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THERMOPHORESIS FREE CONVECTION FROM A VERTICAL CYLINDER EMBEDDED IN A POROUS MEDIUM

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This paper deals with the steady free convection over an isothermal vertical circular cylinder embedded in a fluid-saturated porous medium in the presence of the thermophoresis particle deposition effect. The governing partial differential equations are transformed into a set of non-similar equations, which are solved numerically using an implicit finite-difference method. Comparisons with the previously published work are performed and the results are found to be in excellent agreement. Many results are obtained and a representative set of these results is displayed graphically to illustrate the influence of the various physical parameters on the wall thermophoretic deposition velocity and concentration profiles.

Key words: free convection, thermophoresis, vertical cylinder, boundary layer, porous medium.

1. Introduction

Convective heat transfer in fluid-saturated porous media has been studied quite extensively during the last few decades. This has been motivated by its importance in many natural and industrial problems. Prominent among these are the utilization of geothermal energy, chemical engineering, thermal insulation systems, nuclear waste management, grain storage, fruits and vegetable, migration of moisture through air contained in fibrous insulation, food processing and storage and contaminant transport in ground water and many others. A detailed review of the subject of convective flow in porous media, including an exhaustive list of references, was recently done by Nield and Bejan (1999), Ingham and Pop (1998; 2002), Vafai (2000), Pop and Ingham (2001), and Bejan and Kraus (2003).

Free convection from a vertical or horizontal cylinder embedded in a porous medium is the principal mode of heat transfer in numerous applications such as in connection with oil/gas lines, insulation of horizontal pipes, cryogenics as well as in the context of water distribution lines, underground electrical power transmission lines and burial of nuclear waste, to name just a few applications. The case of a free and mixed convection flow from a vertical cylinder placed in a porous medium has been studied extensively both analytically and numerically. It appears that Minkowycz and Cheng (1996) were the first to present a numerical solution of the problem of the free convective boundary layer flow induced by a heated vertical cylinder embedded in a fluid-saturated porous medium when the surface temperature of the cylinder is taken to be proportional to x^m, where x is the distance from the leading edge/base of the cylinder and m is a constant. The results were obtained for various values of m lying between *0* and *1*. Similarity and local non-similarity methods of solution were used. The problem was later extended by Merkin (1986), Kumari *et al.* (1986), Ingham and Pop (1986), Merkin and Pop ([illegible]), Kumari and Nath (1986), Yücel (1990), Chen *et al.* (1992), Hossain and Nakayama (1993), Bassom and [illegible] (1996), Pop and Na (1998), Yih (1998) and Chen and Horn (1999).

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Over the past two decades, studies in aerosol particle deposition due to thermophoresis have gained importance for engineering applications. There are many systems that require the attainment of high particle deposition efficiency and the precise control of the deposition to minimize costs and maximize the quality of the finished product. Technological problems include particle deposition onto a surface from a condensing vapor-gas mixture, a semi-conductor wafer in the electronic industry, and the blade surface of gas turbines, and problems for nuclear reactor safety. Goren (1977) was one of the first to study the role of thermophoresis in a laminar flow of a viscous and incompressible fluid. He used the classical problem of flow over a flat plate to calculate deposition rates and showed that substantial changes in surface depositions can be obtained by increasing the difference between the surface and free stream temperatures. This was later followed by similarity solutions of two dimensional laminar boundary layers and stagnation point flows by Gokoglu and Rosner (1986), Park and Rosner (1989), Kusnadi and Greif (1997) and Hsu and Greif (2002). Also, Tsai and Lin (1999) have studied the effect of wall suction and thermophoresis on aerosol particle deposition from a laminar flow over a flat plate, while Chiou (1998) obtained similarity solutions for the problem of a continuously moving surface in a stationary incompressible fluid, including the combined effects of convection, diffusion, wall velocity and thermophoresis. Garg and Jayaraj (1988, 1990) discussed the thermophoretic deposition of small particles in a forced convection laminar flow over inclined plates and a circular cylinder, respectively. Epstein *et al.* (1985) and Tsai and Lin (1999) have studied the thermophoretic transport of small particles through a free convection boundary layer adjacent to a vertical deposition surface in a viscous and incompressible fluid, while Chiou (1998) has considered particle deposition from natural convection boundary layer flow onto an isothermal vertical cylinder.

Despite the practical importance of thermophoresis there is, to the best of our knowledge, almost no work devoted to this topic in porous media, except the recent paper by Chamkha and Pop (2003) for a vertical flat plate. Consideration is, therefore, given here to the problem of free convection boundary-layer deposition with thermophoretic transport of aerosol particles on a vertical isothermal circular cylinder embedded in a fluid-saturated porous medium. The Darcy and energy equations yield the velocity and temperature distributions in the boundary layer, which are then used in the coupled concentration equation to calculate the rates of particle deposition.

