RESEARCH ARTICLE OPEN ACCESS

Effect of Soret and Dufour Numbers on Chemically Reacting Powell-Eyring Fluid Flow over an Exponentially Stretching Sheet

K Bhagya Lakshmi*, V Sugunmama**, Janke V Ramana Reddy***
(Department Of Mathematics, Sri Venkateswara University, Tirupati-517502, India)
Corresponding Author : V Sugunamma

ABSTRACT
The aim of this paper is to study the heat and mass transfer in the boundary layer flow of an Eyring-Powell fluid due to an exponentially stretching sheet with chemical reaction and thermal radiation. By utilizing the similarity transformations, the governing equations are changed into a set of non-linear ordinary differential equations. The resulting equations are solved numerically by using bvp4c MATLAB package. The physical significance of different parameters on the velocity, temperature and concentration distributions as well as the skin friction coefficient, Nusselt number and Sherwood number is discussed through graphs and tables. The results indicate that the influence of Soret and Dufour numbers are significantly active in the study of non-Newtonian fluid flows. Also, the mixed convection parameter has an inverse relationship with thermal and concentration fields.
Keywords – Chemical reaction, Cross diffusion, Eyring-Powell fluid, Exponential stretching sheet, Thermal radiation.

Date of submission: 31-03-2018 Date of acceptance: 16-04-2018

NOMENCLATURE

B Magnetic field
B_0 Strength of the magnetic field
C Concentration of the fluid
C_0 Reference concentration
C_f Skin friction coefficient
C_p Specific heat at constant pressure
c_s Concentration susceptibility
C_w Species concentration at the surface
C_∞ Species concentration far away from the surface
D_m Diffusion coefficient
Du Dufour number
d Material fluid parameter
f' Dimensionless velocity
g Acceleration due to gravity
k Fluid thermal conductivity
k^* Rosseland mean absorption coefficient
Kr^* Dimensional chemical reaction parameter
Kr Dimensionless chemical reaction parameter
K_T Thermal diffusion ratio
L Characteristic length
m_w Surface mass flux
M Magnetic field parameter
Nu Nusselt number
$\Pr$ Prandtl number
q_r Radiative heat flux
q_w Surface heat flux
R Radiation parameter
Re_x Local Reynolds number
Sc Schmidt number
Sh Sherwood number
Sr Soret number
T Temperature of the fluid
T_0 Reference temperature
T_m Mean fluid temperature
T_w Temperature at the surface
T_∞ Temperature far away from the surface
u, v Velocity components in the x-, y-directions respectively
u_0 Reference velocity
u_w Stretching velocity of the sheet

Greek symbols

$\varepsilon, \delta, \beta$ Fluid parameters
η Similarity variable
μ Dynamic viscosity
β_T Thermal expansion coefficient
ν Kinematic viscosity
ρ Fluid density
σ Electrical conductivity
σ^* Stefan-Boltzmann constant
θ Dimensionless temperature
ϕ Dimensionless concentration
$\tau_{i,j}$ Shear stress component

τ_w Surface shear stress

λ Mixed convection parameter

I. INTRODUCTION

In recent years, a lot of researchers have been explored the flow analysis of non-Newtonian fluids. Many polymer solutions and molten polymers are non-Newtonian fluids such as starch suspensions, paint, shampoo, foods (ketchup, mayonnaise, soup, butter, jam, and yogurt), natural substances (magma, lava, extracts and gum), biological fluids (blood, saliva, semen) and slurries (plasters, lime and clay). These are various examples of practical applications of non-Newtonian fluid flow over a stretching surface. Erdogan and Imrak [1] studied some properties of unsteady unidirectional flows of a non-Newtonian fluid. Chandra *et al.* [2] discussed various types of non-Newtonian flow characteristics and its implication in engineering applications. Sarpkaya [3] analyzed the flow of non-Newtonian fluids with magnetic field. These types of flow attain special attention because of their active use in industrial applications, chemical engineering, biological and polymer processing.

The boundary layer flow of non-Newtonian fluid over a stretching surface has received unique attentiveness from the researchers because of its abundant significant applications such as metal spinning, metal extrusion, food processing, glass fiber and paper production, slurry transporting, cooling of the metallic plate in a cooling bath, continuous casting of metal and the extrusion of polymer sheet from a die. In view of all these numerous applications, huge number of researchers studied the non-Newtonian fluids over a stretching sheet. This stretching sheet is possibly linear, quadratic, power law, inclined, exponential and so on. Crane [4] examined the boundary layer flow of viscous fluid over a linear stretching surface. Rajagopal *et al*. [5] have extended the work of crane [4] and they discovered the solutions of equation of motion for the boundary layer flow past a stretching plate. Afterwards the features of flow over a stretching surface are pioneered by Siddappa and Abel [6]. Yurusoy and Pakdemirli [7] considered a problem to examine the motion of non-Newtonian fluid induced by stretching surface. They acquire an exact solution of the problem with the assistance of suitable similarity transformations. Hayat *et al.* [8] studied the unsteady unidirectional flows of some non-Newtonian fluids. Siddiqui *et al.* [9] studied the unsteady MHD flow of a non-Newtonian fluid due to eccentric rotations of a porous disk and a fluid at infinity.

Non-Newtonian fluids have promising applications in power industry, engineering science and technology. On the basis of this significance of non-Newtonian fluids, in 1944, Powell and Eyring [10] proposed an inventive fluid model known as Eyring-Powell fluid model. Despite the fact that this model is mathematically more difficult. Even though, it deserves special attention because of its distinct advantages over the non-Newtonian fluid models. Over the period of years, there has been a continuous development in the analysis of Powell-Eyring fluid. Initially, this model is deduced from the kinetic theory of fluids earlier than the experimental relation. In addition to that, it appropriately reduces to Newtonian behavior for low and high shear rates. In recent times, some effective investigations have been done on this fluid with diverse flow situations. Hayat *et al*. [11] studied the steady flow of a Powell-Eyring fluid over a moving surface with convective boundary conditions. The boundary layer flow of Powell-Eyring fluid over a linearly stretching sheet was analyzed by Javed *et al*. [12]. Malik *et al*. [13] discussed the impact of variable viscosity on Powell-Eyring fluid across a stretching cylinder. From this paper, it is identified that the thermal boundary layer decreases with the increasing values of Prandtl number. Panigrahi *et al*. [14] examined the influence of MHD on mixed convection boundary-layer flow of Powell-Eyring fluid over a nonlinear stretched surface. Akbar *et al.* [15] reported the impact of Lorentz force on Eyring-Powell fluid due to a stretching surface. Rahimi *et al*. [16] presented an analytical solution to the boundary layer flow of non-Newtonian liquid over a linear stretching sheet. They noticed that the temperature and thermal boundary layer thickness decreases when the values of fluid parameter are increases.

