Soret and Dufour Effects on Natural Convection Heat and Mass Transfer Flow past a Horizontal Surface in a Porous Medium with Variable Viscosity

M. B. K. MOORTHY
Department of Mathematics
Institute of Road and Transport Technology
Erode -638316, Tamilnadu
INDIA.

T. KANNAN and K. SENTHILVADIVU
Department of Mathematics,
K.S.Rangasamy College of Technology,
Tiruchengode -637215, Tamilnadu
INDIA
E-mail:tkannanmat@gmail.com

Abstract: - The heat and mass transfer characteristics of natural convection about a horizontal surface embedded in a saturated porous medium subject to variable viscosity are numerically analyzed, by taking into account the diffusion-thermo (Dufour) and thermal-diffusion (Soret) effects. The governing equations of continuity, momentum, energy and concentration are transformed into non- linear ordinary differential equations, using similarity transformations and then solved by using Runge-Kutta-Gill method along with shooting technique. The governing parameters of the problem are variable viscosity (θ_c), buoyancy ratio (N), Lewis number (Le), Prandtl number (Pr), Dufour number, Soret number and Schmidt number. The velocity, temperature and concentration distributions are presented graphically. The Nusselt number and Sherwood number are also derived and discussed numerically.

Key-Words: - Heat and Mass transfer, Natural convection, Variable viscosity, Dufour and Soret effects.

1 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 as geothermal energy utilization, thermal energy storage and recoverable systems and petroleum reservoirs. A comprehensive account of the available information in this field is provided in recent books by Pop and Ingham [11], Ingham and Pop [12] and Vafai [13].

The previous studies, dealing with the transport phenomena of momentum and heat transfer, have dealt with one component phases which posses a natural tendency to reach equilibrium conditions. However, there are activities, especially in industrial and chemical engineering processes, where a system contains two or more components whose concentrations vary from point to point. In such a system there is a natural tendency for mass to be transferred, minimizing the concentration differences within the system and the transport of one constituent, from a region of higher concentration to that of a lower concentration. This is called mass transfer.

When heat and mass transfer occurs simultaneously between the fluxes, the driving potential is of more intricate nature, as energy flux can be generated not only by temperature gradients but by composition gradients as well. The energy flux caused by a composition gradient is called the Dufour or diffusion-thermo effect. Temperature gradients can also create mass fluxes, and this is the Soret or thermal-diffusion effect. Generally, the thermal-diffusion and the diffusion-thermo effects are of smaller order magnitude than the effects prescribed by Fourier's or Fick's laws and are often neglected in heat and mass transfer processes. There are, however, exceptions. The Soret effect, for instance, has been utilized for isotope separation, and in mixtures between gases with very light molecular weight (H2, He).For medium molecular weight (N2, air), the Dufour effect was found to be of a considerable magnitude such that it cannot be neglected (Eckert and Drake) [1].

