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Thermo-Diffusion Effect on Free Convection Heat and Mass Transfer in a Thermally Linearly Stratified Non-Darcy Porous Media

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Abstract: Thermo-diffusion effect on free convection heat and mass transfer from a vertical surface embedded in a liquid saturated thermally stratified non - Darcy porous medium has been analyzed using a local non-similar procedure. The wall temperature and concentration are constant and the medium is linearly stratified in the vertical direction with respect to the thermal conditions. The fluid flow, temperature and concentration fields are affected by the complex interactions among the diffusion ratio *Le*, buoyancy ratio *N,* thermo-diffusion parameter S_r and stratification parameter ε. Non-linear interactions of all these parameters on the convective transport has been analyzed and variation of heat and mass transfer coefficients with thermo-diffusion parameter in the thermally stratified non-Darcy porous media is presented through computer generated plots.

Keywords: Free convection, heat transfer, mass transfer, boundary layer, thermo-diffusion effect, thermal stratification, non-Darcy porous media.

INTRODUCTION

Coupled heat and mass transfer phenomenon in a liquid saturated porous medium is gaining attention due to its interesting applications. The flow phenomenon in this case is relatively complex than that in pure thermal/solutal convection process. Processes involving heat and mass transfer in porous media are often encountered in the chemical industry, in reservoir engineering in connection with thermal recovery process, in the study of dynamics of hot and salty springs of a sea. Underground spreading of chemical waste and other pollutants, grain storage, evaporation cooling and solidification are few other application areas where combined thermo/solutal convection in porous media can be observed. Due to the coupling of temperature and concentration, new parameters like buoyancy ratio and Lewis number (diffusion ratio) arise and they influence the convective transport to a greater extent. A review of both natural and mixed convection boundary layer flows in fluid saturated porous media is given in Nield and Bejan [1].

In processes involving vigorous free convection heat and mass transfer in clear fluids as well as in porous media, there may be increase in the heat transfer coefficient because of the concentration gradients and a similar increase in the mass transfer coefficient due to the thermal gradients. Soret (thermo-diffusion) effect corresponds to species differentiation developing in an initially homogeneous mixture submitted to a thermal gradient and Dufour (diffusion-thermo) effect corresponds to diffusion of heat caused by concentration gradients. In the earlier studies, Soret and Dufour effects are neglected, on the basis that they are of smaller order magnitude than the effects described by Fourier's and Fick's laws. These effects are considered as second order phenomenon, but these may become significant in areas such as hydrology, petrology and geo-sciences etc. Stability of Soret driven thermo-solutal convection in clear fluids with large thermal gradients has been analyzed theoretically and experimentally by Hurle and Jakeman [2] and it has been shown that Soret effect could give raise to overstable solutions of the thermo-solutal convection. Platten and Chavepeyer [3] have analyzed the oscillatory motion in Benard cell due to Soret effect. Thermo-solutal convection in liquids with large negative Soret coefficient has been analyzed by Caldwell [4]. Soret effect in incompressible fluids has been analyzed by Benano-Melly *et al.,* [5]. Kafoussias and Williams [6] studied the thermo-diffusion (Soret) and diffusion-thermo (Dufour) effects on forced, free and mixed convection with temperature dependant viscosity. Anghel *et al.,* [7] analyzed both the Soret and Dufour effects on free convection boundary-layer over a vertical surface embedded in a porous medium and noticed an appreciable change in the flow field. Postelnicu [8] analyzed the influence of magnetic field considering Soret and Dufour effects from a vertical surface in porous medium. Partha *et al.,* [9] studied the effect of magnetic field and double dispersion on free convective heat and mass transport considering the Soret and Dufour effects in non-Darcy porous medium. Postelnicu [10] analyzed the influence of chemical reaction on flow field considering Soret and Dufour effects from a vertical surface in porous medium. The effect of Soret and Dufour parameters on free convection heat and mass transfer from a vertical surface in a

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doubly stratified Darcian porous medium has been reported by Lakshmi Narayana and Murthy [11]. Recently, Murthy and Lakshmi Narayana [12] analyzed the influence of Soret and Dufour effects on free convective heat and mass transport from a horizontal plate in non-Darcy porous medium by considering power law variations for the temperature and concentration at the wall. Moreover, Kairi and Murthy [26] studied the effect of melting and thermo-diffusion on natural convection heat mass transfer in a non-Newtonian fluid saturated non-Darcy porous medium.