In recent times, knowledge in boundary layer flow with heat and mass transfer is paying attention to researchers because of its several important applications. In particular, the combined effect of heat and mass transfer plays a vital role in numerous engineering applications. Many researchers are inspired and still engaged with the discussion of heat and mass transfer effects in the flow over a stretching surface. Magyari *et al.* [17] studied the heat and mass characteristics of boundary layer flow. Chen [18] discussed the influence of frictional and Ohmic heating on MHD flow of Newtonian liquid past a vertical surface. Gupta and Gupta [19] extended the work of Chen [18] by including the effect of suction or blowing. Sagar and Dubey [20] studied the heat and mass transport effects on natural convective flow of non-Newtonian fluid with magnetic field.

The combined effects of heat and mass transfer problem with chemical reaction have importance in many processes. The widespread applications of such kind of problems can be found in the processes of drying, energy transfer in a wet cooling tower, evaporation at the surface of a body, damage of crops due to freezing, food processing, hot rolling, continuous casting of metal and spinning of fibers. So, such problems have received a special concentration by the researchers in recent years. The effect of radiation and chemical reaction on micropolar fluid flow over a surface with porous medium was analyzed by Singh and Kumar [21]. Reddy *et al.* [22] investigated the heat and mass transfer characteristics of chemically reacting casson fluid flow past a stretching sheet with magnetic field. Through this investigation, they observed that the chemical reaction parameter has a tendency to control the concentration field. Hayat *et al.* [23] analyzed the motion of a second grade fluid over a plate in the existence of chemical reaction. The heat and mass transfer effects on MHD flow due to stretching of surface with chemical reaction was reported by Kandasamy *et al.* [24]. By this article, it is seen that the temperature of the fluid increases and concentration of the fluid decreases with the increase of chemical reaction parameter. Mukhopadhyay and Bhattacharyya [25] presented an unsteady two-dimensional flow of a Maxwell fluid across a stretching sheet with the aid of chemical reaction. Krishna *et al.* [26] elucidated the flow of Powell-Eyring fluid past an inclined stretching sheet in the presence of radiation and chemical reaction.

It is also important in industrial and engineering applications to consider Soret (thermal-diffusion) and Dufour (diffusion-thermo) effects on flows. The heat and mass transfer simultaneously influencing each other that will cause the effect of cross-diffusion. The heat transfer caused by concentration gradient is called the diffusion-thermo or dufour effect. Mass transfer caused by temperature gradients is called soret or thermal-diffusion effect. Pal and Mondal [27] analyzed the combined effects of soret and dufour on time dependent mixed convection flow over a stretching sheet in the presence of thermal radiation and first-order chemical reaction. They observed that the temperature is strongly influenced by the dufour effect and the soret effect unveils less significance in temperature fields. The cross diffusion effect on non-Newtonian fluid flows over a permeable stretching sheet was reported by Khan and Sultan [28]. Sugunamma *et al.* [29] scrutinized the cross diffusion effect on the flow of casson fluid due to an exponential stretching sheet. They stated that dufour and soret numbers have a tendency to inflate the concentration and temperature fields. Reddy *et al* [30] analyzed the influence of cross diffusion on MHD non-Newtonian fluids flow over a stretching sheet.

In the present investigation, we analyzed the effect of thermo diffusion and diffusion thermo on the flow of Powell-Eyring fluid over an exponential stretching surface with chemical reaction and thermal radiation. The governing partial differential equations are reduced into nonlinear ordinary differential equations by suitable similarity transformation. Graphs are drawn for the flow fields (velocity, temperature and concentration) with the help of MATLAB packages. Also the physical quantities for the flow parameters are examined and presented via tables.

II. MATHEMATICAL FORMULATION

Consider a steady, two-dimensional flow of an incompressible, Powell-Eyring fluid over an exponentially stretching sheet in the presence of Soret and Dufour effects. The *x*-axis is chosen along the sheet and the *y*-axis is normal to it. The sheet is stretching with velocity $u_w = u_0 \exp\left(\frac{x}{L}\right)$ (where u_0 is the reference velocity and L is the characteristic length). We assume that the surface temperature and concentration of the fluid are $T_w = T_\infty + T_0 \exp\left(\frac{x}{2L}\right)$ and $C_w = C_\infty + C_0 \exp\left(\frac{x}{2L}\right)$ respectively. Here T_∞ and C_∞ are the free stream temperature and concentration respectively. T_0 , C_0 are the reference temperature and concentration respectively. A uniform magnetic field $B = B_0 \exp\left(\frac{x}{2L}\right)$ is applied normally to the sheet, where B_0 is the strength of the magnetic field. The magnetic Reynolds number is assumed to be very small and thus the induced magnetic field is negligible. The effects of chemical reaction and thermal radiation are taken into account.

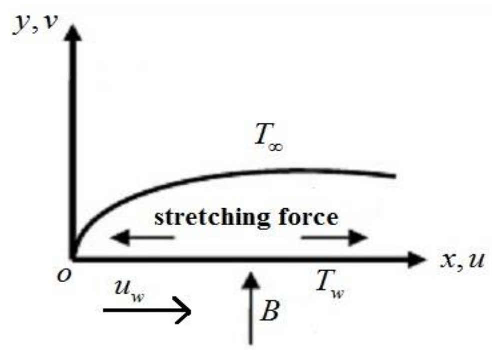

Fig. 1. Physical Model of the Problem

The Cauchy stress tensor A for Eyring-Powell fluid can be given as

$$A = -pI + \tau$$

The shear stress component $\tau_{i,j}$ for the Powell-Eyring fluid is given by

$$\tau_{i,j} = \mu \frac{\partial u_i}{\partial x_j} + \frac{1}{\beta} \sinh^{-1}\left(\frac{1}{d}\frac{\partial u_i}{\partial x_j}\right),$$

where μ is the viscosity coefficient, β and d are the material fluid parameters.

