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Soret and Dufour Effects on Natural Convection Flow Past a Vertical Surface in a Porous Medium with Variable Surface Temperature

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Abstract: Problem statement: In this research the researchers studied and made an analysis to the heat and mass transfer characteristics of natural convection about a vertical surface embedded in a saturated porous medium with surface temperature distribution proportional to x^{λ} by taking into account the diffusion-thermo (Dufour) and thermal-diffusion (Soret) effects. **Approach:** The governing partial differential equations were transformed into a set of coupled non-linear ordinary differential equations, which were solved numerically using the modified fourth order Runge-Kutta method along with Nachtsheim-Swigert shooting technique. **Results:** Numerical results were presented for the distribution of velocity, temperature and concentration profiles within the boundary layer. **Conclusion:** The effects of varying the parameter λ, the sustentation parameter, N, the Lewis number, Le, the Dufour number, Df and Soret number, Sc on the velocity, temperature and concentration profiles of thermally assisting flows and thermally opposing flows were examined.

Key words: Boundary layer, heat and mass transfer, natural convection, porous medium

INTRODUCTION

Coupled heat and mass transfer by natural convection in a fluid-saturated porous medium has received great attention during the last decades due to the importance of this process which occurs in many engineering, geophysical and natural systems of practical interest such geothermal energy utilization, thermal energy storage and recoverable systems, petroleum reservoirs, industrial and agricultural water distribution to name just a few applications. Recent books by Nield and Bejan[1] and Ingham and Pop[2,3] present a comprehensive account of the available information in the area of convective flow in porous media.

The effect of diffusion-thermo and thermal-diffusion of heat and mass has been developed from the kinetic theory of gases by Chapman and Cowling[4] and Hirshfelder *et al*.[5], explained the phenomena and derived the necessary formulae to calculate the thermal-diffusion coefficient and the thermal-diffusion factor for monatomic gases or for polyatomic gas mixtures, these effects have received rather little attention[6-13]. Kafoussias and Williams[14] studied the thermal-diffusion and the diffusion-thermo effects on the mixed free-forced convective and mass transfer steady laminar boundary layer flow, over a vertical flat plate, with temperature dependent viscosity. Alam and Rahman[15] studied the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction.

The range of free-convective flows that can occur in nature and in engineering practice is very large and has been extensively considered by Jaluria[16]. On the other hand, many flows are subjected to a combination of free and forced convection and are known as combined free-forced convective flows. In the bulk of heat and mass transfer over plates by natural, forced or combined convection, many studies involving theoretical or experimental investigations have been published in the literature and most of these studies are based upon the boundary layer approach[17-21]. The mixed free-forced convective and mass transfer flow is a comparatively recent development in the field of fluid mechanics and the different mathematical models and correlations which have been developed can be applied to many industrial applications, such as chemical or drying processes. Recently, Alam *et al*.[22] studied the Dufour and Soret effects on steady MHD combined free-forced convective and mass transfer flow past a semi-infinite vertical plate.

Postelnicu[23] studied the influence of a magnetic field on heat and mass transfer by natural convection from vertical surface embedded in an electrically conducting fluid saturated porous media considering Soret and Dufour effects with constant surface temperature and concentration.

In all of the above mentioned studies the surface temperature was assumed to be constant. The objective of this study is to investigate the heat and mass transfer by natural convection from vertical surface embedded in a fluid saturated porous media considering Soret and Dufour effects with variable surface temperature and constant concentration. Numerical calculations were out for different values of the various dimensionless parameters by using function programmed by a symbolic and computational computer language (Mathematica 7).

Mathematical formulation: Consider the problem of steady natural convection boundary layer from a heated vertical surface embedded in a porous medium of uniform ambient temperature T_∞ and uniform ambient concentration C_∞. The x-coordinate is measured along the plate from its leading edge and y-coordinate normal to it. We assume that Darcy-Boussinesq approximation holds, the temperature distribution of the heat varies as x^λ and constant wall concentration C_w.