Kassoy and Zebib [2] studied the effect of variable viscosity on the onset of convection in porous medium. Cheng and Minkowycz [3] studied the effect of free convection about a vertical plate embedded in a porous medium with application to heat transfer from a dike. Chang and Cheng [4] studied the matched asymptotic expansion for free convection about an impermeable horizontal surface in a porous medium. Bejan and Khair [5] studied the buoyancy induced heat and mass transfer from a vertical plate embedded in a saturated porous medium. Rami. Y. Jumah et al. [7] studied the coupled heat and mass transfer for non-Newtonian fluids. Anghel et al [8] investigated the Dufour and Soret effects on free convection boundary layer over a vertical surface embedded in a porous medium. Kumari [9] analyzed the effect of variable viscosity on free and mixed convection boundary layer flow from a horizontal surface in a saturated porous medium. Postelnicu et al. [10] investigated the effect of variable viscosity on forced convection over a horizontal flat plate in a porous medium with internal heat generation. Seddeek [14, 15] studied the effects of chemical reaction, variable viscosity, and thermal diffusivity on mixed convection heat and mass transfer through porous media. Mohamed E- Ali [16] studied the effect of variable viscosity on mixed convection along a vertical plate. Alam et al [17] analyzed the study of the combined free - forced convection and mass transfer flow past a vertical porous plate in a porous medium with heat generation and thermal diffusion. Pantokratoras [18] analyzed the effect of variable viscosity with constant wall temperature. Partha et al [19] analyzed Soret and Dufour effects in non-Darcy porous medium. Alam and Rahman [20] studied the Dufour and Soret effects on mixed convective flow past a vertical porous plate with variable suction. Seddeek et al [21] studied the effects of chemical reaction and variable viscosity on hydro magnetic mixed convection heat and mass transfer through porous media. Another contribution to the theme of Dufour and Soret effects can be found in the paper by Afify [22], where there is a non-Darcy free convection past a vertical surface with temperature viscosity. Lakshmi Narayana and Murthy [23] studied the Soret and Dufour effects on free convection heat and mass transfer from a horizontal flat plate in a Darcy porous medium. Postelnicu [24] studied the influence of chemical reaction along with Soret and Dufour effects in the absence of magnetic field on free convection. Bansod and Jadhav [25] studied an integral treatment for combined heat and mass transfer by natural convection along a horizontal surface in a porous medium. El-Arabawy [26] studied the Soret and Dufour effects in a vertical plate with variable surface temperature. Postelnicu [27] analyzed the effect of Soret and Dufour on heat and mass transfer at a stagnation point. Tak et al [28] investigated the MHD free convection- radiation in the presence of Soret and Dufour. Vempati et al [29] studied the Soret and Dufour on MHD with thermal radiation. Ching-Yang Cheng [30] studied the Soret and Dufour on heat and mass transfer on a vertical truncated cone with variable wall temperature and concentration. The authors [31] studied variable viscosity on convective heat and mass transfer by natural convection from horizontal surface in porous medium. Recently the same authors [32] studied Soret and Dufour effects on natural convection flow past a vertical surface in a porous medium with variable viscosity. Apart from the existence, survey of literature was taken into account with respect to the effects of (i) thermal stratification (ii) variable viscosity (iii) Dufour and Soret (which is a major factor). The effects of these parameters on heat and mass transfer are discussed elaborately. In particular, the Dufour and Soret effects have the major role in our findings. Therefore, the aim of this paper is to study the effects of Soret and Dufour on heat and mass transfer by natural convection from a horizontal plate with variable viscosity.

2 Mathematical Model

Consider a horizontal surface embedded in a saturated porous medium. The properties of the fluid and porous medium are isotropic and the viscosity of the fluid is assumed to be an inverse linear function of temperature. Using Boussinesq and boundary layer approximations, the governing equations of continuity, momentum, energy and concentration are given by

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

$$u = -\frac{\kappa}{\mu}\left(\frac{\partial p}{\partial x}\right) \tag{2}$$

$$v = -\frac{\kappa}{\mu}\left(\frac{\partial p}{\partial y} + \rho g\right) \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{D_m k_T}{c_s c_p}\frac{\partial^2 c}{\partial y^2} \tag{4}$$

$$u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=D_m\frac{\partial^2 c}{\partial y^2}+\frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{5}$$

and with the Boussinesq approximation

$$\rho=\rho_\infty\left\{1-\beta(T-T_\infty)-\beta^*(c-c_\infty)\right\} \tag{6}$$

The viscosity of the fluid is assumed to be an inverse linear function of temperature and it can be expressed as

$$\frac{1}{\mu}=\frac{1}{\mu_\infty}\left\{1+\gamma(T-T_\infty)\right\} \tag{7}$$

which is reasonable for liquids such as water and oil. Here γ is a constant. The boundary conditions are

$$y=0, v=0, T=T_w, c=c_w \tag{8}$$

$$y\to\infty, u=0, T=T_\infty, c=c_\infty \tag{9}$$

3 Method of Solution

Introducing the stream function $\psi(x,y)$ such that

$$u=\frac{\partial\psi}{\partial y}, v=-\frac{\partial\psi}{\partial x} \tag{10}$$

where

$$\psi=\alpha f(Ra_x)^{1/3} \tag{11}$$

$$\eta=\frac{y}{x}(Ra_x)^{1/3} \tag{12}$$

and

$$Ra_x=\left\{\frac{kg\beta\Delta Tx}{\nu\alpha}\right\}$$ is the Rayleigh number

