ISSN 1749-3889 (print), 1749-3897 (online)
International Journal of Nonlinear Science
Vol.12(2011) No.3,pp.352-364

Influence of the Soret Effect and Double Dispersion on MHD Mixed Convection along a Vertical Flat Plate in Non-Darcy Porous Medium

P. A. Lakshmi Narayana[1] *, P. Sibanda[2]
[1]Department of Mathematics, Indian Institute of Technology, Hyderabad, Ordnance Factory Estate, Yeddumailaram - 502 205 India
[2] School of Mathematical Sciences, University of KwaZulu - Natal, Private Bag X01, Scottsville 3209 Pietermaritzburg, South Africa
(Received 6 June 2011, accepted 6 September 2011)

Abstract: Double diffusive mixed convection along a vertical flat plate in a fluid saturated non-Darcy porous medium is analyzed by considering the effects of a magnetic field, thermosolutal dispersions and the Soret parameter. The vertical wall is permeable and a similarity solution for this problem is presented when the fluid suction/injection velocity profile varies nonlinearly with the distance along the plate surface. The external flow field is assumed to be uniform, and the effect of the Soret parameter in the boundary layer adjacent to the vertical flat plate with fluid suction/injection through it is analyzed in both aiding and opposing flow situations. The non-dimensional heat and mass transfer coefficients are presented for selected values of the flow governing parameters.

Keywords: mixed convection; porous medium; Soret effect; double dispersion; heat and mass transfer

1 Introduction

Combined heat and mass transport in porous media is gaining attention due to its many interesting applications in engineering. The flow phenomenon in this case is relatively complex compared to that of pure thermal or solutal transport. Some examples of particular interest are the migration of moisture in fibrous insulation, the transport of contaminants in saturated soil, drying processes or solute transfer in the mushy layer during the solidification of binary alloys. Combined heat and mass transfer by free convection under the boundary layer approximation has been studied by Bejan and Khair [1], Lai and Kulacki [2], and Murthy and Singh [3]. Cheng [4] and Merkin [5] studied the effect of fluid injection or withdrawal on a free convection boundary layer adjacent to a heated vertical wall. These studies analyzed the convective movement of water discharged from a geothermal power plant into ground water of a different temperature and in natural recharging of an aquifer by groundwater of a different temperature. It was observed that the fluid suction reduced the thermal boundary-layer thickness while enhancing the heat transfer coefficient in the medium.

The inertial and viscous effects on mixed convection about a vertical surface have been studied by Ranganathan and Viskanta [6]. They showed that the effects of inertia and boundary friction are quite significant and cannot be ignored. Using the Forchheimer flow model, Nakayama and Pop [7], and Lai and Kulacki [8] studied the inertia effects on mixed convection along a vertical wall. The combined radiation and mixed convection from a vertical wall with suction/injection in a non-Darcy porous medium has been analyzed by Murthy et al. [9], and reported that fluid suction reduced the thickness of the thermal boundary-layer and enhanced the heat transfer coefficient into the medium whereas fluid injection increased the boundary-layer thickness and reduced the heat transfer in the medium. The effect of solutal and thermal dispersions in homogenous and isotropic Darcian porous media has been studied by Dagan [10]. A systematic derivation of the governing equations with various types of approximations used in application was presented. Using multiple scale analysis arguments, Telles and Trevisan [11] studied the double-dispersion phenomenon in a free convection boundary layer adjacent to a vertical wall in Darcian fluid-saturated porous medium. Depending on the relative magnitude of the dispersion coefficients, four classes of flow were identified and the heat and mass transfer has been analyzed. Murthy

*Corresponding author. *E-mail address*: ananth@iith.ac.in

IJNS.2011.12.15/549

[12] analyzed the effect of double dispersion on thermo-solutal convection along a vertical flat plate in a fluid saturated non-Darcy porous medium. It was reported that in the opposing flow case, the flow separation point depended on the inertial and the buoyancy ratio parameters. A review of recent works in this field is given by Nield and Bejan [13].

In double-diffusive (e.g., thermohaline) convection the coupling between temperature and solutal fields takes place because the density of the fluid mixture depends on both the temperature T and the concentration C (and also, in general, on the pressure P). In some circumstances there is direct coupling. This is when cross-diffusion (Soret and Dufour effects) is not negligible. The Soret effects refer to mass flux produced by a temperature gradient while the Dufour effects refer to heat flux produced by a concentration gradient. For the case of no heat and mass sources we have,

$$\begin{aligned}
\frac{(\rho c)_m}{(\rho c)_f}\frac{\partial T}{\partial t} + \mathbf{v}\cdot\nabla T &= \nabla\cdot(D_T\nabla T + D_{TC}\nabla C),\\
\varphi\frac{\partial C}{\partial t} + \mathbf{v}\cdot\nabla C &= \nabla\cdot(D_C\nabla C + D_{CT}\nabla T),
\end{aligned}$$

where $D_T(=k_m/(\rho c)_f)$ is the thermal diffusivity, $D_C(=D_m)$ is the mass diffusivity, D_{TC}/D_T is the Dufour coefficient, and $D_{CT}/D_C = S_r$ is the Soret coefficient of the porous medium. The Soret and Dufour effects are usually minor and can be neglected in simple models of coupled heat and mass transfer. According to Platten and Legros [14], the mass fraction gradient established under the effect of thermal diffusion is very small. Mojtabi and Charrier-Mojtabi [15] confirm this by noting that in liquids the Dufour coefficient is an order of magnitude smaller than the Soret effect. The thermodiffusion coefficient D_{TC} and the isothermal diffusion coefficient D_T were separately measured by Platten and Costeseque [16] for both a porous medium and the corresponding liquid clear of solid material.

Thermal-diffusion and diffusion-thermo effects on mixed free and forced convection in boundary layer flow in clear fluids with temperature dependent viscosity have been studied by Kafoussias and Williams [17] while El-Aziz [18] analyzed these effects on combined heat and mass transfer by hydromagnetic three-dimensional free convection over a permeable stretching surface with radiation. He showed that the maximum effect of the thermal-diffusion and diffusion-thermal on the velocity occurs in the absence of the magnetic field when the plate is impermeable. Chamkha and Ben-Nakhi [19] analyzed mixed convection along a permeable surface in the presence of magnetic effect along with Soret and Dufour effects. It was observed that the local Nusselt and Sherwood numbers decreased due to the presence of a magnetic field for the whole range of free and mixed convection regime while they remained constant for the forced convection regime. Elhajjar et al. [20] have studied the effect of the Soret parameter alone on the influence of vertical vibration on the separation of a binary mixture in a horizontal layer heated from below. The Soret effect on double-diffusive convection induced in a vertical porous layer, subject to horizontal heat and mass fluxes in the limit of boundary layer regime was investigated analytically and numerically by Er-Raki et al. [21]. It was reported that the Soret parameter had a strong effect on the vertical boundary layer thickness. The boundary layer thickness increased with the Soret parameter when the thermal and solutal buoyancy forces were cooperating ($N > 0$); however, the boundary layer thickness decreased with the Soret parameter when the thermal and solutal buoyancy forces opposed each other ($N < 0$). Recently Postelnicu [22] analyzed the effects of the Soret and Dufour parameters on free convection along a vertical flat plate in Darcy porous media and incorporating magnetic effects. They reported that large differences in the values of the Soret and Dufour parameters lead to a change in the sign of the non-dimensional heat and mass transfer coefficients.

