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Diffusion-thermo and Thermo-diffusion Effects on MHD Fluid Flow over Non-linearly Stretching Sheet through a Non-Darcy Porous Medium

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Authors' contributions

This work was carried out in collaboration between all authors. Author BSK designed the study, performed the mathematical analysis, wrote the protocol and wrote the first draft of the manuscript. Author MSR managed the analyses of the study. Authors GVRR and NR managed the literature searches. All authors read and approved the final manuscript.

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Abstract

In this paper, we discuss Diffusion-thermo and Thermo-diffusion effects on MHD free convective incompressible, Newtonian fluid flow over non linearly stretching sheet with radiation and chemical reaction, through a non-Darcy porous medium. By suitable similarity transformations, the boundary layer equations are transformed to ordinary differential equations. The method, numerical computation with bvp4c (a MATLAB program) is used to solve these equations. The effects of Magnetic parameter, Diffusion -thermo number and Thermo-diffusion number on velocity profiles, heat and mass transfer, Skin-frictions, Nusselt Number and Sherwood Number are computed, discussed and analysed numerically and presented through tables and graphs.

Keywords: MHD flow; magnetic parameter; diffusion-thermo number; thermo-diffusion number.

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1 Introduction

Dufour (diffusion-thermo) and Soret (thermal–diffusion) effects are significant in areas such geosciences, hydrology and chemical engineering. The energy flux caused by a composition gradient is called the Dufour effect. The mass flux, created by temperature gradient is called the Soret effect. The thermal diffusion effect is utilized for isotope separation and in mixtures between gases with very light molecular weight (e.g., H_2 and He) and of medium molecular weight (e.g., N_2 and air), and the diffusion-thermo effect is utilized in the study of chemical pollutants spreading into soil and medicine diffusion in blood veins (Hayat, et al. [1]).

Makinde, et al. [2] analyzed numerical study of chemically-reacting hydromagnetic boundary layer flow with Soret/Dufour effects and a convective surface boundary condition.

Chand, et al. [3] analysed hydromagnetic oscillatory flow through a porous medium bounded by two vertical porous plates with heat source and Soret effect. Sharma, et al. [4] studied the Soret and Dufour effects on unsteady MHD mixed convection flow past an infinite radiative vertical porous plate embedded in a porous medium in the presence of chemical reaction.

Motsa, et al. [5] analyzed the problem of magneto-hydrodynamic fluid flow past a nonlinear stretching sheet in the presence of a transverse magnetic field by an efficient semi-analytical technique. Vasu, et al. [6] studied thermo-diffusion and diffusion-thermo effects on MHD free convective heat and mass transfer from a sphere embedded in a non-Darcy porous medium.

Abbasbandy, et al. [7] studied an approximate solution of the MHD flow over a non-linear stretching sheet by rational chebyshev collocation method. Hayat, et al. [1] studied Soret and Dufour effects on magnetohydrodynamic (MHD) flow of casson fluid over a stretched surface.

Prakash, et al. [8] investigated Dufour effects on unsteady hydromagnetic radiative fluid flow past an impulsively started infinite vertical plate with variable temperature and uniform mass diffusion in the presence of transverse applied magnetic field through porous medium. Awad, et al. [9] investigated the thermo-diffusion effects on magneto-nanofluid flow over a stretching sheet including the effects of Brownian motion and cross-diffusion.

Ahmed, et al. [10] discussed the Finite difference solution of MHD mixed convection flow with heat generation and chemical reaction including the effect of Hall current and thermal radiation.

Srinivasacharya, et al. [11] analysed the free convection in MHD micropolar fluid in the presence of Soret and Dufour effects. Gururaj, A. et al. [12] analysed the nonlinear MHD boundary layer flow of a liquid metal with heat transfer over a porous stretching surface with nonlinear radiation effects.

Sarma, et al. [13] analysed the numerical study of MHD free convection heat and mass transfer from vertical surfaces in porous media considering Soret and Dufour effects.

Gangadhar [14] analysed the Soret and Dufour effects on hydro magnetic heat and mass transfer over a vertical plate with a convective surface boundary condition and chemical reaction.

Mahbub, et al. [15] investigated the Soret-Dufour effects on the MHD flow and heat transfer of microrotation fluid over a nonlinear stretching plate in the presence of suction. Chand, et al. [16] investigated the MHD heat and mass transfer for viscous flow over nonlinearly stretching sheet in a porous medium.

Ibrahim [17] discussed the effects of chemical reaction on dissipative radiative MHD flow through a porous medium over a nonisothermal stretching sheet. Rashidi, et al. [18] discussed the homotopy semi-numerical simulation of Soret and Dufour effects on magneto-convection heat and mass transfer from a transpiring stretching surface.

Yasmin, et al. [19] discussed the diffusion-thermo and thermal-diffusion effects on MHD visco-elastic fluid flow over a vertical plate. Usman, et al. [20] studied the effect of thermal conductivity on MHD heat and mass transfer flow past an infinite vertical plate with Soret and Dufour effects.

