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Unsteady Flow of Nonlinear Radiative Powell-Eyring Fluid Past an Inclined Stretching Sheet with First Order Chemical Reaction

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Abstract: In this study, we investigated the flow, heat and mass transfer of Powell-Eyring fluid past an inclined stretching sheet in the presence of nonlinear thermal radiation, non-uniform heat source/sink and chemical reaction effects. The governing equations are reduced into system of ordinary differential equations using similarity transformations and solved numerically using bvp5c Matlab package. Results display the influence of pertinent parameters on the flow, heat and mass transfer along with friction factor coefficient, local Nusselt and Sherwood numbers. It is found that rising values of nonlinear thermal radiation increases the thermal boundary layer thickness. Increasing values of non-uniform heat source/sink parameters and chemical reaction parameter give rise to heat and mass transfer rates respectively.

Key words: Powell-Eyring fluid · Non-uniform heat source/sink · Nonlinear thermal radiation · Chemical reaction

INTRODUCTION

In general, the flow is categorised into two types viz. steady and unsteady according to its characteristics are independent/dependent on the time at every point respectively. In real life situations, we mostly come across the problems of unsteady type. The effects of heat, heat and mass transfer on unsteady flow past a vertical plate in presence of magnetic field was studied by Helmy [1] and Ibrahim *et al*. [2] respectively. Meanwhile, an analytical solution for the steady flow with slip effects was given by Makinde and Osalusi [3] and found that wall slip parameter suppresses the fluid motion. The combined effects of hall current and magnetic field of an unsteady flow in a rotating frame was discussed by Attia *et al*. [4]. Similar type of study with soret effect and volume fraction of nanoparticles in the base fluid was investigated by Ramana Reddy *et al*. [5] and concluded that inclusion of nanoparticles improves the thermal conductivity of the base fluid.

Non-Newtonian fluids have wide range of applications in both nature and technology such as chemical and petroleum and engineering etc. In view of these applications Erdogan and Imrak [6], Hameed and Nadeem [7] worked on unsteady flow of non-Newtonian fluid. Very recently, Raju and Sandeep [8] numerically studied the effects of thermo diffusion and diffusion thermo on non-Newtonian fluid flow past a cone/plate by using Runge-Kutta-Felhberg method. Through this study they found that increasing values of non-Newtonian fluid parameter enhances the heat and mass transfer rates.

The flow driven by a stretching surface has plenty of applications in chemical engineering processes such as polymer extrusion, cooling of metallic plates and paper production etc. During this type of manufacturing processes the stretching sheet interacts with the fluid. The flow caused by a stretching surface in presence of thermal radiation and heat source was investigated by Siddheshwar and Mahabaleswar [9]. Rapits and Perdikis [10] studied the mass transfer characteristics of the flow past a non-linearly stretching surface by using shooting technique. Mahmoud [11] has investigated the influence of radiation and variable thermal conductivity on micropolar fluid past a stretching sheet. Further, Abel and Mahesha [12] have analyzed the flow of non-Newtonian fluid past a stretching surface with viscous dissipation

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and non uniform heat generation/absorption. Heat and mass transfer effects on electrically conducting fluid over an inclined plate was reported by Alam *et al*. [13]. The flow due to an inclined stretching sheet was investigated by Eldahab *et al*. [14] and Ali *et al*. [15] by assuming various heat and mass transfer effects on the flow. Hayat *et al*. [16] examined the heat and mass transfer characteristics of Burger's fluid past an inclined stretching sheet and concluded that higher values of inclination angle reduces the fluid velocity. Sugunamma *et al*. [17] discussed the flow of a nanofluid past an exponentially stretching sheet with heat source and chemical reaction.

The study of Powell-Eyring fluid has attracted the researchers of fluid dynamics due to its numerous applications in science and technology. Among them Hayat *et al*. [18] carried out the study of three dimensional flow of Powell-Eyring fluid past a stretching sheet. Prasad *et al*. [19] studied the heat transfer effects on Eyring-Powell fluid with heat source/sink. Hayat *et al*. [20] numerically analyzed the unsteady flow of Powell-Eyring fluid over an inclined stretching surface by using HAM method. Krishna *et al*. [21] presented the dual solutions for unsteady flow of a non-Newtonian fluid over an inclined surface. Through this study, they concluded that material fluid parameter increases the Nusselt and Sherwood numbers. Hayat *et al*. [22] analyzed the heterogeneous and homogeneous chemical reactions on Powell-Eyring fluid flow past a stretching sheet.