The boundary layer equations governing the natural convection over a vertical surface embedded in a porous medium are, Nield and Bejan[1]:

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

$$u=\frac{g\,K}{\nu}\left[\beta_T(T-T_\infty)+\beta_C(C-C_\infty)\right] \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_m\frac{\partial^2 T}{\partial y^2}+\frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

Here:

u, v	= The velocity components along x, y coordinates respectively
ν	= The apparent kinematics viscosity
K	= Darcy permeability
g	= Gravitational acceleration
β_T	= The coefficient of thermal expansion
β_C	= The coefficient of expansion with concentration
T	= The temperature inside the boundary layer
α_m	= The thermal diffusivity
C_p and C_s	= The specific heat at constant pressure and concentration susceptibility
k_T	= The thermal diffusion ratio, C concentration of the fluid D_m mass diffusivity

The boundary conditions are given by:

$$\left.\begin{array}{l} y=0 \quad : \quad v=0\ ,\ T=T_w=T_\infty+A\,x^\lambda,\quad C=C_w \\ y\to\infty \ : \ u\to 0,\ \ T\to T_\infty,\quad C\to C_\infty \end{array}\right\} \tag{5}$$

The suitable similarity variables, for the problem under consideration, are:

$$\left.\begin{array}{l} \eta=\dfrac{y}{x}Ra_x^{1/2},\ \ \Psi=\alpha_m Ra_x^{1/2} f(\eta) \\ \theta(\eta)=\dfrac{T-T_\infty}{T_w-T_\infty}\ ,\ \ \varphi(\eta)=\dfrac{C-C_\infty}{C_w-C_\infty} \end{array}\right\} \tag{6}$$

where the stream function Ψ is defined in the usual way:

$$u=\frac{\partial\Psi}{\partial y},\qquad v=-\frac{\partial\Psi}{\partial x} \tag{7}$$

and $Ra_x=gK\beta_T(T_w-T_\infty)x/(\nu\alpha_m)$ is the local Rayleigh number. The governing system of equations become:

$$f'(\eta)-\theta(\eta)-N\phi(\eta)=0 \tag{8}$$

$$\theta''(\eta)+\frac{1+\lambda}{2}f(\eta)\theta'(\eta)-\lambda f'(\eta)\theta(\eta)+Df\phi''(\eta)=0 \tag{9}$$

$$\frac{1}{Le}\phi''(\eta)+\frac{1+\lambda}{2}f(\eta)\phi'(\eta)+Sr\theta''(\eta)=0 \tag{10}$$

where, Df, Le and Sr are Dufour, Lewis and Soret numbers, respectively:

$$\left.\begin{array}{l} Df=\dfrac{D_m k_T(C_w-C_\infty)}{C_s C_p\alpha_m(T_w-T_\infty)}\ ,\qquad Le=\dfrac{\alpha_m}{D_m} \\ Sr=\dfrac{D_m k_T(T_w-T_\infty)}{C_s C_p\alpha_m(C_w-C_\infty)} \end{array}\right\} \tag{11}$$

While N is the sustentation parameter:

$$N=\frac{\beta_c(C_w-C_\infty)}{\beta_T(T_w-T_\infty)} \tag{12}$$

This measures the relative importance of mass and thermal diffusion in the buoyancy-driven flow. We notice that it is positive for thermally assisting flows, negative for thermally opposing flows and zero for thermal-driven flows. Primes denote differentiation with respect to η.

The transformed boundary conditions are:

$$\left.\begin{array}{l} f(0)=0, \quad \theta(0)=1, \quad \phi(0)=1 \\ f'\to 0, \quad \theta\to 0, \quad \phi\to 0 \text{ as } \eta\to\infty \end{array}\right\} \qquad (13)$$

We notice that the problem reduces to that formulated by Bejan and Khair[24] when $\lambda = 0$, Df = 0 and Sr = 0. On the other hand, for $\lambda = 0$ our Eq. 8-10 subjected to the boundary conditions (13) reduce to Eq. 7-10 of Anghel *et al*.[25].

The parameters of engineering interest for the pressent problem are the local Nusselt number and local Sherwood number, which are given by the expressions:

$$Nu_x/Ra_x^{1/2} = -\theta'(0), \qquad Sh_x/Ra_x^{1/2} = -\phi'(0) \qquad (14)$$

MATERIALS AND METHODS

Numerical solution: The nonlinear ordinary differential Eq. 9 can be rewrite as:

$$\begin{array}{l} \theta''(\eta)+\dfrac{1+\lambda}{2}f(\eta)\theta'(\eta)-\lambda(\theta(\eta)+N\phi(\eta))\theta(\eta) \\ +Df\phi''(\eta)=0 \end{array} \qquad (15)$$

