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Radiation and Chemical Reaction Effects on MHD Nanofluid Flow over a Continuously Moving Surface in Porous Medium with Non-Uniform Heat Source/Sink

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Abstract
In this study we analyzed the influence of radiation and chemical reaction on MHD nanofluid flow over a continuously moving surface in porous medium in presence of non-uniform heat source/sink. The governing equations are transformed into system of nonlinear ordinary differential equations by using similarity transformation and solved numerically using bvp5c Matlab package. The effects of non-dimensional governing parameters on velocity, temperature and concentration profiles are discussed and presented with help graphs. Also, friction factor, local Nusselt and Sherwood numbers are calculated and presented through tables. Comparisons of the present results made with the existed studies. Preset results have an excellent agreement with the existed studies under some special conditions.
Keywords: MHD, Radiation, Chemical Reaction, Nanofluid, non-uniform heat source/sink, Thermophoresis.

1. Introduction

Heat transfer is the science that seeks to predict the energy transfer take place between material bodies as a result of a temperature difference. The heat transmissions are very important in engineering fields like design, construction, testing and operation of heat exchange apparatus. Stagnation-point flow and heat transfer behaviour of Cu-water nanofluid towards horizontal and exponentially stretching/shrinking cylinders was discussed by Sulochana and Sandeep (2015). Olajuwon (2010) investigated the heat and mass transfer in an electrically conducting power law fluid past a vertical porous plate in presence of a transverse magnetic field, thermal radiation, and thermal diffusion. Mohammad Ali et al. (2014) presented the steady of MHD free convection heat and mass transfer of a boundary layer flow in a rotating system with heat generation and Hall current. Radiation, inclined magnetic field and cross-diffusion effects on the flow over a stretching surface was analyzed by Raju et al. (2015).

The study of heat and mass transfer in the magneto hydrodynamics flow of a viso-elastic fluid in a rotating porous channel was discussed Jena et al. (2014). The numerical study of the boundary layer flow past an unsteady stretching surface in nanofluid with suction and viscous dissipation is investigated by Ferdows et al. (2013). An integral treatment is proposed for the analysis of the forced convection heat and mass transfer of nanofluids over a stretching sheet was presented by Noghrehabadi et al. (2015). Snadeep et al. (2012) analyzed the magnetohydrodynamic, radiation and chemical reaction effects on unsteady flow, heat and mass transfer characteristics of a viscous, incompressible and electrically conducting fluid over a semi-infinite vertical porous plate through porous media. The study of the combine influence of radiation and dissipation on the convective heat and mass transfer flow of a viscous fluid through a porous medium in a rectangular cavity using Darcy model was presented by Veera Suneela Ranil et al. (2012). The effects of aligned magnetic field, radiation, and rotation on an unsteady hydromagnetic free convection flow of a viscous incompressible electrically conducting fluid past an impulsively moving vertical plate in a porous medium was discussed by Sandeep et al. (2014). Influence of radiation and chemical reaction on MHD convective flow over a permeable stretching surface with suction and heat generation effects was discussed by Mohankrishna et al. (2015).

The analytical solution for MHD boundary layer flow of a viscous incompressible fluid over an exponentially stretching sheet was discussed by Fazle Mabood et al. (2014). Raju et al. (2015) discussed the radiation and chemical reaction effects on thermophoretic MHD flow over an aligned isothermal permeable surface with heat source. An incompressible viscous fluid flow and heat transfer in a collapsible tube with heat source or sink is examined by Odejide (2014). Very recently the researchers Eldo Johns et al. (2015), Kader Murshed et al. (2015), Raju et al. (2015), Ramana Reddy et al. (2014) and Sugunamma et al. (2014) presented a detailed discussion on radiation and magneticfield effects on some base fluids and nanofluids by considering different channels. MHD flow and heat transfer of a viscous incompressible fluid in a porous medium between two vertical wavy walls was discussed by Dadaa and Disub (2014). The influence of inclined magneticfield of a viscous incompressible flow through porous medium was discussed by Sandeep and Sugunamma (2013).