The heat and mass transfer effects on the flow over a plate was reported by many earlier researchers [23-25]. The same effects on the flow of non-Newtonian fluid past an exponentially stretching sheet was studied by Raju *et al*. [26]. Further, Kandasamy *et al*. [27] discussed the heat and mass transfer effects on nanofluid flow with convective boundary. Srinivasacharya and Swamy Reddy [28] discussed the influence of thermal radiation and chemical reaction on Power-law fluid. The researchers [29-30] investigated the heat transfer of different fluids under the influence of non linear thermal radiation and non-uniform heat source/sink on the flow, in their recent studies.

Mathematical Formulation: Consider an unsteady flow of Powell-Eyring fluid past an inclined stretching sheet. The sheet makes an angle á with the vertical direction as shown in Fig. 1. The *x*-axis is taken along the sheet and *y* axis is normal to it. In addition, we considered the effects of nonlinear thermal radiation, chemical reaction and non-uniform heat source/sink.

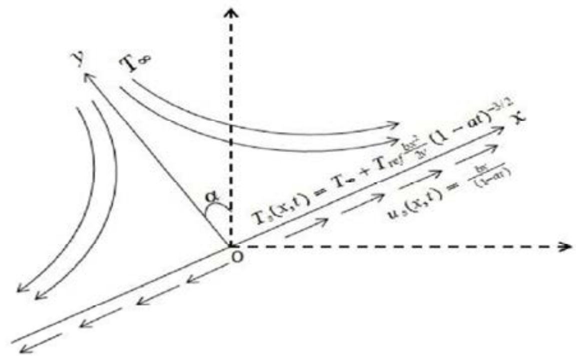

Fig. 1: Physical configuration and coordinate system

The Cauchy stress tensor in Power-Eyring fluid is given by

$$\tau_{ij} = \mu \frac{\partial u_i}{\partial x_j} + \frac{1}{\tilde{\beta}} \sinh^{-1}\left(\frac{1}{\gamma} \frac{\partial u_i}{\partial x_j} \right),$$

where μ is the viscosity coefficient, β and γ are the material fluid parameters. The boundary layer equations comprising the balance laws of mass, linear momentum and energy can be written as

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

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left(\upsilon + \frac{1}{\rho\tilde{\beta}\gamma} \right)\frac{\partial^2 u}{\partial y^2} - \frac{1}{2\rho\tilde{\beta}\gamma^3}\left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial^2 u}{\partial y^2} + g_0\left[\beta_T\left(T - T_\infty \right) + \beta_C\left(C - C_\infty \right) \right]\cos\alpha, \tag{2}$$

$$\rho c_p\left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \right] = k\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^*}{3k}\frac{\partial T}{\partial y}\left(T^3\frac{\partial T}{\partial y} \right) + q''', \tag{3}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} - k_l\left(C - C_\infty \right), \tag{4}$$

where t is the time, $\upsilon = (\mu/\rho)$ is the kinematic viscosity, k is the thermal conductivity of the fluid, ρ is the fluid density, T is the fluid temperature, C is the fluid concentration, c_p is the specific heat, g_o is the acceleration due to gravity, β_T and β_c is the volumetric coefficient of thermal and mass exponential, D_m is the is the molecular diffusivity of the species concentration, k_l is the chemical reaction parameter, α is the inclined angle, k^* is the mean absorption coefficient, σ^* is the Stefan-Boltzmann constant, q''' is the non-uniform heat source (q''' >0) or sink (q''' <0) per unit volume. The non-uniform heat source/sink, q''' is modelled by the following expression, (see Abel and Mahesha [12])

$$q''' = \frac{ku_s(\mathrm{x,t})}{x\upsilon}\left[A^*\left(T_s - T_\infty\right)f' + B^*\left(T - T_\infty\right)\right], \quad (5)$$

in which A^* and B^* are the coefficients of space and temperature dependent heat source/sink, respectively. Here two cases arise. For internal heat generation $A^*>0$ and $B^*>0$ and for internal heat absorption, we have $A^*<0$ and $B^*<0$.

