NUMERICAL STUDY OF DUFOUR AND SORET EFFECTS ON FORCED CONVECTIVE NON-NEWTONIAN POWER LAW FLUID PAST A CONTINUOUSLY MOVING STRETCHING SHEET

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Abstract

In this present study the heat and mass transfer characteristics of forced convection about a stretching sheet is considered taking into account the chemical reaction, heat generation, thermal radiation, viscous dissipation and Dufour/Soret effects. The stretching sheet is assumed to continuously moving with a power-law velocity and maintaining a uniform surface heat flux. The governing equations of continuity, momentum, energy and concentration are transformed into non-linear ordinary differential equations, using similarity transformations and then solved by sixth order Runge-Kutta integration scheme with Nachtsheim-Swigert shooting iterative technique. The combined effects of Dufour and Soret was investigated and presented graphically with controlling pertinent physical parameters. The local Skin-friction coefficient, local Nusselt number and local Sherwood number are also derived and discussed numerically.

Keywords: Dufour and Soret effects, Forced Convection, Non-Newtonian power-law fluid, Skin friction, Nusselt number, Sherwood number.

Introduction

Forced convection should be considered as one of the main methods of useful heat transfer as significant amounts of heat energy can be transported very efficiently and this mechanism is found very commonly in everyday life, including central heating, air conditioning, heating and cooling of parts of the body by blood circulation, steam turbines and designing or analyzing heat exchangers, pipe flow, and flow over a plate at a different temperature than the stream. A simple example of forced convection would be

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melting an ice cube with warm water. Although some types of artificial forced convection are far more efficient than free convection, as they are not limited by natural mechanisms. For instance, a convection oven works by forced convection, as a fan which rapidly circulates hot air forces heat into food faster than would naturally happen due to simple heating without the fan. The heat, mass and momentum transfer of non-Newtonian power law fluid on stretching sheets are important because of their wider applications to polymer technology, metallurgy, many mechanical forming processes, such as extrusion, melt-spinning, cooling, manufacture of plastic and rubber sheets, glass blowing, continuous casting and spinning of fibers etc. Dufour effect is the inverse phenomenon of thermal diffusion. If two chemically different nonreacting gases or liquids, which were initially at the same temperature, are allowed to diffuse into each other, then there arises a difference of temperatures in the system. In gases this difference can reach several degrees (for example, for N_2 with H_2) while in liquids, it measures approximately 10^3°C. The difference in temperatures is retained if a concentration gradient is maintained. Soret effect (thermo diffusion) is the diffusion of material in an unevenly heated mixture of gases or a solution caused by the presence of a temperature gradient in the system. This normally applies to liquid mixtures, which behave according to different, less well-understood mechanisms than gaseous mixtures. It has been utilized for isotope separation and in mixture between gases with very light molecular weight (H_2, He) and of medium molecular weight (N_2, air). Both Soret and Dufour effects are significant when density differences exist in the flow regime.

The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists. Chemical reactions can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single-phase volume reaction. A reaction is said to be of first order, if the rate of reaction is directly proportional to the concentration itself. In many chemical engineering processes, there occur the chemical reaction between a foreign mass and the fluid in which the plate is moving. In view of heat and mass transfer, chemical reactions have numerous and wide-ranging applications in various fields like polymer processing industry in particular in manufacturing process of artificial film and artificial fibers and in some applications of dilute polymer solution.