In this paper we study the mixed convection heat and mass transfer along a vertical flat plate in a fluid saturated non-Darcy porous medium considering the Soret effect along with the thermal and solutal dispersions in the presence of the magnetic effect. The vertical wall is assumed to be permeable and a similarity solution is presented and the effects of the flow governing parameters are analyzed on the non-dimensional heat and mass transfer coefficients at the wall.

2 Governing equations

Consider the steady, laminar, two-dimensional double diffusive mixed convection due to double dispersion and the Soret effect on the boundary layer flow over a semi-infinite vertical flat plate embedded in a fluid saturated non-Darcy porous medium. The coordinate system is chosen such that x measures the distance along the plate and y measures the distance normal to it. The vertical wall is maintained at uniform wall temperature and concentration T_w and C_w which are greater than the ambient medium temperature and concentration T_∞ and C_∞ respectively. The thermo physical properties of the fluid are assumed to be constant except for density dependency of the buoyancy term in the momentum equation. The Boussinesq approximation is valid and the fluid and porous medium are in local thermodynamic equilibrium. Under these assumptions the boundary layer equations may be written as

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

$$\left(1+\frac{K\sigma\mu_e^2H_0^2}{\mu}\right)\frac{\partial u}{\partial y}+\frac{c\sqrt{K}}{\nu}\frac{\partial^2 u}{\partial y^2}=\pm\frac{Kg\beta_T}{\nu}\left\{\frac{\partial T}{\partial y}+\frac{\beta_C}{\beta_T}\frac{\partial C}{\partial y}\right\}, \tag{2}$$

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

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{\partial}{\partial y}\left(D_e\frac{\partial T}{\partial y}\right)+S_T\frac{\partial^2 T}{\partial y^2}, \tag{4}$$

with the boundary conditions;

$$y=0: \quad v=Ax^{-1/2},\ T=T_w(\text{const}),\ C=C_w(\text{const}), \tag{5}$$

$$y\to\infty: \quad u\to u_\infty,\ T=T_\infty,\ C=C_\infty. \tag{6}$$

Here u and v are the Darcian velocity components along the x- and y- directions, A is a constant, u_∞ is the free stream velocity, K is the permeability constant, g is the acceleration due to gravity and c is an empirical constant. T and C are temperature and concentration respectively and β_T is the coefficient of thermal expansion and β_C is the coefficient of solutal expansion. Here σ, μ_e and H_0 are electrical conductivity, magnetic permeability and magnetic field intensity respectively. The effective thermal and solutal diffusivities are represented by α_e and D_e respectively. The subscripts w and ∞ indicate the conditions at the wall and at the outer edge of the boundary layer, respectively.

Following Telles and Trevisan [11] the expressions for α_e and D_e can be written as $\alpha_e=\alpha+\gamma du$ and $D_e=D+\xi du$, where α and D are the molecular thermal and solutal diffusivities, respectively, $\gamma d\,u$ and $\xi d\,u$ represent the thermal and solutal dispersions in the medium respectively.

Using the following similarity transformations

$$\eta=\frac{y}{x}Pe_x^{1/2},\quad \psi=\alpha Pe_x^{1/2}f(\eta),\quad \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\quad \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}, \tag{7}$$

the governing partial differential equations reduce to the following ordinary differential equations

$$(1+M)f''+2F_cf'f''=\pm\frac{Ra}{Pe}(\theta'+N\phi'), \tag{8}$$

$$\theta''+Pe_\gamma(f''\theta'+f'\theta'')=-\frac{1}{2}f\theta', \tag{9}$$

$$\frac{1}{Le}\phi''+Pe_\gamma(f''\phi'+f'\phi'')+S_r\theta''=-\frac{1}{2}f\phi'. \tag{10}$$

The corresponding boundary conditions are

$$\eta=0: \quad f=f_w,\quad \theta=1,\quad \phi=1, \tag{11}$$

$$\eta\to\infty: \quad f'\to 1,\quad \theta\to 0,\quad \phi\to 0. \tag{12}$$

In the above equations, the non-dimensional parameters are the inertia parameter $F_c=c\sqrt{K}u_\infty/\nu$, the buoyancy ratio parameter $N=\beta_C\nabla C/\beta_T\nabla T$, the diffusivity ratio parameter $Le=\alpha/D$, the pore diameter-dependant Peclet number $Pe=u_\infty d/\alpha$, the pore diameter-dependant Rayleigh number $Ra=Kg\beta_T\nabla Td/\alpha\nu$, the magnetic parameter $M=K\sigma\mu_e^2H_0^2/\mu$ and the Soret parameter $S_r=S_T\nabla T/\alpha\nabla C$. The flow governing parameter Ra/Pe is independent of x. If $Ra/Pe=0$, then this represents forced convection flow. The flow asymptotically reaches the free convection flow in the limit as the parameter Ra/Pe tends to ∞. The mixed convection parameter Ra/Pe is positive when the buoyancy is aiding the external flow (aiding flow) and is negative when the buoyancy is opposing the external flow (opposing flow).

The parameters Pe_γ and Pe_ξ represent thermal and solutal dispersion parameters, respectively and these are defined as $Pe_\gamma=\gamma Pe$ and $Pe_\xi=\xi Pe$. The definition for the thermal dispersion in the media can be found in Lai and Kulacki [8], where the coefficient of the thermal dispersion have been assigned to the range $1/7$ to $1/3$. Gorla et al. [23], Hong and Tien [24], and Hong et al. [25] have made important contributions on the effect of thermal dispersion, treating it as a single parameter ($Ds=\gamma Pe$), as the value of γ depends on the experiment. The present study involves a similar representation for the thermal and solutal dispersion effects. Here $N > 0$ represents the aiding buoyancy and $N < 0$ represents the opposing buoyancy. The suction or injection parameter in its non-dimensional form is written as

$$f_w = -\frac{2x}{A\alpha} v_w(x) Pe_x^{-1/2}. \tag{13}$$

The case $f_w < 0$, represents the injection of fluid into the boundary layer through the vertical wall, and $f_w > 0$ represents the suction of fluid from the boundary layer. When $f_w = 0$ the wall is impermeable.

The non-dimensional heat and mass transfer coefficients, in terms of the Nusselt and Sherwood numbers in the presence of thermal and solutal dispersions can be written as

$$\frac{Nu_x}{Pe_x^{1/2}} = -[1 + Pe_\gamma\, f'(0)]\theta'(0), \tag{14}$$

$$\frac{Sh_x}{Pe_x^{1/2}} = -[1 + Pe_\xi\, f'(0)]\phi'(0). \tag{15}$$

3 Results and discussion

The set of ordinary differential equations (8) - (10), along with the boundary conditions are integrated by giving appropriate initial guess values for $f'(0)$, $\theta'(0)$ and $\phi'(0)$ to match the solutions with the corresponding boundary conditions at $f'(\infty)$, $\theta(\infty)$ and $\phi(\infty)$ using Newton-Raphson and fourth order Runge-Kutta methods. For numerical computation, the following ranges for the governing parameters have been considered, $0 \le F_c \le 1$, $0 \le M \le 1$, $0 < Le \le 30$, $-2 \le S_r \le 2$, $0 \le Pe_\gamma,\ Pe_\xi \le 3$, $-1 \le f_w \le 1$ and $0 \le Ra/Pe \le 30$.