The surface velocity is denoted by $u_s(x,t) = \frac{bx}{(1-at)}$, whereas the surface temperature $T_s(x,t) = T_\infty + T_{ref}\frac{bx^2}{2\upsilon}(1-at)^{-3/2}$ and surface concentration $C_s(x,t) = C_\infty + C_{ref}\frac{bx^2}{2\upsilon}(1-at)^{-3/2}$. Here b (stretching rate) and a are positive constants having dimension time. Also T_{ref}, C_{ref} are constant reference temperature and concentration respectively.

The boundary conditions are taken as follows:

$$\begin{aligned} &u = u_s(x,t), v = 0, T = T_s(x,t), C = C_s(x,t) \ at \ y = 0,\\ &u \to 0, T \to T_\infty, C \to C_\infty \ as \ y \to \infty, \end{aligned} \quad (6)$$

By introducing the similarity transformations

$$\begin{aligned} &u = \frac{bx}{(1-at)}f'(\eta), v = -\sqrt{\frac{\upsilon b}{(1-at)}}f(\eta), \theta = \frac{T - T_\infty}{T_s - T_\infty},\\ &\eta = \sqrt{\frac{b}{\upsilon(1-at)}}y, \phi = \frac{C - C_\infty}{C_s - C_\infty}, k_l = \frac{k_0}{(1-at)}, \end{aligned} \quad (7)$$

Equation (1) is identically satisfied and equations (2)-(6) become

$$(1+\Gamma)f''' - (f')^2 + ff'' - \Gamma\beta f''^2 f''' - A\left(f' + \frac{1}{2}\eta f''\right) + (Gr\theta + Gc\phi)\cos\alpha = 0, \quad (8)$$

$$\theta'' + \Pr\left(f\theta' - 2f'\theta - \frac{1}{2}A(3\theta + \eta\theta')\right) + A^*f' + B^*\theta + R\left[\left(1 + (\theta_w - 1)\theta\right)^3\theta'' + 3(\theta_w - 1)\theta'^2\left(1 + (\theta_w - 1)\theta\right)^2\right] = 0, \quad (9)$$

$$\frac{1}{Sc}\phi'' - \frac{1}{2}A(3\phi + \eta\phi') - 2\phi f' + f\phi' - Kr\phi = 0, \quad (10)$$

Boundary conditions are

$$\begin{aligned} &f = 0, f' = 1, \theta = 1, \phi = 1 \ \ at \ \eta = 0,\\ &f' \to 0, \theta \to 0, \phi \to 0 \ as \ \eta \to \infty, \end{aligned} \quad (11)$$

where prime denotes differentiation with respect to η, f is the dimensionless stream function, θ is the dimensionless temperature, ϕ is the dimensionless concentration and the dimensionless numbers are

$$\begin{aligned} &\Gamma = \frac{1}{\mu\beta\gamma}, R = \frac{4\sigma^* T_\infty^3}{kk^*}, \beta = \frac{\rho u_s^3}{\mu x\gamma^2}, Gr = \frac{g_0\beta_T(T_s - T_\infty)x^3/\upsilon^2}{u_s^2x^2/\upsilon^2} = \frac{Gr_x}{\mathrm{Re}_x^2}, \mathrm{S} = -\frac{v_0}{\sqrt{\nu b}},\\ &Gc = \frac{g_0\beta_C(C_s - C_\infty)x^3/\upsilon^2}{u_s^2x^2/\upsilon^2} = \frac{Gc_x}{\mathrm{Re}_x^2}, A = \frac{a}{b}, \Pr = \frac{\mu c_p}{k}, Sc = \frac{\upsilon}{D_m}, Kr = \frac{k_0}{b}, \end{aligned} \quad (12)$$

Where Γ and β are the dimensionless material fluid parameters, R is the radiation parameter, Gr is the thermal Grashof number, Gc is the mass Grashof number, A is the unsteadiness parameter, Pr is the Prandtl number and Sc is the Schmidt number and Kr is the chemical reaction parameter.

For engineering interest the coefficient of skin friction, local Nusselt and Sherwood numbers are defined as

$$C_f \mathrm{Re}_x^{1/2} = f''(0), \quad (13)$$

$$Nu_x \mathrm{Re}_x^{-1/2} = -\theta'(0), \quad (14)$$

$$Sh_x \mathrm{Re}_x^{-1/2} = -\phi'(0), \quad (15)$$

where $\mathrm{Re}_x = \frac{u_s x}{v}$ is the local Reynolds number.