2. Basic equations

Consider a vertical cylinder of radius r_0, constant surface temperature T_w and constant surface concentration C_w, which is embedded in a fluid-saturated porous medium of ambient temperature T_∞ and concentration C_∞, respectively. In the porous media, the following assumptions are made: (i) the convective fluid and the porous medium are in local thermal equilibrium; (ii) the properties of the fluid and the porous media are constants; (iii) the viscous drag and inertia terms of the momentum equations are negligible; (iv) the Darcy-Boussinesq approximation is valid. Under these assumptions, the conservation equations for mass, momentum and energy for the two-dimensional steady natural convection in the porous cavity are

$$\frac{\partial}{\partial \bar{x}}(\bar{r}\bar{u}) + \frac{\partial}{\partial \bar{r}}(\bar{r}\bar{v}) = 0, \tag{2.1}$$

$$\bar{u} = \frac{gK}{\nu}\left[\beta_T(T - T_\infty) + \beta_C(C - C_\infty)\right], \tag{2.2}$$

$$\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{r}} = \frac{\alpha_m}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial T}{\partial \bar{r}}\right), \tag{2.3}$$

$$\bar{u}\frac{\partial C}{\partial \bar{x}} + \bar{v}\frac{\partial C}{\partial \bar{r}} + \frac{\partial(\bar{v}_t C)}{\partial \bar{r}} = \frac{D_m}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial C}{\partial \bar{r}}\right), \tag{2.4}$$

$$\bar{v}_t = -k\frac{\nu}{T}\frac{\partial T}{\partial \bar{r}}, \tag{2.5}$$

subject to the boundary conditions

$$\begin{aligned} &\bar{v}=0, \quad T=T_w, \quad C=C_w, \quad \bar{r}=r_0, \\ &\bar{u}\to 0, \quad T\to T_\infty, \quad C\to C_\infty, \quad \bar{r}\to\infty. \end{aligned} \tag{2.6}$$

In order to transform these equations, we introduce the following non-dimensional variables

$$\begin{aligned} &x=\bar{x}/r_0, \quad r=\mathrm{Ra}^{1/2}(\bar{r}/r_0), \quad u=\bar{u}/U_c, \quad v=Ra^{1/2}(\bar{v}/U_c), \\ &v_t=\mathrm{Ra}^{1/2}(\bar{v}_t/U_c), \quad \theta=(T-T_\infty)/(T_w-T_\infty) \ \phi=(C-C_\infty)/(C_w-C_\infty) \end{aligned} \tag{2.7}$$

where Ra and U_c are the Rayleigh number and the characteristic velocity, respectively, which are defined as

$$\mathrm{Ra}=gK\beta_T(T_w-T_\infty)r_0/\alpha_m\nu, \quad U_c=gK\beta_T(T_w-T_\infty)/\nu. \tag{2.8}$$

Thus, Eqs.(2.1)-(2.5) can be written as

$$\frac{\partial}{\partial x}(ru)+\frac{\partial}{\partial r}(rv)=0, \tag{2.9}$$

$$u=\theta+N\phi, \tag{2.10}$$

$$u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right), \tag{2.11}$$

$$u\frac{\partial\phi}{\partial x}+v\frac{\partial\phi}{\partial r}+\frac{\partial(v_t\phi)}{\partial r}=\frac{1}{\mathrm{Le}}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\phi}{\partial r}\right), \tag{2.12}$$

$$v_t=-k\frac{\mathrm{Pr}}{N_t+\theta}\frac{\partial\theta}{\partial r} \tag{2.13}$$

and the boundary conditions (2.6) become

$$\begin{aligned} &v=0, \quad \theta=1, \quad \phi=1, \quad \text{on} \quad r=1, \\ &u\to 0, \quad \theta\to 0, \quad \phi\to 0 \quad \text{as} \quad r\to\infty. \end{aligned} \tag{2.14}$$

The thermophoresis and buoyancy parameters N_t and N are defined as

$$N_t=\frac{T_\infty}{T_w-T_\infty}, \quad N=\beta_C(C_w-C_\infty)/\beta_T(T_w-T_\infty). \tag{2.15}$$

$$\bar{v}_t = -k\frac{\nu}{T}\frac{\partial T}{\partial \bar{r}}, \tag{2.5}$$

subject to the boundary conditions

$$\begin{aligned} &\bar{v} = 0, \quad T = T_w, \quad C = C_w, \quad \bar{r} = r_0, \\ &\bar{u} \to 0, \quad T \to T_\infty, \quad C \to C_\infty, \quad \bar{r} \to \infty. \end{aligned} \tag{2.6}$$