Some literature surveys and reviews of pertinent work in this field are documented by (Howell et al., 1997) analyzed momentum and heat transfer on a continuous moving surface in a power law fluid. (Rahman et al., 2008) investigated MHD forced convective flow of a micropolar fluid past a non-linear stretching sheet with a variable viscosity. (Anderson et al., 1992) and (Mahmoud et al., 2006) adopted the non-linearity relation as power-law dependency of shear stress on rate of strain. (Chen, 2008) studied the effects of magnetic field and suction/injection on the flow of power-law non-Newtonian fluid over a power law stretched sheet subject to a surface heat flux. (O. D. Makinde et al., 2012) studied chemically-reacting hydromagnetic boundary layer flow with Soret/Dufour effects and a convective surface boundary condition. (M. J. Subhakar et al., 2012) analyzed Soret and Dufour effects on MHD convective flow of heat and mass transfer over a moving non-isothermal vertical plate with heat generation/absorption. (M. S. Alam et al., 2006) investigated Dufour and Soret effects on unsteady MHD free convection and mass transfer flow past a vertical porous plate in a porous medium.(Mahdy, 2010) studied Soret and Dufour effect on double diffusion mixed convection from a vertical surface in a porous medium saturated with a non-Newtonian fluid. (Chen et al., 2010) analyzed Soret and Dufour effects on free convection flow of non-Newtonian fluids along a vertical plate embedded in a porous medium with thermal radiation. (Abreu et.al., 2006) discussed about boundary layer flows with Dufour and Soret effects on Forced and natural convection. (B. Lavanya and A. Leela Ratnam, 2014) studied the Dufour and Soret effects on steady MHD free convective flow past a vertical porous plate embedded in a porous medium with chemical reaction, radiation heat generation and viscous dissipation.

Numerical and graphical computations for the velocity, temperature and concentration profiles have been carried out of different values Dufour (Du) and Soret (Sr) numbers only in presence of Suction parameter (f_w), Prandtl number (Pr), Magnetic parameter (M), Radiation parameter (N), Heat source parameter (Q), Schmidt number (Sc), Eckert number (Ec), velocity index (p), power-law fluid index (n)and chemical reaction (Kr). The local skin friction coefficient, local Nusselt number and local Sherwood number have been obtained to investigate more practical and physical effect of Dufour (Du) and Soret (Sr) numbers on different non-Newtonian fluids. Finally the effects of Dufour (Du) and Soret (Sr) numbers are investigated for shear thinning (e.g. fruit juice, shampoo etc.), Newtonian (e.g. water, air etc.) and shear thickening (e.g. wet sand, concentrated starch suspensions etc.) fluids.

Mathematical Formulation

When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of a more intricate nature. An energy flux can be generated not only by temperature gradients, but also by concentration gradients. This caused by a concentration gradient is termed the diffusion-thermo (Dufour) effect and mass fluxes can be created by temperature gradients embodies the thermal-diffusion (Soret) effect. Here we analyze the Soret and Dufour effects in the flow field. Let us consider a steady 2D MHD forced convective laminar boundary layer flow of a viscous incompressible, electrically conducting fluid obeying the power-law model along a permeable stretching sheet with the influence of chemical reaction, thermal radiation, heat generation and viscous dissipation. The origin is located at the slit through which the sheet is drowning through the fluid medium. The flow is assumed to be in the x-direction, which is taken along the sheet and y-axis is normal to it. Two equal and opposite forces are introduced along the x-axis, so that the sheet is stretched keeping the origin fixed. The plate is maintained at a constant temperature T_w and the ambient temperature is T_{∞}. This continuous sheet is assumed to move with a velocity according to a power-law form, i.e. $u_w = Cx^p$. The fluid is considered to be gray, absorbing emitting radiation but non-scattering medium and the Rosseland approximation is used to describe the radiative heat flux in the energy equation.