RESULTS AND DISCUSSIONS

The dimensionless equations (8)-(10) with respect to the boundary conditions in Eqn, (11) are non linear and coupled. So Shooting technique is employed to convert them into first order and then solved numerically by using Runge-Kutta fourth order method. Further, graphs and tabular forms are presented to analyze the flow, heat and mass transfer characteristics. Throughout the study of results, we considered the values of governing parameters as Pr = 1, $\alpha = \pi/3$, $\beta = 0.2$, $\Gamma = 0.2$, $\varepsilon = 0.5$, $Gr = 1$, $Gc = 0.5$, $R = 0.5$, $A^* = B^* = 0.1$, $\theta_w = 0.1$, Sc = 0..6 and $Kr = 0.2$. These values are taken as default unless otherwise specified in the graphs and tables.

Figures 2-4 depict the influence of material fluid parameter (Γ) on velocity, temperature and concentration distribution respectively. From Fig. 2, we perceive that rising values of Γ elevates the fluid velocity.

But from Figs. 3 and 4, we found that both temperature and concentration are decreasing functions of Γ. Moreover, it is worth to mention that Γ shows significant effect on velocity profiles. We also found that thermal boundary layer thickness is little bit greater than that of concentration. As we seen in material fluid parameter (Γ), similar type of behaviour on velocity, temperature and concentration profiles is observed in case of inclination angle (α) of the stretching sheet. The graphs are presented in Figs. 5-7.

The variation of thermal Garshof number (Gr) on velocity, temperature and concentration profiles is plotted in Figs. 8-10. These figures enable us to conclude that an increase in Gr enhances the fluid velocity but suppresses the temperature and concentration distribution. The variation of temperature profiles for unsteadiness parameter (A) is displayed in Fig. 11. It is seen that increase in A diminishes the fluid temperature. From Fig. 12 one can say that increase in the values of radiation parameter (R) inflates the velocity profiles.

Figures 13-16 depict the effect of radiation parameter (R), temperature ratio parameter (θ_w) and non uniform heat source/sink parameters (A^*, B^*) on temperature respectively. From these figures, we may conclude that increasing values of any parameter among R, θ_w, A^*, B^* produces heat energy to the flow and enlarges the thermal boundary layer. Because of this reason we observe a hike in temperature profiles. Finally Fig. 17 is plotted to examine the variation of concentration profiles under the influence of chemical reaction parameter (Kr). As we expected, we observe a decrease in concentration with increasing values of Kr.

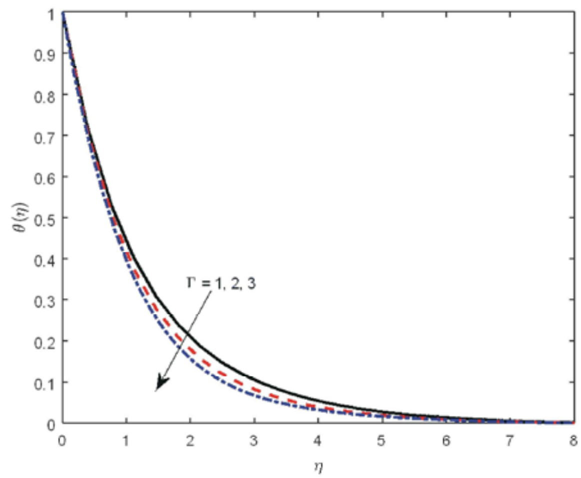

Fig. 3: Influence of material fluid parameter Γ on temperature.