The set of nonlinear ordinary differential Eq. 8, 10 and 15 with boundary conditions (13) have been solved by using the modified fourth order Runge-Kutta method along with Nachtsheim-Swigert shooting technique[26]. The parameters involved in the present problem are λ, Df, Le, N and Sr. The computations were done by a program which uses a symbolic and computational computer language (Mathematica 7) on a Pentium 4 PC machine. A step size of $\Delta\eta = 0.001$ was selected to be satisfactory for a convergence criterion of 10^{-7} in nearly all cases. The value of η_∞ was found to each iteration loop by the assignment statement $\eta_\infty = \eta_\infty+\Delta\eta$. The maximum value of η_∞, to each group of parameters λ, Df, Le, N and Sr determined when the values of unknown boundary conditions at $\eta = 0$ not change to successful loop with error less than 10^{-7}.

To assess the accuracy of the present method, comparisons between the present results and previously published data[25], Table 1 shows the comparison between values of Nusselt number of $Nu_x/Ra_x^{1/2}$, also Table 2 shows the comparison between values of Sherwood number $Sh_x/Ra_x^{1/2}$. In fact, this results show a close agreement, hence an encouragement for further study of the effects of other varies of parameters on the continuous moving surface.

Table 1: Comparison between values of Nusselt number $Nu_x/Ra_x^{1/2}$

					Postelnich[26]		Present results	
λ	Le	N	Df	Sr	$Nu_x/Ra_x^{1/2}$		$Sh_x/Ra_x^{1/2}$	
0	1	1.0	0.050	1.2	0.67678	0.18354	0.676775	0.1835530
	1	1.0	0.075	0.8	0.65108	0.34150	0.651080	0.3415100
	1	1.0	0.030	2.0	0.71444	-0.13597	0.714438	-0.1395500
	1	1.0	0.037	1.6	0.69686	0.02339	0.696857	0.0234089
	1	1.0	0.600	0.1	0.42002	0.63313	0.420029	0.6331360
	1	0.2	0.150	0.4	0.46331	0.38100	0.463312	0.3810000
	1	0.5	0.075	0.8	0.55508	0.28764	0.555082	0.2876380
	1	0.8	0.030	2.0	0.67028	-0.13736	0.670281	-0.1373450
	1	-0.5	0.150	0.4	0.28512	0.23211	0.285118	0.2321040

Table 2: Comparison between values of Sherwood number $Sh_x/Ra_x^{1/2}$

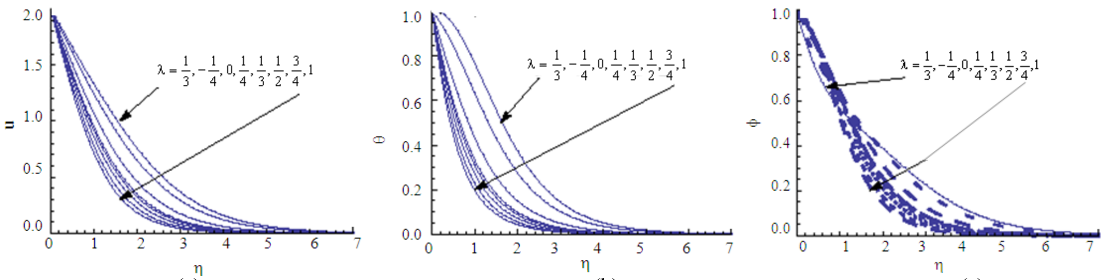
λ	Le	N	Df	Sr	Postelnich[26]	Present results
0	1	1.0	0.050	1.2	0.18354	0.1835530
	1	1.0	0.075	0.8	0.34150	0.3415100
	1	1.0	0.030	2.0	-0.13597	-0.1395500
	1	1.0	0.037	1.6	0.02339	0.0234089
	1	1.0	0.600	0.1	0.63313	0.6331360
	1	0.2	0.150	0.4	0.38100	0.3810000
	1	0.5	0.075	0.8	0.28764	0.2876380
	1	0.8	0.030	2.0	-0.13736	-0.1373450
	1	-0.5	0.150	0.4	0.23211	0.2321040

RESULTS

The group of parameters involved in the present problem is λ, Df, Le, N and Sr. Eq. 8, 10 and 15 with boundary conditions (13) are solved numerically for a range values of λ between $-\frac{1}{3}$ and 1, see Cheng and Mynkowycz[27], with considered three cases for the parameters Df, Le, N and Sr according to Anghel *et al*.[25].