In this paper we analyzed the influence of radiation and chemical reaction on MHD nanofluid flow over a continuously moving surface in porous medium in presence of non-uniform heat source/sink. The governing equations are transformed into system of nonlinear ordinary differential equations by using similarity transformation and solved numerically. The effects of non-dimensional governing parameters on velocity, temperature and concentration profiles are discussed and presented with help graphs. Also, friction factor, local Nusselt and Sherwood numbers are calculated and presented through tables.

2. Mathematical formulation

Consider a steady two-dimensional electrically conducting, viscous, incompressible flow past a continuously moving surface in porous medium with uniform velocity U. Let the *x*-axis be taken along the surface and y-axis normal to it. A uniform transverse magnetic field of strength B_0 is applied along y-direction. It is assumed that the induced magnetic field, the external electric field are negligible due to the polarization of charges. Radiation and chemical reaction effects are taken into account. The properties of fluid considered to be isotropic and constant, except for the fluid viscosity which is assumed to be an inverse linear function of temperature

$$\frac{1}{\mu}=\frac{1}{\mu_\infty}\left[I+\gamma(T-T_\infty)\right]\Rightarrow\frac{1}{\mu}=a(T-T_\infty)\text{, where }\quad a=\frac{\gamma}{\mu_\infty}\quad and\quad T_\gamma=T_\infty-\frac{1}{\gamma}$$

Here μ be the coefficient of viscosity, μ_∞ is a reference viscosity, γ is a constant, T and T_∞ are the temperature of the fluid near and far away from the moving plate, a and T_γ are constants and their values depend on the reference state and the thermal property of the fluid. In general $a>0$ for liquids $a<0$ for gases. Under the above the assumptions the governing equations are describing below:

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

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\frac{\partial^2 u}{\partial y^2}-\sigma B_0^2 u-\frac{\mu}{k_1}u, \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma B_0^2 u}{\rho c_p}+\tau\left\{D_B\left(\frac{\partial T}{\partial y}.\frac{\partial C}{\partial y}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\text{q}''', \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_r}{T_\infty}\frac{\partial^2 T}{\partial y^2}-k_l(C-C_\infty), \tag{4}$$

with the boundary conditions

$$u=U=ax,\quad v=0,\quad T=T_w(x),\quad C=C_w(x)\qquad at\quad y=0$$
$$u=0,\ T=T_{\infty,}\ C=C_\infty\quad as\quad y\to\infty, \tag{5}$$

where , α is the thermal diffusivity, ρ is the density, σ is the electrical conductivity, α is the thermal diffusivity, c_p is the specific heat at constant pressure, μ is the thermal viscosity, D_B is the Brownian diffusion coefficient, D_T is the thermophoresis diffusion coefficient and k_l is the rate of chemical reaction. The radiative heat flux q_r under Rosseland approximation is of the form

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

where σ^* is the Stefan-Boltzmann constant and k^* is the mean absorption coefficient. The temperature differences within the flow are assumed to be sufficiently small such that T^4 may be expressed as a linear function of temperature. Expanding T^4 using Taylor series and neglecting higher order terms yields $T^4\cong 4T_\infty{}^3T-3T_\infty{}^4$.

The space and temperature dependent heat generation/absorption (non-uniform heat source/sink) q''' is defined as

$$q'''=\left(\frac{kU(x)}{xv}\right)\left(A^*(T_w-T_\infty)f'(\eta)+B^*(T-T_\infty)\right), \tag{7}$$

Where A^* and B^* are parameters of the space and temperature dependent internal heat generation/absorption. The positive and negative values of A^* and B^* represents heat generation and absorption respectively.
We are introducing the similarity transformations as

$$\eta = y\sqrt{\frac{a}{\upsilon}},\ \ \psi = x\sqrt{a\upsilon}\, f(\eta),\ \ \theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty},\ \ \phi(\eta) = \frac{C-C_\infty}{C_w-C_\infty}, \tag{8}$$

where υ is a reference kinematic viscosity. It is assumed that the temperature difference between the moving surface and the free steam varies as Ax^n.