Joo [13] studied the instabilities in Marangoni convection in liquid mixtures with Soret effect theoretically and pointed out that a cross-coupling in the temperature field, namely Dufour effect, could exist, but is usually insignificant for liquid mixtures. Also, the terms Soret effect and Dufour coefficient give rise to interaction between the thermal and solute fields even when the fluid is at rest. But it is well known from the literature that the Soret coefficient has a considerable effect on convection process in liquids whereas the Dufour effect can be negligible in liquids but it plays a prominent role in gaseous mixtures.

Stratification is a characteristic of all fluid bodies surrounded by differentially heated and salted side walls. An important engineering application can be found in the problem of natural convection in an enclosed rectangular cell filled with fluid saturated porous medium with one wall heated and the other cooled. Heated fluid raising from the hot wall overlays the top of the cell and the cool fluid falling from the cold wall lies along the bottom thereby creating stratification inside the cell. Although the effect of stratification of the medium on the heat removal process in a porous medium is important, fairly little work has been reported in the literature. Bejan [14], Singh and Sharma [15] and Kalpana and Singh [16] studied the problem of boundary layer free convection along an isothermal vertical plate immersed in a thermally stratified fluid saturated porous medium using integral and series solution techniques. The case of power law variation of wall temperature with thermal stratification of the medium was discussed at length by Nakayama and Koyama [17], and by Lai *et al.,* [18]. Takhar and Pop [19] investigated the free convective transport from a vertical flat plate in a thermally stratified Darcian fluid saturated porous medium where the ambient temperature varies as $x^{1/3}$ using the similarity solution technique. Murthy *et al.,* [20] extended the work of Takhar and Pop [19] to uncover 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. Chamkha and Khaled [21] reported the coupled mixed convection from a vertical plate embedded in stratified porous medium with thermal dispersion effects. Hossain *et al.,* [22] investigated the viscous dissipation effects on natural convection with uniform surface heat flux placed in a thermally stratified media. Also, natural convection flow with combined buoyancy effects due to thermal and mass diffusion in a thermally stratified media was introduced by Saha and Hossain [23].

The present investigation is undertaken to see the effect of thermo-diffusion parameter on the free convection heat and mass transfer in a thermally stratified porous medium. Quite often we encounter thermal stratification in a closed environment and also in the semi infinite porous media. In the present investigation, the medium is assumed to be linearly thermally stratified which is physically more realistic rather than considering an arbitrary power law variation for the thermal stratification.

GOVERNING EQUATIONS

Consider the natural boundary-layer flow near a vertical impermeable surface embedded in a porous medium saturated with Newtonian liquid. The x-coordinate is taken along the plate, in the ascending direction, the y-coordinate is measured normal to the plate, while the origin of the reference system is considered at the leading edge of the vertical plate. The wall is maintained at constant temperature and concentration, T_w and C_w respectively, while the temperature in the ambient medium varies linearly on the x-coordinate (thermally linearly stratified). Viscous resistance due to the solid boundary is neglected under the assumption that the medium is with low permeability. For this boundary-layer problem in porous media, we assume the flow is governed by non-Darcy's law, Boussinesq approximation is valid, the fluid and the porous medium are in local thermodynamic equilibrium. Under these assumptions the governing equations for the flow in the medium may be written as,

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

$$\frac{\partial u}{\partial y}+\frac{c\sqrt{K}}{v}\frac{\partial u^2}{\partial y}=\frac{K\,g}{\nu}\left(\beta_T\frac{\partial T}{\partial y}+\beta_C\frac{\partial C}{\partial y}\right) \tag{2}$$

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

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{D_1 k}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

The boundary conditions are given by

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

$$y\to\infty:\quad u\to 0,\ T\to T_{\infty,0}+Ax,\quad C=C_\infty\,(\text{constant}) \tag{5b}$$