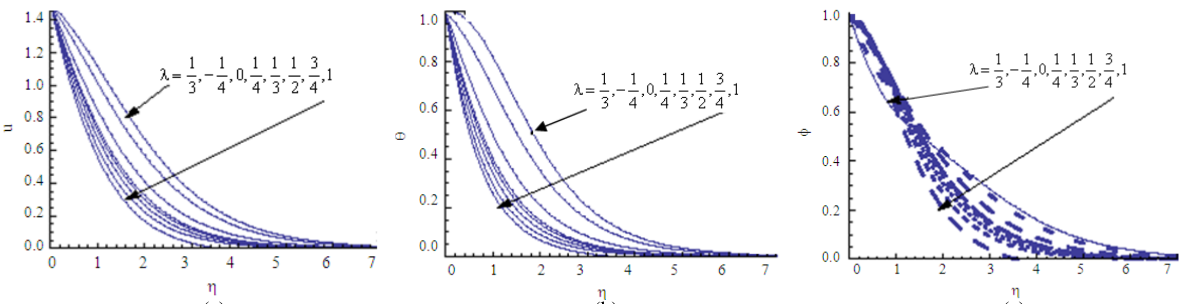
Case 1: Le = 1, N = 1, (Df, Sr) = ((0.05, 1.2), (0.075, 0.8), (0.03, 2.0), (0.037, 1.6), (0.6, 0.1))
Case 2: Le = 1, (N, Df, Sr) = ((0.2, 0.15, 0.4), (0.5, 0.07, 0.8) (0.8, 0.03, 2.0))
Case 3: Le = 1, (N, Df, Sr) = (-0.5, 0.15, 0.4)

Table 3-5 show local Nusselt and Sherwood numbers calculated for each set of parameters with different values of λ. Table 6 and 7 show local Nusselt and Sherwood numbers calculated for each set of parameters with different values of Le. Firstly, Fig. 1a-3a shows the velocity profiles of thermally assisting flows (N>0) and thermally opposing flows (N<0) showing the effect of parameter λ. Figure 1b-3b shows the temperature profiles of thermally assisting flows and thermally opposing flows showing the effect of parameter λ. Figure 1c-3c shows the concentration profiles of thermally assisting flows and thermally opposing flows showing the effect of parameter λ. Secondly, Fig. 4-6, show the velocity, temperature and concentration profiles of thermally assisting flows (N>0) for different values of Lewis number Le.



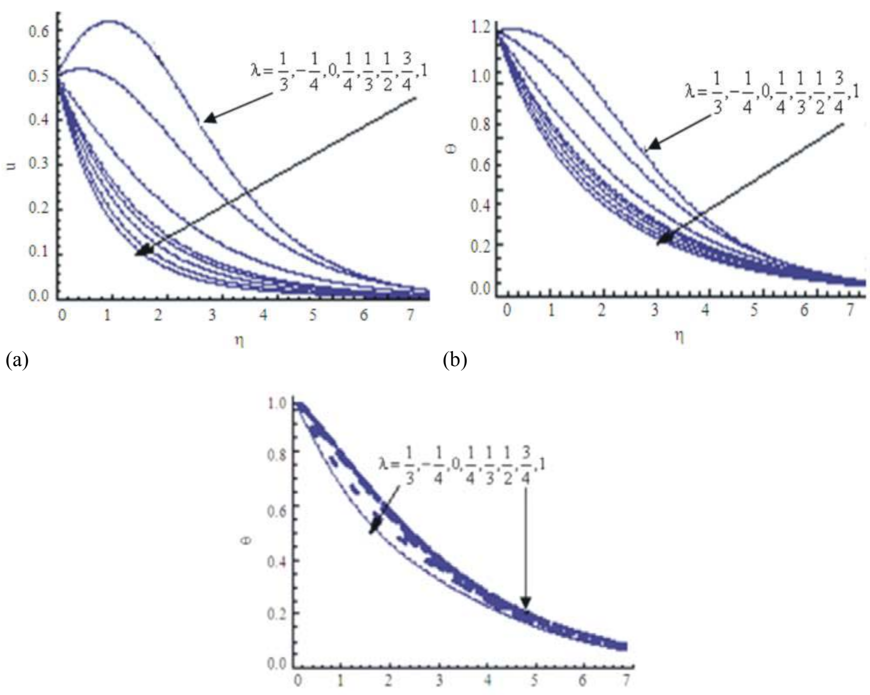
(a) (b) (c)