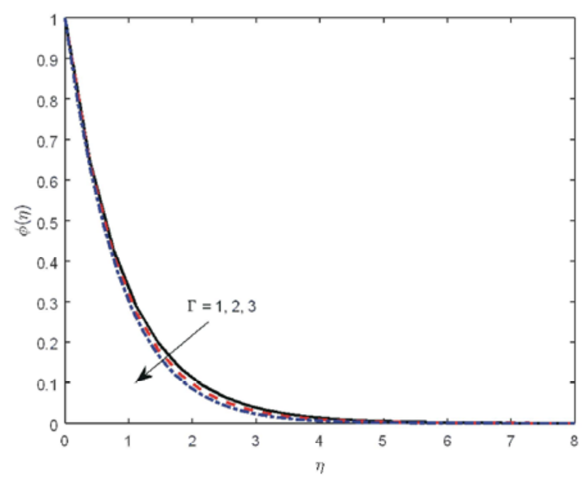

Fig. 4: Influence of material fluid parameter Γ on concentration

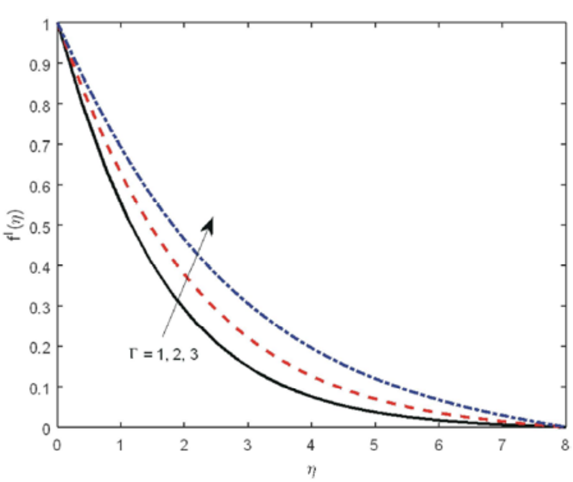

Fig. 2: Influence of material fluid parameter Γ on velocity.

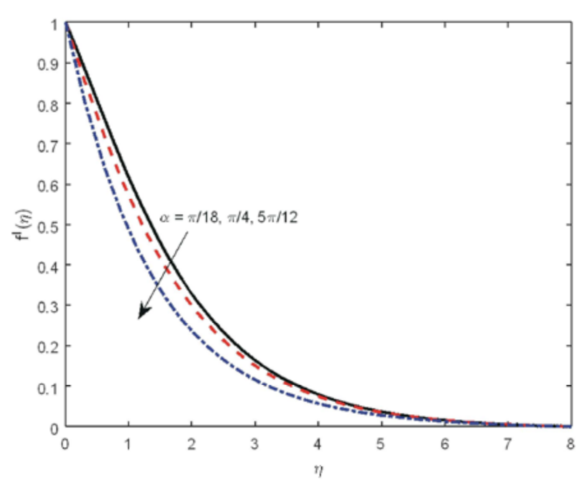

Fig. 5: Influence of inclination angle α on velocity.

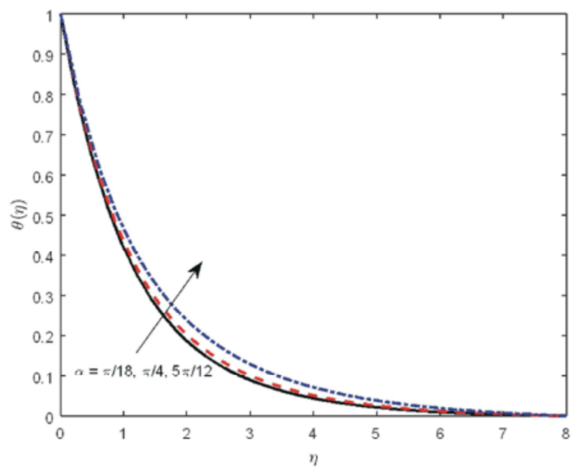

Fig. 6: Influence of inclination angle α on temperature.

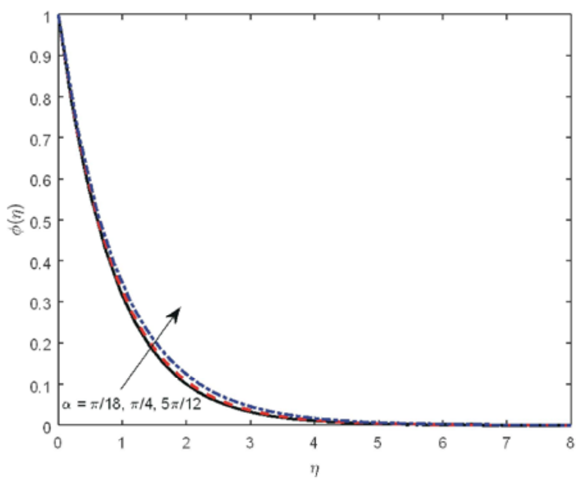

Fig. 7: Influence of inclination angle α on concentration.