Here x and y are the Cartesian coordinates along and normal to the plate respectively, u and v are the averaged velocity components in x and y directions respectively, T and C are temperature and concentration respectively, β_T and β_C are the coefficient of thermal and solutal expansion respectively, v is the kinematic viscosity of the fluid, c($\neq$ 0) is the Forchheimer (non-Darcy) coefficient, c = 0 lead the above system of equations represent the heat and mass transport in the Darcy porous medium. K is the permeability, g is the acceleration due to gravity, α, D are the thermal and solutal diffusivities of the medium, k is the thermal diffusion ratio, D_1 is the Soret coefficient, T_m is the mean fluid temperature. The suffix '∞' indicates the conditions in the ambient medium. The velocity components u and v are written in terms of stream function ψ, using the following transformation,

$$\eta=\frac{y}{x}Ra_x^{1/2},\qquad \varepsilon=\frac{Ax}{T_w-T_\infty},\qquad \psi(x,y)=\alpha Ra_x^{1/2} f(\varepsilon,\eta),$$

$$\theta(\varepsilon,\eta)=\frac{T-T_{\infty,0}}{T_w-T_{\infty,0}}-\frac{Ax}{T_w-T_{\infty,0}},\quad \phi(\varepsilon,\eta)=\frac{C-C_\infty}{C_w-C_\infty},$$

the governing equations and the boundary conditions (1) – (5) are transformed as:

$$f'' + 2F_c f' f'' = \theta' + N\phi' \tag{6}$$

$$\theta'' + \frac{1}{2} f\theta' = \varepsilon\left(f'\frac{\partial\theta}{\partial\varepsilon}-\theta'\frac{\partial f}{\partial\varepsilon}\right)+\varepsilon f' \tag{7}$$

$$\phi'' + Le\ Sr\ \theta'' + \frac{1}{2} Le\ f\phi' = Le\ \varepsilon\left(f'\frac{\partial\phi}{\partial\varepsilon}-\phi'\frac{\partial f}{\partial\varepsilon}\right) \tag{8}$$

$$f(\varepsilon,0)=0,\ \theta(\varepsilon,0)=1-\varepsilon,\ \phi(\varepsilon,0)=1 \text{ at } \eta=0 \tag{9a}$$

$$f'(\varepsilon,\infty)\to 0,\ \theta(\varepsilon,\infty)\to 0,\ \phi(\varepsilon,\infty)\to 0 \text{ as } \eta\to\infty \tag{9b}$$

In the above, " ' " represents differentiation with respect to the variable η. The second-level non-similarity method is used to convert the non-similar equations into a system of ordinary differential equations. This procedure is given in Sparrow *et al.,* [25], for brevity, it is not repeated here. Writing $F=\frac{\partial f}{\partial\varepsilon}, G=\frac{\partial\theta}{\partial\varepsilon}, H=\frac{\partial\varphi}{\partial\varepsilon}$ and differentiation of Eqs. (6)-(9) with respect to ε, the size of the system of equations will increase and we have the second level non-similar equations along with the boundary conditions as:

$$f'' + 2F_c f' f'' = \theta' + N\phi' \tag{10}$$

$$\theta'' + \frac{1}{2} f\theta' = \varepsilon\left(f' G-\theta' F\right)+\varepsilon f' \tag{11}$$

$$\phi'' + Le\ Sr\ \theta'' + \frac{1}{2} Le\ f\phi' = Le\ \varepsilon\left(f' H-\phi' F\right) \tag{12}$$

$$(1+2F_c f')F'' + 2F_c F' f'' = G' + N\phi' \tag{13}$$

$$G'' + \frac{1}{2}(F\theta' + fG') = f' G - \theta' F + \varepsilon F' + f' \tag{14}$$

$$H'' + Le\ Sr\ G'' + \frac{1}{2} Le(F\phi' + fH') = Le\left(f' H-\phi' F\right) \tag{15}$$

$$f(\varepsilon,0)=0,\ \theta(\varepsilon,0)=1-\varepsilon,\ \phi(\varepsilon,0)=1, F(\varepsilon,0) = 0,\ G(\varepsilon,0)=-1, H(\varepsilon,0)=0 \tag{16a}$$

at $\eta = 0$

$$f'(\varepsilon,\infty)=\theta(\varepsilon,\infty)=\phi(\varepsilon,\infty)=F'(\varepsilon,\infty) = G(\varepsilon,\infty)=H(\varepsilon,\infty)=0 \tag{16b}$$

as $\eta\to\infty$

In the above, $\theta_w = T_w - T_{\infty,0}$ and $\phi_w = C_w - C_\infty$. The non-dimensional parameters are $Ra_x=\frac{Kg\beta_T\theta_w x}{\alpha\nu}$ the Rayleigh number defined based on the thermal conditions, inertia parameter $F_c=\frac{c\sqrt{K}Kg\beta_T(T_w-T_\infty)}{\nu^2}$, the diffusivity ratio $Le=\frac{\alpha}{D}$ and the buoyancy ratio $N=\frac{\beta_c\phi_w}{\beta_T\theta_w}$. Positive values of N indicate aiding buoyancy, where both the thermal and solutal buoyancies are in the same direction and negative values of N indicate opposing buoyancy where the solutal buoyancy is in the opposite direction to the thermal buoyancy. Also $S_r=\frac{D_1 k\theta_w}{T_m\alpha\varphi_w}$ is the Soret parameter. This parameter can be both positive and negative as ϕ_w can be positive or negative.