Fig. 1: Variation of (a): Velocity; (b): Temperature; (c): Concentration across the boundary layer of thermally assisting flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



(a) (b) (c)

Fig. 2: Variation of (a): Velocity; (b): Temperature; (c): Concentration across the boundary layer of thermally assisting flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



(c)

Fig. 3: Variation of (a): Velocity; (b): Temperature; (c): Concentration across the boundary layer of thermally opposing flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1

Table 3: Values of Nusselt and Sherwood numbers of thermally assisting flows with different λ, case 1

Le	N	Df	Sr	λ	$Nu_x/Ra_x^{1/2}$	$Sh_x/Ra_x^{1/2}$
1	1	0.050	1.2	-1/3	0.0387267	0.7745530
				-1/4	0.2131900	0.5557090
				0	0.6767750	0.1835530
				1/4	0.9841660	-0.0403589
				1/3	1.0702700	-0.1000990
				1/2	1.2265300	-0.2055350
				3/4	1.4319100	-0.3388940
				1	1.6129100	-0.4521800
1	1	0.075	0.8	-1/3	-0.0528302	0.7044130
				-1/4	0.1961330	0.5652780
				0	0.6510800	0.3415100
				1/4	0.9512780	0.2160260
				1/3	1.0352500	0.1837670
				1/2	1.1875200	0.1280660
				3/4	1.3875200	0.0597950
				1	1.5636800	0.0036080
1	1	0.030	2.0	-1/3	-0.0277762	0.9259020
				-1/4	0.2320570	0.5421450
				0	0.7144380	-0.1395500
				3/4	1.0360300	-0.5696930
1	1	0.037	1.6	-1/3	-0.0313778	0.8480720
				-1/4	0.2242060	0.5478600
				0	0.6968570	0.0234089
				1/4	1.0112600	-0.3018430
				1/3	1.0994000	-0.3898940
				1/2	1.2594200	-0.5465790
				3/4	1.4698400	-0.7470210
1	1	0.600	0.1	--1/3	-0.3717910	0.6196530
				-1/4	-0.0713946	0.6111160
				0	0.4200290	0.6331360
				1/4	0.7191560	0.6719060
				1/3	0.8006040	0.6856360
				1/2	0.9464710	0.7132920
				3/4	1.1351900	0.7543340
				1	1.2993600	0.7942170

Table 4: Values of Nusselt and Sherwood numbers of thermally assisting flows with different λ, case 2

Le	N	Df	Sr	λ	$Nu_x/Ra_x^{1/2}$	$Sh_x/Ra_x^{1/2}$
1	0.2	0.150	0.4	-1/3	-0.0775537	0.5170330
				-1/4	0.1226320	0.4571880
				0	0.4633120	0.3810000
				1/4	0.6801390	0.3508810
				1/3	0.7402940	0.3448040
				1/2	0.8490630	0.3360200
				3/4	0.9915070	0.3283020
				1	1.1167400	0.3245250
1	0.5	0.075	0.8	-1/3	-0.0463039	0.6174000
				-1/4	0.1698060	0.4891100
				0	0.5550820	0.2876380
				1/4	0.8067000	0.1760140
				1/3	0.8769600	0.1473790
				1/2	1.0043200	0.0979616
				3/4	1.1715600	0.0373954
				1	1.3188600	-0.0124785
1	0.8	0.030	2.0	-1/3	-0.0263140	0.8771640
				-1/4	0.2188500	0.5095610
				0	0.6702810	-0.1373450
				1/4	0.9703050	-0.5436770

Thirdly, Fig. 7-9, show the velocity, temperature and concentration profiles of thermally opposing flows (N>0) for the different values of Lewis number Le.