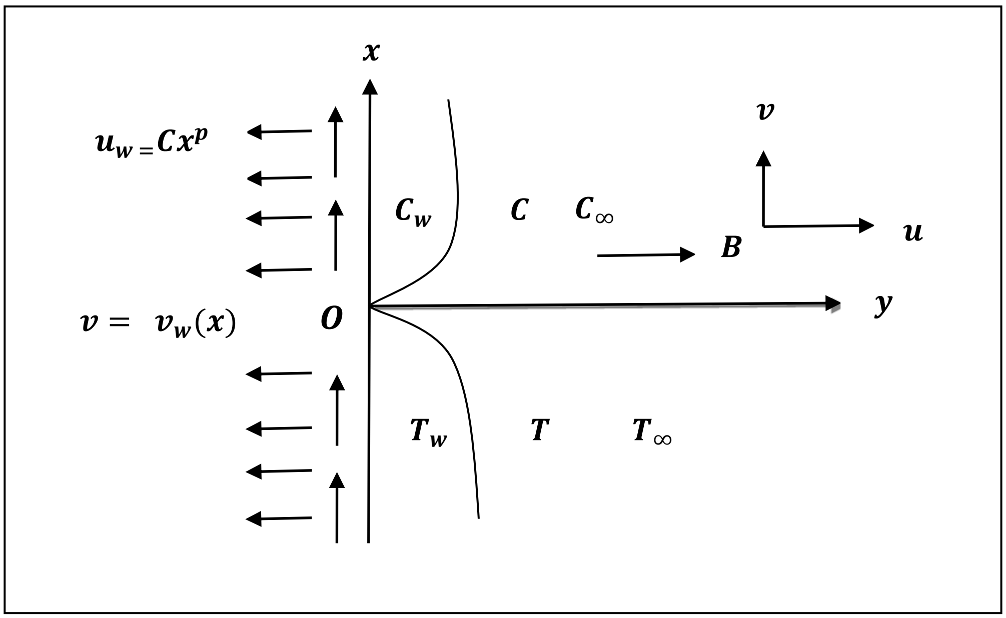

Fig. 1. Flow configuration and coordinate system

The radiative heat flux in the x-direction is considered negligible in comparison to the y-direction. A strong magnetic field B is applied in y-direction. The magnetic Reynolds number is assumed to be small so that induced magnetic field is negligible. The electrical current flowing in the fluid gives rise to an induced magnetic field if the fluid were an electrical insulator, but here have taken the fluid to be the electrically conducting. Hence, the applied magnetic field B Plays a role which gives rise to magnetic forces $F_x = \frac{\sigma B u}{\rho}$ in the x-direction. Under the usual boundary layer approximation, the flow, heat and mass transfer are governed by the following equations:

Continuity Equation: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$ (1)

Momentum Equation: $u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{K}{\rho}\frac{\partial}{\partial y}\left(\left|\frac{\partial u}{\partial y}\right|^{n-1}\frac{\partial u}{\partial y}\right) - \frac{\sigma B^2 u}{\rho}$ (2)

Energy Equation: $u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}(T - T_\infty) - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} + \frac{K}{\rho C_p}\left(\left|\frac{\partial u}{\partial y}\right|^{n-1}\frac{\partial u}{\partial y}\right)^2 + \frac{D_m K_T}{\rho C_p C_s}\frac{\partial^2 C}{\partial y^2}$ (3)

Concentration Equation: $u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} + kr'(C - C_\infty)$ (4)

Where u and v are the velocity components along x and y-directions respectively, T be the temperature of the fluid layer, ν is the kinematic viscosity, ρ is the density, σ is the electric conductivity, κ is the thermal conductivity, B is the uniform magnetic field, C_p is the specific heat at constant pressure, α is the thermal diffusivity, q_r is the radiative heat flux, K is the consistency coefficient, n is the flow behavior/power-law fluid index, D_m is mass diffusivity, K_T is thermal diffusion ratio, C_s is concentration susceptibility, kr' is chemical reaction and T_m is mean fluid temperature. The radiative heat flux q_r is described by the Rosseland approximation such that,

$$q_r = -\frac{4\sigma_1}{3k_1}\frac{\partial T^4}{\partial y} \quad (5)$$

Where σ_1 is the Stefan-Boltzman constant and k_1 is the Rosselend mean absorption coefficient. It is assumed that the temperature differences within the flows are sufficiently small such that T^4 in a Taylor series about the free steam temperature T_∞ and then neglecting higher-order terms which results the approximation, $T^4 \approx 4T_\infty^3 - 3T_\infty^4$ (6)

Using (5) and (6) we have, $\frac{\partial q_r}{\partial y} = -\frac{16\sigma_1 T_\infty^3}{3\kappa_1}\frac{\partial^2 T}{\partial y^2}$ (7)

Energy Equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}(\mathrm{T} - \mathrm{T}_\infty) + \frac{1}{\rho C_p}\frac{16\sigma_1 T_\infty^3}{3k_1}\frac{\partial^2 T}{\partial y^2} + \frac{K}{\rho C_p}\left(\left|\frac{\partial u}{\partial y}\right|^{n-1}\frac{\partial u}{\partial y}\right)^2 + \frac{D_m K_T}{\rho C_p C_s}\frac{\partial^2 C}{\partial y^2} \quad (8)$$