The fundamental interest of the present investigation is to examine the variations in the heat and mass transfer coefficients with various values of these physical parameters that influence the system. These non-dimensional heat and mass transfer coefficients are written as,

$$\frac{Nu_x}{Ra_x^{1/2}}=-\theta'(\varepsilon,0) \text{ and } \frac{Sh_x}{Ra_x^{1/2}}=-\phi'(\varepsilon,0) \text{ respectively.}$$

RESULTS AND DISCUSSION

The system of ordinary differential equations (10)-(15) subject to the boundary conditions (16a,b) have been solved numerically by means of the fourth-order Runge-Kutta method with shooting technique. The step size $\Delta\eta=0.05$ is used while obtaining the numerical solution with $\eta_{\max}=12$ and five-decimal accuracy as the criterion for convergence. Extensive calculations have been performed to obtain the flow, temperature and concentration fields for $0\le F_c\le 1.0$, $0<Le\le 10$, $-0.5\le N\le 1.5$, $-0.1\le S_r\le 1.0$ and $0\le\varepsilon\le 0.7$. The numerical results are analyzed and presented for aiding and opposing buoyancies in the presence and absence of the Soret parameters in both Darcy and the non-Darcy thermally stratified porous media. $F_c=0$ correspond to Darcy porous media while the results for non-Darcy case are presented for

$F_c = 0.2$; and also $\varepsilon = 0$ represents that the medium is unstratified porous medium. For the surrounding fluid to be stable, A should be positive, and the range of ε should from 0 to 1, for the wall temperature to exceed the surrounding ambient temperature. Seeking verification, Fig. (**1**) shows a comparison between the current results and the published results by Lakshmi Narayana and Murthy [26] of the mass transfer coefficient against stratification parameter ε, at N=2, Fc=0.0, Le=1 and Sr=0.1. The comparison shows a good agreement between the present calculations and the results in [26].

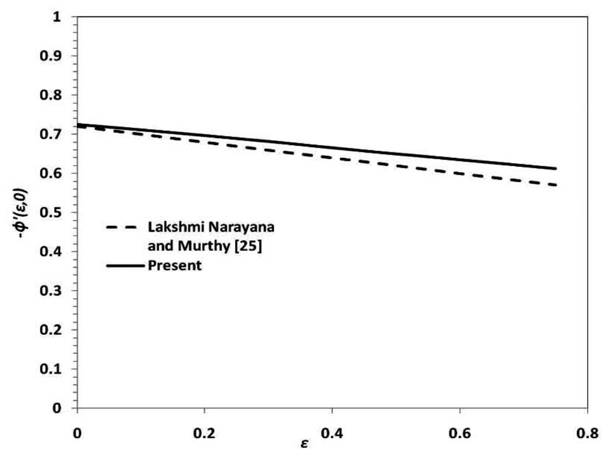

Fig. (1). Comparison between the current results and the published results by Lakshmi Narayana and Murthy [25] of the mass transfer coefficient against stratification parameter ε, at N=2, Fc=0.0, Le=1 and Sr=0.1.

Variations of non-dimensional velocity, temperature and concentration fields against the similarity variable η for different values of the stratification parameter ε are shown in Figs. (**2-4**). The non-dimensional velocity f' and temperature θ decrease with increasing values of the stratification parameter ε. On the other hand the non-dimensional concentration increased with the value of ε. For relatively large values of $\varepsilon \geq 0.5$ the non-dimensional temperature attains negative values inside the boundary layer, afterwards it tends