Two values are given for the buoyancy ratio parameter, $N = 1$ for the aiding buoyancy case and $N = -0.5$ represent the opposing buoyancy. When $f_w = 0$, in the absence of the Soret and magnetic effects numerical results are given for this case in Tables 1 - 2. While the effect of magnetic parameter along with the Soret parameter on velocity, heat and mass transfer coefficients in both opposing and aiding flow cases are shown in Tables 3 - 4 respectively.

Table 1: Numerical results in the absence of the Soret effect and Magnetic effect in aiding flow. Here $Le = 1$, $M = 0$, $f_w = 0$, $Pe_\xi = 0$, $F_c = 1$ and $S_r = 0$.

	Ra/Pe		$Pe_\gamma = 0$	$Pe_\gamma = 1$
		f'	$\theta'(0)$	$\theta'(0)$
$N = -0.5$	0	1.0	0.564190	0.398942
		1.0	0.5641	
	1	1.158312	0.592235	0.490901
$N = 1.0$	0	1.0	0.564190	0.398942
	1	1.561553	0.660277	0.389174

Table 2: Numerical results in the absence of the Soret effect and Magnetic effect in opposing flow. Here $Le = 1$, $M = 0$, $f_w = 0$, $Pe_\gamma = 0$ and $F_c = 1$.

	Ra/Pe		$Pe_\xi = 0$	$Pe_\xi = 1$
		f'	$\phi'(0)$	$\phi'(0)$
$N = -0.5$	0	1.0	0.564190	0.398942
	1	1.158312	0.592235	0.388333
$N = 1.0$	0	1.0	0.564190	0.398942
	1	1.561552	0.660277	0.389174

3.1 Aiding flow

The variation of non-dimensional heat transfer coefficient is shown as functions of in Figure 1 for both opposing and aiding buoyancy ratio cases respectively.

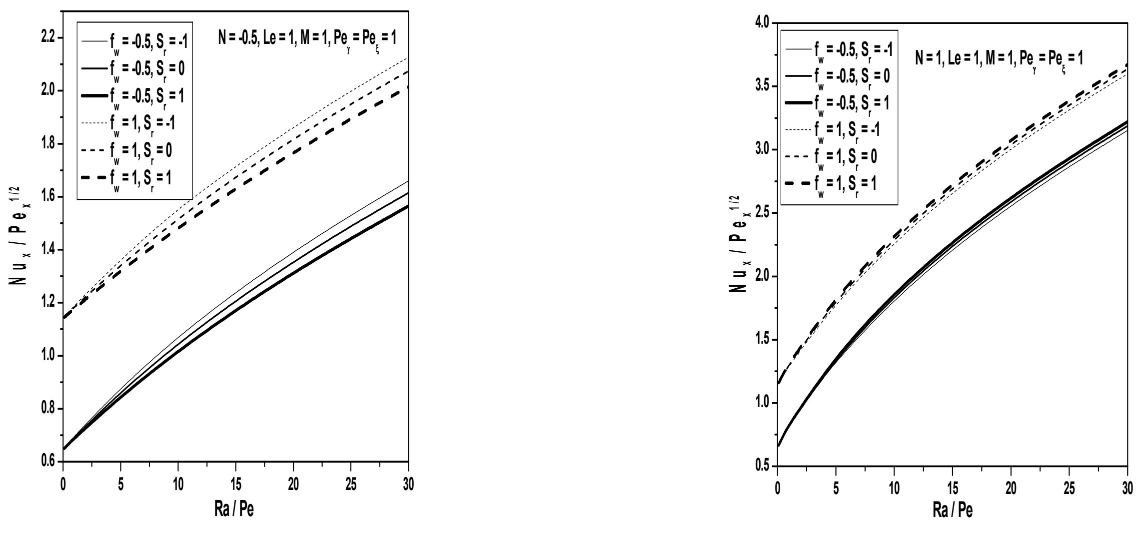
It is observed that when $f_w < 0$, the heat transfer coefficient is less than that when $f_w > 0$ for opposing and aiding buoyancy ratio cases. Increasing the Soret parameter reduced the heat transfer coefficient for opposing buoyancy ratio case while increase in the Soret parameter enhanced the heat transfer coefficient for aiding buoyancy ratio parameter. In both cases, the non-dimensional heat transfer coefficient increases with the mixed convection parameter Ra/Pe.

Table 3: Effect of the magnetic parameter along with the Soret parameter on velocity, heat and mass transfer coefficients in opposing flow. Here $Ra/Pe = 1$, $Le = 1$, $f_w = 0$, $Pe_\gamma = Pe_\xi = 1$ and $F_c = 1$.

M	S_r		$N=-0.5$			$N=1$	
		$f'(0)$	$Nu_x/Pe_x^{1/2}$	$Sh_x/Pe_x^{1/2}$	$f'(0)$	$Nu_x/Pe_x^{1/2}$	$Sh_x/Pe_x^{1/2}$
0.01	-2	0.823542	0.715823	1.103854	0.009805	0.559982	1.137760
	-1	0.823542	0.723817	0.920860	0.009805	0.502049	0.781892
	1	0.823542	0.739297	0.536300	0.009805	0.438239	0.212132
	2	0.823542	0.746803	0.334956	0.009805	0.401500	0.099272
0.5	-2	0.850781	0.728453	1.118277	0.280776	0.580251	1.059041
	-1	0.850781	0.735090	0.932461	0.280776	0.561295	0.788719
	1	0.850781	0.748033	0.545805	0.280776	0.520596	0.318338
	2	0.850781	0.754352	0.345092	0.280776	0.498660	0.120585
1	-2	0.870829	0.737778	1.128910	0.414213	0.613640	1.060538
	-1	0.870829	0.743446	0.941080	0.414213	0.598897	0.814221
	1	0.870829	0.754560	0.552829	0.414213	0.567893	0.369334
	2	0.870829	0.760010	0.352479	0.414213	0.551547	0.171725