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where Ra and U_c are the Rayleigh number and the characteristic velocity, respectively, which are defined as

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$$u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial r} + \frac{\partial(v_t\phi)}{\partial r} = \frac{1}{\mathrm{Le}}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \phi}{\partial r}\right), \tag{2.12}$$

$$v_t = -k\frac{\mathrm{Pr}}{N_t + \theta}\frac{\partial \theta}{\partial r} \tag{2.13}$$

and the boundary conditions (2.6) become

$$\begin{aligned} &v = 0, \quad \theta = 1, \quad \phi = 1, \quad \text{on} \quad r = 1, \\ &u \to 0, \quad \theta \to 0, \quad \phi \to 0 \quad \text{as} \quad r \to \infty. \end{aligned} \tag{2.14}$$

The thermophoresis and buoyancy parameters N_t and N are defined as

$$N_t = \frac{T_\infty}{T_w - T_\infty}, \quad N = \beta_C(C_w - C_\infty)/\beta_T(T_w - T_\infty). \tag{2.15}$$

We now look for a solution to Eqs.(2.9)-(2.12) of the form

$$\xi = 2x^{1/2}, \quad \eta = \left(r^2 - 1\right)/\xi, \quad \psi = (\xi/2) f(\xi,\eta), \quad \theta = \theta(\xi,\eta), \quad \phi = \phi(\xi,\eta) \tag{2.16}$$

where ψ is the stream function, which is defined in the usual way as

$$u = \frac{1}{r}\frac{\partial \psi}{\partial r}, \quad v = -\frac{1}{r}\frac{\partial \psi}{\partial x}. \tag{2.17}$$

Thus, Eqs.(2.10)-(2.12) become

$$\frac{\partial f}{\partial \eta} = \theta + N\phi, \tag{2.18}$$

$$\frac{\partial}{\partial \eta}\left[(1+\xi\eta)\frac{\partial \theta}{\partial \eta}\right] + \frac{1}{2} f \frac{\partial \theta}{\partial \eta} = \frac{1}{2}\xi\left(\frac{\partial f}{\partial \eta}\frac{\partial \theta}{\partial \xi} - \frac{\partial f}{\partial \xi}\frac{\partial \theta}{\partial \eta}\right), \tag{2.19}$$

$$\begin{gathered}\frac{1}{\mathrm{Le}}\frac{\partial}{\partial \eta}\left[(1+\xi\eta)\frac{\partial \phi}{\partial \eta}\right] + \frac{1}{2} f \frac{\partial \phi}{\partial \eta} + k\frac{\Pr}{N_t+\theta}\left[\frac{\xi}{2(1+\xi\eta)}\phi\frac{\partial \theta}{\partial \eta} + \right. \\ \left. + \phi\frac{\partial^2 \theta}{\partial \eta^2} + \frac{\partial \theta}{\partial \eta}\frac{\partial \phi}{\partial \eta} - \frac{\phi}{N_t+\theta}\left(\frac{\partial \theta}{\partial \eta}\right)^2\right] = \frac{1}{2}\xi\left(\frac{\partial f}{\partial \eta}\frac{\partial \phi}{\partial \xi} - \frac{\partial f}{\partial \xi}\frac{\partial \phi}{\partial \eta}\right),\end{gathered} \tag{2.20}$$

subject to the boundary conditions

$$\begin{gathered} f = 0, \quad \theta = 1, \quad \phi = 1 \quad \text{on} \quad \eta = 0, \\ \frac{\partial f}{\partial \eta} \to 0, \quad \theta \to 0, \quad \phi \to 0 \quad \text{as} \quad \eta \to \infty. \end{gathered} \tag{2.21}$$

The physical parameters of interest are the local Nusselt and Sherwood numbers, Nu and Sh, which are given by

$$\mathrm{Nu}/\mathrm{Ra}_x^{1/2} = -\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}, \quad \mathrm{Sh}/\mathrm{Ra}_x^{1/2} = -\left(\frac{\partial \phi}{\partial \eta}\right)_{\eta=0} \tag{2.22}$$

where Ra_x is the local Rayleigh number.