Define

$$\theta=\frac{T-T_\infty}{T_w-T_\infty} \tag{13}$$

$$\phi=\frac{c-c_\infty}{c_w-c_\infty} \tag{14}$$

and

$$N=\frac{\beta^*(c_w-c_\infty)}{\beta(T_w-T_\infty)} \tag{15}$$

Substitution of these transformations (10) to (15) to equations (2) to (5) along with the equations (6) and (7), the resulting nonlinear ordinary differential equations are

$$f''=\frac{f'\theta'}{\theta-\theta_c}-\frac{2}{3}\left(\frac{\theta-\theta_c}{\theta_c}\right)(\eta\theta'+\eta\phi'N) \tag{16}$$

$$\theta''+\Pr Du\phi''+\frac{1}{3}f\theta'=0 \tag{17}$$

$$\phi''+S_cS_r\theta''+\frac{Le}{3}f\phi'=0 \tag{18}$$

together with the boundary conditions

$$\eta=0, f=0, \theta=1, \phi=1 \tag{19}$$

$$\eta\to\infty, f'=0, \theta=0, \phi=0 \tag{20}$$

where $\Pr=\frac{\nu}{\alpha}$ is the Prandtl number, $Du=\frac{D_m k_T(c_w-c_\infty)}{c_s c_p \nu(T_w-T_\infty)}$ is the Dufour number, $Sc=\frac{\nu}{D_m}$ is the Schmidt number, $Sr=\frac{D_m k_T(T_w-T_\infty)}{T_m\nu(c_w-c_\infty)}$ is the Soret number $Le=\frac{\alpha}{D_m}$ is the Lewis number and $\theta_c=-\frac{1}{\gamma(T_w-T_\infty)}$ is the parameter characterizing the influence of viscosity. For a given temperature difference, large values of θ_c implies either γ or (T_w-T_∞) are small. In this case, the effect of variable viscosity can be neglected.

The effect of variable viscosity is important if θ_c is small. Since the viscosity of liquids decreases with increasing temperature while it increases for gases, θ_c is negative for liquids and positive for gases. The concept of this parameter θ_c was first introduced by Ling and Dybbs [6] in their study of forced convection flow in porous media. The parameter N measures the relative importance of mass and thermal diffusion in the buoyancy-driven flow. It is clear that N is zero for thermal-driven flow, infinite for mass driven flow, positive for aiding flow and negative for opposing flow.

4 Numerical analysis and Discussion

The equations (16), (17) and (18) together with the boundary conditions (19) and (20) are integrated numerically by using the fourth order Runge-Kutta -Gill method along with a systematic guessing of $-\theta'(0)$ and $-\phi'(0)$ by the shooting technique. The step size $\Delta\eta=0.0625$ is used to obtain the numerical solution with seven decimal place accuracy as the criterion of convergence.

The parameters involved in this problem are θ_c – the variable viscosity, Le- Lewis number , N-the buoyancy parameter, Pr- Prandtl number, Du- Dufour number, Sr- Soret number and Sc- Schmidt number. To observe the effect of variable viscosity on heat and mass transfer we have plotted the velocity function f' , temperature function θ and the concentration function ϕ against η for various values of θ_c, Le and N. The value of Prandtl number Pr is taken equal to 0.71 which corresponds to air. The values of the Dufour number and Soret number are taken in such a way that their product is constant according to their definition provided that the mean temperature is kept constant as well. The parameter θ_c is used to represent the effect of variable viscosity. The case $\theta_c < 0$ corresponds to the case of liquids and $\theta_c > 0$ corresponds to the case of gases.

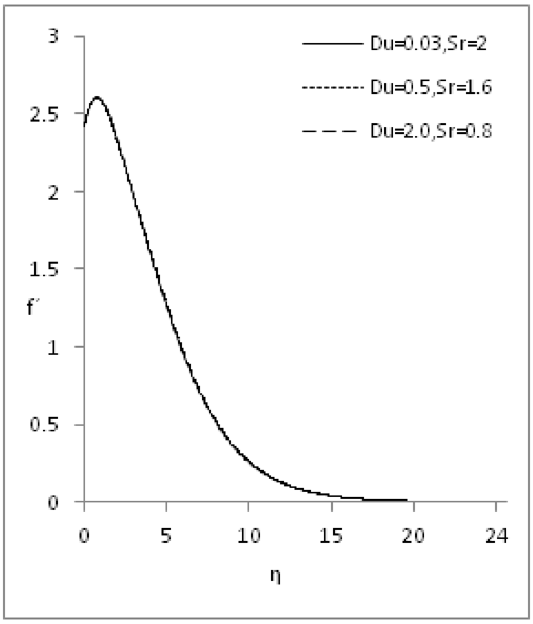

Fig.1: Velocity profile for different values of Dufour and Soret for θ_c=5, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