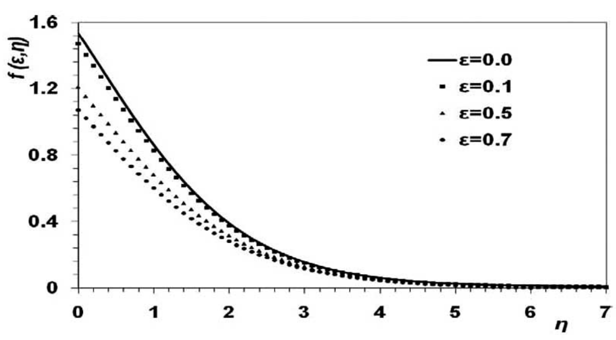

Fig. (2). Effects of stratification (ε = 0.0, 0.1, 0.5, 0.7) on velocity profiles of the non-Darcy flow at N=1, Fc=0.2, Le=1 and Sr=0.1.

to zero as η approaches to the edge of the boundary layer. These results for linear stratification are consistent with those reported in Murthy *et al.,* [20] for non-linear stratification. It was reported in the earlier study by Lakshmi Narayana and Murthy [11] that due to the double stratification of the medium, the non-dimensional temperature and concentration are becoming negative in the boundary layer region. Also, by considering the Soret and Dufour effects in the medium, Postelnicu [15], and Partha *et al.,* [16] reported that for certain combinations of values of these parameters, the non-dimensional heat and mass transfer coefficients become negative.

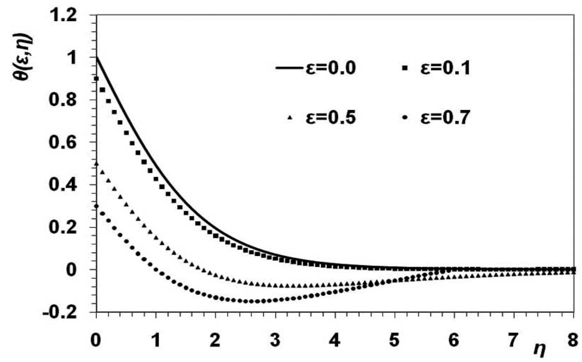

Fig. (3). Effects of stratification (ε= 0.0, 0.1, 0.5, 0.7) on temperature profiles of the non-Darcy flow at N=1, Fc=0.2, Le=1 and Sr=0.1.

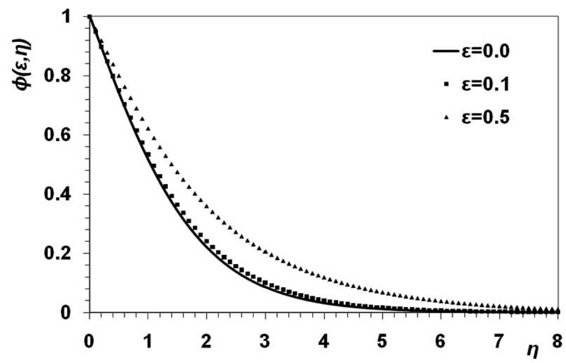

Fig. (4). Effects of stratification (ε=0.0, 0.1, 0.5) on concentration profiles of the non-Darcy flow at N=1, Fc=0.2, Le=1 and Sr=0.1.

The non-dimensional heat and mass transfer coefficients are plotted against the thermal stratification parameter in the Darcy and Forchheimer porous media in Figs. (**5** and **6**) respectively. It is clear that Nusselt and Sherwood numbers decrease with ε for all F_c. It is evident that the effect of F_c on the Nusselt and Sherwood numbers is more significant for small values of ε.

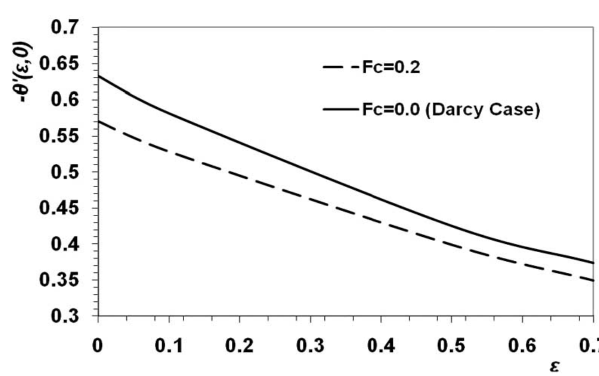

Fig. (5). Variations of Nusselt number against stratification parameter ε for various values of the parameter Fc at Sr=0.1, N=1 and Le=1.