3. Results and discussion

Equations (2.18)-(2.20) which represent an initial-value problem with ξ playing the role of time are non-linear, coupled, partial differential equations, which possess no closed-form solution. Therefore, they must be solved numerically subject to the boundary conditions given by Eq.(2.21). The implicit, iterative finite-difference method discussed by Blottner (1970) has proven to be adequate for the solution of this type of equations. For this reason, this method is employed in the present work. Equations (2.19) and (2.20) are discretized using three-point central difference quotients with the first derivatives with respect to ξ being discretized using two-point backward difference quotients. This converts these differential equations into linear sets of algebraic equations at each line of constant ξ, which can be readily solved by the well-known Thomas algorithm (Blottner, 1970). On the other hand, Eq.(2.18) is discretized and solved subject to the appropriate boundary condition by the trapezoidal rule. The computational domain (ξ, η) was made up of *196* non-uniform grid points in the η direction and *101* uniform grid points in the ξ direction. It is expected that most changes in the dependent variables occur in the region close to the cylinder surface where viscous effects dominate. However, small changes in the dependent variables are expected far away from the cylinder surface. For these reasons, variable step sizes in the η direction are employed. The initial step size $\Delta\eta_1$ and the growth factor K^* employed such that $\Delta\eta_{i+1} = K^*\Delta\eta_i$ (where the subscript i indicates the grid location) were 10^{-3} and *1.03*, respectively. These values were found (by performing many numerical experimentations) to give accurate and grid-independent solutions. However, constant step sizes of *0.01* were used in the ξ direction since the changes in the dependent variables in this direction are not expected to be great. The problem was solved line by line starting with $\xi = 0$ and marching forward in the ξ direction until the desired ξ value is reached. At $\xi = 0$, Eqs.(2.18)-(2.20) reduce to a set of ordinary differential equations which can be easily solved by the Thomas algorithm. This solution is then used as the initial solution to set off the marching process. The convergence criterion employed in the present work was based on the difference between the values of the dependent variables at the current and the previous iterations. When this difference reached 10^{-5}, the solution was assumed converged and the iteration process was terminated.

The results are given for several values of the parameters k, Pr, Le, N and N_t. However, to check the present numerical results, we have calculated the values of the reduced heat transfer, $-\theta'(0,0)$ and mass transfer, $-\phi(0,0)$, for $\xi = 0$ (flat plate) with $k = 0$, $N = 0$, 1 and $\mathrm{Le} = 1$. Thus, for $N = 0$ we obtained $-\theta'(0,0) = 0.44325$, while the value found by Minkowycz and Cheng (1976) is $-\theta'(0,0) = 0.444$. Also, for $k = 0$ and $N = \mathrm{Le} = 1$, we get $-\theta'(0,0) = -\phi'(0,0) = 0.62783$, while Bejan and Khair (1985) obtained $-\theta'(0,0) = -\phi'(0,0) = 0.628$. A comparison of the present results for the local Nusselt number, $-\partial\theta(\xi, 0)/\partial\eta$ with those reported by Minkowycz and Cheng (1976) is also given in Tab.1 for $N = 0$ and different values of the curvature parameter ξ. It can thus be concluded that the present results are in excellent agreement with those of Bejan and Khair (1985), and those of Minkowycz and Cheng (1976) and we are, therefore, confident that the present numerical results are very accurate.

Table 1. Values of the local Nusselt number, $-\partial\theta(\xi, 0)/\partial\eta$, for $N = 0$ and some values of the parameter ξ.

ξ	Minkowycz and Cheng (1976)	Present results
0.25	*0.4855*	*0.490341*
0.50	*0.5272*	*0.535189*
0.75	*0.5664*	*0.578418*
1.00	*0.6049*	*0.620125*
2.00	*0.7517*	*0.776314*
3.00	*0.8915*	*0.922123*
4.00	*1.024*	*1.059965*
5.00	*1.154*	*1.191509*
6.00	*1.283*	*1.320432*
7.00	*1.413*	*1.446461*
8.00	*1.544*	*1.570056*
9.00	*1.678*	*1.691356*
10.00	*1.815*	*1.813875*