$$i.e.,\ T_w - T_\infty = Ax^n, \tag{9}$$

Also the concentration difference between the moving surface and the free stream varies as Bx^n.

$$i.e.,\ C_w(x) - C_\infty = Bx^n, \tag{10}$$

where A, B are constants, n is exponent parameter and x is measured from the leading edge of the surface.
From the above transformations we obtain the non-dimensional, nonlinear, coupled ordinary differential equations as

$$f''' + ff'' - f'^2 - (M+K)f' = 0, \tag{11}$$

$$\frac{1}{\Pr}\left(1+\frac{4}{3}R\right)\theta'' - nf'\theta + f\theta' + Ecf''^2 + MEcf'^2 + Nb\theta'\varphi' + Nt\theta'^2 + \frac{1}{\Pr}(A^* f' + B^*\theta) = 0, \tag{12}$$

$$\phi'' + Lef\phi' - nLef'\phi + \left(\frac{Nt}{Nb}\right)\theta'' - KrLe\,\mathrm{Re}_x\,\phi = 0, \tag{13}$$

The corresponding boundary conditions are

$$\left.\begin{aligned} &f=0,\ \ f'=1,\ \ \theta=1,\ \ \varphi=1,\ \ at\ \ n=0,\\ &f'=0,\ \ \theta=0,\ \ \phi=0,\ \ \ \ as\ \ \ y\to\infty, \end{aligned}\right\} \tag{14}$$

where the notation prime denotes the differentiation with respect to η and M is the magneticfiled parameter, K is the porous medium, Pr is the Prandtl number, R is the radiation parameter, Ec is the Eckert number, Nb is the Brownian motion parameter, Nt is the thermophoresis parameter, Le is the Lewis number, Kr is the chemical reaction parameter and Re_x is the local Reynolds number, is denoted by

$$\begin{aligned} &M = \frac{\sigma B_0^2}{\rho a}, K = \frac{\upsilon}{k_1 a}, Ec = \frac{U^2}{C\upsilon(T_w - T_\infty)}, \Pr = \frac{\upsilon}{\alpha}, R = \frac{4\sigma^* T_\infty^3}{k^* k}, \mathrm{Re}_x = \frac{ax^2}{\upsilon}, Kr = \frac{\upsilon k_l}{U^2},\\ &Le = \frac{\upsilon}{D_B}, Nb = \frac{(\rho c)_p D_B (C_w - C_\infty)}{\upsilon(\rho c)_f}, Nt = \frac{(\rho c)_p D_T (T_w - T_\infty)}{\upsilon T_\infty (\rho c)_f}, \end{aligned} \tag{15}$$

The physical quantities of interest the Skin-friction coefficient, the reduced Nusselt number and reduced Sherwood number are calculated respectively by the following equations. $C_f(\mathrm{Re}_x)^{-\frac{1}{2}} = -f''(0)$,

$$Nu(\mathrm{Re}_x)^{-\frac{1}{2}} = -\theta'(0),\ \ Sh(\mathrm{Re}_x)^{-\frac{1}{2}} = -\phi'(0). \tag{16}$$

where $\mathrm{Re}_x = \frac{ax^2}{\upsilon}$ is the Local Reynolds number.