Under the above assumptions, the governing equations for this problem can be written as

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\left(\nu+\frac{1}{\rho\beta d}\right)\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B^2}{\rho}u -\frac{1}{2\rho\beta d^3}\left(\frac{\partial u}{\partial y}\right)^2\frac{\partial^2 u}{\partial y^2}+g\,\beta_T\left(T-T_\infty\right), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}- \frac{1}{\rho C_p}\left(\frac{\partial q_r}{\partial y}\right)+\frac{D_m K_T}{c_s C_p}\frac{\partial^2 C}{\partial y^2}, \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2} +\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2}-Kr^*(C-C_\infty), \tag{4}$$

With The Following Boundary Conditions

$$\left.\begin{aligned}&u=u_w(x),\ v=0,\\ &T=T_w(x),\ C=C_w(x), at\ y=0\\ &u\to 0,\ \frac{\partial u}{\partial y}\to 0,\\ &T\to T_\infty,\ C\to C_\infty\ as\ y\to\infty,\end{aligned}\right\} \tag{5}$$

In equations (1) - (4), u and v are the velocity components in the $x-$ and $y-$directions respectively. $\nu=\frac{\mu}{\rho}$ is the kinematic viscosity, where μ is the dynamic viscosity and ρ is the fluid density, k is thermal conductivity, g is the acceleration due to gravity, β_T thermal expansion coefficient, σ is the electrical conductivity, c_s is the concentration susceptibility, C_p is the heat capacitance, D_m is the mass diffusivity, K_T is the thermal diffusion ratio and T_m is the mean fluid temperature, $Kr^*=k_0\,e^{x/L}$ is the dimensional chemical reaction parameter, T, C are the temperature and concentration of the fluid respectively.

The radiative heat flux obeys the Roseland approximation, which is given by

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

where k^* and σ^* is the Roseland mean absorption coefficient and the Stefan-Boltzmann constant respectively.

The Taylor's series expansion of T^4 about T_∞ is given by

$$T^4\cong 4T_\infty^3 T-3T_\infty^4, \tag{7}$$

Using Eqs. (6) and (7) in Eq.(3), We obtain

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+ \frac{1}{\rho C_p}\left(\frac{16\sigma^* T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2}\right)+\frac{D_m K_T}{c_s C_p}\frac{\partial^2 C}{\partial y^2}, \tag{8}$$

Consider the following similarity transformations to convert the governing PDE's of flow into ODE's.

$$\left.\begin{aligned}&\eta=y\sqrt{\frac{u_0}{2\nu L}}\exp\left(\frac{x}{2L}\right),\ u=u_0\exp\left(\frac{x}{L}\right)f'(\eta),\\ &v=-\sqrt{\frac{u_0\nu}{2L}}\exp\left(\frac{x}{2L}\right)\left[f(\eta)+\eta f'(\eta)\right],\\ &\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty},\end{aligned}\right\} \tag{9}$$

where η is the similarity variable. f', θ and ϕ are the dimensionless velocity, temperature and concentration respectively.

Using the similarity transformations (9), in Eqs. (1), (2), (4) and (8). Eq. (1) is automatically satisfied and Eqs. (2), (4) and (8) become

$$(1+\varepsilon)f'''+f\ f''-2(f')^2- \varepsilon\,\delta\,(f'')^2 f'''+2\lambda\,\theta-Mf'=0, \tag{10}$$

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

$$\phi''+Sc\left(f\phi'-\phi f'\right)+Sc\,Sr\,\theta''-Sc\,Kr\,\phi=0, \tag{12}$$

The corresponding boundary conditions are

$$f(0)=0,\ f'(0)=1,\quad \theta(0)=1,\ \phi(0)=1\ at\ \eta=0, \tag{13}$$

$$f'(\eta)\to 0,\ f''(\eta)\to 0,\quad \theta(\eta)\to 0,\ \phi(\eta)\to 0\ as\ \eta\to\infty, \tag{14}$$

In equations (10) - (12), prime (') denotes the differentiation with respect to η, $\varepsilon=\frac{1}{\mu\beta d}$,

$\delta = \dfrac{\left(u_0 e^{\frac{x}{L}}\right)^3}{4\nu L d^2}$ are the fluid parameters, $\lambda = \dfrac{2g\beta_T (T_w - T_\infty) L}{u_0^2 \exp\left(\dfrac{2x}{L}\right)}$ is the mixed convection parameter, $M = \dfrac{2\sigma B_0^2 L}{\rho u_0}$ is the magnetic field parameter, $R = \dfrac{4\sigma^* T_\infty^3}{k^* k}$ is the radiation parameter and $Pr = \dfrac{\mu C_p}{k}$ is the Prandtl number. $Sc = \dfrac{\nu}{D_m}$ is the Schmidt number, $Sr = \dfrac{D_m K_T (T_w - T_\infty)}{\nu T_m (C_w - C_\infty)}$ is the Soret number, $Du = \dfrac{D_m K_T (C_w - C_\infty)}{\nu c_s C_p (T_w - T_\infty)}$ is the Dufour number and $Kr = \dfrac{2k_0 L}{u_0}$ is the chemical reaction parameter.

The skin-friction coefficient (C_f), local Nusselt number (Nu) and Sherwood number (Sh) are defined as

$$C_f = \frac{2\tau_w}{\rho u_w^2}, Nu = \frac{x q_w}{k(T_w - T_\infty)}, Sh = \frac{m_w x}{D_m (C_w - C_\infty)}, \qquad (15)$$

where $\tau_w = \left[\left(\mu + \dfrac{1}{\beta d}\right)\dfrac{\partial u}{\partial y} - \dfrac{1}{6\beta}\left(\dfrac{1}{d}\dfrac{\partial u}{\partial y}\right)^3\right]_{y=0}$ is the shear stress, $q_w = \left[-k\dfrac{\partial T}{\partial y} - \dfrac{16\sigma^* T_\infty^3}{3k^*}\dfrac{\partial T}{\partial y}\right]_{y=0}$ and $m_w = -D_m\left[\dfrac{\partial C}{\partial y}\right]_{y=0}$ correspondingly indicate the surface heat and mass fluxes.