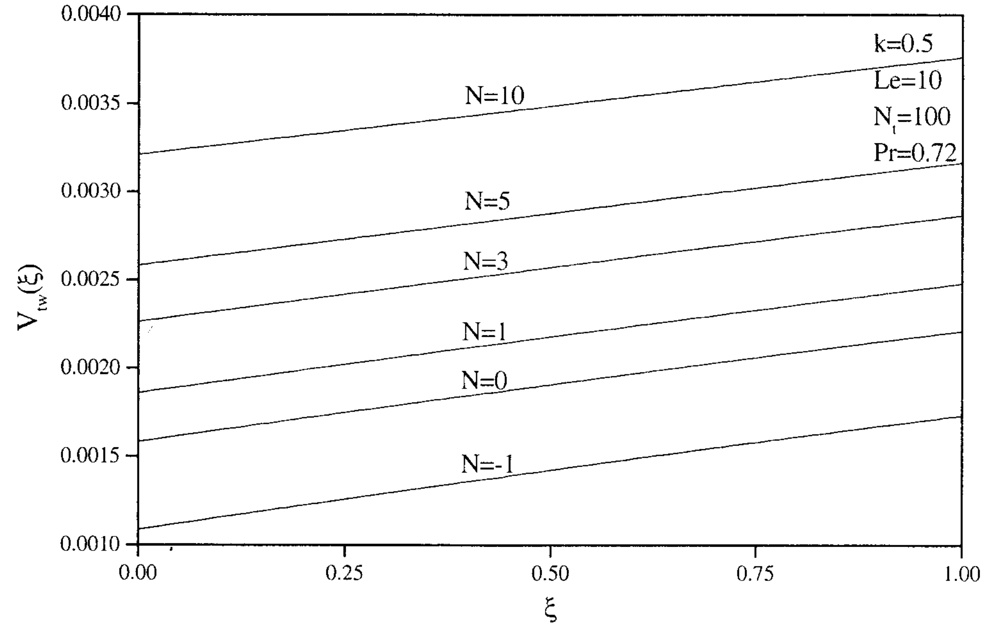

Fig.1. Effects of N on local wall thermophoretic deposition velocity.

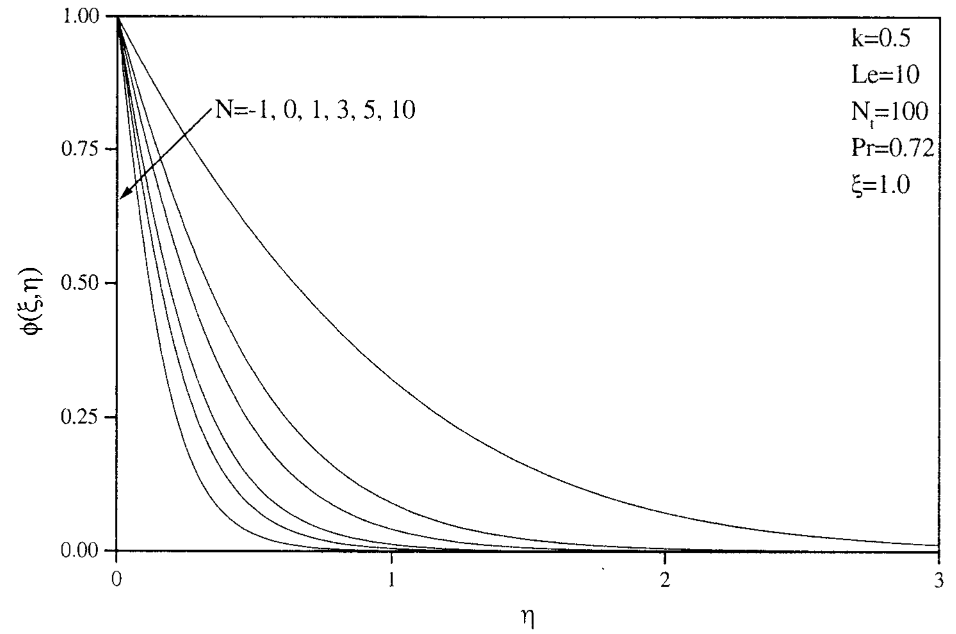

Fig.2. Effects of N on concentration profiles.

Typical concentration profiles, $\phi(\xi,\eta)$, wall thermophoretic deposition velocity, $V_{tw}(\xi)$ and wall mass transfer, $-\partial\phi(\xi, 0)/\partial\eta$, are shown in Figs.1-8 for $\Pr = 0.72$ and some values of the governing parameters k, Le, N and N_t. These figures show how the concentration boundary layer and the wall thermophoretic deposition velocity react to changes in the governing parameters. Thus, the concentration profiles, $\phi(\xi,\eta)$, indicate the characteristic shape of a non-dimensional concentration with a rapid development close to the plate. Thus, the concentration profiles decrease with an increase of the buoyancy parameter N and also with an increase of the Lewis number Le (Figs.2 and 7), which is on line with the results reported by Bejan and

Khair (1985) for the case when the thermophoesis effects are absent. This will give rise to a large wall concentration gradient, $-\partial\phi(\xi, 0)/\partial\eta$, as the parameters N and Le increase (Figs.3 and 8). It also causes a high deposition of the velocity on the surface, which increases as the thermophoretic parameter k increases, as can be seen from Fig.4. It can be also seen in Figs.1, 5 and 6 that the wall thermophoretic deposition velocity, $V_{tw}(\xi)$, becomes sensitive to the variation of the parameters Le, N and N_t. Thus, the deposition velocity profile on the wall is reduced as N and Le are decreased (Figs.1 and 6). However, the wall thermophoretic deposition velocity profiles decrease as the values of the thermophoretic parameter N_t are increased. This is of particular benefit in processes, which require extreme cleanliness of the surfaces.