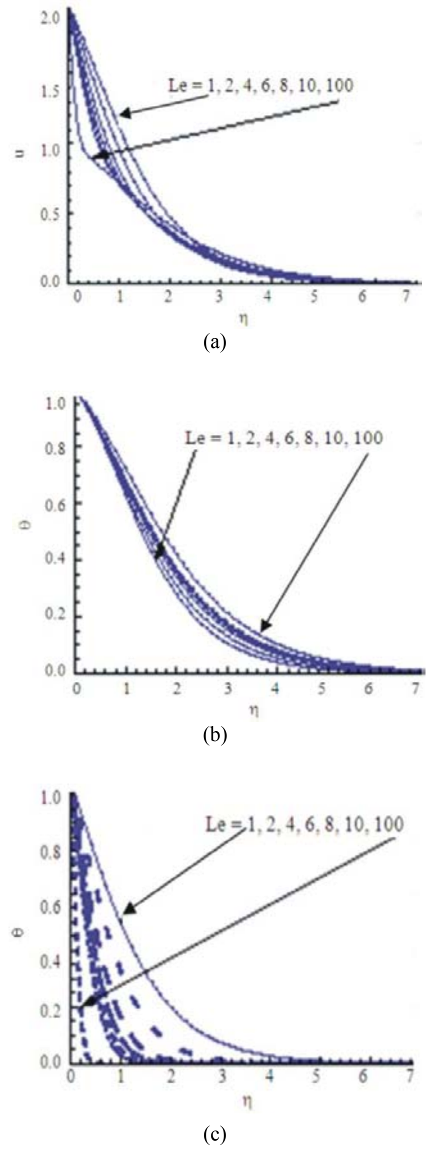
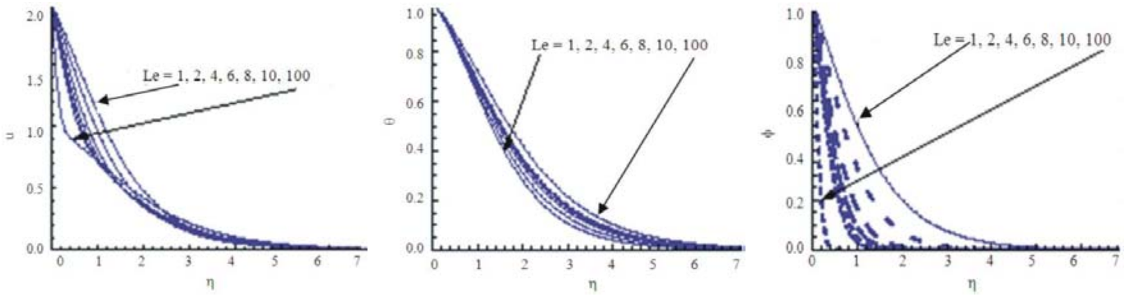


Fig. 4: Variation of (a): Velocity; (b): Temperature; (c): Concentration across the boundary layer of thermally assisting flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1

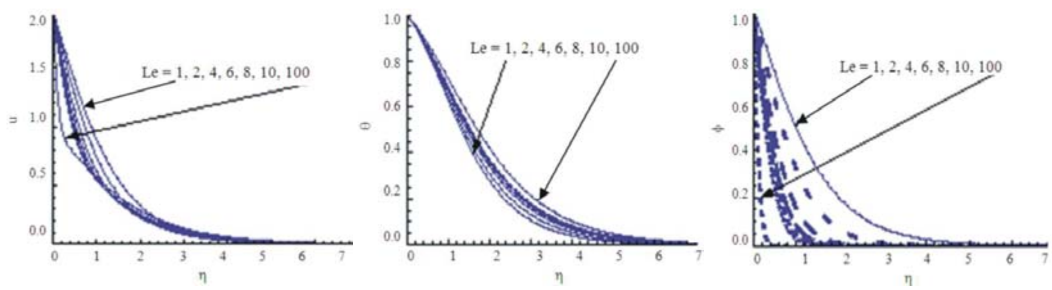
Table 5: Values of Nusselt and Sherwood numbers of thermally opposing flows with different λ, case 3

Le	N	Df	Sr	λ	$Nu_x/Ra_x^{1/2}$	$Sh_x/Ra_x^{1/2}$
1	-0.5	0.15	0.4	-1/3	-0.0567801	0.378547
				-1/4	0.0852667	0.313748
				0	0.2851181	0.232104
				1/4	0.3991220	0.196525
				1/3	0.4300250	0.188493
				1/2	0.4855180	0.175699
				3/4	0.5578240	0.161866
				1	0.6213190	0.151995