Substituting Eq. (9) in Eq. (15), we obtain

$$C_f\, (\mathrm{Re}_x)^{\frac{1}{2}} \left(\frac{2x}{L}\right)^{\frac{-1}{2}} = \left[1 + \varepsilon\left(1 - \frac{\delta}{3}\left[f''(0)\right]^2\right)\right] f''(0), \qquad (16)$$

$$Nu\, (\mathrm{Re}_x)^{\frac{-1}{2}} \left(\frac{x}{2L}\right)^{\frac{-1}{2}} = -\left(1 + \frac{4}{3}R\right)\theta'(0), \qquad (17)$$

$$Sh\, (\mathrm{Re}_x)^{\frac{-1}{2}} \left(\frac{x}{2L}\right)^{\frac{-1}{2}} = -\phi'(0), \qquad (18)$$

where $\mathrm{Re}_x = \dfrac{u_0\, e^{\frac{x}{L}}\, L}{\nu}$ is the local Reynolds number.

III. RESULTS AND DISCUSSION

The set of nonlinear ordinary differential equations (10)-(12), subject to the boundary conditions (13) and (14) have been solved numerically by Runge-Kutta and shooting methods. The variations in velocity, temperature, concentration, local skin friction coefficient, Nusselt and Sherwood number for different values of physical parameters are displayed in Figs. 2-26 and tables 1-2. In the present study, we have chosen M=2; λ=0.5; ε=0.1; Du=0.5; δ=0.1; Pr=7; Sc=0.5; Kr=0.5; Sr=0.5; R=0.5 for obtaining the results. These values have been kept as common throughout our analysis except the varied values shown in respective figures and tables.

Fig. 2 shows the effect of magnetic field parameter (M) on the velocity. It is seen that the fluid velocity is diminishing by enhancing the value of M . Figs. 3 and 4 depict the influence of magnetic field parameter (M) on temperature and concentration distributions respectively. From these figures, it is observed that the temperature and concentration increase with an increase of M . This is due to the fact that the application of M to an electrically conducting fluid produces a resistive force called the Lorentz force. This force has a tendency to slow down the motion of the fluid in the boundary layer. This force also produces some heat energy. Hence an enhancement in both thermal and concentration boundary layer thickness is noted.

Figs. 5-7 illustrate the influence of fluid parameter (ε) on velocity, temperature and concentration fields. It is noticed that the fluid velocity increases with an increase in ε . So, the viscosity of fluid decreases. As a consequence, we notice decay in the temperature and concentration fields with an increase in ε . From fig. 8, it is observed that the fluid velocity decreases with the increasing value of fluid parameter (δ). This is due to the fact that the viscosity of the fluid increases by increasing the value of δ , which causes a decrease in the velocity of fluid. Figs. 9 -10, depict the impact of fluid parameter (δ) on temperature and concentration distributions. It is obvious that both the temperature and concentration increases by increasing the value of δ .

Fig. 11, describes the effect of mixed convection parameters (λ) on velocity field. From this figure we notice that the fluid velocity enhances with an enhancement in λ . This is because of an enhancement in the mixed convection parameter causes larger buoyancy force which accelerates the fluid motion. From Figs. 12 - 13, we found that the increasing values of λ reduces both the temperature and concentration fields. The effect of radiation parameter (R) on velocity, temperature and concentration fields is shown in Figs. 14 - 16. It is observed that the velocity and temperature increases with the increasing values of R. This is due to the fact that higher values of the radiation parameter provide more heat to the fluid. An opposite trend is seen in the case of concentration field. i.e. the concentration field decreases with an increase in R.

Figs. 17 and 18 elucidates the influence of Prandtl number $(\Pr)$ on temperature and concentration. Generally, thermal conductivity of the fluid decreases with an increase in $\Pr$. So, the increase in the Prandtl number $(\Pr)$ reduces the thermal boundary layer thickness. So heat transfer happens rapidly which causes a drop in fluid temperature. But an opposite behavior is observed in the case of $\phi(\eta)$.

Figs. 19 and 20 depict the effect of Soret number (Sr) on temperature and concentration distributions. It is observed that the temperature distribution across the thermal boundary layer thickness reduces with the increase of Sr. An opposite behavior can be observed in concentration distribution with the increasing values of Sr. The reason behind this phenomenon is that, higher values of Sr reduces the thermal diffusivity.

The effect of Schmidt number (Sc) on temperature profile is shown in fig. 21. It is noticed that the fluid temperature reduces with an increase in Sc. Fig. 22 depict that the concentration field decreases as we increase the values of Sc. Schmidt number is defined as the ratio of momentum diffusivity (viscosity) to mass diffusivity. Therefore increase in Sc decreases the mass diffusion, which in turn reduces the concentration.

The influence of chemical reaction parameter (Kr) on temperature and concentration distribution is shown in Figs. 23 and 24. It is observed that the increasing value of Kr increases the fluid temperature but suppresses the concentration. Due to an increase in the interfacial mass transfer we observe a fall in the concentration field.

The impact of Dufour number (Du) on temperature is shown in fig. 25. It is observed that the temperature increases with the increasing values of Du. Fig. 26 demonstrates the variation in concentration distribution ϕ with Du. We observe that an increase in Dufour parameter (Du) causes a depreciation in the concentration.