The appropriate boundary conditions are:

$$\left.\begin{array}{ll} u_w = Cx^p,\ \ v = v_w,\ \ \frac{\partial T}{\partial y} = -\frac{q_w}{\kappa},\ \ C = C_\infty + bx & at\ \ y = 0\ ,\ \ x > 0 \\ u_w \to 0,\ \ T \to T_\infty,\ \ C \to C_\infty & as\ \ y \longrightarrow \infty \end{array}\right\} \quad (9)$$

Where v_w is the surface mass flux and q_w is the surface heat flux. It should be noted that positive p indicates that the surface is accelerated while negative p implies that surface is decelerated from the slit. Positive v_w is for fluid injection and negative v_w for fluid suction at the sheet surface. The last term in the energy equation (3) has been introduced to investigate the Dufour effect and last term in the concentration equation (4) for Soret effect respectively.

In order to obtain a similarity solution of the problem, introduce a similarity parameter $\delta(x)$, such that $\delta(x)$ is a length scale. Introducing the following dimensionless quantities, we have,

$$\eta = \frac{y}{\delta(x)} = \left(\frac{C^{2-n}}{K/\rho}\right)^{1/(n+1)} x^{\{p(2-n)-1\}/(n+1)} y \tag{10}$$

$$\psi = \left(\frac{C^{1-2n}}{K/\rho}\right)^{-1/(n+1)} x^{\frac{\{p(2n-1)+1\}}{n+1}} f(\eta) \tag{11}$$

$$\theta(\eta) = \frac{(T-T_\infty) Re_x^{1/(n+1)}}{q_w x/\kappa} \tag{12}$$

$$\phi(\eta) = \frac{C-C_\infty}{bx} \tag{13}$$

Where ψ is the stream function, η is the dimensionless distance normal to the sheet, f is the dimensionless stream function and θ and ϕ is the dimensionless fluid temperature and concentration respectively. The stream function ψ satisfy the continuity equation (1), so we get the velocity components u and v as follows.

$$u = \frac{\partial \psi}{\partial y} = u_w f'(\eta) \tag{14}$$

$$v = -\frac{\partial \psi}{\partial x} = -u_w Re_x^{-\frac{1}{(n+1)}} \left[\frac{\{p(2n-1)+1\}}{(n+1)} f(\eta) + \frac{\{p(2-n)-1\}\eta}{(n+1)} f'(\eta)\right] \tag{15}$$

Introducing similarity variables, we get the following:

Momentum Equation: $(|f''|^{n-1} f'')' + \frac{\{p(2n-1)+1\}}{(n+1)} f f'' - p(f')^2 - Mf' = 0$ (16)

Energy Equation: $\frac{3N+4}{3N\mathrm{Pr}}\theta'' + \frac{\{p(2-n)-1\}}{(n+1)} f'\theta + \frac{\{p(2n-1)-1\}}{(n+1)} f\theta' + Q\theta +$

$Ec(|f''|^{n-1} f'')^2 + Du\phi'' = 0$ (17)

Concentration Equation: $\frac{1}{Sc}\phi'' + Sr\theta'' + \frac{\{p(2n-1)+1\}}{(n+1)} f\phi' - f'\phi + kr\phi = 0$ (18)

The transformed boundary conditions are:

$$\left.\begin{array}{ll} f' = 1,\ \ f = \frac{n+1}{p(2n-1)+1} f_w,\ \ \theta' = -1,\ \ \phi = 1 & at\ \eta = 0 \\ f' \to 0,\ \ \theta \to 0,\ \ \phi \to 0 & as\ \eta \to \infty \end{array}\right\} \tag{19}$$