The influence of Dufour number Du and Soret number Sr on velocity, temperature and concentration profiles are shown in Figs.1,2 and 3 respectively for θ_c= 5, N=1, Le=0.1, Pr=0.71 and Sc=0.1. Fig.1 shows that the velocity decreases slightly with the increase of Dufour number whereas it decreases with the decrease of Soret number.

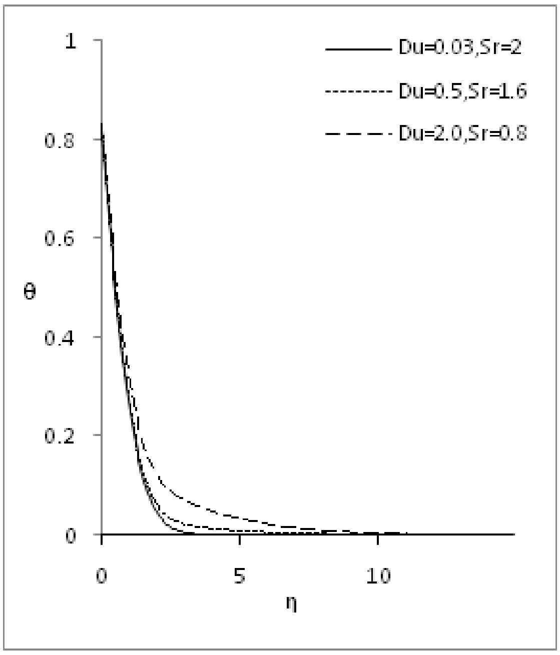

Fig.2: Temperature profile for different values of Dufour and Soret for θ_c=5, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

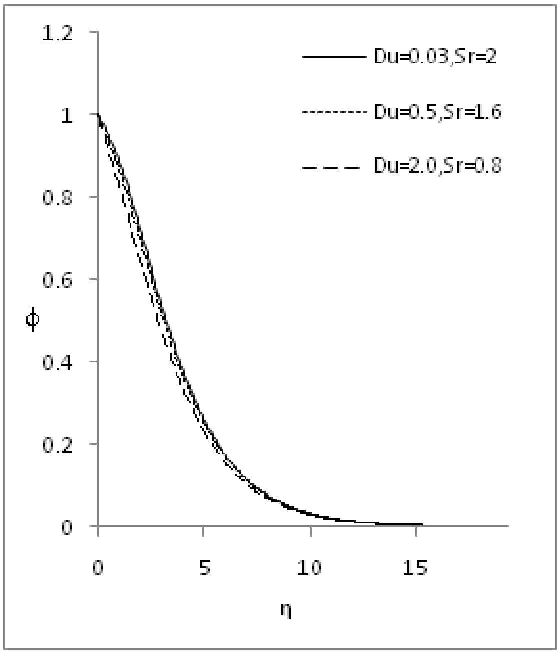

Fig.3: Concentration profile for different values of Dufour and Soret for θ_c=5, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

Fig. 3 shows that the concentration decreases with the increase of Dufour number whereas it increases with the increase of Soret number.