3. Results and Discussion

Equations (11) to (13) with the boundary conditions (14) have been solved numerically using bvp5c Matlab Package. Equations (12) to (14) are transformed into systems of first order differential equations. For numerical illustrations we considered $K = R = Nt = Nb = 0.5$, $M = n = \mathrm{Re}_x = 1, Ec = A^* = B^* = 0.1, Le = Kr = 2, \Pr = 6.2$. These values are kept as constant in entire study except the varied values as shown in respective figures and tables. The results obtained shows the influences of the non-dimensional governing parameters, namely magneticfield parameter, thermal radiation parameter, non-uniform heat generation/absorption, chemical reaction parameter, thermophoresis parameter, Brownian motion parameter, Reynolds number, exponent parameter and porous medium parameter on velocity, temperature, concentration, skin friction, local Nusselt and Sherwood numbers.

Figs. 1 and 2 show the effect of magneticfield parameter on velocity and temperature profiles of the flow. It is observed from the figures that enhancement in the magneticfield parameter declines the velocity profiles and enhances the temperature profiles of the flow. This is due to the Lorentz force acts opposite to the flow direction. Figs. 3 and 4 illustrate influence of porosity parameter on velocity and temperature profiles of the flow. It is clear that an increase in porosity parameter depreciates the velocity and increases the temperature profiles of the flow. It is due to the fact that the enhancement in porosity parameter widens the porous layers this causes to reduce the velocity boundary layer and enhance the thermal boundary layer thickness.

The influence of thermal radiation on temperature profiles of the flow was displayed in Fig.5. It is noticed from the figure that a raise in the value of radiation parameter enhances the temperature profiles of the flow. This is due to the fact that the raise in the radiation parameter releases the heat energy to the flow. This agrees the general physical behaviour of the radiation parameter. Fig.6 displays the effect of exponent parameter on temperature profiles of the flow. It is evident from the figure that an increase in exponent parameter depreciates the temperature profiles of the flow.

Figs. 7 and 8 illustrate the effect of non-uniform heat source/sink parameters on temperature profiles of the flow. It is clear that the enhancement in non-uniform heat source/sink parameters increases the temperature profiles of the flow. This may happen due to the fact that the positive values of A^* and B^* acts like heat generators and negative values are acts like heat observers. Generally generating the heat enhances the temperature profiles of the flow. Fig. 9 shows the influence of thermophoresis parameter on the temperature profiles of the flow. It is clear that an increase in the value of thermophoresis parameter enhances the temperature profiles of the flow.

Figs. 10 and 11 represent the influence of Brownian motion parameter on temperature and concentration profiles of the flow. It evident from the figures that the enhancement Brownian motion parameter increases the temperature profiles and depreciates the concentration profiles of the flow. Brownian motion helps to heat the fluid in the boundary layer at the same time it exacerbates particle deposition away from the fluid regime, these reduces the concentration near the boundary layer. Fig.12 displays the effect of Reynolds number on concentration profiles of the flow. It is noticed that an increase in Reynolds number depreciates the concentration profiles of the flow.

Figs. 13 and 14 depict the influence of Lewis number and Chemical reaction parameter on concentration profiles of the flow. It is observed from the figures that a raise in the values of Lewis number and Chemical reaction parameter depreciates the concentration profiles of the flow. This causes to enhance the mass transfer rate.

Table 1 shows the comparison of the present results with the existed studies. Present results have an excellent agreement with the existed studies. This shows the validity of the present results along with the numerical technique we used in this study. Table 2 represent the influence of non-dimensional governing parameters on friction factor, reduced Nusselt and Sherwood numbers. It is evident from the table that the enhancement in the values of non-uniform heat source/sink parameters, chemical reaction parameter, thermophoresis, Brownian motion parameter and Reynolds number does not shown significant difference in skin friction coefficient. But it depreciates the Nusselt number and enhances the mass transfer rate. A raise in the value of exponent parameter enhances the heat and mass transfer rate. An increase in the value of radiation parameter showed opposite results to the exponent parameter. A raise in magneticfield parameter depreciates the friction factor, Nusselt number and enhances the mass transfer rate. An increase in porosity parameter declines the heat and mass transfer rate and skin friction coefficient.