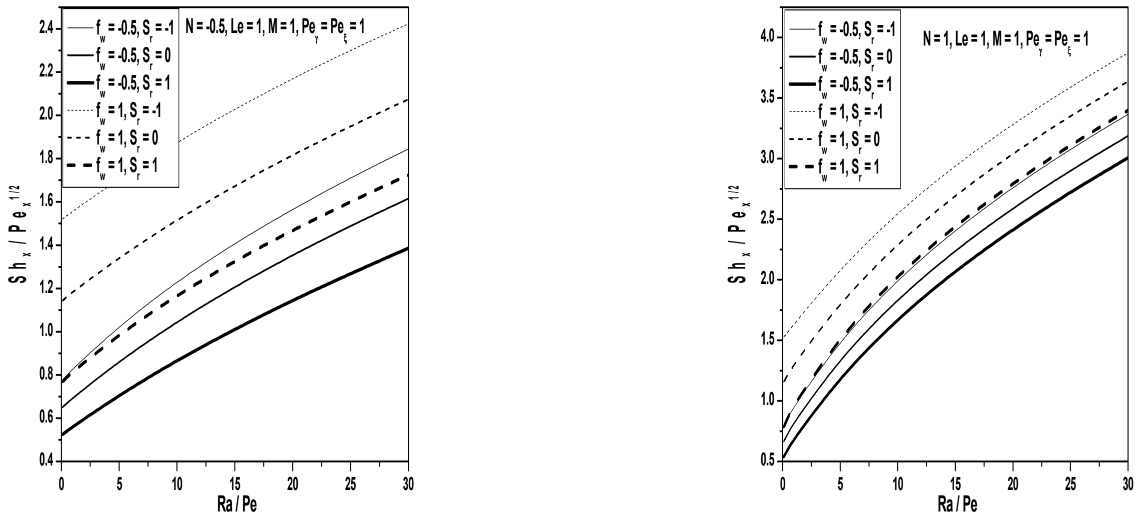
Table 4: Effect of the magnetic parameter along with the Soret parameter on velocity, heat and mass transfer coefficients in aiding flow. Here $Ra/Pe = 1$, $Le = 1$, $f_w = 0$, $Pe_\gamma = Pe_\xi = 1$ and $F_c = 1$.

M	S_r		$N=-0.5$			$N=1$	
		$f'(0)$	$Nu_x/Pe_x^{1/2}$	$Sh_x/Pe_x^{1/2}$	$f'(0)$	$Nu_x/Pe_x^{1/2}$	$Sh_x/Pe_x^{1/2}$
0.01	-2	1.157836	0.870648	1.277474	1.560194	0.999183	1.396143
	-1	1.157836	0.864714	1.066344	1.560194	1.008972	1.209531
	1	1.157836	0.852552	0.654522	1.560194	1.027764	0.823063
	2	1.157836	0.846312	0.453886	1.560194	1.036811	0.623288
0.5	-2	1.137459	0.861219	1.267072	1.499999	0.975911	1.371705
	-1	1.137459	0.855988	1.057318	1.499999	0.984774	1.184670
	1	1.137459	0.845314	0.647198	1.499999	1.001913	0.798049
	2	1.137459	0.839864	0.446872	1.499999	1.010207	0.598526
1	-2	1.121320	0.853770	1.258850	1.449489	0.956784	1.351861
	-1	1.121320	0.849110	1.050211	1.449489	0.964858	1.164297
	1	1.121320	0.839632	0.641424	1.449489	0.980534	0.777307
	2	1.121320	0.834809	0.441305	1.449489	0.988157	0.577936



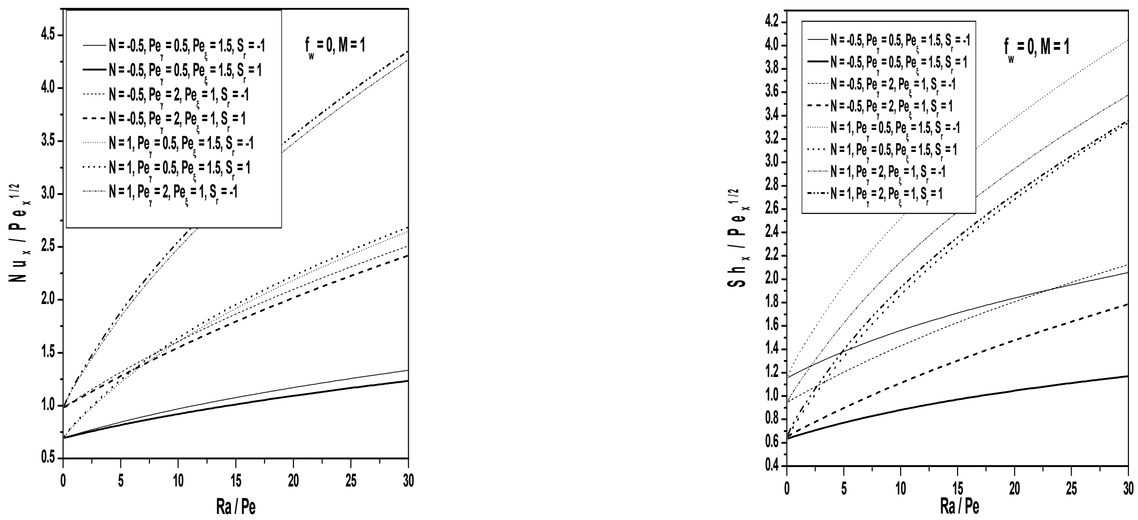
(a) (b)

Figure 1: Variation of non-dimensional heat transfer coefficient as a function of Ra/Pe for varying f_w and S_r: (a) opposing buoyancy and (b) aiding buoyancy.



(a) (b)

Figure 2: Variation of non-dimensional mass transfer coefficient as a function of Ra/Pe for varying f_w and S_r: (a) opposing buoyancy and (b) aiding buoyancy.

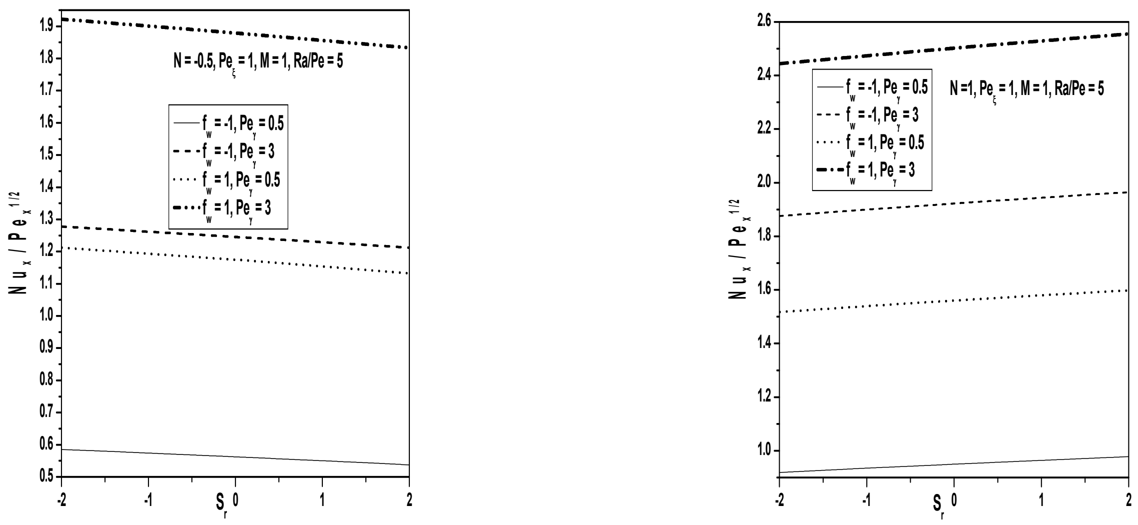


(a) (b)

Figure 3: Variation of (a) heat transfer coefficient, and (b) mass transfer coefficient as a function of Ra/Pe for varying N, Pe_γ, Pe_ξ and S_r.

