International Journal of Heat and Mass Transfer 52 (2009) 3064–3069

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Natural convection from a vertical cone in a porous medium due to the combined effects of heat and mass diffusion with non-uniform wall temperature/concentration or heat/mass flux and suction/injection

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ARTICLE INFO

*Article history:*
Received 29 February 2008
Received in revised form 23 September 2008
Accepted 1 October 2008
Available online 3 April 2009

*Keywords:*
Natural convection
Vertical cone
Porous medium
Heat and mass diffusion

ABSTRACT

An analysis has been carried out to study the non-Darcy natural convention flow of Newtonian fluids on a vertical cone embedded in a saturated porous medium with power-law variation of the wall temperature/concentration or heat/mass flux and suction/injection with the streamwise distance *x*. Both non-similar and self-similar solutions have been obtained. The effects of non-Darcy parameter, ratio of the buoyancy forces due to mass and heat diffusion, variation of wall temperature/concentration or heat/mass flux and suction/injection on the Nusselt and Sherwood numbers have been studied.



## 1. Introduction

The natural convention flow over a surface embedded in saturated porous media is encountered in many engineering problems such as the design of pebble-bed nuclear reactors, catalytic reactors and compact heat exchangers, geothermal energy conversion, use of fibrous material in the thermal insulation of buildings, heat transfer from storage of agricultural products which generate heat as a result of metabolism, petroleum reservoirs, storage of nuclear wastes, etc. The comprehensive reviews of papers on this topic have been presented by Cheng [1,2], Pop et al. [3], Nield and Bejan [4], Vafai [5], Pop and Ingham [6] and Ingham and Pop [7].

The natural convection on vertical, inclined and horizontal surfaces in porous media has been studied by a number of authors [8–14] who used Darcy's law. Bejan and Khair [15] have used scale analysis to study the heat and mass transfer by natural convection over a vertical plate in a Darcy porous medium and showed that the natural convection phenomenon conforms to one of four possible regimes depending on the buoyancy ratio and Lewis number. They have discussed nicely the limits of the Lewis number *Le* and the buoyancy ratio force. The non-Darcy effect on the natural convection boundary layer on an isothermal vertical flat plate embedded in a porous medium was studied by Plumb and Huenefeld [16], Chen and Lin [17] and Chamkha [18]. Hung et al. [19] considered the non-Darcy free convection from a non-isothermal vertical surface in a thermally stratified porous medium. Minto et al. [20] studied the natural convection flow driven by an exothermic reaction over a vertical surface in a porous medium. Rees and Pop [21] examined the effect of the variable permeability on the natural convection flow on a vertical surface in a porous medium. Recently, Singh and Singh [22] and Kumari and Nath [23] have considered certain aspects of the buoyancy-induced flow on vertical and horizontal surfaces in a porous medium. Yih [24] has reported the effect of uniform mass flux on the free convection flow from an isothermal vertical cone embedded in a saturated porous medium using Darcy model.

In this analysis, the natural convection non-Darcy flow over a vertical permeable cone embedded in a saturated porous medium has been considered. The buoyancy forces arise due to the combined effects of thermal and mass diffusion. The effect of the surface mass transfer has also been considered. The wall temperature/concentration or surface heat/mass flux and the surface suction/injection are assumed to have power-law variation with the distance measured from the vortex of the cone. Recently, Kumari and Jayanthi [25] have considered the effect of uniform lateral mass flux on the natural convection flow on a vertical cone embedded in a porous medium saturated with a power-law fluid for the constant wall temperature case. The present problem for $S = 0$ (without mass diffusion), $M = N = 0$ (uniform heat and mass flux) reduces to that of Kumari and Jayanthi [25] for the Newtonian fluid

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0017-9310/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.ijheatmasstransfer.2008.10.037