Haile, et al. [21] discussed the heat and mass transfer through a porous media of MHD flow of nanofluids with thermal radiation, viscous dissipation and chemical reaction effects. Sengupta, et al. [22] studied the MHD free convective chemically reactive flow of a dissipative fluid with thermal diffusion, fluctuating wall temperature and concentrations in velocity slip regime.

Sharma, et al. [23] discussed the influence of chemical reaction, heat source, Soret and Dufour effects on separation of a binary fluid mixture in MHD natural convection flow in porous media. Pal, et al. [24] discussed Soret-Dufour effects on hydromagnetic non-Darcy convective-radiative heat and mass transfer over a stretching sheet in porous medium with viscous dissipation and ohmic heating.

Yasmin, et al. [25] discussed the diffusion-thermo and thermal-diffusion effects on MHD visco-elastic fluid flow over a vertical plate. Animasaun, et al. [26] discussed the effect of variable viscosity, Dufour, Soret and thermal conductivity on free convective heat and mass transfer of non-Darcian flow past porous flat surface. Ishak, et al. [27] discussed hydromagnetic flow and heat transfer adjacent to a stretching vertical sheet. Chen [28] discussed laminar mixed convection adjacent to vertical continuously stretching sheets.

The work is bases on Pal, et al. [24].

In the above work study of Soret and Dufour effects on MHD free convective Newtonian fluid flow through a non-Darcy porous medium over nonlinearly stretching sheet, where stretching velocity of sheet varies nonlinearly with distance from the origin, and temperature and concentration vary nonlinearly in the boundary layer region, using bvp4c is not discussed.

Present problem deals with the study of Soret and Dufour effects on MHD free convective Newtonian fluid flow over nonlinearly stretching sheet, through a non Darcy porous medium, where stretching velocity of the sheet varies nonlinearly with distance from the origin, and temperature and concentration at the surface of the sheet, vary nonlinearly in the boundary layer region using bvp4c.

2 Formulation of Problem

We consider Newtonian fluid which is viscous, incompressible, and electrically conducting and without phase change. Fluid is steady, two-dimensional laminar with free convection boundary layer flow. It is in saturated non-Darcy porous medium. It is caused by nonlinearly stretching surface (by two equal and opposite forces keeping origin unaltered) placed at the bottom of the porous medium. In Cartesian coordinate system the x-axis is along the direction of the stretching surface and y-axis is normal to it (Fig. 1). The stretching velocity varies nonlinearly with the distance from the origin. A uniform magnetic field of strength B is applied normal to sheet. Surface temperature of the sheet is assumed as $T_w > T_\infty$, where T_∞ is the uniform temperature of the ambient fluid. There exists a homogeneous chemical reaction between the fluid and species concentration. The flow along the sheet (at the interface of solid and liquid, solid particles, A dissolve in the liquid B) contains a species A slightly soluble in the fluid B, the concentration at the sheet surface is C_w and the solubility of A in B far away from the sheet is C_∞.

In porous medium for low velocity, Darcy law is used, for high velocity Forchheimer law is used, and for viscous nature of the fluid, Brinkman law is used in momentum equation.

It is assumed that the induced magnetic field, the external electric field and the electric field due to the polarization of charges are negligible in comparison to the applied magnetic field and so Hall effects and Joule heating are neglected.

It is assumed that heat and mass transfer possesses the presence of thermal radiation, Soret and Dufour effects. Under these assumptions, the governing Oberbeck-Bosensque approximation (following Pal D, et al. [24]) for boundary layer equations for the momentum, heat and mass transfer are as follows.

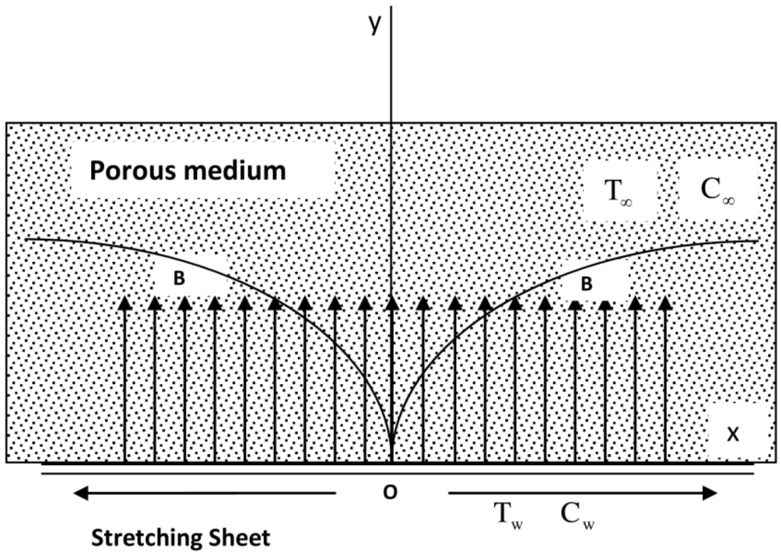

Fig. 1. Physical model and coordinate system

The equation of continuity:

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

The Equation of Momentum:

$$u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2}{\rho_f}u - \frac{\mu}{K}u - \frac{C_b}{\sqrt{K}}u^2 \tag{2}$$

The equation of Energy:

$$u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{D_m K_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{3}$$

The equation of Mass:

$$u\frac{\partial C}{\partial x} + \upsilon\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} - K_r\left(C - C_\infty\right) \tag{4}$$

where x and y are Cartesian coordinates along the stretching sheet and normal to it, respectively. u and v are the velocity components along the x-axis and y-axes. T is the temperature of the fluid, C is the concentration of the fluid, K is the permeability of the porous medium, C_p is specific heat capacity, C_s is concentration susceptibility, B is magnetic field, and C_b is Forchheimer coefficient. ρ, ν and μ are density, kinematic viscosity and dynamic viscosity of the fluid respectively.

Further, (ρC_p) is the heat capacity of the fluid, α is the thermal diffusivity of the fluid. D_m is mass diffusion coefficient and K_T is thermal diffusion ratio. The strength of magnetic field is assumed to vary spatially by $B(x) = B_0 x^{\frac{(n-1)}{2}}$ where B_0 is constant.

It is assumed that velocity, temperature and concentration vary non-linearly in spatial coordinates with same index in the boundary layer region.

So boundary conditions for Eqs. (1)–(4) are as follows:

$$\begin{aligned} & y = 0 : \upsilon = 0, u = u_w(x) = c\,x^n, \upsilon = \upsilon_w = 0, T = T_w = T_\infty + T_0\, x^{2n}, \\ & C = C_w = C_\infty + C_0 x^{2n}; \\ & y \to \infty : u \to 0, T \to T_\infty, C \to C_\infty \end{aligned} \tag{5}$$

where $n > 0$ for accelerated sheet and $n < 0$ for decelerated sheet.

Rosseland approximation (following Raptis A. [29]) requires that the media is optically dense media and radiation travels only a short distance before being scattered or absorbed.

Rosseland equation which is a simplified model of Radiative Transfer Equation (RTE) is adopted to account for this effect.

The radiative heat flux q_r is simplified by using Rosseland approximation as

$$q_r = \frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

where σ^* is the Stefan –Boltzmann constant and k^* is the mean absorption coefficient.

This approximation is valid at points optically far away from the boundary surface and it is good for intensive absorption, which is for optically thick boundary layer. It is assumed that the temperature difference within the flow is such that the term T^4 may be expressed as a linear function of temperature. Hence, expanding T^4 by Taylor's series about T_∞

$$T^4 = T_\infty^4 + 4T_\infty^3(T - T_\infty) + 6T_\infty^2(T - T_\infty)^2 + \dots \dots$$

and then neglecting higher order terms beyond the first degree in $(T - T_\infty)$ we get

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \ .$$

and so

$$q_r = -\left(4\sigma^*/3k^*\right)\left(\partial\left(4T_\infty^3 T - 3T_\infty^4\right)/\partial y\right) = -\left(16\sigma^*/3k^*\right)T_\infty^3\left(\partial T/\partial y\right)$$

and

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma^* T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2}. \tag{7}$$

Using equations (6) and (7), equation (3) reduces to:

$$\rho C_p\left(u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y}\right) = \left(k + \frac{16\sigma^* T_\infty^3}{3k^*}\right)\frac{\partial^2 T}{\partial y^2} + \frac{D_m K_T}{C_s C_p}\frac{\partial^2 C}{{}_p\partial y^2}. \tag{8}$$

Dimensional Analysis: We define

$$\psi = \left(\frac{2\nu c}{n+1}\right)^{\frac{1}{2}} x^{\frac{n+1}{2}} f(\eta), \eta = \left(\frac{c(n+1)}{2\nu}\right)^{\frac{1}{2}} x^{\frac{n-1}{2}} y,$$
$$\theta(\eta) = \frac{(T - T_\infty)}{(T_w - T_\infty)},\ \phi(\eta) = \frac{(C - C_\infty)}{(C_w - C_\infty)}, u = \frac{\partial \psi}{\partial y}, \upsilon = -\frac{\partial \psi}{\partial x}. \tag{9}$$

Here η is similarity variable, ψ is a stream function, f is non-dimensional stream function, θ is non-dimensional Temperature, ϕ is non-dimensional concentration, u is x -component of velocity, v is y-component of velocity.

Using (9) equations (2), (8), and (4) can be written as

$$f''' + ff'' - \frac{2n}{n+1}(f')^2 - \frac{1}{n+1}\left(\left(M + \frac{1}{K1}\right)f' + Fs(f')^2\right) = 0 \tag{10}$$

$$\left(1 + \frac{4R}{3}\right)\theta'' + \Pr\left(f\theta' - \frac{4n}{n+1}f'\theta\right) + Du\phi'' = 0 \tag{11}$$

$$\phi'' + Sc\left(f\phi' - \frac{4n}{n+1}f'\phi\right) + Sc\ Sr\ \theta'' - Sc\ K_r^{'}\ \phi = 0 \tag{12}$$

and boundary conditions (5) as

$$f(0) = 0,\ f'(0) = 1, \theta(0) = 1, \phi(0) = 1$$
$$f'(\eta) \to 0, \theta(\eta) \to 0, \phi(\eta) \to 0, as, \eta \to \infty \tag{13}$$

Here prime denotes differentiation with respect to η .