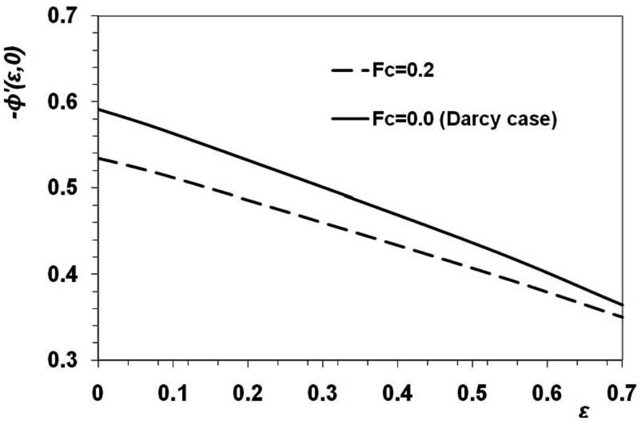

Fig. (6). Variations of Sherwood number against stratification parameter ε for various values of the parameter Fc at Sr=0.1, N=1 and Le=1.

In Figs. (**7-9**) the non-dimensional velocity, temperature and concentration profiles are plotted by varying ε and F_c for fixed S_r, N and Le. The velocity profile decreases with increasing F_c and ε. Also a decrease in the temperature is seen with ε, while it increases with F_c in the boundary layer. It is easy to understand that increasing the value of the thermal stratification parameter reduces the temperature difference between the vertical surface and ambient medium which causes reduction in the temperature distribution. The concentration profile increases with the non-Darcy parameter F_c and also with the stratification parameter ε in the boundary layer.

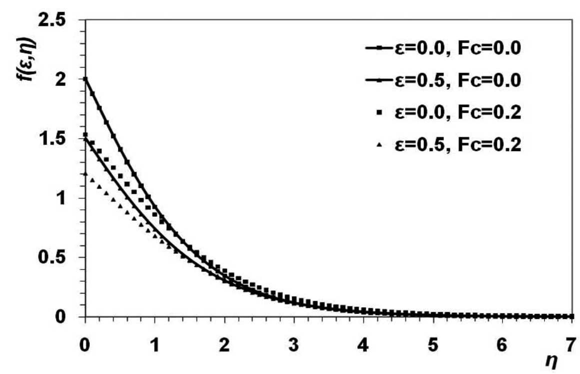

Fig. (7). Variations of velocity profiles for various values of parameters ε and Fc at Sr=0.1, N=1 and Le=1.

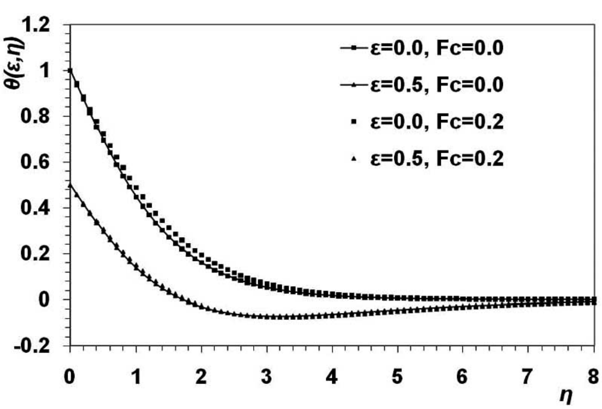

Fig. (8). Variations of temperature profiles for various values of parameters ε and Fc at Sr=0.1, N=1 and Le=1.

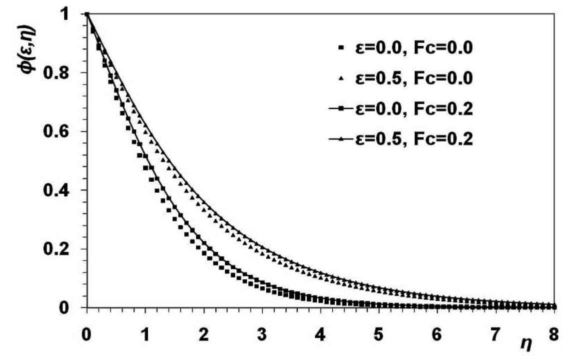

Fig. (9). Variations of concentration profiles for various values of parameters ε and Fc at Sr=0.1, N=1 and Le=1.