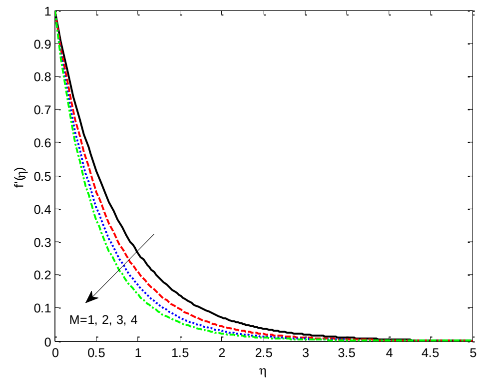

Fig. 2. Impact of M on $f'(\eta)$

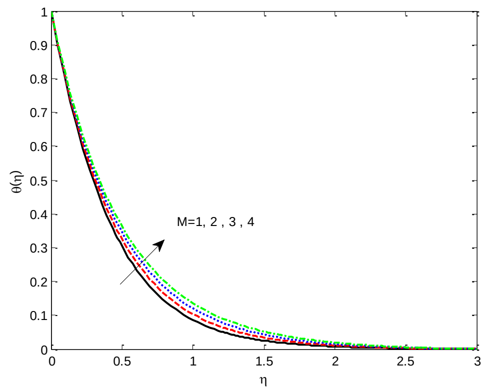

Fig. 3. Impact of M on $\theta(\eta)$

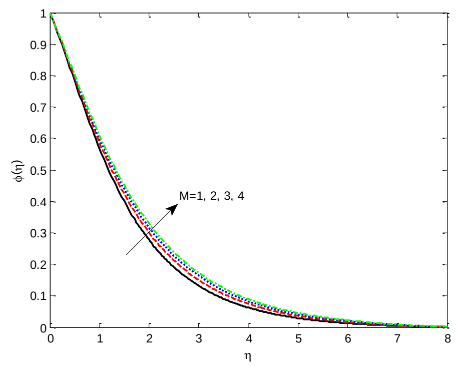

Fig. 4. Impact of M on $\phi(\eta)$

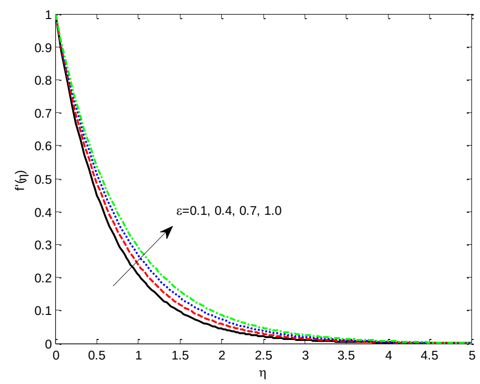

Fig.5 Impact of ε on $f'(\eta)$

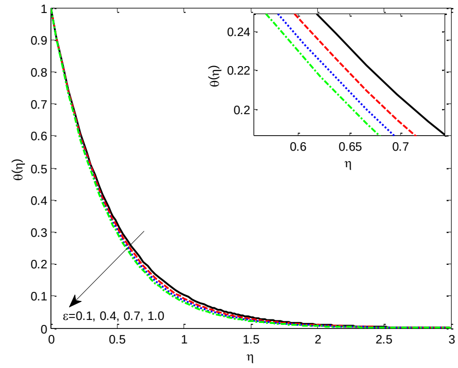

Fig. 6. Impact of ε on $\theta(\eta)$

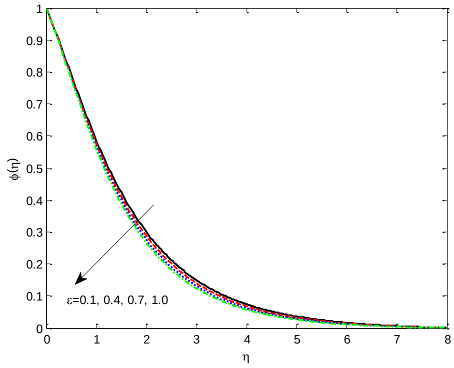

Fig.7. Impact of ε on $\phi(\eta)$

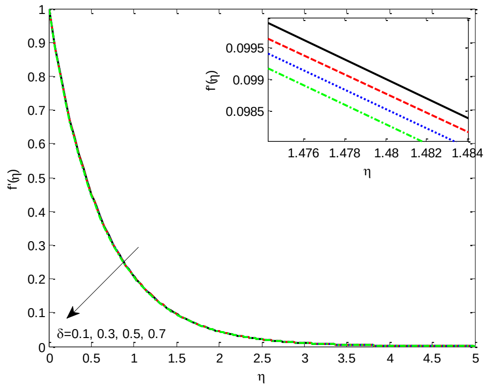

Fig. 8. Impact of δ on $f'(\eta)$

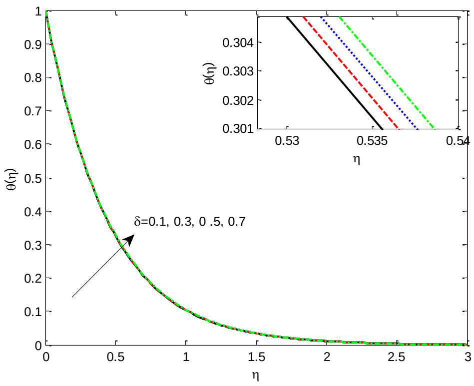

Fig. 9. Impact of δ on $\theta(\eta)$

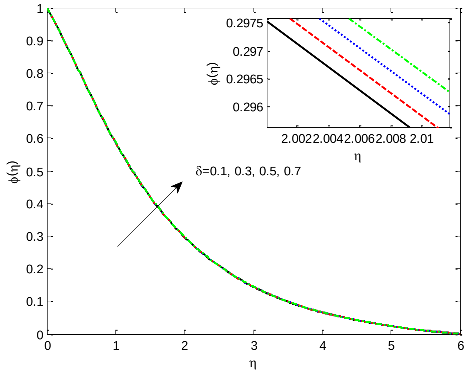

Fig. 10. Impact of δ on $\phi(\eta)$

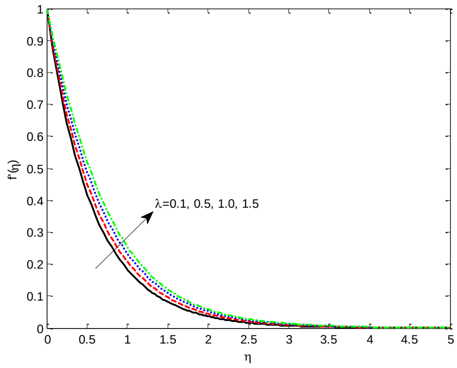

Fig. 11. Impact of λ on $f'(\eta)$

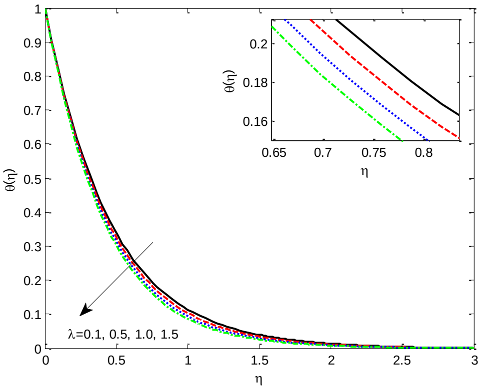

Fig. 12. Impact of λ on $\theta(\eta)$

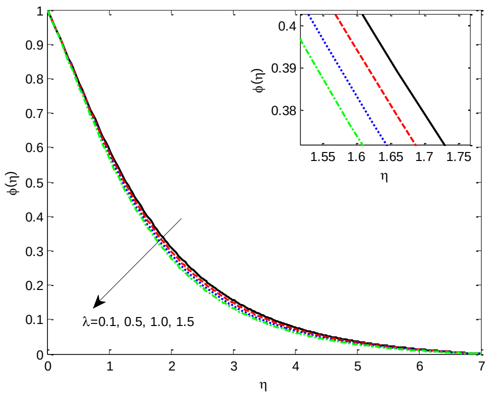

Fig. 13. Impact of λ on $\phi(\eta)$

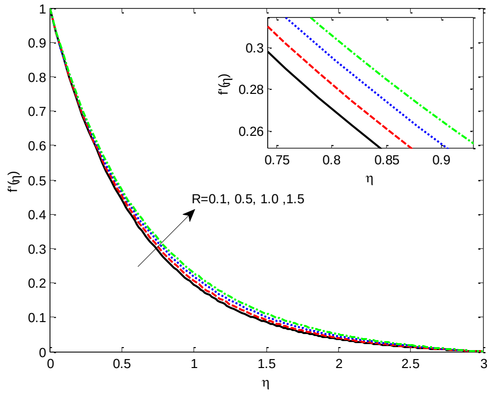

Fig. 14. Impact of R on $f'(\eta)$

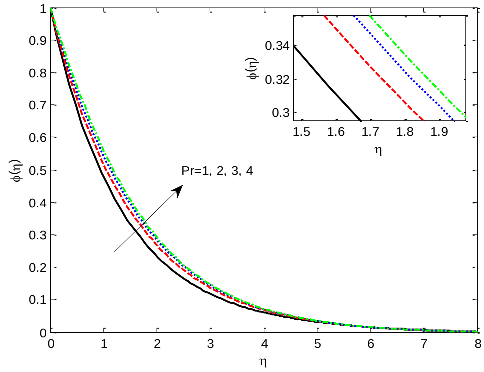

Fig. 18. Impact of Pr on $\phi(\eta)$

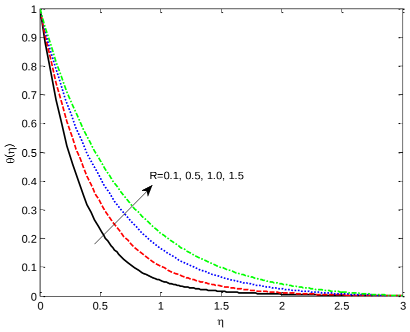

Fig. 15. Impact of R on $\theta(\eta)$

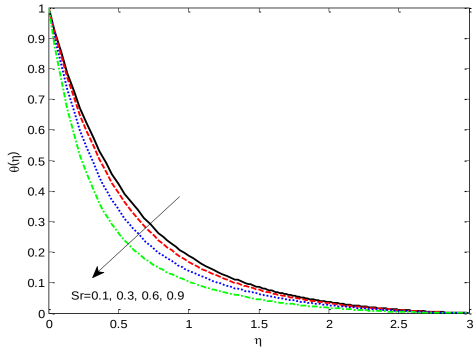

Fig. 19. Impact of Sr on $\theta(\eta)$

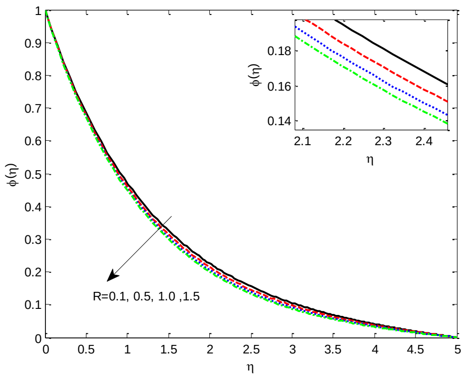

Fig. 16. Impact of R on $\phi(\eta)$

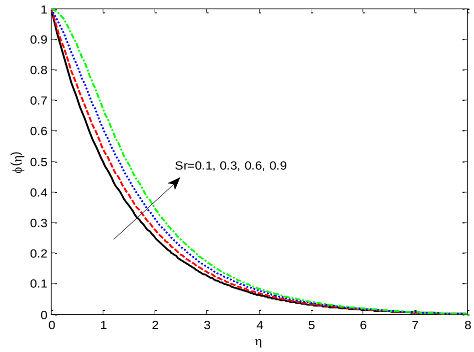

Fig. 20. Impact of Sr on $\phi(\eta)$

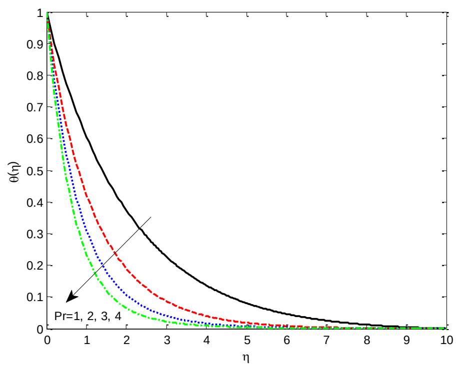

Fig.17. Impact of Pr on $\theta(\eta)$

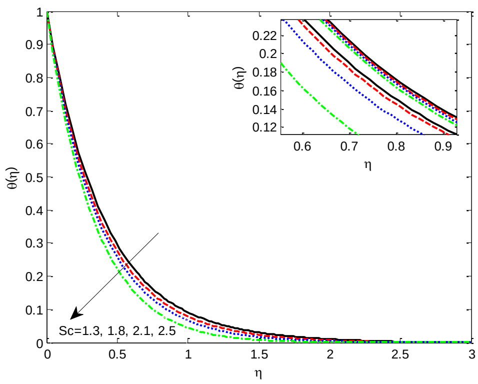

Fig. 21. Impact of Sc on $\theta(\eta)$

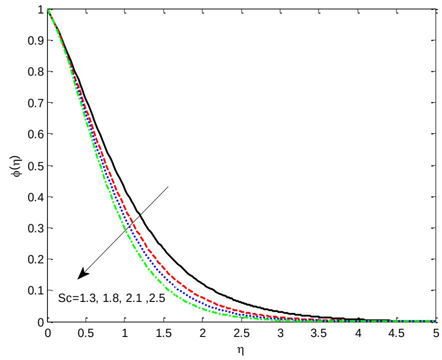

Fig. 22. Impact of *Sc* on $\phi(\eta)$

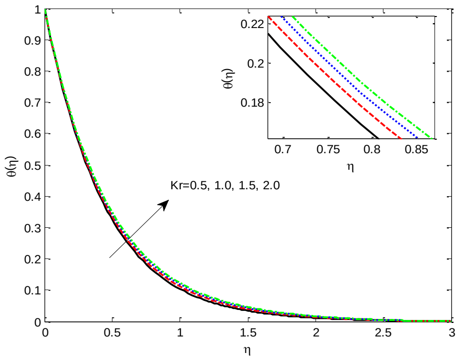

Fig. 23. Impact of *Kr* on $\theta(\eta)$

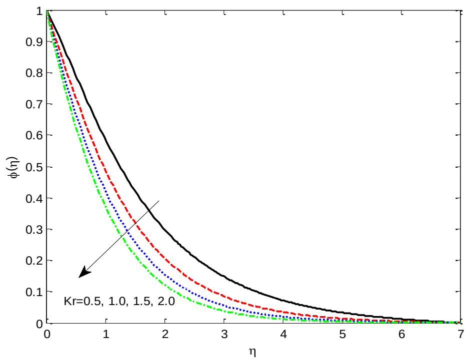

Fig. 24. Impact of *Kr* on $\phi(\eta)$

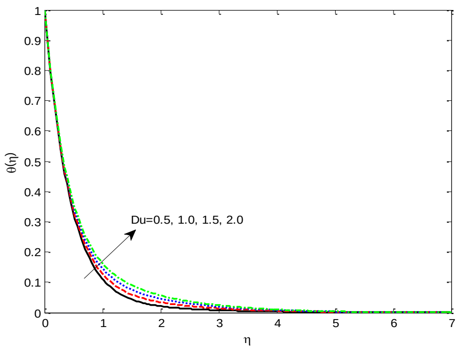

Fig. 25. Impact of *Du* on $\theta(\eta)$

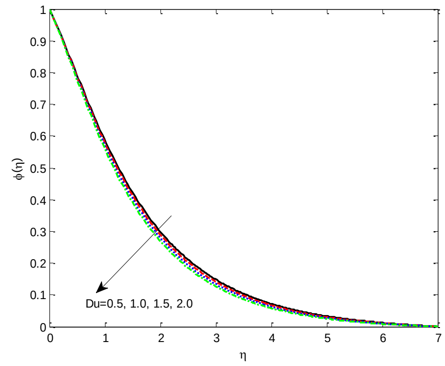

Fig.26. Impact of *Du* on $\phi(\eta)$