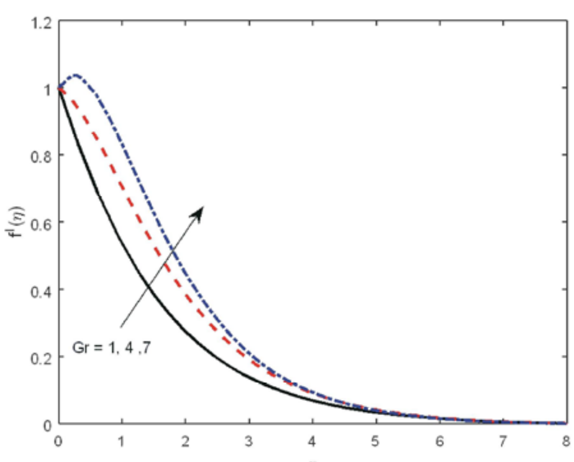

Fig. 8: Influence of thermal Garshof number (*Gr*) on velocity.

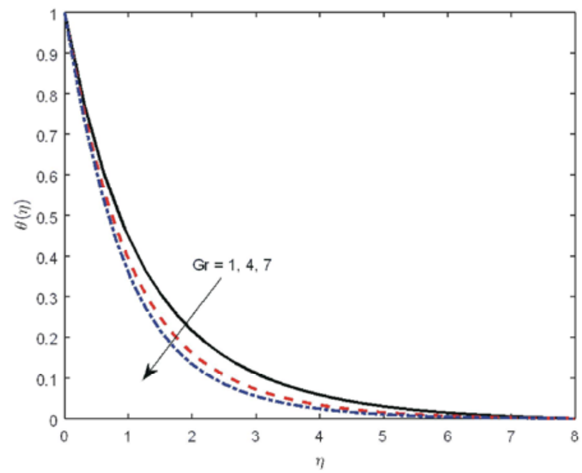

Fig. 9: Influence of thermal Garshof number (*Gr*) on temperature.

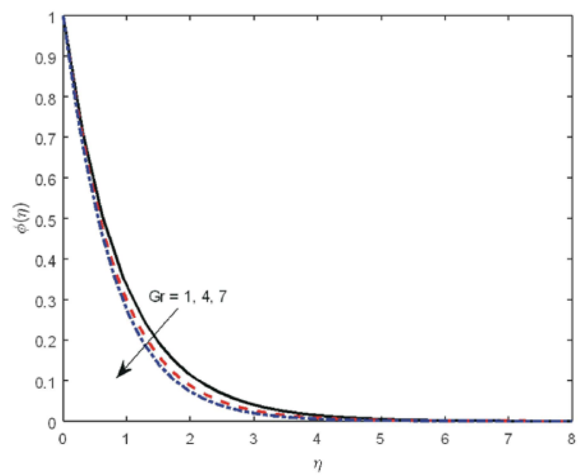

Fig. 10: Influence of thermal Garshof number (*Gr*) on concentration.

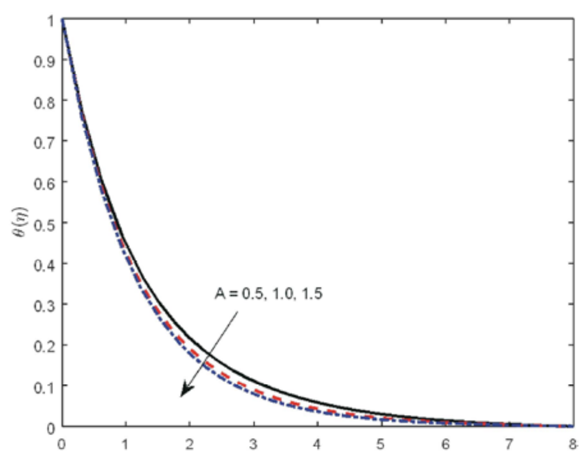

Fig. 11: Influence of unsteadiness parameter (*A*) on temperature.