The parameters occurring in (10) to (12) are defined as follows.

$$M = \frac{2\sigma B_0^2}{\rho_f\ c}, K1 = \frac{K\ c\ x^{n-1}}{2\nu}, Fs = \frac{2C_b\ x}{\sqrt{K}}, \Pr = \frac{\nu}{\alpha}, \alpha = \frac{k}{\rho C_p}, Sc = \frac{\nu}{D_m}$$
$$Du = \frac{D_m\ K_T}{\alpha\ C_s\ C_p}\frac{(C_w - C_\infty)}{/(T_w - T_\infty)},\ Sr = \frac{D_m\ K_T}{T_m\ \nu}\frac{(T_w - T_\infty)}{/(C_w - C_\infty)}, \nu = \frac{\mu}{\rho},\ K_r^{'} = \frac{2K_r}{(n+1)c\,x^{n-1}} \tag{14}$$

Du is Dufour parameter or Thermo-Diffusion parameter, α thermal diffusivity of heat in fluid, k thermal conductivity of heat in fluid, Pr Prandtl number, Sc Schmidth number, Fs Forchheimer parameter, M Magnetic parameter, $K1$ Permeability parameter, $K_r^{'}$ Chemical reaction rate parameter, Sr Soret number or Diffusion -Thermo parameter.

The quantities of physical interest for this problem are the Local Skin-friction (C_f), Nusselt number (Nu_x), and Sherwood Number, (Sh_x) and the Reynold Number (Re). These are defined as follows:

$$C_f = \frac{\tau_w}{\frac{\rho U_w^2}{2}} = \frac{\mu\left(\frac{\partial u}{\partial y}\right)_{y=0}}{\frac{\rho U_w^2}{2}} \Rightarrow C_f = \frac{2}{\sqrt{\mathrm{Re}}} f''(0), C_f = \frac{\nu\left(\frac{\partial u}{\partial y}\right)_{y=0}}{U_w^2 e^{\frac{2x}{L}}}$$
$$Nu_x = -\frac{x\left(\frac{\partial T}{\partial y}\right)_{y=0}}{T_w - T_\infty} = -\sqrt{\mathrm{Re}}\theta'(0);\ Sh_x = -\frac{x\left(\frac{\partial C}{\partial y}\right)_{y=0}}{C_w - C_\infty} \tag{15}$$

3 Method of Numerical Solution

The numerical solutions are obtained using the above equations for some values of the governing parameters, namely, the Magnetic Parameter (M), the Soret number (Sr),and the Dufour number(Du). Effects of M, Sr, Du, on the steady boundary layer flow are discussed in detail. The numerical computation is done using the MATLAB in-built numerical solver bvp4c. In the computation we have taken $\eta_\infty = 4,\ and\ 10$, and axis according to the clear figure-visuality.

4 Results and Discussion

To ensure the numerical accuracy, the values $-\theta'(0)$ by present method are compared with the results of Ishak et al. [27], Chen [28] and D. Pal et al. [24] in Table 1 without magnetic field (M = 0), non porous media (K1=infinity, Fs=0) and having Sc=0 and with linearly stretching sheet (n1=1) and those are found in excellent agreement. Thus, we are very much confident that the present results are accurate.

Table 1. Comparison of the local Nusselt number $-\theta'(0)$ with Ishak et al. [27], Chen [28] and D. Pal et al. [24] for various values of Pr

M=Fs=Pr=Sc=Du=Sr=Kr'=R=0, K1=inf, n1=1				
		$-\theta'(0)$		
Pr	**Ishak et al. [27]**	**Chen [28]**	**D. Pal et al. [24]**	**Present results**
1.0	1.3333	1.33334	1.333333	1.333344188017813
3.0	2.5097	2.50997	2.509715	2.509711475816613
10	4.7969	4.79689	4.796871	4.796362196985356

The non-dimensional linear velocity $f'(\eta)$, rotational velocity $g(\eta)$, temperature $\theta(\eta)$, and concentration $\phi(\eta)$ for various values of different parameters are shown in Figs. 2 to 10.