Where $f_w = -\frac{v_w}{u_w} Re_x^{\frac{1}{(n+1)}}$ is the suction parameter, $M = \frac{\sigma B^2 x}{\rho u_w}$ is the magnetic field parameter, $Re_x = \frac{\rho u_w^{2-n} x^n}{K}$ is the local Reynolds number, $\mathrm{Pr} = \frac{x u_w}{\alpha} Re_x^{\frac{-2}{(n+1)}}$ is the generalized Prandtl number, $N = \frac{\kappa \kappa_1}{4\sigma_1 T_\infty^3}$ is the radiation parameter, $Q = \frac{Q_0 x}{u_w \rho C_p}$ is the heat source parameter, $Ec = \frac{\left(u_w^{\frac{n+1}{2}}\right)^2}{C_p . \frac{q_w}{k} x^n} Re_x^{\frac{n}{n+1}}$ is the Eckert number, $Du = \frac{D_m K_T b k}{\rho C_p C_s q_w}\left(\frac{u_w^{3(1-n)} Re_x}{(kx/\rho)^2}\right)^{\frac{1}{n+1}}$ is the Dufour number, $Sc = \frac{u_w x^2}{D_m} Re_x^{\frac{-2}{(n+1)}}$ is the local Schmidt number, $Sr = \frac{D_m K_T}{b T_m} \frac{q_w}{\kappa} \frac{Re_x^{\frac{1}{(n+1)}}}{x u_w}$ is the Soret number and $kr = \frac{k r' x}{u_w}$ is the chemical reaction parameter.

The parameters of engineering interest for the present problem are the skin-friction coefficient, the local Nusselt number and the local Sherwood number, which are given respectively by the following expressions.

The wall shear stress, $\tau_w = \mathrm{K}\left(\left|\frac{\partial \mathrm{u}}{\partial \mathrm{y}}\right|^{\mathrm{n}-1} \frac{\partial \mathrm{u}}{\partial \mathrm{y}}\right)\Big|_{\mathrm{y}=0} = \rho u_w{}^2 Re_x{}^{-\frac{1}{(n+1)}} |f''(0)|^{n-1} f''(0).$

So, Skin friction coefficient, $\mathrm{C_f} = \frac{\tau_w}{\frac{1}{2}\rho u_w{}^2}$ or, $Re_x^{\frac{1}{(n+1)}} \mathrm{C_f} = 2|f''(0)|^{n-1} f''(0).$

The local Nusselt number, $Nu_x = \frac{hx}{k} = \frac{Re_x^{1/(n+1)}}{\theta(0)}$ or, $Re_x^{\frac{-1}{(n+1)}} Nu_x = \frac{1}{\theta(0)}$ and local Sherwood number, $Sh = \frac{x M_w}{D_m (C - C_\infty)}$ or, $Sh Re_x^{\frac{-1}{(n+1)}} = -\phi'(0).$

Here, skin friction coefficient (C_f), local Nusselt number (Nu_x) and local Sherwood number (Sh) are proportional to $2|f''(0)|^{n-1} f''(0), 1/\theta(0)$ and $-\phi'(0)$respectively.

Results and discussion

For Pseudo plastic fluids (Power law fluid index, $n < 1$):

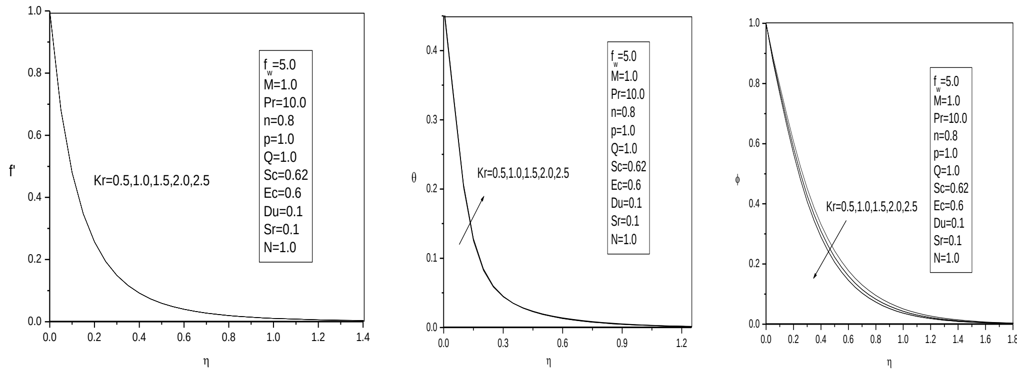

Fig. 2. Velocity, temperature and concentration profiles for different values of kr