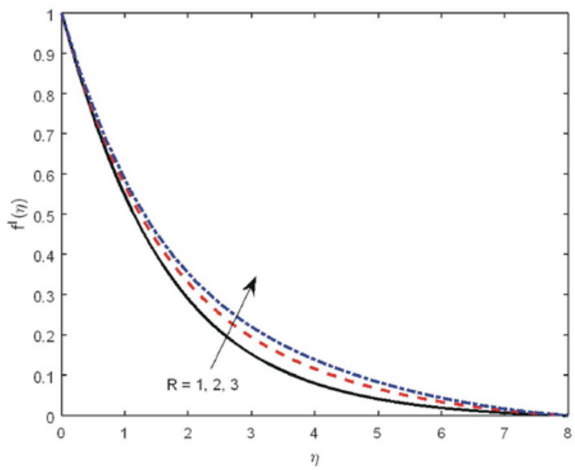

Fig. 12: Influence of radiation parameter (R) on velocity.

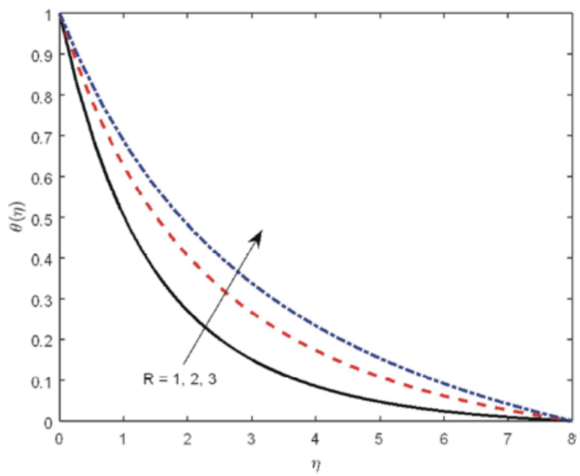

Fig. 13: Influence of radiation parameter (R) on temperature.

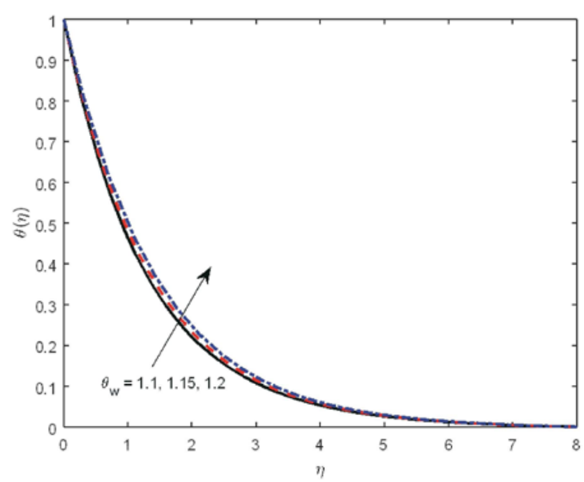

Fig. 14: Influence of temperature ratio parameter (θ_w) on temperature.

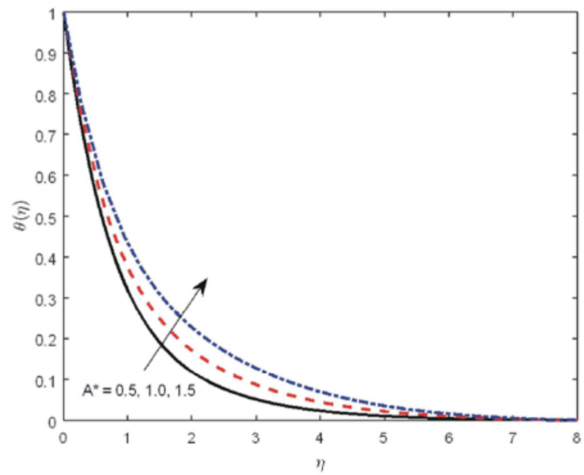

Fig. 15: Influence of non uniform heat source/sink (A^*) on temperature.