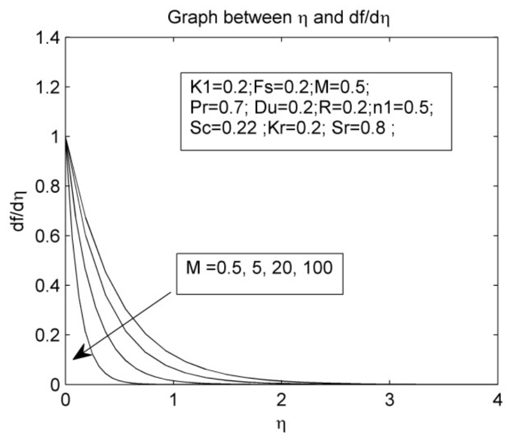

Fig. 2. Velocity profile $f'(\eta)$ with respect to similarity transformation η for some values of magnetic parameter M

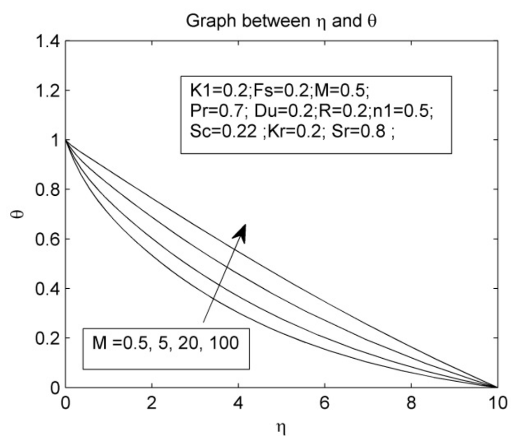

Fig. 3. Temperature profile $\theta(\eta)$ with respect to η for some values of magnetic parameter M

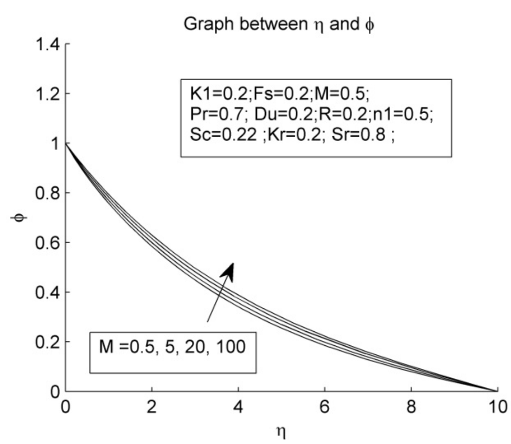

Fig. 4. Concentration profile $\phi(\eta)$ with respect to η for some values of magnetic parameter M

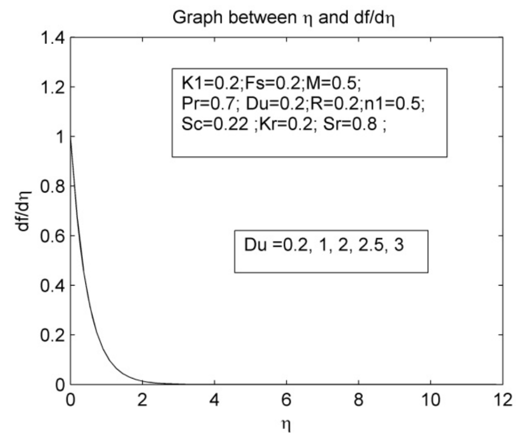

Fig. 5. Velocity profile $f'(\eta)$ with respect to similarity transformation η for some values of Dufour parameter Du

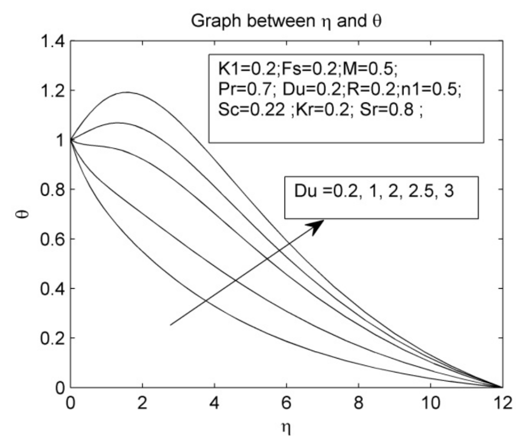

Fig. 6. Temperature profile $\theta(\eta)$ with respect to η for some values of Dufour parameter Du

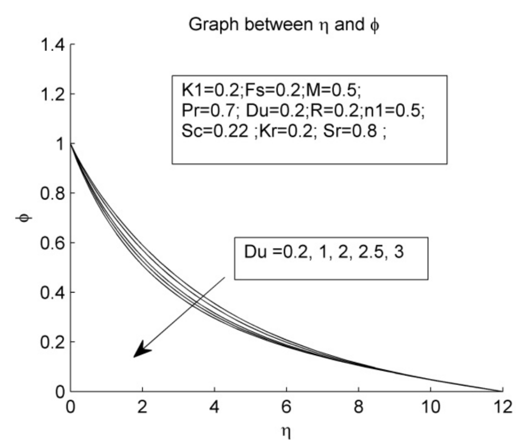

Fig. 7. Concentration profile $\phi(\eta)$ with respect to η for some values of Dufour parameter Du

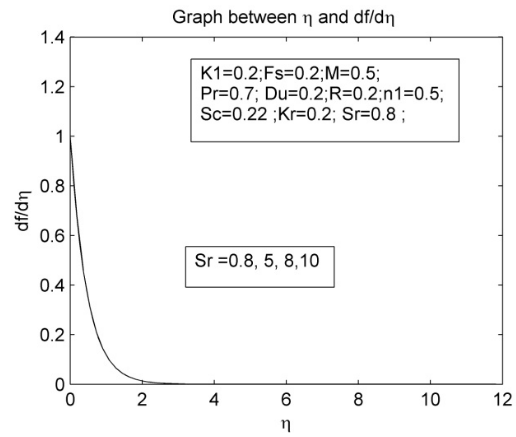

Fig. 8. Velocity profile $f'(\eta)$ with respect to similarity transformation η for some values of Soret parameter Sr.