In Figure 2 the variation of non-dimensional mass transfer coefficient is shown as a function of Ra/Pe for both the aiding and the opposing buoyancy ratio cases respectively. It is observed that the non-dimensional mass transfer coefficient when $f_w < 0$ is less than that obtained when $f_w > 0$. Increasing the Soret parameter reduced the mass transfer coefficient while increasing the mixed convection parameter enhanced the mass transfer coefficient in the medium for both aiding and opposing buoyancy ratio cases. From Figure 1-2 it is observed that increasing the value of f_w reduced the thermal/solutal boundary layers thickness and hence enhanced the heat/mass transfer coefficients at the wall.

The variation of the heat and mass transfer coefficients against the mixed convection parameter for varying thermal and solutal dispersion parameters along with the Soret parameter are plotted in Figure 3. From Figure 3(a) it is observed that in the opposing buoyancy ratio case, for both the cases $Pe_\gamma > Pe_\xi$ and $Pe_\gamma < Pe_\xi$, increasing the Soret parameter value reduced the heat transfer coefficient while increase in the Soret parameter enhanced the heat transfer coefficient in the aiding buoyancy case. For both buoyancy cases, when $Pe_\gamma > Pe_\xi$, the heat transfer coefficient is larger compared to when $Pe_\gamma < Pe_\xi$. The non-dimensional heat transfer coefficient increases with the increasing values of the parameter Ra/Pe.



(a) (b)

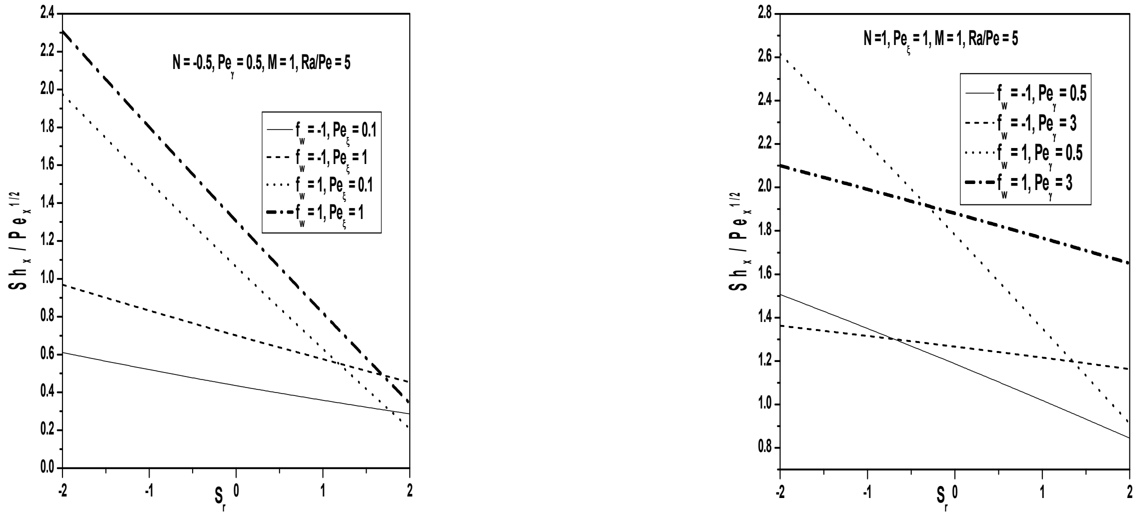
Figure 4: Effect of the Soret parameter in opposing buoyancy (a) heat transfer coefficient with varying f_w and Pe_γ and (b) mass transfer coefficient with varying f_w and Pe_ξ.

Similarly, from Figure 3(b), it is observed that in the opposing buoyancy case, when $Pe_\gamma > Pe_\xi$ and $Pe_\gamma < Pe_\xi$, the mass transfer coefficient increases with Ra/Pe while increasing the Soret parameter reduces the mass transfer coefficient. For the aiding buoyancy case, when $Pe_\gamma < Pe_\xi$ and $Pe_\gamma > Pe_\xi$, the mass transfer coefficient reduces with the Soret parameter.

Figure 4 shows the effect of the Soret parameter on the heat transfer coefficient for two different values of f_w and Pe_γ for fixed Pe_ξ in the opposing and aiding buoyancy ratio cases respectively. In the opposing buoyancy ratio case, increasing the value of the Soret parameter decreased the heat transfer coefficient while in the aiding buoyancy ratio case, the heat transfer coefficient at the wall increased with the value of the Soret parameter.

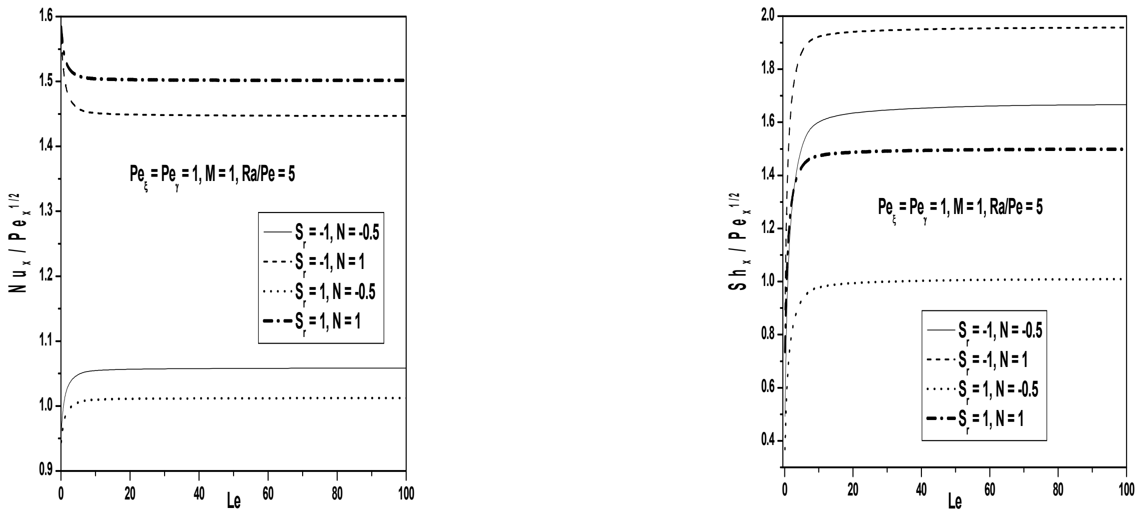
Figure 5 shows the effect of the Soret parameter on the mass transfer coefficient for two different values of f_w and Pe_ξ for fixed Pe_γ in opposing and aiding buoyancy ratios respectively. Increasing Pe_ξ enhanced the mass transfer coefficient in the opposing buoyancy ratio case. Increasing the Soret parameter value reduced the mass transfer coefficient in the medium while increasing the values of f_w and Pe_γ enhanced the heat transfer coefficient at the wall.