**Nomenclature**

| | |
|---|---|
| $C$ | species mass fraction or concentration |
| $C_0$ | species mass fraction at $x = L$ |
| $D$ | binary diffusion coefficient |
| $Er_x$ | Ergun number |
| $f$ | reduced stream function |
| $f'$ | dimensionless velocity |
| $g$ | gravitational accelaration |
| $k$ | effective thermal conductivity of the saturated porous medium |
| $K$ | permeability of the porous medium |
| $K^*$ | inertial coefficient of the Ergun equation |
| $L$ | characteristic length |
| $Le$ | Lewis number |
| $m$ | mass flux of diffusing species |
| $m_0$ | value of $m$ at $x = L$ |
| $M$ | index in the power-law variation of wall temperature/concentration or wall heat/mass flux with the streamwise distance $x$ |
| $N$ | index in the power-law variation of the normal velocity at the surface with the streamwise distance $x$ |
| $Nu_x$ | local Nussselt number |
| $Pr$ | Prandtl number |
| $q_w,\ q_0$ | local surface heat transfer and its value at $x = L$, respectively |
| $r$ | local radius of the cone |
| $Ra_x,\ Ra_x^*$ | local Rayleigh numbers for PWT/PWC and PHF/PMF cases, respectively |
| $S,\ S^*$ | ratio of the buoyancy force due to mass diffusion to the buoyancy force due to the thermal diffusion for PWT/PWC and PHF/PMF cases, respectively |
| $Sc,\ Sh_x$ | Schmidt number and local Sherwood number, respectively |
| $T,\ T_0$ | temperature of the fluid and its values at $x = L$, respectively |
| $u,\ v$ | velocity components in $x$ and $y$ directions, respectively |
| $x,\ y$ | co-ordinates along the cone and normal to it, respectively |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | effective thermal diffusivity of saturated porous medium |
| $\beta,\ \beta^*$ | volumetric coefficients of thermal expansion and expansion with mass fraction, respectively |
| $\eta,\ \xi$ | transformed co-ordinates |
| $\eta_\infty$ | dimensionless boundary layer thickness |
| $\theta$ | dimensionless temperature |
| $\lambda,\ \lambda^*$ | non-Darcy parameter for PWT/PWC and PHF/PMF cases, respectively |
| $\mu,\ \nu$ | dynamic and kinematic viscosities of the fluid, respectively |
| $\rho$ | fluid density |
| $\phi$ | dimensionless concentration |
| $\psi,\ \Omega$ | stream function and semi-vertical angle of the cone |

*Subscripts*

| | |
|---|---|
| $w$ | condition at the wall |
| $\infty$ | ambient condition |

*Superscript*

| | |
|---|---|
| $'$ | prime denotes derivative with respect to $\eta$ |

(i.e., when we put $n = 1$ in their equations). Hence for the Newtonian fluids, our problem is more general than that of Kumari and Jayanthi [25]. The non-linear coupled parabolic partial differential equations governing the non-similar flow have been solved by an implicit finite difference scheme [26]. For some particular cases, self-similar solutions have been obtained. The results have been compared with those of Bejan and Khair [15], Yih [24] and Kumari and Jayanthi [25]. The present results are more general than those available in the literature and they will be useful in catalytic reactors and storage of agricultural products.

## 2. Analysis

Consider a vertical cone with semi-vertical angle $\Omega$ embedded in a saturated porous medium with ambient temperature $T_\infty$ and concentration $C_\infty$. The streamwise co-ordinate $x$ is measured from the tip of the cone along the ray, and the transverse co-ordinate $y$ is measured normal to it. The wall temperature $T_w$ and the concentration $C_w$ or the heat flux $q_w$ and mass flux $m_w$ as well as surface mass transfer $f_w$ are assumed to have power-law variation with the streamwise distance $x$. For low concentrations of the diffusing species with negligible diffusion-thermo and thermo-diffusion effects with the assumptions of negligible effects of the buoyancy-induced streamwise pressure gradient terms and imposing Boussinesq approximations along with the boundary layer assumptions and using the non-Darcy model of Ergun [27], one can write the conservation equations for the steady laminar boundary layer along a vertical cone as [11,24].

$$\frac{\partial}{\partial x}(ru) + \frac{\partial}{\partial y}(rv) = 0, \tag{1}$$

$$\frac{\partial u}{\partial y} + \frac{\rho K^*}{\mu}\frac{\partial}{\partial y}(u^2) = \frac{g\beta K\cos\Omega}{\nu}\frac{\partial T}{\partial y} + \frac{g\beta^* K\cos\Omega}{\nu}\frac{\partial C}{\partial y}, \tag{2}$$