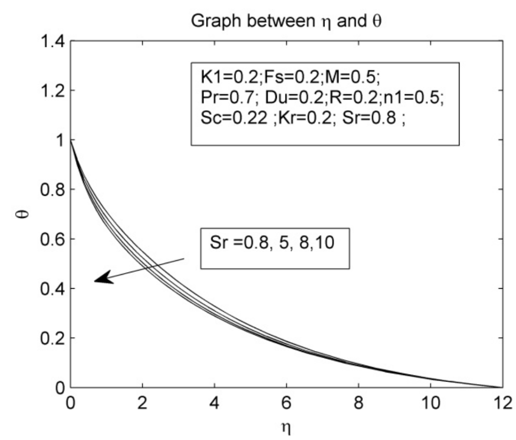

Fig. 9. Temperature profile $\theta(\eta)$ with respect to η for some values of Soret parameter Sr.

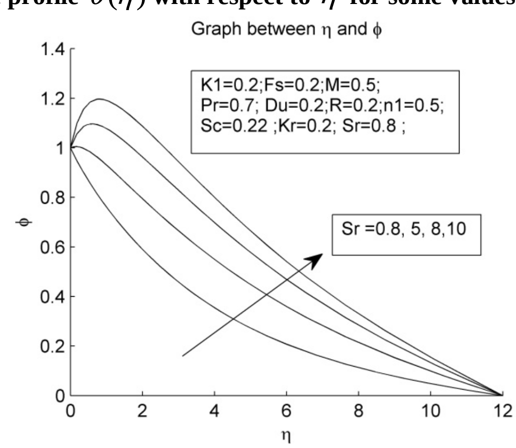

Fig. 10. Concentration profile $\phi(\eta)$ with respect to η for some values of Soret parameter Sr.

Fig. 2 shows the behaviour of velocity profile for increasing value of magnetic parameter M. The increasing values of M decreases the velocity and this causes boundary layer to shrink towards the wall. Thus the increase in magnetic parameter decreases fluid velocity and results in thinning boundary layer.

Fig. 3 shows the behaviour of temperature profile for increasing value of magnetic parameter M. It is observed that higher values of M increase the fluid temperature significantly and boundary layer expands away from the wall. The explanation of this phenomenon is that the increasing M leads to an increase in thermal diffusion and results in thickening boundary layer.

Fig. 4 shows the behaviour of concentration profile for increasing values of magnetic parameter M. It is observed that higher values of M increase the fluid concentration significantly and boundary layer expands away from the wall. The explanation of this phenomenon is that the increasing M leads to an increase in concentration diffusion and results in thickening boundary layer.

Fig. 5 shows the behaviour of velocity profile for increasing value of Dufour number Du. The increasing values of Du does not affect the fluid velocity as well as velocity boundary layer thickness.

Fig. 6 shows the behaviour of temperature profile for increasing value of Dufour number Du. It is observed that higher values of Du increase the fluid temperature significantly and boundary layer expands away from the wall. The explanation of this phenomenon is that the increasing Du leads to an increase in thermal diffusion and results in thickening boundary layer.

Fig. 7 shows the behaviour of concentration profile for increasing values of Dufour number Du. It is observed that higher values of Du decrease the fluid concentration significantly and boundary layer shrinks toward the wall. The explanation of this phenomenon is that the increasing Du leads to a decrease in concentration diffusion and results in thinning boundary layer.

Fig. 8 shows the behaviour of velocity profile for increasing value of Soret number Sr. The increasing values of Sr do not affect the fluid velocity as well as velocity boundary layer thickness.

Fig. 9 shows the behaviour of temperature profile for increasing value Soret number Sr. It is observed that higher values of Sr, decrease the fluid temperature significantly and boundary layer shrinks towards the wall. The explanation of this phenomenon is that the increasing Sr leads to a decrease in thermal diffusion and results in thinning boundary layer.

Fig. 10 shows the behaviour of concentration profile for increasing values of Soret number Sr. It is observed that higher values of Sr, increase the fluid concentration significantly and boundary layer expands away from the wall. The explanation of this phenomenon is that the increasing Sr leads to a increase in concentration diffusion and results in thickening boundary layer.