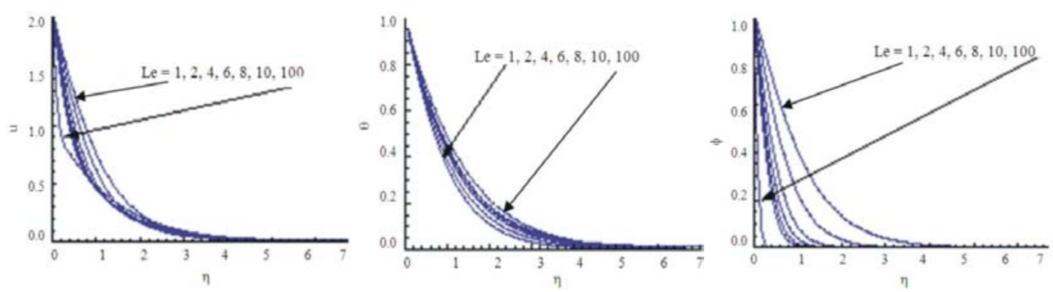
(a) (b) (c)

Fig. 5: Variation of (a) velocity, (b) temperature, (c) concentration across the boundary layer of thermally assisting flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



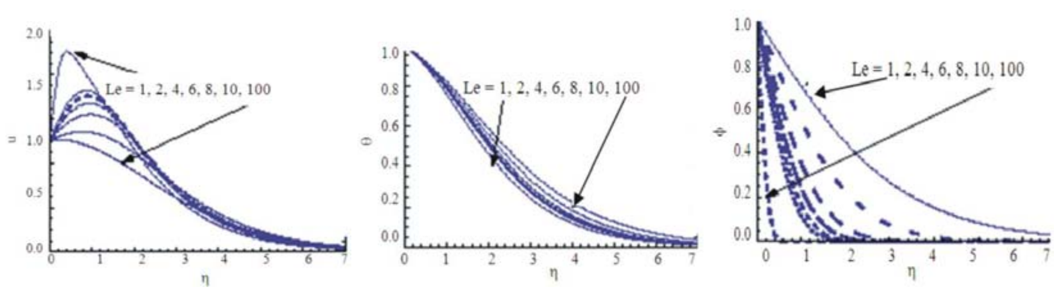
(a) (b) (c)

Fig. 6: Variation of (a): Velocity; (b): Temperature; (c): concentration across the boundary layer of thermally assisting flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



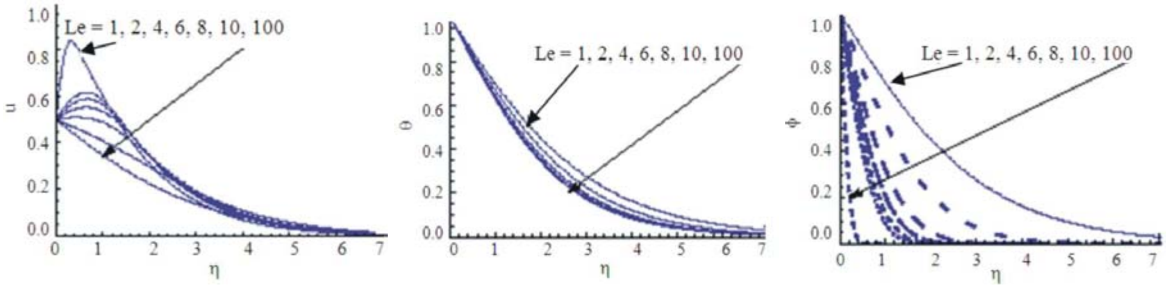
(a) (b) (c)

Fig. 7: Variation of (a) velocity, (b) temperature, (c) concentration across the boundary layer of thermally opposing flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



(a) (b) (c)

Fig. 8: Variation of (a) velocity, (b) temperature, (c) concentration across the boundary layer of thermally opposing flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1



(a) (b) (c)

Fig. 9: Variation of; (a): Velocity; (b): Temperature; (c): Concentration across the boundary layer of thermally opposing flows N = 1, Df = 0.075, Sr = 0.8 and Le = 1

Table 6: Values of Nusselt and Sherwood numbers of thermally assisting flows with different Le number