Figs. (**10-12**) depict variation of non-dimensional velocity, temperature and concentration profiles against the similarity variable η for different values of N and S_r. It is observed that the non-dimensional velocity increases, while temperature and concentration distributions decrease with the buoyancy parameter N. A raise in the velocity and concentration profiles is seen with increasing S_r for all values of N (<, =, > 0) in the boundary layer. On the other hand temperature profile decreases with the increasing S_r for aiding buoyancy while reverse phenomenon is noted in the case of opposing buoyancy. It is interesting to note that the non-dimensional concentration takes negative values for large negative value of $S_r(\leq -1)$ inside the boundary layer and finally it attains its outer edge boundary condition $\phi = 0$ as the value of η approaches the edge of the boundary layer.

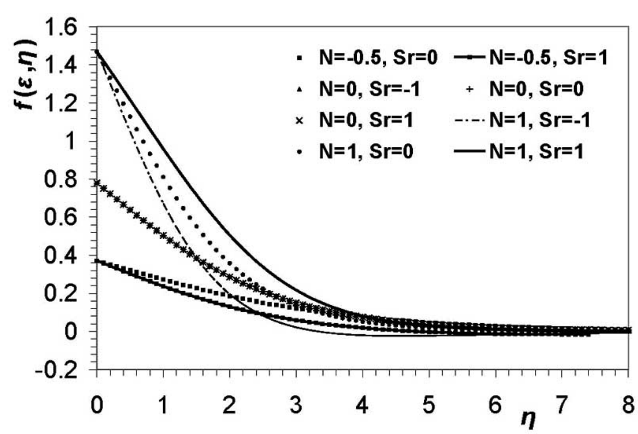

Fig. (10). Variations of velocity profiles for various values of parameters N and Sr at ε=0.1, Fc=0.2 and Le=1.

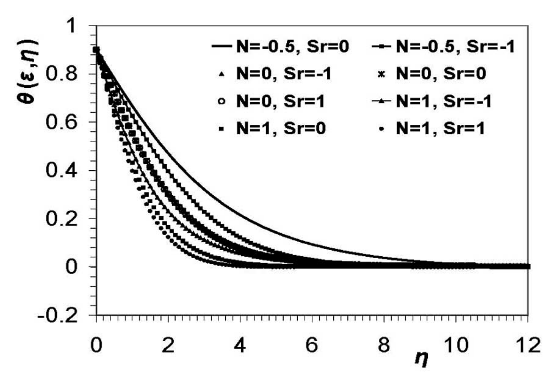

Fig. (11). Variations of temperature profiles for various values of parameters N and Sr at ε=0.1, Fc=0.2 and Le=1.

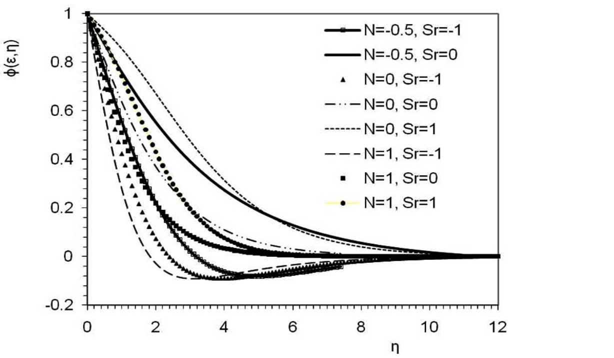

Fig. (12). Variations of concentration profiles for various values of parameters N and S_r at ε=0.1, Fc=0.2 and Le=1.

The effect of diffusivity ratio *Le* on the Nusselt and Sherwood numbers is shown in Figs. (**13** and **14**), respectively, with fixed ε and F_c. As *Le* increases the Nusselt number decreases in aiding buoyancy while it increases for opposing buoyancy. The Nusselt number increases with increasing S_r in aiding buoyancy while it decreases in case of opposing buoyancy, this is due to the variations in the thickness of the boundary layers. The Sherwood number increases with *Le* and decreases with S_r as increasing S_r increased concentration boundary layer thickness for all *N,* which is evident from the earlier figures, for both aiding and opposing buoyancies. Also the effect of S_r on the Sherwood number increases as the value of the buoyancy parameter increased. The impact of S_r on the Nusselt and Sherwood number is more significant for large values *Le*.