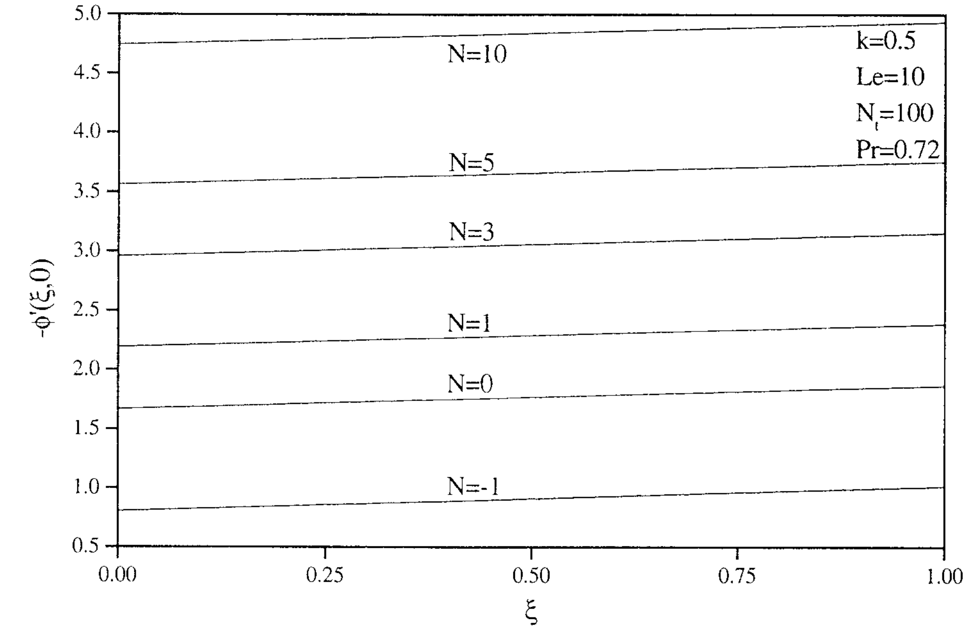

Fig.3. Effects of N on local wall concentration gradient.

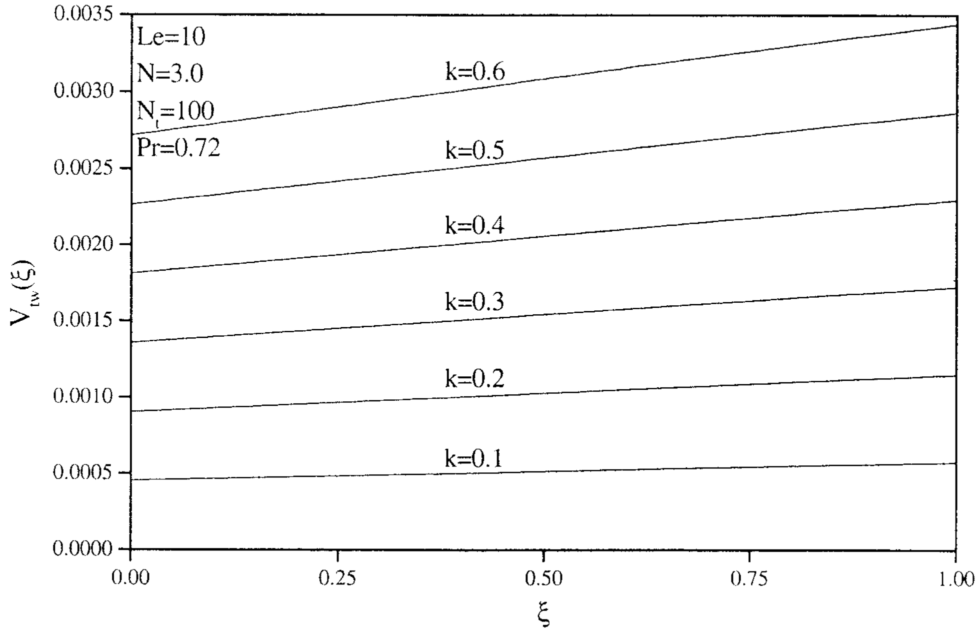

Fig.4. Effects of k on local wall thermophoretic deposition velocity.