Le	N	Df	Sr	λ	$Nu_x/Ra_x^{1/2}$	$Sh_x/Ra_x^{1/2}$
1	1	0	0	-1/4	0.219543	0.563420
2					0.204821	0.829150
4					0.192031	1.202460
6					0.186000	1.486920
8					0.182385	1.725870
10					0.179935	1.935930
100					0.166819	6.213210
1	1	0	0	0	0.627556	0.627556
2					0.592601	0.929544
4					0.558504	1.357470
6					0.540770	1.684710
8					0.529445	1.959950
10					0.521401	2.202080
100					0.470035	7.139130
1	1	0	0	1/4	0.899681	0.690194
2					0.854011	1.024960
4					0.807143	1.501490
6					0.781763	1.866630
8					0.761763	2.173980
10					0.753159	2.444450
100					0.671904	7.963470

Table 7: Values of Nusselt and Sherwood numbers of thermally opposing flows with different Le number

Le	N	Df	Sr	λ	$Nu_x/Ra_x^{1/2}$	$Sh_x/Ra_x^{1/2}$
1	-0.5	0	0	-1/4	0.124145	0.311507
2					0.135541	0.491798
4					1436920	0.736505
6					0.147301	0.921330
8					0.149436	1.076180
10					0.150879	1.212150
100					0.158813	3.974150
1	-0.5	0	0	0	0.313779	0.313779
2					0.342967	0.515377
4					0.366566	0.792139
6					0.378243	1.002740
8					0.385638	1.179790
10					0.390891	1.335560
100					0.425197	4.517090
1	-0.5	0	0	1/4	0.429340	0.327759
2					0.469188	0.550290
4					0.502777	0.856957
6					0.519998	1.091000
8					0.531142	1.288040
10					0.539176	1.461550
100					0.594393	5.014220

DISCUSSION

Now, we discuss the result. In Table 3-5, One can readily remark that for fixed Df, Le, N and Sr, Nusselt number increases as λ increase while Sherwood number decreases as λ increase.

Table 6 shows the effect of Lewis number on Nusselt and Sherwood numbers for thermally assisting flows while keeping the others parameters constant. Note that, the Nusselt number decreases with increases of Lewis number whereas the Sherwood number increases monotonically with Lewis number.

Also, Table 7 shows the effect of Lewis number on Nusselt and Sherwood numbers for thermally opposing flows while keeping the other parameters constant. Note that, the Nusselt number and Sherwood number increase monotonically with Lewis number.

In Postelnicu[23], there exists a written mistake in Eq. 8 implies to an error in the plot of Fig. 1a-3a of variations of velocity. The error takes place in sign not in value.

Firstly, in Fig. 1a-3a can be seen that the velocity increases monotonically with absolute values of λ<0 and decreases with increase in λ>0. The velocity at the plate increases monotonically with N. As for absolute values of λ<0 the thermally opposing flows, the velocity reaches a maximum and then decays to zero. As the absolute values of λ<0 increase, the location of the maximum value of the velocity moves away from the surface.

In Fig. 1b-3b can be seen that the temperature increases monotonically with absolute values of λ<0 and decreases with increase in λ>0. The thickness of the thermal boundary layer increases with thermally opposing flows than with thermally assisting flows.

In Fig. 1c-3c can be seen that concentration of thermally opposing flows increases monotonically with λ>0 and decreases with increase in absolute values of λ<0. As for thermally assisting flows, there exist two points of accumulation of concentration curves. The first takes place in λ>0 and the second takes place in λ<0. The thickness of the concentration boundary Layer increases with thermally opposing flows than with thermally assisting flows.

Secondly, in Fig. 4-6 is remarked that the thickness of the hydrodynamic/ thermal/concentration increases with $\lambda<0$ than the thickness with $\lambda>0$.

Thirdly, in Fig. 7-9, the velocity of the thermally opposing flows reaches a maximum and then decays to zero. Increasing values of Le move the location of the maximum value of the velocity away from the surface.

CONCLUSION

The heat and mass transfer by natural convection from vertical surface embedded in a fluid saturated porous media considering Soret and Dufour effects with variable surface temperature and constant concentration is studied. The variable surface temperature serves to introduce one extra parameter into the problem, namely λ. The effects of the parameter λ, the sustentation parameter, N, the Lewis number, Le, the Dufour number, Df and Soret number, Sc on the velocity, temperature and concentration profiles of thermally assisting flows and thermally opposing flows are examined. In general, the effects of the parameter λ are clear on the velocity, temperature and concentration profiles of thermally assisting flows and thermally opposing flows in Table 3-7 and Fig. 1-9.

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