Table 2. Comparison of effect of Sr and M on $f''(0)$

K1=0.2; Fs=0.2; Pr=0.7; Du=0.2; R=0.2; n1=0.5; Sc=0.22; Kr=0.2;			
Sr	**M=0.5,** $f''(0)$	**M=1.0,** $f''(0)$	**M=1.5,** $f''(0)$
0.0	-2.129453637589066	-2.206311687842895	-2.280583896032681
0.5	-2.129453637589066	-2.206311687842895	-2.280583896032681
1.0	-2.129453637589066	-2.206311687842893	-2.280583896032681
1.5	-2.129453637589066	-2.206311687842893	-2.280583896032681
2.0	-2.129453637589066	-2.206311687842893	-2.280583896032681
2.5	-2.129455186461798	-2.206313699977524	-2.280585969522976
3.0	-2.129453707532143	-2.206312080949249	-2.280584213503552
3.5	-2.129453588861189	-2.206311960402409	-2.280584091911233
4.0	-2.129453535186276	-2.206311922336846	-2.280584055071427
4.5	-2.129457428652740	-2.206316351637782	-2.280589074535067

The variations of the physical quantities of engineering importance, that is, the local Skin-friction coefficient C_f and the local Nusselt number Nu_x and the local Sherwood number Sh_x for different values of, Du, and Sr are tabulated in Tables 2 to 7.

Table 3. Comparison of effect of Sr and M on $-\theta'(0)$

K1=0.2; Fs=0.2; Pr=0.7; Du=0.2; R=0.2; n1=0.5; Sc=0.22; Kr=0.2;			
Sr	**M=0.5,** $-\theta'(0)$	**M=1.0,** $-\theta'(0)$	**M=1.5,** $-\theta'(0)$
0.0	0.472442529888213	0.461072323592159	0.450566493344804
0.5	0.478039613444985	0.466555761136498	0.455940869977051
1.0	0.483802220334626	0.472202569610289	0.461476733757687
1.5	0.489738018566573	0.478020554349210	0.467181476522984
2.0	0.495855477789990	0.484017946318595	0.473063274256170
2.5	0.502163165029037	0.490203275883486	0.479130923275693
3.0	0.508670767800704	0.496586212351175	0.485393766932293
3.5	0.515388013386731	0.503176396860135	0.491861414964914
4.0	0.522325874992461	0.509984584780638	0.498544547477804
4.5	0.529495526524369	0.517022095143440	0.505454405589978

Table 4. Comparison of effect of Sr and M on $-\phi'(0)$

K1=0.2; Fs=0.2; Pr=0.7; Du=0.2; R=0.2; n1=0.5; Sc=0.22; Kr=0.2;			
Sr	**M=0.5,** $-\phi'(0)$	**M=1.0,** $-\phi'(0)$	**M=1.5** $-\phi'(0)$,
0.0	0.368294623429481	0.363992496826957	0.360044410991088
0.5	0.330162007573604	0.326888416800299	0.323897457048161
1.0	0.290867992858419	0.288644863023714	0.286632160734045
1.5	0.250358453138480	0.249208293973472	0.248195675430645
2.0	0.208575764364092	0.208521818939670	0.208531742904141
2.5	0.165458483511769	0.166524647317131	0.167580250371985
3.0	0.120940813913980	0.123151708416886	0.125276928555141
3.5	0.074952941213480	0.078333949017345	0.081553468139781
4.0	0.027419815303066	0.031997137367145	0.036336439393004
4.5	-0.021738362244118	-0.015937737287444	-0.010452312287148

Table 5. Comparison of effect of Du and M on $f''(0)$

K1=0.2; Fs=0.2; Pr=0.7; R=0.2; n1=0.5; Sc=0.22; Kr=0.2; Sr=0.8;			
Du	**M=0.5,** $f''(0)$	**M=1.0,** $f''(0)$	**M=1.5,** $f''(0)$
0.0	-2.129453637589066	-2.206311687842893	-2.280583896032681
0.5	-2.129453637589066	-2.206311687842895	-2.280583896032681
1.0	-2.129453612672262	-2.206311904759494	-2.280584039350451
1.5	-2.129453544888521	-2.206311918017333	-2.280584091865871
2.0	-2.129454071068507	-2.206312465071568	-2.280586143756926
2.5	-2.129454780242731	-2.206313273666490	-2.280583896032681
3.0	-2.129453637589064	-2.206311687842895	-2.280583896032681
3.5	-2.129453637591982	-2.206311687838796	-2.280583896043238
4.0	-2.129453637591982	-2.206311687838796	-2.280583896043231
4.5	-2.129453637591379	-2.206311687847275	-2.280583896042264