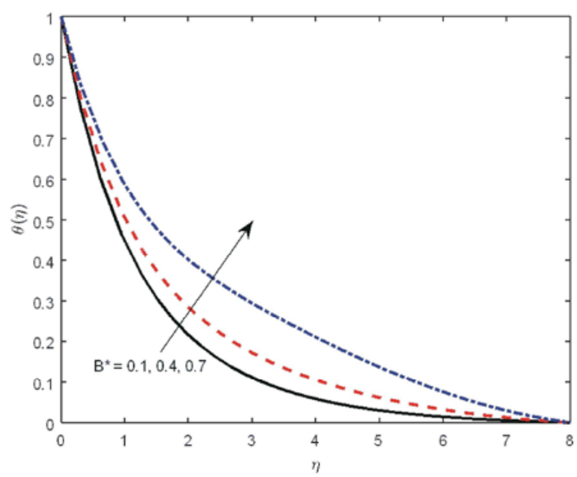

Fig. 16: Influence of non uniform heat source/sink (B^*) on temperature.

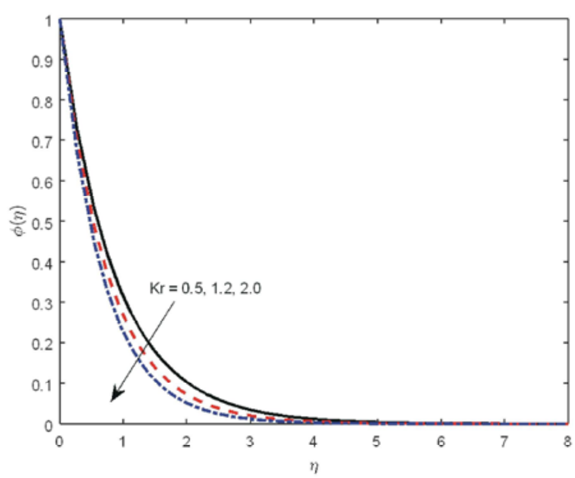

Fig. 17: Influence of chemical reaction parameter (Kr) on concentration.

Table 1 depict the influence of various governing parameters on friction factor, Nusselt and Sherwood numbers. We found that increasing values of either fluid material parameter (Γ) or inclination angle of the stretching sheet (α) enhances the heat and mass transfer rates. The same behaviour is observed in case of thermal Garshof number (Gr). It is interesting to observe that higher values of (R) increases the Nusselt number but reduces the Sherwood number. Skin friction coefficient increases with an increase in the values of temperature ratio parameter (θ_w) or non uniform heat source/sink parameters (A^*,B^*) or chemical reaction parameter (Kr).

Table 1: Influence of various governing parameters on Skin friction coefficient, local Nusselt number and Sherwood number.

Γ	α	Gr	A	R	θ_w	A^*	B^*	Kr	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
1.0									-0.5586	0.8518	1.1206
2.0									-0.4387	0.8801	1.1415
3.0									-0.3478	0.9018	1.1581
	$\pi/18$								-0.3568	0.8809	1.1437
	$\pi/4$								-0.4885	0.8612	1.1282
	$5\pi/12$								-0.7128	0.8224	1.0990
		1.0							-0.5900	0.8446	1.1155
		4.0							-0.1081	0.9162	1.1722
		7.0							0.3301	0.9670	1.2152
			0.5						-0.5900	0.8446	1.1155
			1.0						-0.6034	0.8781	1.0980
			1.5						-0.6123	0.8981	1.0855
				1.0					-0.5788	0.7176	1.1183
				3.0					-0.5544	0.4893	1.1249
				5.0					-0.5423	0.3931	1.1282
					1.10				-0.5866	0.7741	1.1161
					1.15				-0.5833	0.7246	1.1169
					1.20				-0.5799	0.6792	1.1177
						0.5			-0.6148	1.1848	1.1094
						1.0			-0.6039	1.0675	1.1123
						1.5			-0.5926	0.9484	1.1153
							0.1		-0.5900	0.8446	1.1155
							0.4		-0.5782	0.7437	1.1188
							0.7		-0.5603	0.6203	1.1240
								0.5	-0.6257	1.2769	1.1787
								1.2	-0.6303	1.2757	1.3302
								2.0	-0.6343	1.2747	1.4845

CONCLUSIONS

- Temperature and concentration fields increase with an increase in Eyring-Powell fluid parameter.
- Non linear thermal radiation parameter and non uniform heat source/sink parameters hike the fluid temperature.
- An increase in inclination angle of the stretching sheet leads to a reduction in the heat transfer performance of the fluid.
- Thermal Garshof number, Chemical reaction parameter, Eyring-Powell fluid parameter can enhance the mass transfer rate significantly.

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