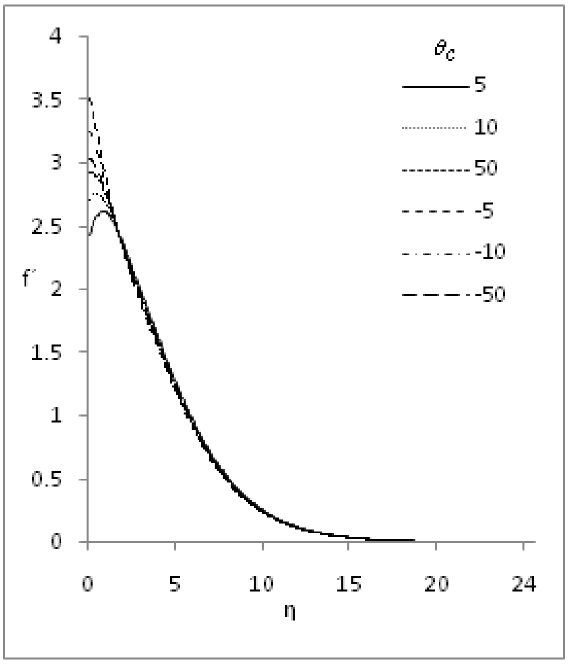

Fig.4: Velocity profile for different values of θ_c for Du=0.03, Sr=2, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

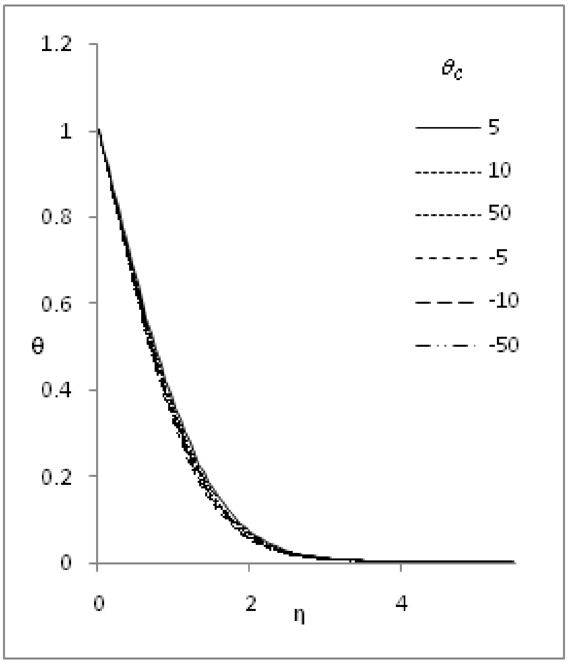

Fig.5: Temperature profile for different values of θ_c for Du=0.03, Sr=2, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

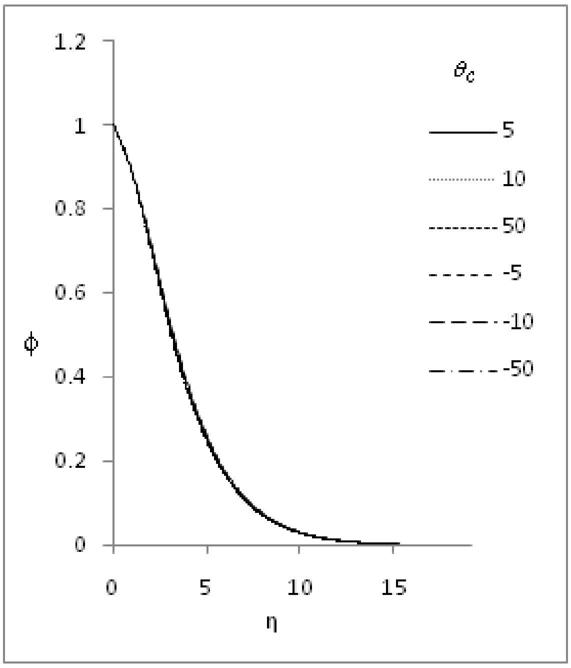

Fig.6: Concentration profile for different values of θ_c for Du=0.03, Sr=2, N=1, Le=0.1, Pr=0.71 and Sc=0.1.

The effect of variable viscosity θ_c on velocity, temperature and concentration are shown in Figs. 4, 5 and 6 respectively for N=1, Le = 0.1, Pr= 0.71, Sc = 0.1, Du = 0.03 and Sr = 2. From Fig. 4 it is realized that the velocity increases near the plate and decreases away from the plate as $\theta_C \to 0$ in the case of liquids ($\theta_c < 0$) and decreases near the plate and increases away from the plate as $\theta_C \to 0$ in the case of gases ($\theta_c > 0$). From Figs. 5 and 6 it is evident that the temperature and concentration increase as $\theta_C \to 0$ for $\theta_c > 0$ (i.e. for gases) and decreases as $\theta_C \to 0$ for $\theta_c < 0$ (i.e. for liquids).