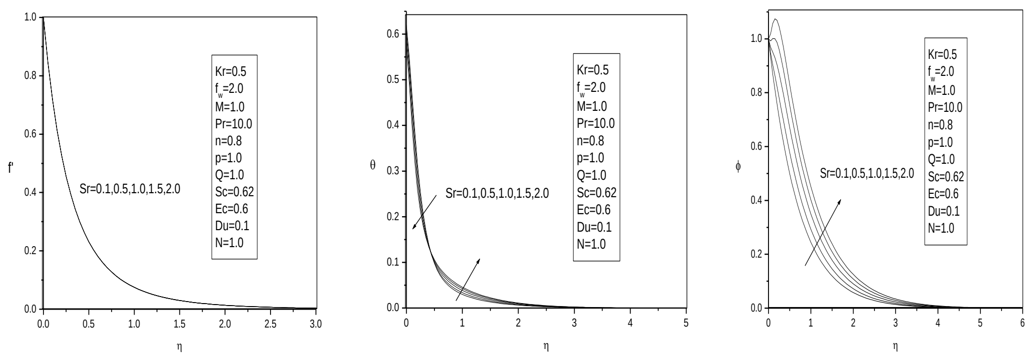

Fig. 3. Velocity, temperature and concentration profiles for different values of Sr

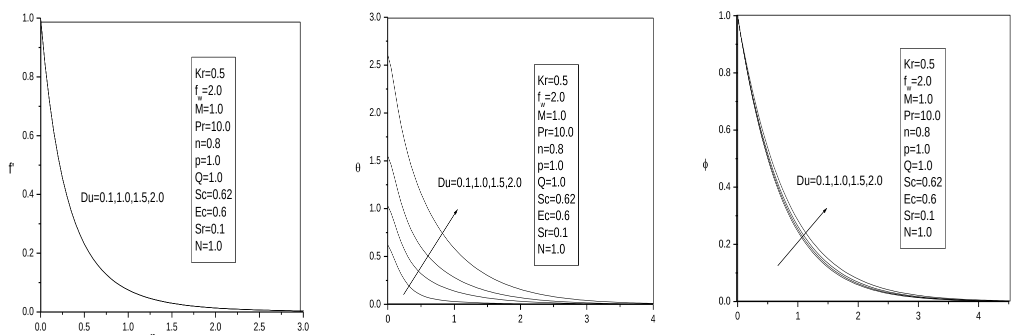

Fig. 4. Velocity, temperature and concentration profiles for different values of Du

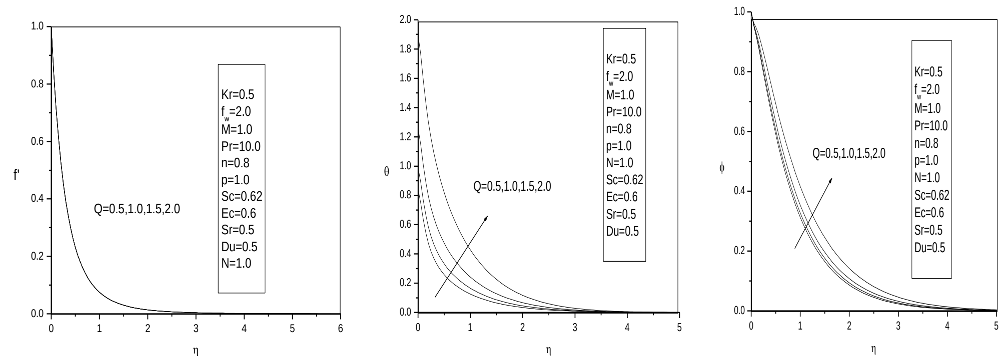

Fig. 5. Velocity, temperature and concentration profiles for different values of Q