Table 1 gives the numerical values of skin friction coefficient for various values of M, λ, ε and δ. We noticed that the skin friction coefficient decreases with the increasing values of magnetic field parameter (M) and fluid parameter (δ). But an opposite result is noticed with fluid parameter (ε) and mixed convection parameter (λ).

Table 2 and 3 depict the variation in local Nusselt and Sherwood numbers for various values of governing parameters. We see that Soret number has a tendency to enhance the heat transfer rate and depreciate the mass transfer rate. But we observe opposite results to the above in the presence of Dufour number.

Table 1. Influence of various parameters on skin friction coefficient

M	ε	δ	λ	$f''(0)$
1				-1.3335
2				-1.6116
3				-1.8557
4				-2.0764
	0.1			-1.6116
	0.4			-1.4585
	0.7			-1.3399
	1.0			-1.2454
		0.1		-1.6116
		0.3		-1.6305
		0.5		-1.6513
		0.7		-1.6742
			0.1	-1.7911
			0.5	-1.6116
			1.0	-1.3980
			1.5	-1.1934

Table 2. Impact of various parameters on local Nusselt number and Sherwood number

Sr	Du	Sc	Pr	Kr	R	$-\theta'(0)$	$-\phi'(0)$
0.1						2.0860	0.7022
0.3						2.1195	0.5377
0.6						2.1729	0.2787
0.9						2.2306	0.0034
	0.5					2.1564	0.3707
	1.0					2.1458	0.3751
	1.5					2.1373	0.3795
	2.0					2.1315	0.3836
		1.3				2.1731	0.4340
		1.8				2.1930	0.4227
		2.1				2.2080	0.4039
		2.5				2.2320	0.3664
			1			0.5398	0.7597
			2			0.9244	0.6661
			3			1.2347	0.5905
			4			1.5019	0.5256
				0.5		2.1552	0.3677
				1.0		2.1216	0.5683
				1.5		2.0929	0.7286
				2.0		2.0671	0.8663
					0.1	2.7404	0.2278
					0.5	2.1552	0.3677
					1.0	1.7515	0.4648
					1.5	1.5007	0.5255

The local Nusselt number increases and local Sherwood number decreases with an increase in the magnitude of the Schmidt number (Sc). An increase in the Prandtl number ($\Pr$) causes an enhancement in the rate of heat transfer and reduces the rate of mass transfer. The reason behind that is, the smaller values of the Prandtl number gives rise to higher thermal conductivities therefore, heat is able to diffuse away from the heated surface more rapidly in fluids with high Prandtl number. It is also noted that an increase in the values of chemical reaction parameter (Kr) leads to a decrease in the rate of heat transfer and increase in the rate of mass transfer. It is also examined that nusselt number is a decreasing function of radiation parameter (R) where as Sherwood number is an increasing function of the same parameter.