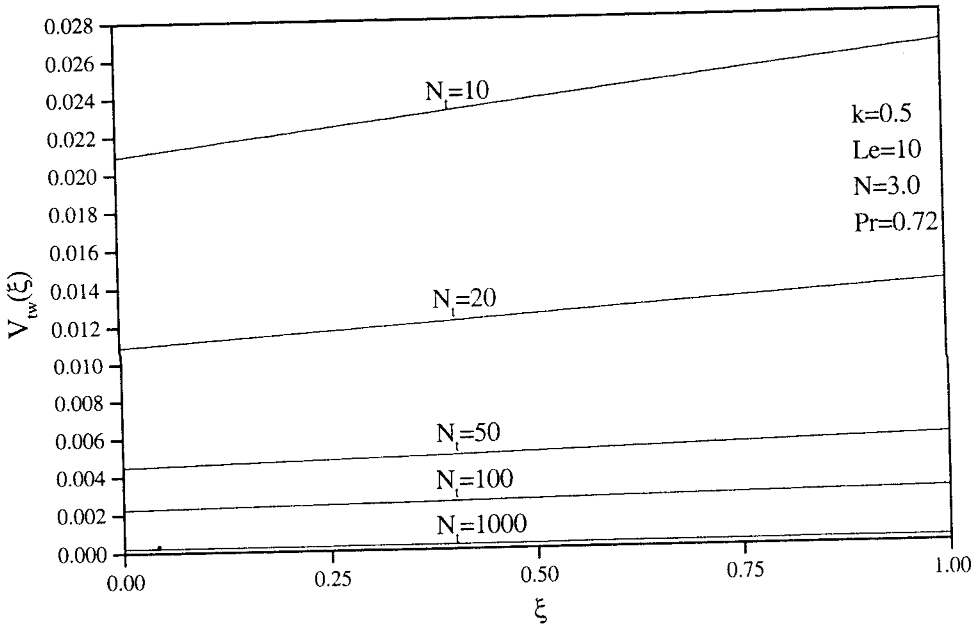

Fig.5. Effects of N_t on local wall thermophoretic deposition velocity.

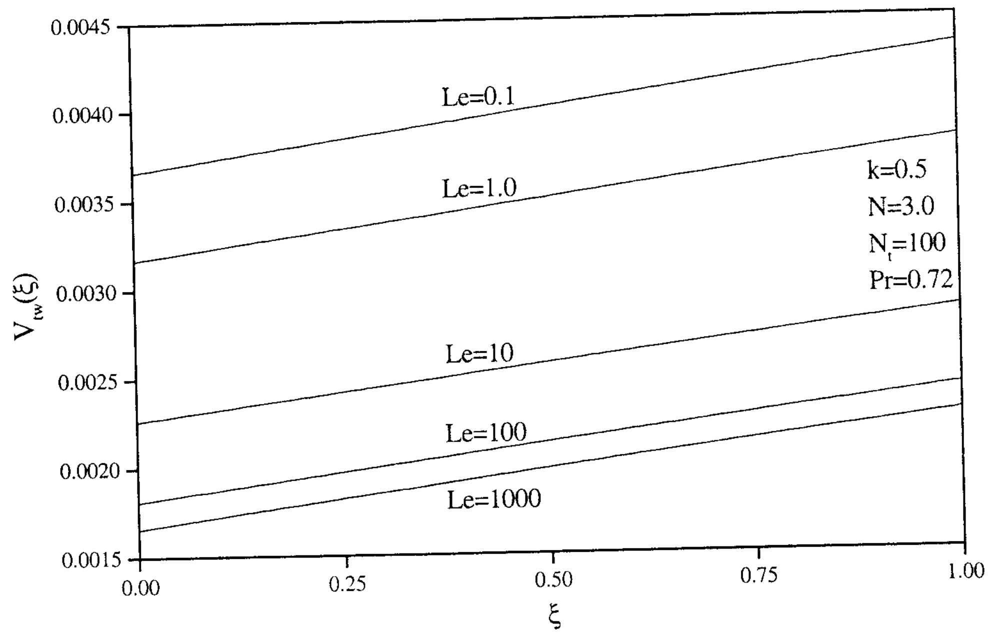

Fig.6. Effects of Le on local wall thermophoretic deposition velocity.

4. Concluding remarks

Numerical solutions for heat and mass transfer by steady boundary layer free convection over a heated isothermal vertical cylinder embedded in a porous medium in the presence of thermophoresis particle deposition effect were reported. A finite-difference method, as proposed by Blottner (1970), has been used to calculate the effect of thermophoresis on the deposition of particles, the concentration profiles and the concentration gradient at the surface of cylinder. Calculations clearly show the effect of thermophoresis on particle deposition. To the best of the authors' knowledge, there are no experimental data on particle deposition from naturally convected flows in porous media. It is hoped that the present treatment will facilitate future comparisons of the natural convection deposition theory with laboratory data.