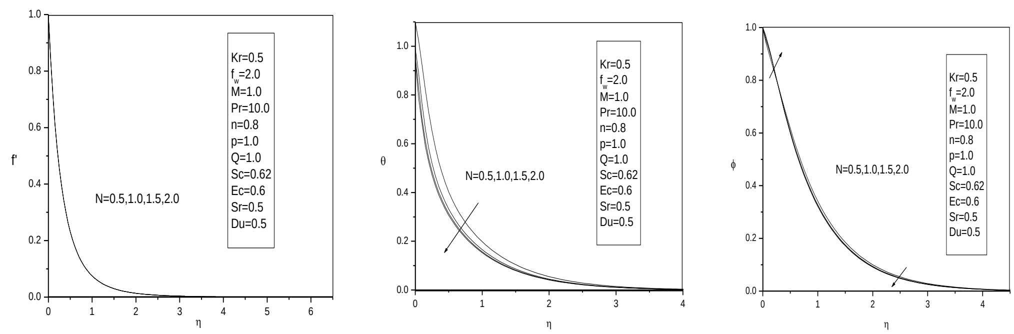

Fig. 6. Velocity, temperature and concentration profiles for different values of N

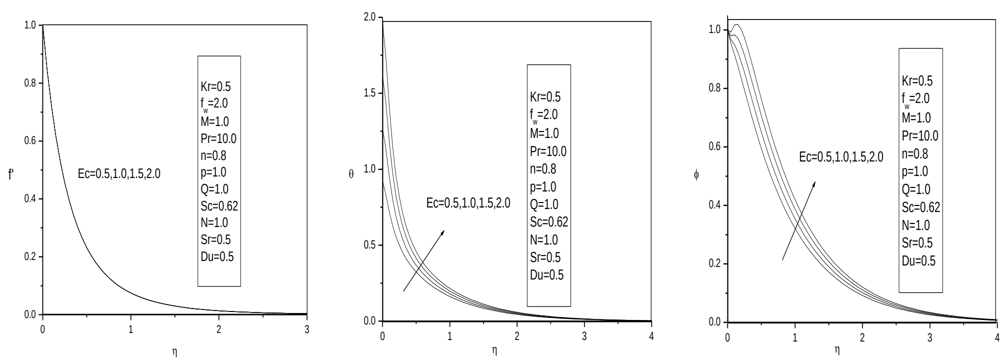

Fig. 7. Velocity, temperature and concentration profiles for different values of Ec

The effects of the chemical reaction parameter Kr on the velocity, temperature and concentration profiles are shown in Fig. 2. As the chemical reaction parameter (Kr) increases the concentration decreases but temperature increases.

From Fig. 3, it is visualized that the velocity remains unchanged for the increase of the Soret number (Sr). The momentum boundary layer thickness remains unaffected with the increase of the Soret number (Sr). The temperature profiles first start to increase and then begin to decrease. We indicate a cross flow here near $\eta = 0.5$. There is a very sharp rise on concentration profiles near the stretching sheet that indicates that Soret number (Sr) controls concentration boundary layer which has powerful mutual interacting effect on temperature profiles of the flow field.

Fig. 4 shows that, it is observed that the velocity remains unchanged i.e. the momentum boundary layer thickness remains unaffected with the increase of the Dufour number (Du). The temperature and concentration profiles rapidly increase with the Dufour number (Du). The heat and mass transfer rate are strongly influenced with the increasing Dufour number. So, the temperature and concentration of the flow field can be controlled with Dufour number (Du). This explains by the fact that Dufour number (Du) shows excellent mutual interaction between temperature and concentration of the flow field which plays a vital role in assisting the flow and able to increase mass and thermal energy in the boundary layer.

Fig. 5 depict the velocity, temperature and concentration profiles for different values of the heat generation parameter (Q). It is noticed that an increase in the heat generation parameter (Q) results in increase in concentration and temperature within the boundary layer. This is due to the fact that as more heat is generated within the fluid, the fluid temperature and concentration increases leading to a sharp inclination of the heat and mass gradient between the plate surface and the fluid.

The effects of the radiation parameter (N) are shown in Fig. 6. It is seen that the temperature decreases as the radiation parameter (N) increases. This result qualitatively agrees with expectations, since the effect of radiation is to decrease the rate of energy transport to the fluid, thereby decreasing the temperature of the fluid. The cross flow is seen on concentration profile with the increase of radiation parameter (N).

By analyzing Fig. 7, it is clearly revealed that the effect of Eckert number Ec is to increase both the temperature and concentration distributions in the flow region. This is due to the face that the heat and mass energy is stored due to the fluid friction.