IV. CONCLUSION

In the present investigation, we examined the Soret and Dufour effects on MHD heat and mass transfer flow of an Eyring-Powell fluid over an exponential stretching sheet. The governing equations are transformed into a system of non-linear ordinary differential equations and then solved numerically by using Runge-Kutta fourth order method with shooting technique. The main observations of present research are given below.

i) The velocity and momentum boundary layer thickness are decreased with the rise of magnetic field parameter (M), whereas an opposite trend in the temperature and concentration distributions is observed.

ii) Raising the values of one fluid parameter (ε) increases the fluid velocity, but decreases the temperature and concentration. Increasing the values of another fluid parameter (δ) decreases the fluid velocity but increases the temperature and concentration.

iii) An increase in the mixed convection parameter (λ) increases the velocity field, but decreases the temperature and concentration fields.

iv) With the increasing values of chemical reaction parameter (Kr), the temperature distribution increases and concentration decreases.

v) The velocity and temperature increases and concentration decreases with increasing values of the radiation parameter (R).

vi) Soret and Dufour number plays prominent role in the heat and mass transfer performances.

Acknowledgements

Sincere thanks to university grants commission (India) for providing BSR fellowship to Mr. J V Ramana Reddy (Third author).

REFERENCES

[1] M. E. Erdogan and C. E. Imrak, On some unsteady flows of a non-Newtonian fluid, Applied Mathematical Modeling, 31, 2007, 170–180.

[2] B. P. Chandra, K. R. Raj, A. Das and M. R. Islam, An overview of non-Newtonian fluid, International Journal of Applied Science and Engineering, 4, 2016, 97-101.