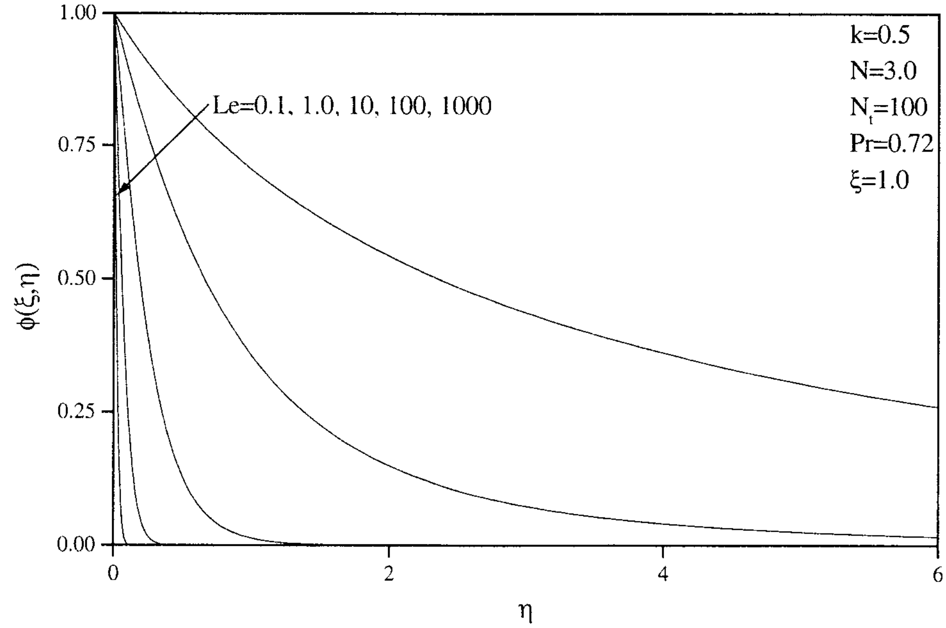

Fig.7. Effects of Le on concentration profiles.

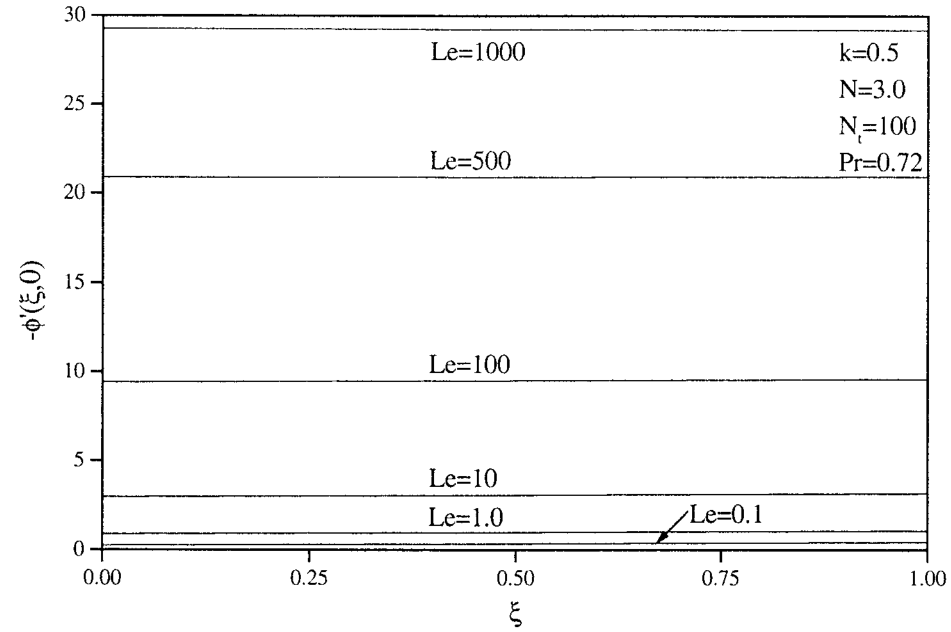

Fig.8. Effects of Le on local concentration gradient.

Nomenclature

C – concentration
D_m – mass diffusivity
f – reduced stream function

g – gravitational acceleration
k – thermophoretic parameter
K – permeability of the porous medium
Le – Lewis number
N – buoyancy parameter
N_t – thermophoretic parameter
Nu – local Nusselt number
Pr – Prandtl number
r – radial coordinate
r_0 – radius of the cylinder
Ra – Rayleigh number based on r_0 for a porous medium
Ra_x – local Rayleigh number based on $\bar{x}$
Sh – Sherwood number
T – fluid temperature
u, v – velocity components in the x- and r-directions
v_t – thermophoretic velocity
x – axial coordinate
α_m – equivalent thermal diffusivity
β_C – chemical expansion coefficient
β_T – thermal expansion coefficient
η – pseudo-similarity variable
θ – dimensionless temperature
ν – kinematic viscosity
ξ – stretched streamwise coordinate
ϕ – dimensionless concentration
ψ – stream function

Subscripts

w – condition at the wall
∞ – condition in the ambient fluid

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