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

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

The boundary conditions are given by

$$\begin{aligned}
&v(x,0) = v_w(x),\ \ u(x,\infty) = 0,\ \ T(x,\infty) = T_\infty,\ \ C(x,\infty) = C_\infty,\\
&T(x,0) = T_w(x),\ \ C(x,0) = C_w(x),\ \ (\text{PWT/PWC case}),\\
&\partial T(x,0)/\partial y = -q_w(x)/k,\ \ \partial C(x,0)/\partial y = -m_w(x)/D,\ \ (\text{PHF/PMF case}),\\
&u(0,y) = 0,\ \ T(0,y) = T_\infty,\ \ C(0,y) = C_\infty,\ \ y > 0.
\end{aligned} \tag{5}$$

It is convenient to reduce the number of equations as well as transform them in dimensionless form. In order to achieve these objectives, we apply the following transformations

$$\begin{aligned}
&\xi = 2v_w x/(\alpha Ra_x^{1/2}),\quad \eta = yx^{-1}Ra_x^{1/2},\quad r = x\sin\Omega,\\
&\psi = \alpha r Ra_x^{1/2} f(\xi,\eta),\quad ru = \partial\psi/\partial y,\quad rv = -\partial\psi/\partial x,\\
&T_w(x) - T_\infty = (T_0 - T_\infty)(x/L)^M,\quad C_w(x) - C_\infty = (C_0 - C_\infty)(x/L)^M,\\
&v_w = v_0(x/L)^N,\quad Ra_x = g\beta\cos\Omega(T_w - T_\infty)Kx/\nu\alpha,\\
&\theta(\xi,\eta) = (T - T_\infty)/(T_w - T_\infty),\quad \phi(\xi,\eta) = (C - C_\infty)/(C_w - C_\infty),\\
&Pr = \nu/\alpha,\quad Sc = \nu/D,\quad Er_x = K^*\alpha/(\nu x),\\
&S = (C_0 - C_\infty)\beta^*/(T_0 - T_\infty)\beta,\quad Le = \alpha/D = Sc/Pr,\\
&f(\xi,0) = f_w = -2^{-1}(N+2)^{-1}\xi,\quad \lambda = Er_x Ra_x,
\end{aligned} \tag{6}$$

to Eqs. (1)–(4) and we find that (1) is identically satisfied and (2)–(4) reduce to

$$f' + \lambda (f')^2 = \theta + S\phi, \tag{7}$$

$$\theta'' + 2^{-1}(M+3)f\theta' - Mf'\theta = 2^{-1}(2N - M + 1)\xi(f'\partial\theta/\partial\xi - \theta'\partial f/\partial\xi), \tag{8}$$

$$Le^{-1}\phi'' + 2^{-1}(M+3)f\phi' - Mf'\phi = 2^{-1}(2N - M + 1)\xi(f'\partial\phi/\partial\xi - \phi'\partial f/\partial\xi), \tag{9}$$

where boundary conditions are

$$f(\xi,0) = -2^{-1}(N+2)^{-1}\xi, \quad \theta(\xi,0) = \phi(\xi,0) = 1, \quad f'(\xi,\infty) = \theta(\xi,\infty) = \phi(\xi,0) = 0. \tag{10}$$

For the prescribed heat/mass flux case (PHF/PMF), we apply the following transformations

$$\begin{aligned}
&\xi = 2v_w x/(\alpha(Ra_x^*)^{1/3}), \quad \eta = yx^{-1}(Ra_x^*)^{1/3}, \quad \psi = \alpha r(Ra_x^*)^{1/3} f(\xi,\eta),\\
&\theta(\xi,\eta) = (T - T_\infty)k(Ra_x^*)^{1/3}/(q_w x),\\
&\phi(\xi,\eta) = (C - C_\infty)D(Ra_x^*)^{1/3}/(m_w x), \quad Ra_x^* = g\beta\cos\Omega q_w K x^2/(v\alpha k),\\
&S^* = \beta^*(m_w/D)/\beta(q_w/k), \quad q_w/q_0 = (x/L)^M,\\
&m_w/m_0 = (x/L)^M, \quad v_w = v_0(x/L)^N, \quad \lambda^* = Er_x Ra_x^*(\alpha/2v_w x),\\
&N_1 = 3^{-1}(3N - M + 1),
\end{aligned} \tag{11}$$

to (1)–(4), and we find that (1) is identically satisfied and (2)–(4) can be expressed as