Table 6. Comparison of effect of Du and M on $-\theta'(0)$

K1=0.2; Fs=0.2; Pr=0.7; R=0.2; n1=0.5; Sc=0.22; Kr=0.2; Sr=0.8;			
Du	**M=0.5, $-\theta'(0)$**	**M=1.0, $-\theta'(0)$**	**M=1.5, $-\theta'(0)$**
0.0	0.515992976471438	0.504274705948937	0.493431930444854
0.5	0.426830347245987	0.415508838724430	0.405056510023779
1.0	0.327171381150390	0.316179396763918	0.306060907830782
1.5	0.214977134466426	0.204217464801666	0.194349239308821
2.0	0.087593502304750	0.076929226569302	0.067191172224133
2.5	-0.058520927932485	-0.069281459604498	-0.079062762521477
3.0	-0.228233868728730	-0.239359376262187	-0.249426118555875
3.5	-0.428475392254226	-0.440345879517772	-0.451048767845028
4.0	-0.669563433252605	-0.682726068759179	-0.694575323359925
4.5	-0.967737602385723	-0.983002791204020	-0.996764961855174

Table 7. Comparison of effect of Du and M on $-\phi'(0)$

K1=0.2; Fs=0.2; Pr=0.7; R=0.2; n1=0.5; Sc=0.22; Kr=0.2; Sr=0.8 ;			
Du	**M=0.5, $-\phi'(0)$**	**M=1.0, $-\phi'(0)$**	**M=1.5 $-\phi'(0)$,**
0.0	0.301581364687369	0.298955773380282	0.296569970872321
0.5	0.314903105944613	0.312229192204953	0.309793624724648
1.0	0.329891776757534	0.327180627027648	0.324704578958220
1.5	0.346886521721831	0.344154149461420	0.341651300904889
2.0	0.366331137806846	0.363600263949214	0.361090393223269
2.5	0.388820639663608	0.386123317034153	0.383635535231300
3.0	0.415175889413641	0.412557483456373	0.410132450770526
3.5	0.446569248715833	0.444094490292255	0.441791835413839
4.0	0.484752115132033	0.482514869809145	0.480422092562419
4.5	0.532490094469384	0.530630033314054	0.528879392495182

Table 2 shows zigzag variation in the value of skin friction with the increase in the value of Sr keeping the value of M fix. But for fix value of Sr, with the increase in the value of M, the value of skin friction decreases.

Table 3 shows for fix value of M, as Sr increases the Nusselt number increases. Also for fix value of Sr as the value of M increases, the value of Nusselt number decreases.

Table 4 shows for fix value of M, as Sr increases the Sherwood number decreases. Also for fix value of Sr, as the value of M increases the Sherwood number decreases.

Table 5 shows zigzag variation in the value of skin friction with the increase in the value of Du keeping the value of M fix. But for fix value of Du, with the increase in the value of M, the value of Skin friction decreases.

Table 6 shows for fix value of M, as Du increases the Nusselt number decreases. Also for fix value of Du as the value of M increases, the value of Nusselt number decreases.

Table 7 shows for fix value of M, as Du increases the Sherwood number increases. Also for fix value of Du, as the value of M increases the Sherwood number decreases.

5 Conclusion

In the paper, we discussed the numerically the Soret and Dufour effects on MHD free convective incompressible, Newtonian fluid flow over non linearly stretching sheet with radiation and chemical reaction, through a non-Darcy porous medium, where stretching velocity of sheet varies nonlinearly with distance from the origin and, temperature and concentration vary non-linearly in the boundary layer region. From the result and discussion our conclusions are as follows.

Figs. 2 to 10 shows with the increase in the value of η , all velocity profile $f'(\eta)$, temperature profile $\theta(\eta)$, and concentration profile $\phi(\eta)$ decrease.

Fig. 2 shows the increase in M decreases fluid velocity and results in thinning boundary layer.

Figs. 3 and 6 show the increasing M, Du leads to increase in thermal diffusion and results in thickening boundary layer.

Figs. 4 and 10 show the increasing values of M, and Sr, increase the fluid concentration as well as concentration boundary layer thickness.

Fig. 7 shows the increasing values of Du, decrease the fluid concentration as well as concentration boundary layer thickness.

Fig. 9 shows the increasing Sr, leads to a decrease in thermal diffusion and results in thinning boundary layer.

Figs. 5 and 8 show the increasing value of Du, and Sr, does not affect the fluid velocity as well as velocity boundary layer thickness.

Tables 2 and 5 show there is zigzag variation in the value of skin friction with the increases in the value of Sr and Du respectively for fix value of M. And for fix value of Sr or Du, skin-friction decreases with the increase in the value of M.

Table 3 show there is increase in the value of Nusselt number with the increases in the value of Sr for fix value of M. And for fix value of Sr, Nusselt number decreases with the increase in the value of M.

Table 4 show there is decrease in the value of Sherwood number with the increases in the value of Sr for fix value of M. And for fix value of Sr, Sherwood number decreases with the increase in the value of M.

Table 6 shows there is decrease in the value of Nusselt number with the increases in the value of Du for fix value of M. And for fix value of Du, Nusselt number decreases with the increase in the value of M.

Table 7 shows there is increase in the value of Sherwood number with the increases in the value of Du, for fix value of M. And for fix value of Du, Sherwood number decreases with the increase in the value of M.

Competing Interests

Authors have declared that no competing interests exist.

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