The effect of Lewis number Le on temperature and concentration are shown in Figs.7 and 8 respectively for N = 1, Pr = 0.71, Sc = 0.1, Du = 0.03, Sr = 2 and for different values of θ_c and Le.

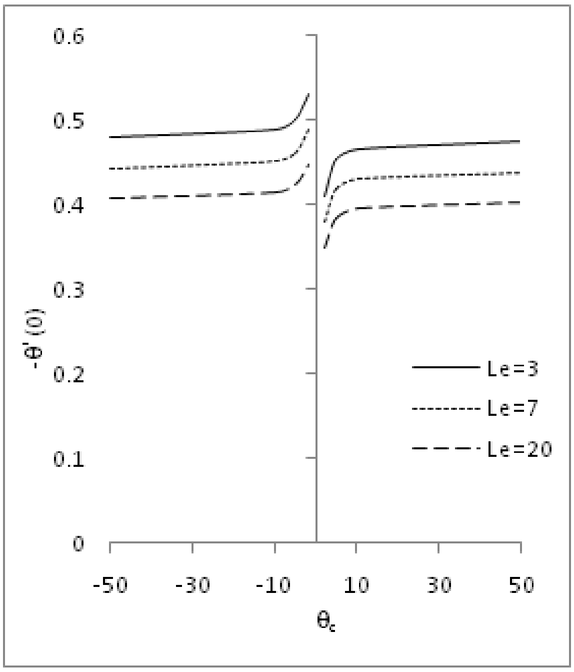

Fig.7: Effect of Lewis number Le on the rate of heat transfer for different values of θ_c, for Du=0.03, Sr=2,N=1,Pr=0.71 and Sc=0.1.

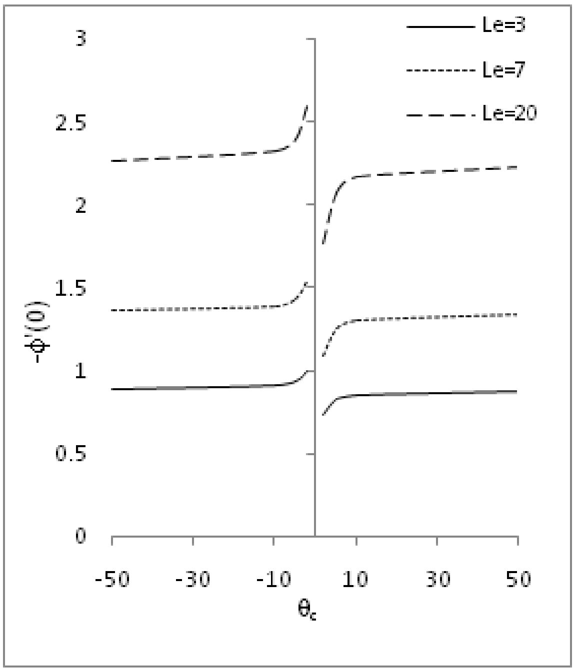

Fig.8: Effect of Lewis number Le on the rate of mass transfer for different values of θ_c ,for Du=0.03, Sr=2, N=1, Pr=0.71 and Sc=0.1.

From Fig. 7, it is observed that as Le increases, the heat transfer decreases for both gases and liquids. From Fig. 8, it is realized that as Le increases, the mass transfer increases for both gases and liquids.