Table. 1. Skin friction coefficient$\left(C_f\right)$, local Nusselt number(Nu_x) and local Sherwood number (Sh) different values of Dufour number $(Du =$ 0.5,1.0,1.5,2.0)

n	$Re_x^{\frac{1}{(n+1)}} C_f$	$Re_x^{\frac{-1}{(n+1)}} Nu_x$	$Sh Re_x^{\frac{-1}{(n+1)}}$
Pseudo plastic fluid, $n = 0.8$	-5.3501358	0.3180862	1.4603213
Newtonian fluid $n = 1.0$	-5.4640998	0.3239829	1.4905085
Dilatants fluid, $n = 1.2$	-5.5700522	0.3267715	1.5144335

Table. 2. Skin friction coefficient $\left(C_f\right)$, local Nusselt number (Nu_x) and local Sherwood number (Sh) different values of Soret number $(Sr =$ 0.5,1.0,1.5,2.0)

n	$Re_x^{\frac{1}{(n+1)}} C_f$	$Re_x^{\frac{-1}{(n+1)}} Nu_x$	$Sh Re_x^{\frac{-1}{(n+1)}}$
Pseudo plastic fluid, $n = 0.8$	-10.5915861	2.2676260	1.7153279
Newtonian fluid $n = 1.0$	-10.7445485	2.4123810	1.7465069
Dilatants fluid, $n = 1.2$	-10.8919488	2.4287932	1.7746589

Table. 1 and Table. 2 show the effects of Dufour number (Du) and Soret number (Sr) on skin friction coefficient $\left(C_f\right)$, local Nusselt number (Nu_x) and local Sherwood number(Sh) which remain unchanged with the increase of Dufour number (Du) and Soret number (Sr). With the increase of power-law fluid index (n), skin friction coefficient $\left(C_f\right)$ decreases slowly. But the local Nusselt number (Nu_x) and local Sherwood number (Sh) both increase significantly with the power-law fluid index (n). So, temperature and concentration of the flow field are affected by the Dufour number (Du) and Soret number (Sr).

Conclusion

In this present analysis, forced convection heat and mass transfer along a continuously moving stretching sheet embedded in a power-law fluid in presence of the

Soret and Dufour effects has been considered. It can be concluded that in case of shear thinning ($n = 0.8$), Newtonian ($n = 1.0$) and shear thickening ($n = 1.2$) fluids, the skin friction coefficient $\left(C_f\right)$ decreases slowly but both local Nusselt number (Nu_x) and local Sherwood number (Sh) increase for Dufour number (Du) and Soret number (Sr). So, the combined effects of thermal diffusion, diffusion thermo and the other embedded parameters can help controlling the flow kinematics and enhances both the heat and mass transfer process.

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Nomenclature

B	Magnetic field strength	Kr	Chemical reaction parameter	u, v	Velocity components along x and y directions respectively.
B_0	Magnetic induction.	M	Magnetic field parameter.	x, y	Dimensional coordinates along and normal to the plane respectively.
C	Constant.	n	Power-law fluid index.	Greek symbols	
C_p	Specific heat at constant pressure.	N	Radiation parameter.	α	Thermal diffusivity.
C_f	Skin Friction Coefficient	Nu_x	Local Nusselt number.	β	Volumetric coefficient of thermal expansion.
C_s	Concentration susceptibility.	p	Velocity index.	κ	Thermal conductivity.
D_m	Mass diffusivity.	Pr	Prandtl number.	μ	Dynamic viscosity.
Du	Dufour number.	q_r	Radiative heat flux.	ν	Kinematic viscosity.
Ec	Eckert number.	Sc	Schmidt number.	ρ	Density of the fluid.
f	Dimensionless stream function.	Sh	Local Sherwood number.	σ	Electric conductivity
f_w	Suction parameter.	Sr	Soret number.	σ_1	Stefan-Boltzman constant.
h	Convection heat transfer coefficient.	T	Dimensionless temperature.	τ_w	Local wall shear stress.
k_1	Mean absorption coefficient.	T_∞	Temperature away from the boundary layer	η	Similarity variable.
K	Consistency coefficient.	T_w	Temperature near the boundary layer.	ϕ	Dimensionless concentration.
K_T	Thermal diffusion ratio.	T_m	Mean fluid temperature.	ψ	Stream function.