The variation of the heat and mass transfer coefficients are plotted as functions of the Lewis number in Figure 6, for both the negative and positive values of the buoyancy ratio parameter and the Soret parameter. From Figure 6(a), for the opposing buoyancy ratio parameter, increasing the Soret parameter reduces the heat transfer coefficient at the wall, while the heat transfer coefficient is increased with the diffusivity ratio parameter. For the aiding buoyancy ratio case, increasing the Soret parameter value enhanced the heat transfer coefficient while the heat transfer coefficient decreases



(a) (b)

Figure 5: Effect of the Soret parameter in aiding buoyancy (a) heat transfer coefficient with varying f_w and Pe_γ and (b) mass transfer coefficient with varying f_w and Pe_ξ.



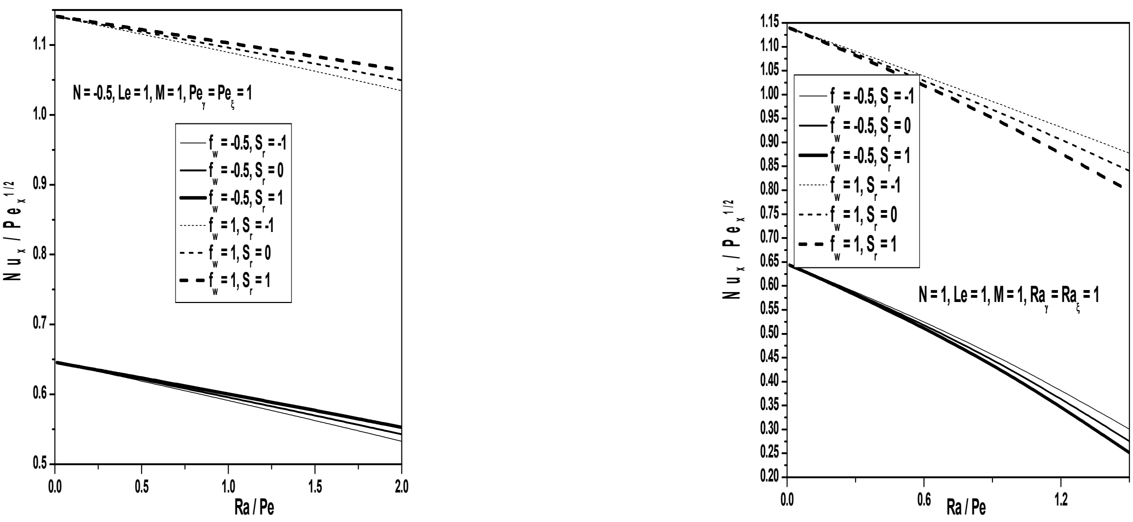
(a) (b)

Figure 6: Influence of the Lewis number on (a) heat transfer coefficient and (b) mass transfer coefficient with varying S_r and N.

with the diffusivity ratio parameter. It is interesting to note that beyond a certain value of the diffusivity ratio parameter, the distribution of the heat transfer coefficient at the wall is found to be uniform for increasing diffusivity ratio parameter in both the aiding and opposing buoyancy ratio cases. From Figure 6(b), the non-dimensional mass transfer coefficient is found to be increasing up to certain value of the diffusivity ratio parameter and beyond this critical value of the diffusivity ration parameter the distribution of the mass transfer coefficient is constant for higher values of the diffusivity ratio parameter. Increasing the Soret parameter reduced the mass transfer coefficient at the wall while increasing the value of the buoyancy ratio parameter enhanced the mass transfer coefficient.

3.2 Opposing flow

In Figure 7 the variation of the heat transfer coefficient is shown as a function of the mixed convection parameter Ra/Pe in opposing and aiding buoyancy ratio cases respectively. In the opposing buoyancy ratio case, Figure 7(a), it is seen that the heat transfer coefficient increases with increasing values of the Soret parameter for both blowing and suction. The heat transfer coefficient decreases with the mixed convection parameter.



(a) (b)

Figure 7: Variation of non-dimensional heat transfer coefficient as a function of Ra/Pe for varying f_w and S_r. (a) opposing buoyancy and (b) aiding buoyancy.

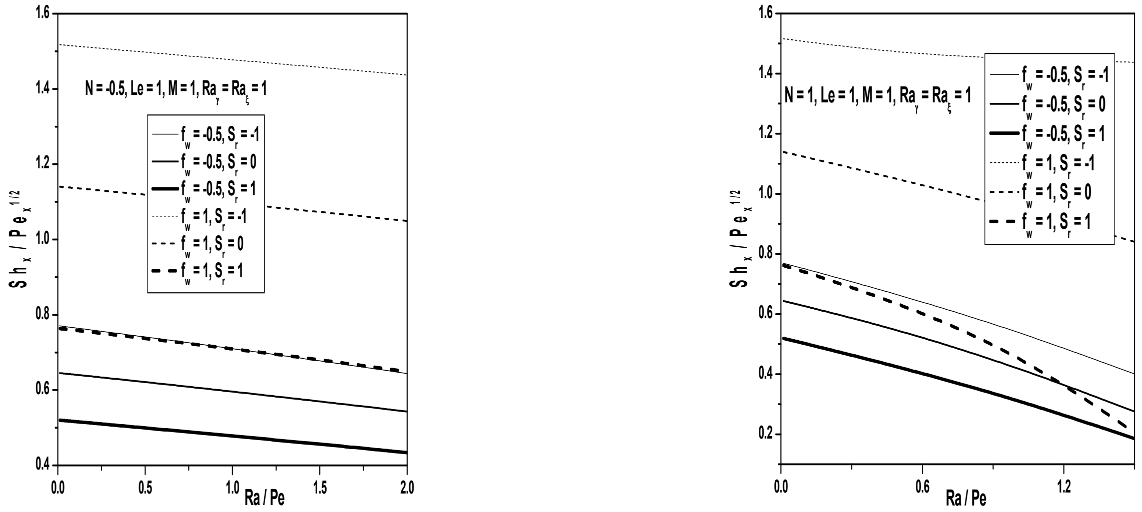
In Figure 7(b), for the aiding buoyancy ratio case, it is seen that the heat transfer coefficient decreases with increasing values of Ra/Pe while increasing the Soret parameter enhanced the heat transfer coefficient at the wall.

In Figure 8 the variation of mass transfer coefficient is shown as a function of the mixed convection parameter in the opposing and aiding buoyancy ratio cases respectively. The non-dimensional mass transfer coefficient decreases with the increasing value of the Soret parameter in the medium. The mass transfer coefficient also decreases with the mixed convection parameter for both the blowing and suction cases.

In Figure 9, the variation of the non-dimensional heat transfer coefficient is shown against the Soret parameter values in the opposing and aiding buoyancy ratio cases respectively. In Figure 9(a), it is observed that when $Pe_\gamma > Pe_\xi$ the heat transfer coefficient increases with the increasing values of the Soret parameter. When $f_w > 0$, the heat transfer coefficient is enhanced compared to the case when $f_w < 0$. Contrary to what has been observed in the opposing buoyancy ratio case, in the aiding buoyancy ratio case, Figure 9(b), the non-dimensional heat transfer coefficient decreases with increasing values of the Soret parameter.