[3] T. Sarpkaya, Flow of non-Newtonian fluids in magnetic field, AICHE Journal, 7, 1961, 324-328.

[4] L. J. Crane, Flow past a stretching plate, Journal of Applied Mathematics and Physics (ZAMP), 21, 1970, 645-647.

[5] K. R. Rajagopal, A. S. Gupta and A. S. Wineman, On a boundary layer theory for non-Newtonian Fluids, International Journal of Engineering Science, 18, 1980, 875-883.

[6] B. Siddappa and S. Abel, Non-Newtonian flow past a stretching plate, Journal of Applied Mathematics and Physics (ZAMP), 36, 1985, 890-892.

[7] M. Yurusoy and M. Pakdemirli, Exact solutions of boundary layer equations of a special non-Newtonian fluid over a stretching sheet, Mechanics Research Communications, 26, 1999, 171-175.

[8] T. Hayat, S. Asghar and A. M. Siddiqui, Some unsteady unidirectional flows of a non-Newtonian fluid, International Journal of Engineering Science, 38, 2000, 337-346.

[9] A.M. Siddiqui, T. Haroon, T. Hayat and S. Asghar, Unsteady MHD flow of a non-Newtonian fluid due to eccentric rotations of a porous disk and a fluid at infinity, Acta Mechanica, 147, 2001, 99–109.

[10] R. E. Powell and H. Eyring, Mechanism for the relaxation theory of viscosity, Nature, 154, 1944, 427-428.

[11] T. Hayat, Z. Iqbal, M. Qasim and S. Obidat, steady flow of an Eyring-Powell fluid over a moving surface with convective boundary conditions, International Journal of Heat And Mass Transfer, 55, 2012, 1817– 1822.

[12] T. Javed, N. Ali, Z. Abbas and M. Sajid, Flow of an Eyring-Powell non-Newtonian fluid over a stretching sheet, Chemical Engineering Communications, 200, 2013, 327-336.

[13] M. Y. Malik, A. Hussain and S. Nadeem, Boundary layer flow of an Eyring-Powell model fluid due to a stretching cylinder with variable viscosity, Scientia Iranica B, 20, 2013, 313-321.

[14] S. Panigrahi, M. Reza and A. K. Mishra, MHD effect of mixed convection boundary-layer flow of Powell-Eyring fluid past nonlinear stretching surface, Applied Mathematics and Mechanics 35, 2014, 1525-1540.

[15] N. S. Akbar, A. Ebaid and Z. H. Khan, Numerical analysis of magnetic field effects on Eyring-Powell Fluid Flow towards a stretching sheet, Journal of Magnetism and Magnetic Materials 382, 2015, 355–358.

[16] J. Rahimi, D. D. Ganji , M. Khaki and K. Hosseinzadeh, Solution of the boundary layer flow of an Eyring-Powell non-Newtonian fluid over a linear stretching sheet by collocation method, Alexandria Engineering Journal, 56, 2017, 621-627.

[17] E. Magyari, M. E. Ali and B. Keller, Heat and mass transfer characteristics of the self-similar boundary layer flows induced by continuous surfaces stretched with rapidly decreasing velocities, Heat and Mass Transfer, 38, 2001, 65-74.

[18] C. H. Chen, Combined Heat and mass transfer in MHD free convection from a vertical surface with Ohmic heating and viscous dissipation, International Journal of Engineering Science, 42, 2004, 699–713.

[19] P. S. Gupta and A. S. Gupta, Heat and mass transfer on a stretching sheet with suction or blowing, The Canadian Journal of Chemical Engineering, 55, 1977, 744–746.

[20] S. S. Sagar and G. K. Dubey, MHD free convection heat and mass transfer flow of viscoelastic fluid embedded in a porous medium of variable permeability with radiation effect and heat source in slip flow regime, Advances in Applied Science Research, 2, 2011, 115-129.

[21] K. Singh and M. Kumar, Influence of chemical reaction on heat and mass transfer flow of a micropolar fluid over a permeable channel with radiation and heat generation, Journal of Thermodynamics, 2016, 2016, 1-10 .

[22] J. V. R. Reddy, V. Sugunamma and N. Sandeep, Dual solutions for heat and mass transfer in chemically reacting radiative non-Newtonian fluid with aligned magnetic field, Journal of Naval Architecture and Marine Engineering, 14, 2017, 25-38.

[23] T. Hayat, Z. Abbas and M. Sajid , Heat and mass transfer analysis on the flow of a second grade fluid in the presence of chemical reaction, Physics Letters A, 372, 2008, 2400–2408.

[24] R. Kandasamy, K. Periasamy and K. K. S. Prabhu, Chemical reaction, heat and mass transfer on MHD flow over a vertical stretching surface with heat source and thermal stratification effects, International Journal of Heat and Mass Transfer, 48, 2005, 4557- 4561.

[25] S. Mukhopadhyay and K. Bhattacharyya, Unsteady flow of a Maxwell fluid over a stretching surface in presence of chemical reaction, Journal of the Egyptian Mathematical Society, 20, 2012, 229–234.

[26] P. M. Krishna, N. Sandeep , J. V. R. Reddy and V. Sugunamma, Dual solutions for unsteady flow of Powell-Eyring fluid past an inclined stretching sheet, Journal of Naval Architecture and Marine Engineering, 13, 2016, 89-99.

[27] D. Pal and H. Mondal, Effects of Soret Dufour, chemical reaction and thermal radiation on MHD non-Darcy unsteady mixed convective heat and mass transfer over a stretching sheet, Communications in Nonlinear Science and Numerical Simulation, 16, 2011, 1942–1958.

[28] N. A. Khan and F. Sultan, On the double diffusive convection flow of Eyring-Powell fluid due to cone through a porous medium with Soret and Dufour effects, AIP Advances, 5, 2015, 057140.

[29] V. Sugunamma, K. B. Lakshmi, N. Sandeep and J. V. R. Reddy, Boundary layer flow of Casson fluid past a bidirectional stretching surface with cross diffusion, Global Journal of Pure and Applied Mathematics, 12, 2016, 88-94 .

[30] J. V. R. Reddy, K. A. Kumar, V. Sugunamma and N. Sandeep, Effects of cross diffusion on MHD non-Newtonian fluids flow past a stretching sheet with non-uniform heat source/sink: A comparative study, Alexandria Engineering Journal, 2017, http://dx.doi.org/10.1016/j.aej.2017.03.008