$$f' + \lambda^*\xi(f')^2 = \theta + S^*\phi, \tag{12}$$

$$\theta'' + 3^{-1}[(M+5)f\theta' - (2M+1)f'\theta] = N_1\xi(f'\partial\theta/\partial\xi - \theta'\partial f/\partial\xi), \tag{13}$$

$$Le^{-1}\phi'' + 3^{-1}[(M+5)f\phi' - (2M+1)f'\phi] = N_1\xi(f'\partial\phi/\partial\xi - \phi'\partial f/\partial\xi), \tag{14}$$

with boundary conditions

$$f(\xi,0) = -2^{-1}(N+2)^{-1}\xi, \quad \theta'(\xi,0) = \phi'(\xi,0) = -1, \quad f'(\xi,0) = \theta(\xi,\infty) = \phi(\xi,\infty) = 0. \tag{15}$$

It may be noted that (7)–(10) and (12)–(15) for $\lambda = \lambda^* = M = N = 0$ reduce to those of Yih [24].

The quantities of physical interest are the Nusselt and Sherwood numbers and for PWT/PWC case are given by

$$\begin{aligned}
Nu_x &= -x(\partial T/\partial y)_{y=0}/(T_w - T_\infty) = -(Ra_x)^{1/2}\theta'(\xi,0),\\
Sh_x &= -x(\partial C/\partial y)_{y=0}/(C_w - C_\infty) = -(Ra_x)^{1/2}\phi'(\xi,0),
\end{aligned} \tag{16}$$

For PHF/PMF case, they are expressed as

$$Nu_x = (Ra_x^*)^{1/3}/\theta(\xi,0), \quad Sh_x = (Ra_x^*)^{1/3}/\phi(\xi,0). \tag{17}$$

## 3. Results and discussion

We have solved Eqs. (7)–(9) under conditions (10) governing the PWT/PWC case and Eqs. (17)–(19) under conditions (20) governing the PHF/PMF case by using Keller-box method which is described in detail in [26]. We have carried out the sensitivity analysis to examine the effects of step size $\triangle\eta$, $\triangle\xi$ and the edge of the boundary layer $\eta_\infty$ on the solutions. The results presented here are independent of $\triangle\eta$, $\triangle\xi$ and $\eta_\infty$ at least up to three decimal places. In order to assess the accuracy of our solutions, we have compared the Nusselt and Sherwood numbers for PWT/PWC and PHF/PMF cases when $\lambda = \lambda^* = M = N = 0$ (i.e., Darcy flow with uniform wall temperature/concentration or uniform wall heat/mass flux), $-2 \leqslant \xi \leqslant 1$ with those of Yih [24] and found them in good agreement. The maximum difference is about one percent. Hence for the sake of brevity, the comparison is not shown here. We have also compared the Nusselt and Sherwood numbers ($Ra_x^{-1/2}Nu_x$, $Ra_x^{-1/2}Sh_x$) for the Darcy flow ($\lambda = 0$) corresponding to the flat plate case for the self-similar flow with those of Bejan and Khair [15] and found them in very good agreement. The comparison is presented in Table 1. Further, the heat transfer results ($-\theta'(\xi,0)$) for the PWT case when $S = M = N = 0$ have been compared with those of Kumari and Jayanthi [25] with $n = 1$ (Newtonian fluid) and they are found to be in very good agreement. However, for the sake of conciseness, the comparison is not presented here.

The variation of the local Nusselt and Sherwood numbers for the PWT/PWC and PHF/PMF cases with suction/injection $\xi$ when $S = S^* = -0.5,\ 2.0,\ M = N = 0.25,\ Le = 5,\ \lambda = \lambda^* = 0.01,\ 0.05, 0.1$ is shown in Fig. 1. In general, the Nusselt and Sherwood numbers increase with suction, but decrease with injection due to the reduction of the thermal and concentration boundary layers by suction and thickening of these boundary layers by injection. The Nusselt and Sherwood numbers increase with $S$ or $S^*$, since the net positive buoyancy force acts like a favourable pressure gradient that accelerates the fluid in the boundary layer which results in the reduction of the boundary layer thicknesses. Consequently, the temperature and concentration gradients at the surface and the Nusselt and Sherwood numbers increase with $S$ or $S^*$. When the other parameters are fixed, the Nusselt and Sherwood numbers decrease with increasing $\lambda$ or $\lambda^*$ due to the more resistance being offered by the porous medium to the fluid motion as $\lambda$ or $\lambda^*$ increases. For $Le > 1$, the Sherwood number has higher values than the Nusselt number, because increase in $Le$ $(= Sc/Pr)$ implies either increase in $Sc$ or reduction in $Pr$. Consequently, the concentration boundary layer becomes thinner than the thermal boundary layer. Hence, the gradient of the concentration at the surface as well as the Sherwood number are higher than the gradient of temperature and the Nusselt number, respectively. If $Le < 1$, then the Nusselt number is greater than the Sherwood number.