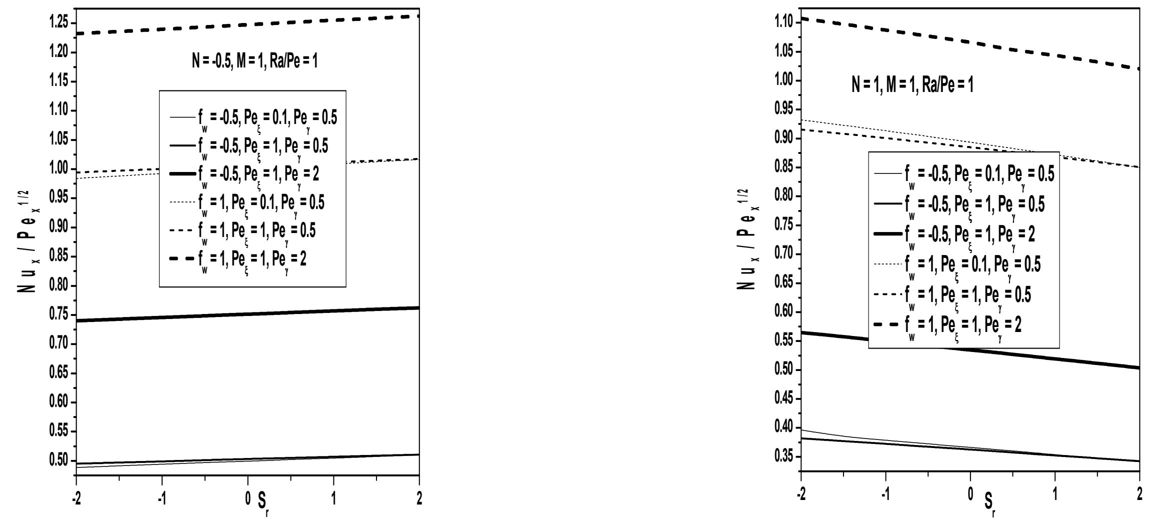
The non-dimensional mass transfer coefficient is shown in Figure 10 against the Soret parameter in the opposing and aiding buoyancy cases respectively.

From Figure 10(a) in the opposing buoyancy ratio case, the non-dimensional mass transfer coefficient at the wall is found to decrease with increasing values of the Soret parameter. For higher values of the Soret parameter, when the



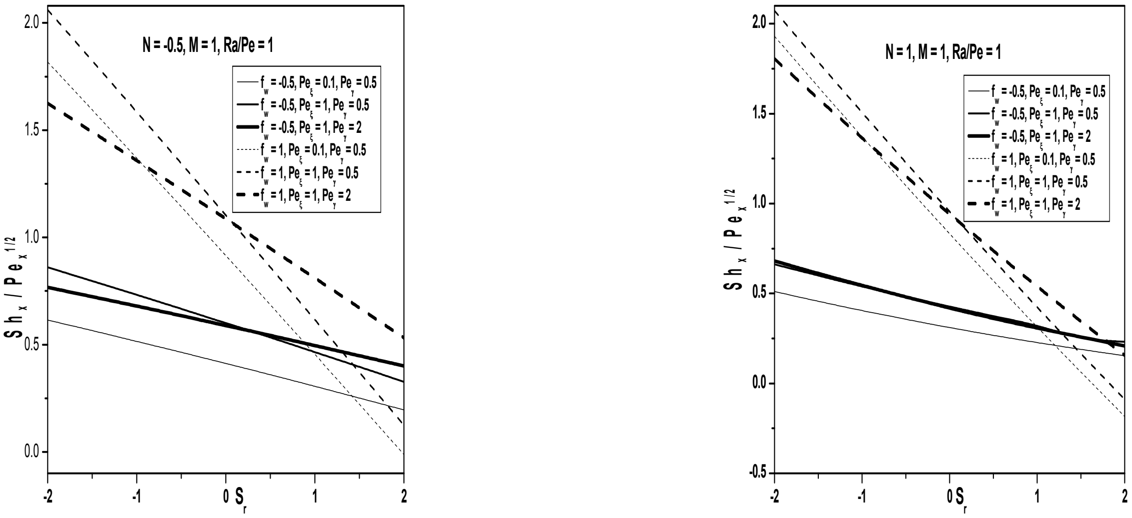
(a) (b)

Figure 8: Variation of non-dimensional mass transfer coefficient as a function of Ra/Pe for varying f_w and S_r; (a) opposing buoyancy and (b) aiding buoyancy



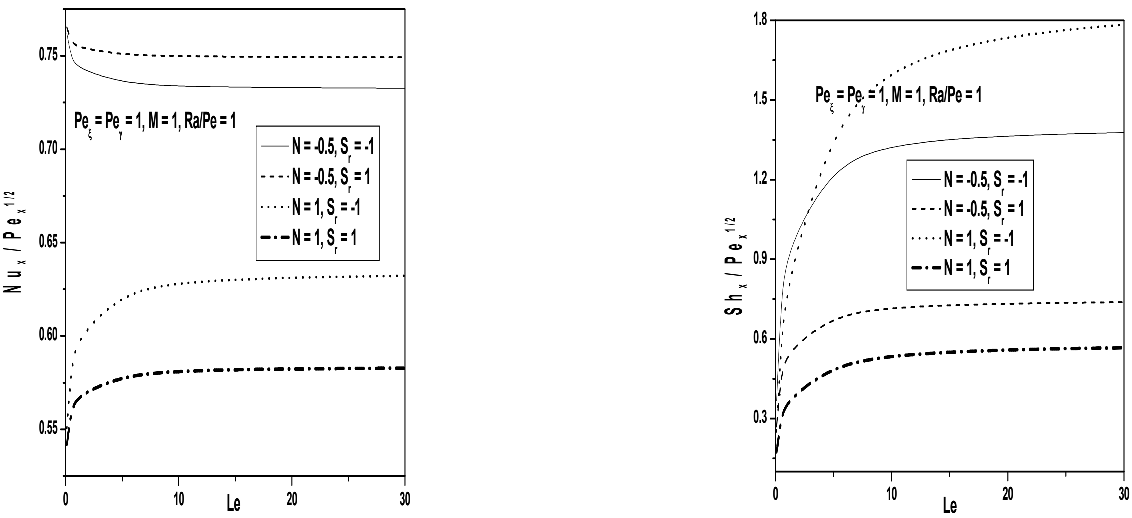
(a) (b)

Figure 9: Effect of the Soret parameter in opposing buoyancy (a) heat transfer coefficient with varying f_w and Pe_γ and (b) mass transfer coefficient with varying f_w and Pe_ξ.



(a) (b)

Figure 10: Effect of the Soret parameter in aiding buoyancy (a) heat transfer coefficient with varying f_w and Pe_γ and (b) mass transfer coefficient with varying f_w and Pe_ξ.



(a) (b)

Figure 11: Influence of the Lewis number on (a) heat transfer coefficient and (b) mass transfer coefficient with varying S_r and N.