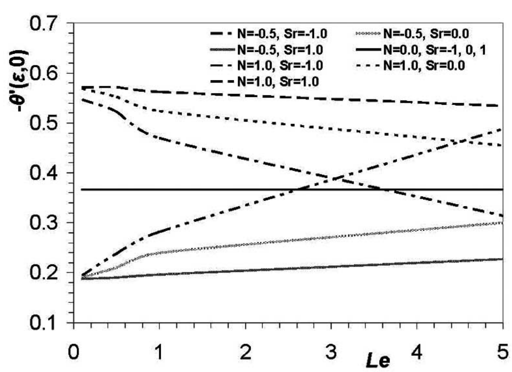

Fig. (13). Variations of Nusselt number against Le for various values of parameters N and Sr at ε=0.1 and Fc=0.2.

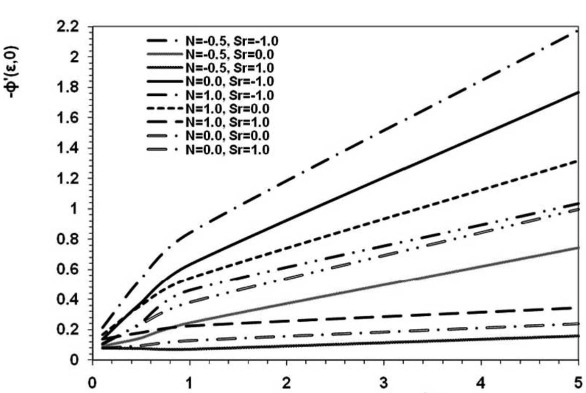

Fig. (14). Variations of Sherwood number against Le for various values of parameters N and Sr at ε=0.1 and Fc=0.2.

CONCLUSIONS

Thermo-diffusion effect on free convection heat and mass transfer from a vertical surface embedded in a thermally stratified non - Darcy porous medium has been analyzed using a local non-similar procedure. The wall temperature and concentration are constant and the medium is linearly stratified in the vertical direction with respect to the thermal conditions. Both the aiding and opposing buoyancies are considered for the analysis, non-dimensional velocity, temperature, concentration distribution and the heat and mass transfer coefficients are obtained for various values of flow influencing parameters. It is reported that the non-dimensional velocity f' and temperature θ decrease with increasing values of the stratification parameter ε. On the other hand the non-dimensional concentration increases with the value of ε. For relatively large values of $\varepsilon \geq 0.5$ the non-dimensional temperature attains negative values inside the boundary layer, afterwards it tends to zero as η approaches to the edge of the boundary layer. A raise in the velocity and concentration profiles is seen with the increasing values of S_r for all values of *N* (<, =, > 0) in the boundary layer. On the other hand temperature profile decreases with the increasing S_r for aiding buoyancy while reverse phenomenon is noted in the case of opposing buoyancy. It is interesting to note that the non-dimensional concentration takes negative values for large negative value of S_r ($\leq$-1) inside the boundary layer and finally it attains its outer edge boundary condition $\phi = 0$ as the value of η app-roaches the edge of the boundary layer. The Sherwood number increases with *Le* and decreases with S_r. The impact of S_r on the Nusselt and Sherwood numbers is more significant for large values *Le* in the thermally stratified medium.

NOMENCLATURE

c	Forchheimer constant
d	Pore diameter [m]
D	Solutal diffusivity [m^2/s]
D_1	Soret coefficient
ε	thermal stratification parameter which depends on the local coordinate x.
f	Dimensionless stream function
g	Acceleration due to gravity [m/s^2]
K	Permeability of the porous medium [m^2]
F_c	non-Darcy (inertia) parameter
N	Buoyancy ratio
Nu	Nusselt number
Sh	Sherwood number
S_r	Thermal-diffusion or Soret parameter
Le	Lewis number
T	Temperature
C	Concentration
x, y	Axial and normal co-ordinates [m]
u, v	Velocity components in x and y directions [m/s]

GREEK SYMBOLS

μ Viscosity [kg/(ms)]

ρ_∞ Reference density at some point [kg/m^3]

α Thermal diffusivity [m^2/s]

β_T Coefficient of thermal expansion [1/K]

β_c Coefficient of solutal expansion [1/K]

ψ Dimensionless stream function

η Similarity variable

θ Dimensionless temperature

ϕ Dimensionless concentration

$\theta_w = T_\infty - T_m$

$\phi_w = C_w - C_\infty$

SUBSCRIPTS

w, ∞ Conditions on the wall and at the ambient medium

ACKNOWLEDGEMENT

None declared.

CONFLICTS OF INTEREST

None declared.

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