Fig. 2 presents the effect of the index $M$ on the local Nusselt and Sherwood numbers when $Le = 5,\ \lambda = \lambda^* = 0.1,\ N = 0.25,\ S = S^* = -0.5,\ 2.0,\ -2 \leqslant \xi \leqslant 2$. Since increase in $M$ implies increase in temperature/concentration or heat/mass flux which causes reduction

**Table 1**
Nusselt and Sherwood numbers for $\lambda = \xi = M = N = 0$ with those of Bejan and Khair [15].

| $S$ | $Le$ | Present results | | Bejan and Khair [15] | |
|---|---|---|---|---|---|
| | | $Ra_x^{-1/2}Nu_x$ | $Ra_x^{-1/2}Sh_x$ | $Ra_x^{-1/2}Nu_x$ | $Ra_x^{-1/2}Sh_x$ |
| 2.0 | 1 | 0.76900 | 0.76900 | 0.769 | 0.769 |
| | 2 | 0.71061 | 1.12150 | 0.710 | 1.122 |
| | 4 | 0.65251 | 1.62213 | 0.650 | 1.624 |
| | 6 | 0.62123 | 2.00180 | 0.618 | 2.009 |
| | 8 | 0.60176 | 2.32521 | 0.597 | 2.332 |
| | 10 | 0.58900 | 2.61100 | 0.582 | 2.617 |
| | 100 | 0.50080 | 8.37626 | 0.490 | 8.424 |
| 1.0 | 1 | 0.62801 | 0.62801 | 0.628 | 0.628 |
| 0.8 | 1 | 0.59500 | 0.59500 | 0.595 | 0.595 |
| 0.5 | 1 | 0.54301 | 0.54301 | 0.543 | 0.543 |
| 0.2 | 1 | 0.48601 | 0.48601 | 0.486 | 0.486 |
| 0.1 | 1 | 0.46501 | 0.46501 | 0.465 | 0.465 |
| 0.0 | 1 | 0.44401 | 0.44401 | 0.444 | 0.444 |
| −1.1 | 1 | 0.14424 | 0.14424 | 0.144 | 0.144 |
| −1.2 | 1 | 0.19930 | 0.19930 | 0.199 | 0.199 |
| −1.5 | 1 | 0.31509 | 0.31509 | 0.314 | 0.314 |
| −1.9 | 1 | 0.42130 | 0.42130 | 0.421 | 0.421 |
| −2.0 | 1 | 0.44522 | 0.44522 | 0.444 | 0.444 |

