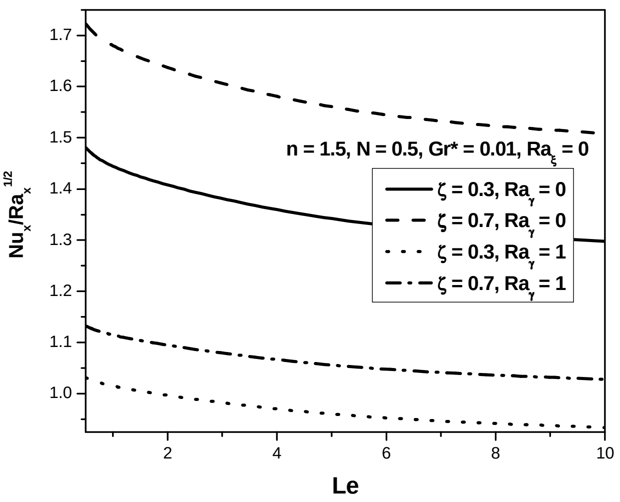

Fig. 6b: Variation of heat transfer coefficient with *Le* for $n = 1.5$

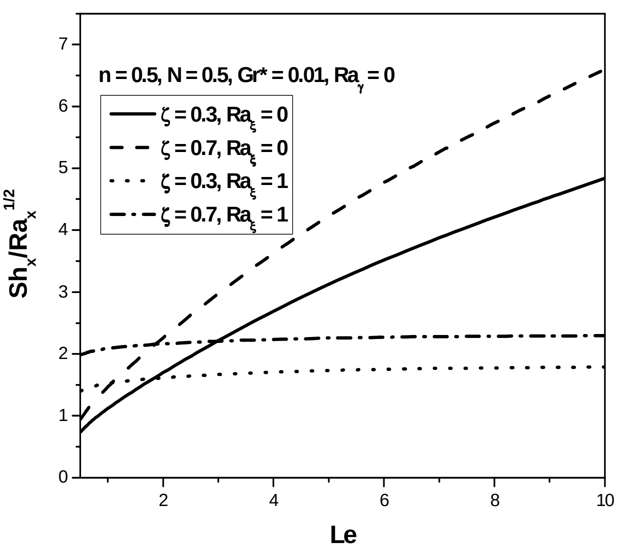

Fig. 7a: Variation of mass transfer coefficient with *Le* for $n = 0.5$

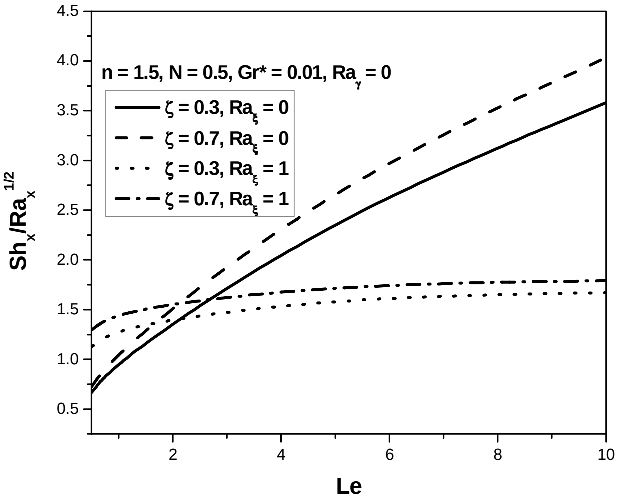

Fig. 7b: Variation of mass transfer coefficient with *Le* for $n = 1.5$

Table1: Comparison of values of $\theta'(0)$ and $\phi'(0)$ **for** $n = 1,\ \ Gr^* = 0$ and $\zeta = 0$ **in absence of dispersion**

N	*Le*	θ'(0)		ϕ'(0)	
		Yih (1999)	Present	Yih (1999)	Present
1	1	1.0869	1.0870	1.0869	1.0870
1	10	0.9030	0.9032	3.8139	3.8142
1	100	0.8141	0.8144	12.3645	12.3652
4	1	1.7186	1.1786	1.1786	1.1786
4	10	1.1795	1.1797	5.6977	5.6979
4	100	0.9019	0.9022	18.2208	18.2230