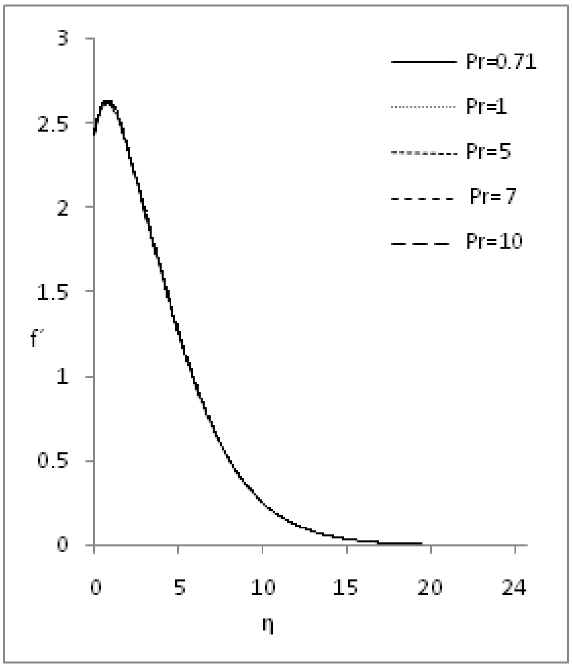

Fig.9: Velocity profile for different values of Pr, for Du=0.03, Sr=2, θ_c =5, Le=0.1, N=1 and Sc=0.1.

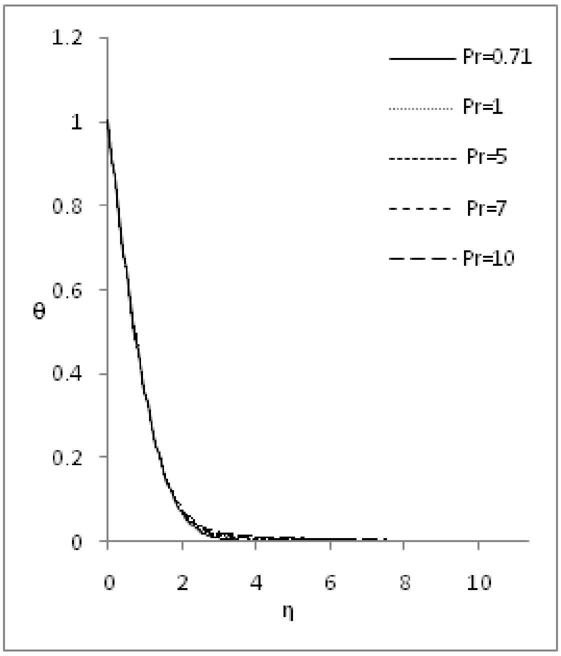

Fig.10: Temperature profile for different values of Pr, for Du=0.03, Sr=2,θ_c =5, Le=0.1,N=1.

The effect of Prandtl number Pr on velocity, temperature and concentration are shown in Figs. 9, 10 and 11 respectively for N = 1, Sc= 0.1,Du = 0.03, Sr = 2, Le = 0.1 and θ_c = 5. From Figs. 9 and 10, it is evident that as the Prandtl number increases, the velocity and temperature increases.

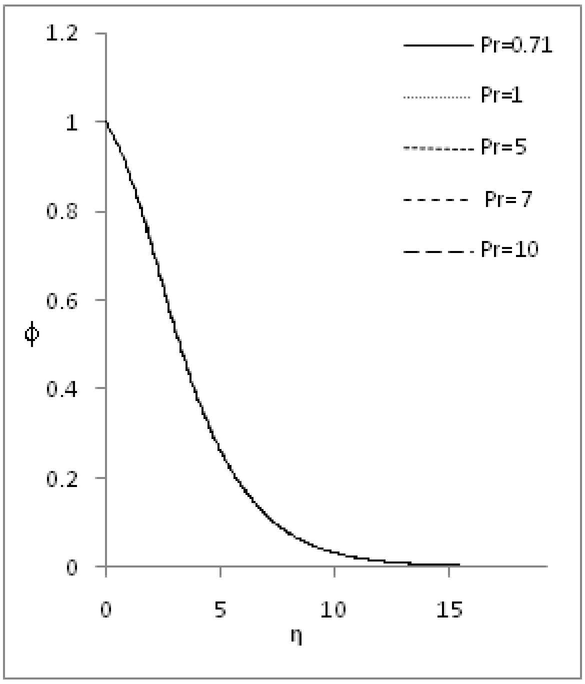

Fig.11: Concentration profile for different values of Pr, for Du=0.03, Sr=2, θ_c=5, Le=0.1, N=1 and Sc=0.1.

Fig. 11 shows that as the Prandtl number increases, the concentration decrease.