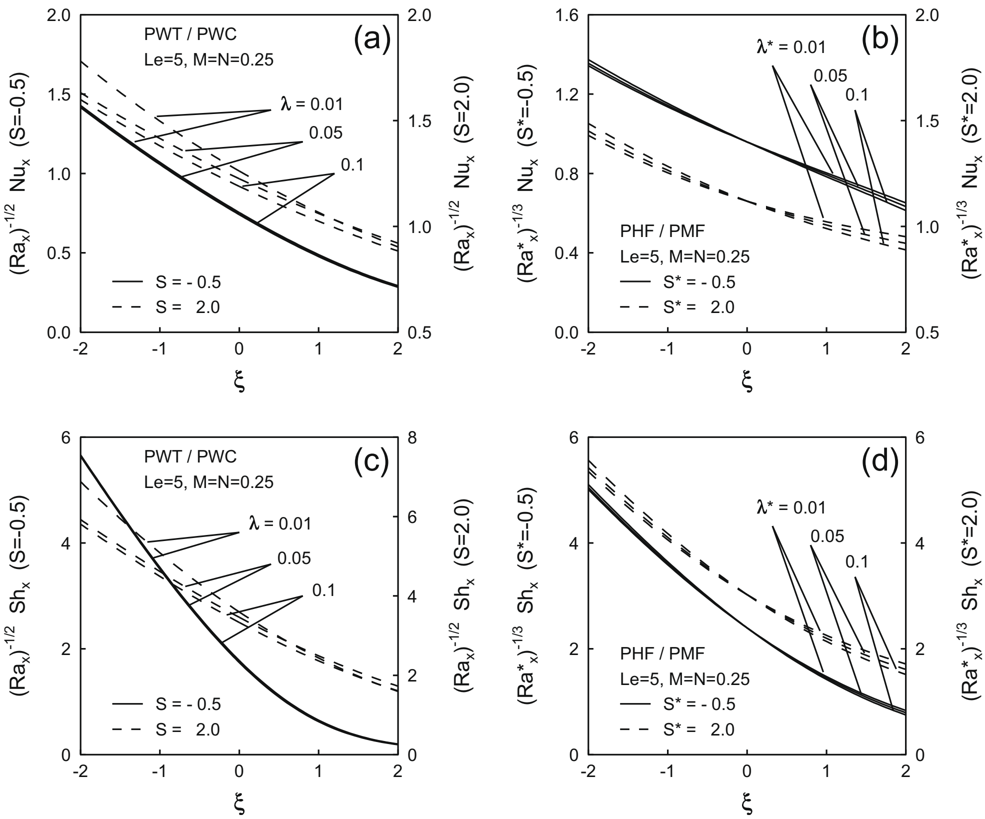


**Fig. 1.** Effect of $\lambda$ and $\lambda^*$ on the local Nusselt and Sherwood numbers.

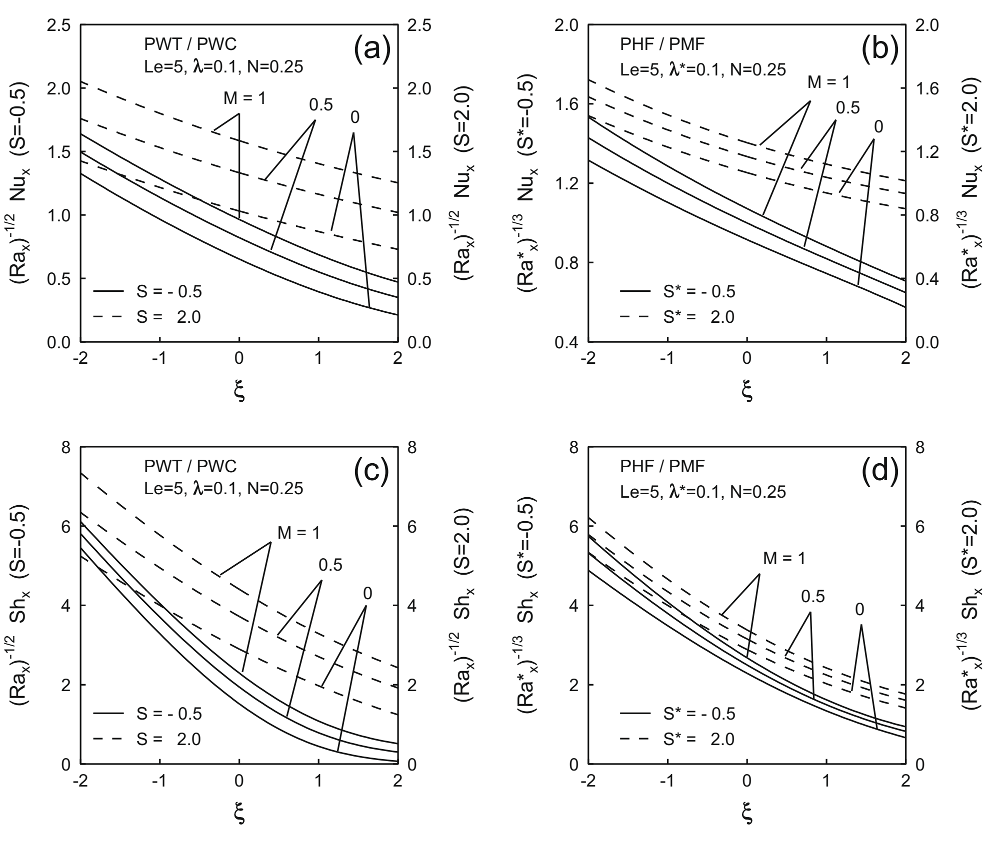


**Fig. 2.** Effect of $M$ on the local Nusselt and Sherwood numbers.

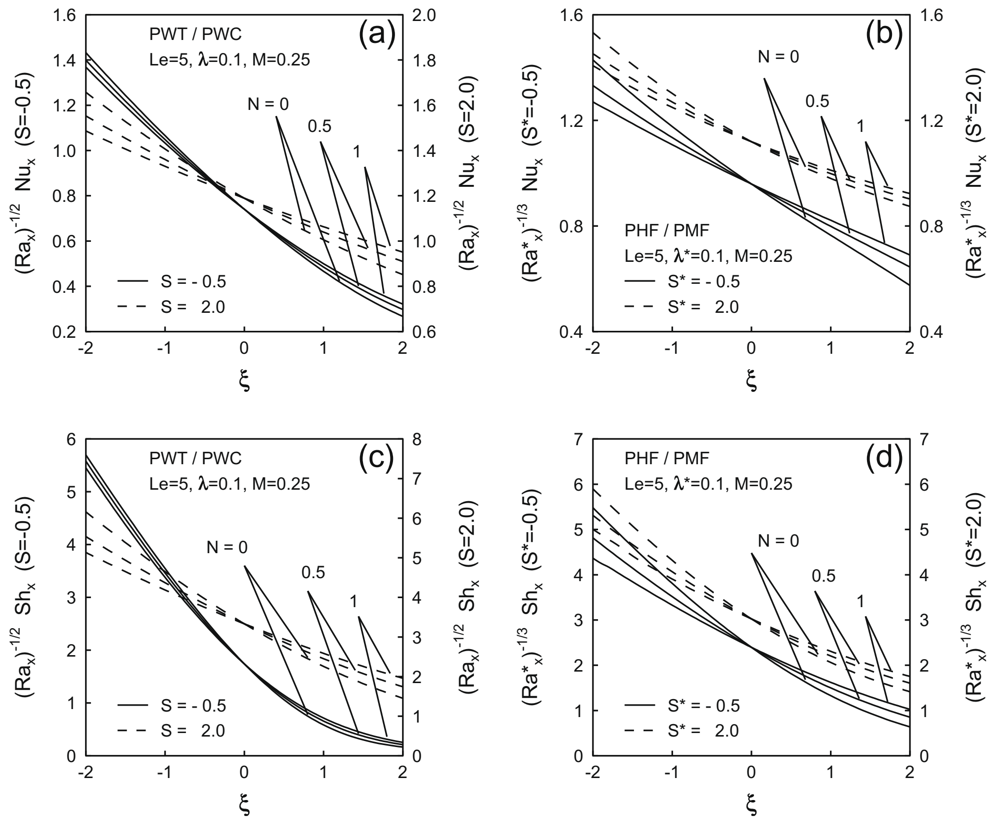


**Fig. 3.** Effect of $N$ on the local Nusselt and Sherwood numbers.

in the boundary layer thicknesses. Consequently, the Nusselt and Sherwood numbers increase.

Fig. 3 shows the effect of the parameter $N$ which characterizes the variation of the normal velocity at the surface $v_w$ with the distance $\xi$ on the Nusselt and Sherwood numbers for the PWT/PWC and PHF/PMF cases when $-2 \leqslant \xi \leqslant 2$, $Le = 5$, $\lambda = \lambda^* = 0.1$, $M = 0.25$, $S = S^* = -0.5,\ 2.0$. Since increase in $N$ implies reduction in the suction/injection rate at the surface $(f_w = -\xi/2(N+1))$, the Nusselt and Sherwood numbers decrease for suction $(-2 \leqslant \xi < 0)$ as $N$ increases when all other parameters are kept constant, but opposite trend is observed for injection $(0 < \xi \leqslant 2)$.

## 4. Conclusions

The natural convection non-Darcy flow over a vertical cone embedded in a saturated porous medium under more general conditions has been studied. The results show that the local Nusselt and Sherwood numbers are strongly influenced by suction/injection, and variation in wall temperature/concentration or wall heat/mass flux.

## Acknowledgement

One of the authors (M.K.) gratefully acknowledges the financial support by University Grants Commission, India, under the Research Scientists Scheme.

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