Sherwood number is taking negative values and this trend can also be observed for the mass transfer coefficient if the Soret parameter is increased further in the medium. In the aiding buoyancy ratio case, Figure 10(b), it is found that the Sherwood number also takes negative values for large values of the Soret parameter. The Sherwood number decreases with the Soret parameter. In Figure 11, the variation of the non-dimensional heat and mass transfer coefficients respectively are plotted against the diffusivity ratio parameter. From Figure 11(a) we observe that the heat transfer coefficient in the opposing buoyancy ratio case decreases with the diffusivity ratio parameter while it increases with the diffusivity ratio parameter in the aiding buoyancy ratio parameter. In the opposing buoyancy case, the heat transfer coefficient at the wall is enhanced compared to the heat transfer coefficient at the wall in the aiding buoyancy. From Figure 11(b), it is observed that the mass transfer coefficient at the wall is enhanced with the diffusivity ratio parameter. In the opposing buoyancy case, mass transfer coefficient at the wall is larger compared to the heat transfer coefficient at the wall in aiding buoyancy.

4 Conclusion

Mixed convection along a permeable vertical wall in a fluid saturated non-Darcy porous medium is analyzed in the presence of magnetic effect, double dispersion and the Soret effect using similarity solution technique. Effects of the thermal and solutal dispersion parameters, magnetic parameter, diffusivity ratio parameter, buoyancy ratio parameter and the Soret parameter are analyzed on the non-dimensional heat and mass transfer coefficients in the medium in both aiding and opposing flows. In the aiding flow case, increasing the Soret parameter reduced the heat transfer coefficient for opposing buoyancy ratio case while increase in the Soret parameter enhanced the heat transfer coefficient for aiding buoyancy ratio parameter and increasing the Soret parameter reduced the mass transfer coefficient. In both cases, the non-dimensional heat and mass transfer coefficients increased with the mixed convection parameter Ra/Pe.

In the opposing flow case, increasing the Soret parameter enhanced the heat transfer coefficient in the opposing buoyancy wile a reduction in heat transfer coefficient was found with the increasing value of the Soret parameter for the aiding buoyancy, whereas increasing the value of the Soret parameter reduced the mass transfer coefficient in both aiding and opposing buoyancy cases. In the opposing flow case, for opposing buoyancy, increasing the value of the magnetic parameter enhanced the heat transfer coefficient in the medium while a reduction was observed in the mass transfer coefficient. In the aiding buoyancy case, increasing the magnetic parameter value reduced the heat and mass transfer coefficients at the wall. In the aiding flow, increasing the magnetic parameter value reduced the heat and mass transfer coefficients in the medium.

References

[1] A. Bejan, K.R. Khair. Heat and mass transfer by natural convection in a porous medium. *Int. J. Heat Mass Transfer*, 28(1985): 909-918.

[2] F.C. Lai, F.A. Kulacki. Non-Darcy mixed convection along a vertical wall in saturated porous media. *Trans ASME J. Heat Transfer*. 113(1991): 252-255.

[3] P.V.S.N. Murthy, P. Singh. Thermal dispersion effects in non-Darcy natural convection with lateral mass flux. *Heat Mass Transfer*, 33(1997): 1-5.

[4] P. Cheng. The influence of lateral mass flux on the free convection boundary layers in a saturated porous medium. *Int. J. Heat Mass Transfer*, 20(1977): 201-205.

[5] J.H. Merkin. Free convection with blowing and suction. *Trans ASME J. Heat Transfer*, 15(1972): 989-999.

[6] P. Ranganathan, R. Viskanta. Mixed convection boundary-layer flow along a vertical wall in saturated porous medium. *Num. Heat Transfer*, 7(1984): 305-317.

[7] A. Nakayama, I. Pop. A unified similarity transformation for free, forced, and mixed convection in Darcy and non-Darcy porous media. *Int. J. Heat Mass Transfer*, 34(1991): 357-367.

[8] F.C. Lai, F.A. Kulacki. Thermal dispersion effects on non-Darcy convection over horizontal surfaces in saturated porous media. *Int. J. Heat Mass Transfer*, 32(1989): 356-362.

[9] P.V.S.N. Murthy, S. Mukherjee, D. Srinivasacharya, P.V.S.S.S.R. Krishna. Combined radiation and mixed convection from a vertical wall with suction/injection in a non-Darcy porous medium. *Acta Mechanica*, 168(2004): 145-156.

[10] G. Dagan. Some accepts of heat and mass transport in porous media, Developments in soil science: Fundamentals of transport phenomena in porous media, International Association for Hydraulic Research, *Elsevier: London* (1972).

[11] R.S. Telles, O.V. Trevisan. Dispersion in heat and mass transfer natural convection along vertical boundaries in porous media. *Int. J. Heat Mass Transfer*, 36(1993): 1357-1365.

[12] P.V.S.N. Murthy. Effect of double dispersion on mixed convection heat and mass transfer in non-Darcy porous medium. *Trans ASME J. Heat Transfer*, 122(2000): 476-484.

[13] D.A. Nield, A. Bejan. Convection in Porous Media, 3rd Edition, *Springer* (2006).

[14] J.K. Platten, J.C. Legros. Convection in Liquids, *Springer: Berlin* (1984).

[15] A. Mojtabi, M.C. Charrier-Mojtabi: Double diffusive convection in porous media, *Handbook of Porous Media*, 2nd Edition (2005).

[16] J.K. Platten, P. Costeseque. The Soret coefficient in porous media. *Journal of Porous Media*, 7(2004)(4): 1-13.

[17] N.G. Kafoussias, E.W. Williams. Thermal-diffusion and diffusion-thermo effects on mixed free-forced convective and mass transfer boundary layer flow with temperature dependent viscosity. *Int. J. Engng. Sci.*, 33(1995): 1369-1384.

[18] M.A. El-Aziz. Thermal-diffusion and diffusion thermo effects on combined heat and mass transfer by hydromagnetic three-dimensional free convection over a permeable stretching surface with radiation. *Phys. Lett A*, 372(2008): 263-272.

[19] A.J. Chamkha, A. Ben-Nakhi. MHD mixed convection-radiation interaction along a permeable surface immersed in a porous medium in the presence of Soret and Dufour effects. *Heat Mass Transfer*, 44(2008): 845-856.

[20] B. Elhajjar, A. Mojtabi, M.C. Charrier-Mojtabi. Influence of vertical vibrations on the separation of a binary mixture in a horizontal porous layer heated from below. *Int. J. Heat Mass Transfer*, 52(2009)(1-2): 165-172.

[21] M. Er-Raki, M. Hasnaoui, A. Amahmid, M. Mamou. Soret effect on the boundary layer flow regime in a vertical porous enclosure subject to horizontal heat and mass fluxes. *Int. J. Heat Mass Transfer*, 49(2006): 3111-3120.

[22] A. Postelnicu. Influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects. *Int. J. Heat Mass Transfer*, 47(2004): 1467-1472.

[23] R.S.R. Gorla, A.Y. Bakier, L. Byrd. Effects of thermal dispersion and stratification on combined convection on a vertical surface embedded in a porous medium. *Transp. Porous Media*, 25(1996): 275-282.

[24] J.T. Hong, C.L. Tien. Analysis of thermal dispersion effect on vertical plate natural convection in porous meida. *Int. J. Heat Mass Transfer*, 30(1987): 143-150.

[25] J.T. Hong, Y. Yamada, C.L. Tien. Effect of non-Darcian and non-uniform porosity on vertical plate natural convection in porous media. *Trans ASME J. Heat Transfer*, 109(1987): 356-362.