The parameters of engineering interests for the present problem are the local Nusselt number Nu_x and Sherwood number Sh_x, which are given by

$$\frac{Nu_x}{(Ra_x)^{1/3}} = -\theta'(0) \tag{21}$$

$$\frac{Sh_x}{(Ra_x)^{1/3}} = -\phi'(0) \tag{22}$$

Table 1: Values of local Nusselt number for an isothermal plate for Le=1,N=0,M=0,Du=0,Sr=0 and $\theta_c \to \infty$

Chang and Cheng [4]	Bansod and Jadhav [25]	Present case
0.429	0.421	0.429

Table 1 represents a comparison of the numerical values of Nusselt number obtained in the present case with those of Chang and Cheng [4] and Bansod and Jadhav [25] for an isothermal plate for Le=1, N=0, M=0, Du=0, Sr=0 and $\theta_c \to \infty$. It is clearly seen that there is a good agreement between the results.

Table 2: Numerical values of Nusselt numbers for various values of N and θ_c for Le = 0.1, Du = 0.03, Sr = 2, and Sc = 0.1.

Nusselt number			
	N		
θ_c	1	2	5
5	0.7338743	0.8919685	1.1819310
10	0.7569678	0.9203725	1.2198963
50	0.7747059	0.9422032	1.2490883
-5	0.8205859	0.9987185	1.3247071
-10	0.8002210	0.9736245	1.2911228
-50	0.7833500	0.9528458	1.2633233

Table 3: Numerical values of Sherwood number for various values of N and θ_c for Le = 0.1, Du = 0.03, Sr = 2, and Sc = 0.1.

Sherwood number			
	N		
θ_c	1	2	5
5	0.0989015	0.1254325	0.1709522
10	0.0974540	0.1237351	0.1687599
50	0.0963345	0.1224187	0.1670559
-5	0.0934128	0.1189691	0.1625774
-10	0.0947139	0.1205077	0.1645771
-50	0.0957867	0.1217735	0.1662196

The values of Nusselt number and Sherwood number for different values of variable viscosity θ_c and the buoyancy ratio N are presented in Table 2 & 3 for Le=0.1, Sc=0.1, Du=0.03,Sr = 2 and Pr = 0.71.

It is evident that as $\theta_c \to 0$ for gases the Nusselt number decreases and the Sherwood number increases. It is also realized that as $\theta_c \to 0$ for liquids the Nusselt number increases and the Sherwood number decreases for other parameters fixed.

5 Conclusion

The Dufour and Soret effect on free convective heat and mass transfer flow past a semi-infinite horizontal plate under the influence of variable viscosity has been studied. Using usual similarity transformations, the governing equations have been transformed into non-linear ordinary differential equations. The similarity solutions are obtained numerically by applying Runge-Kutta-Gill method along with shooting technique.

Nomenclature

c - Concentration at any point in the flow field
c_p - Specific heat at constant pressure
c_s - Concentration susceptibility
c_w - Concentration at the wall
c_∞ - Concentration at the free stream
D_m - Mass diffusivity
Du - Dufour number
f - Dimensionless velocity function
g - Acceleration due to gravity
k - Permeability
k_T - Thermal diffusion ratio
Le - Lewis number [Le = α / D_m]
N – Buoyancy ratio
$[N = \beta^*(c_w - c_\infty)/\beta(T_w - T\infty)]$
Nu_x - Nusselt number
$[Nu_X = -x(\partial T/\partial y)_{y=0}/(T_W - T_\infty)]$
p - Pressure
Pr - Prandtl number
Ra_x - Rayleigh number $Ra_x = [kg\beta\Delta Tx/\nu\alpha]$
Sc - Schmidt number
Sh_x - Sherwood number $[Sh_X = mx/D(c_W - c_\infty)]$
Sr - Soret number
T - Temperature of the fluid
T_w - Temperature of the plate
T_∞ - Temperature of the fluid far from the plate
T_m - Mean fluid temperature
u,v - Velocity components in x and y direction
x,y - Coordinate system

Greek letters

α - Thermal diffusivity
β - Coefficient of thermal expansion
β^* - Concentration expansion coefficient
γ - Constant defined in equation (7)
η - Dimensionless similarity variable
θ - Dimensionless temperature
θ_c - $-1/\gamma\,(T_w - T_\infty)$
μ - Viscosity [pas]
ν - Kinematic viscosity
ρ - Density
ϕ - Dimensionless concentration
ψ - Dimensionless stream function

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