Table 1 Comparison of the present results for reduced Nusselt number $-\theta'(0)$ when $M = kr = n = R = A^* = B^* = Nb = Nt = \mathrm{Re}_x = 0$

Pr	Gorla and Sidawi (1994)	Khan et al. (2014)	Present Study
0.07	0.0656	0.0660	0.066012
0.20	0.1691	0.1693	0.169332
0.70	0.5349	0.4545	0.454523
2	0.9114	0.9117	0.911721
7	1.8904	1.8944	1.894432
20	3.3539	3.3542	3.354214
70	6.4622	6.4625	6.462523

Table 2 Variation in $f''(0), -\theta'(0)$ and $-\phi'(0)$ for different non-dimensional parameters.

M	R	K	n	A^*	B^*	Kr	Nt	Nb	Re_x	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
1										-1.581194	0.513237	2.574804
2										-1.870834	0.419052	2.587726
3										-2.121321	0.332330	2.607065
	1									-1.581139	0.530291	2.531295
	2									-1.581139	0.521664	2.485257
	3									-1.581139	0.492325	2.466274
		1								-1.732067	0.486150	2.566332
		2								-2.000002	0.435484	2.555160
		3								-2.236068	0.388535	2.549426
			0.5							-1.581194	0.256834	2.556688
			1.0							-1.581194	0.513237	2.574804
			1.5							-1.581194	0.731232	2.610395
				-1						-1.581194	0.609512	2.534555
				0						-1.581194	0.522113	2.571082
				1						-1.581194	0.432162	2.608923
					-1					-1.581194	0.622613	2.536908
					0					-1.581194	0.523662	2.571676
					1					-1.581194	0.413125	2.597808
						1				-1.581194	0.568556	2.018334
						2				-1.581194	0.513237	2.574804
						3				-1.581194	0.480175	3.004760
							0.2			-1.581194	0.617085	2.529105
							0.4			-1.581194	0.542274	2.559970
							0.6			-1.581194	0.488511	2.587836
								0.2		-1.581194	0.790613	2.247485
								0.4		-1.581194	0.589943	2.536265
								0.6		-1.581194	0.449080	2.592309
									0.5	-1.581143	0.568615	2.018084
									1.0	-1.581143	0.513255	2.574696
									1.5	-1.581143	0.480192	3.004670

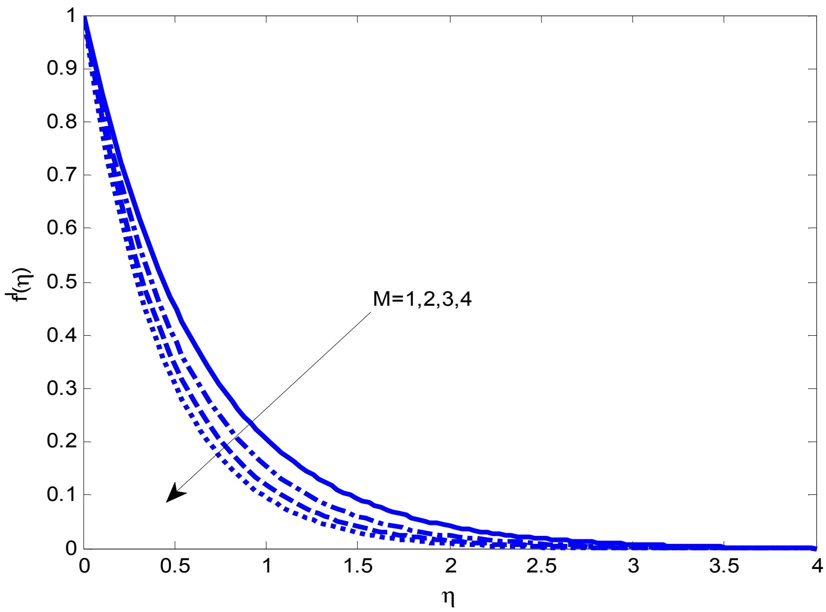

Fig.1 Velocity profiles for various values of M

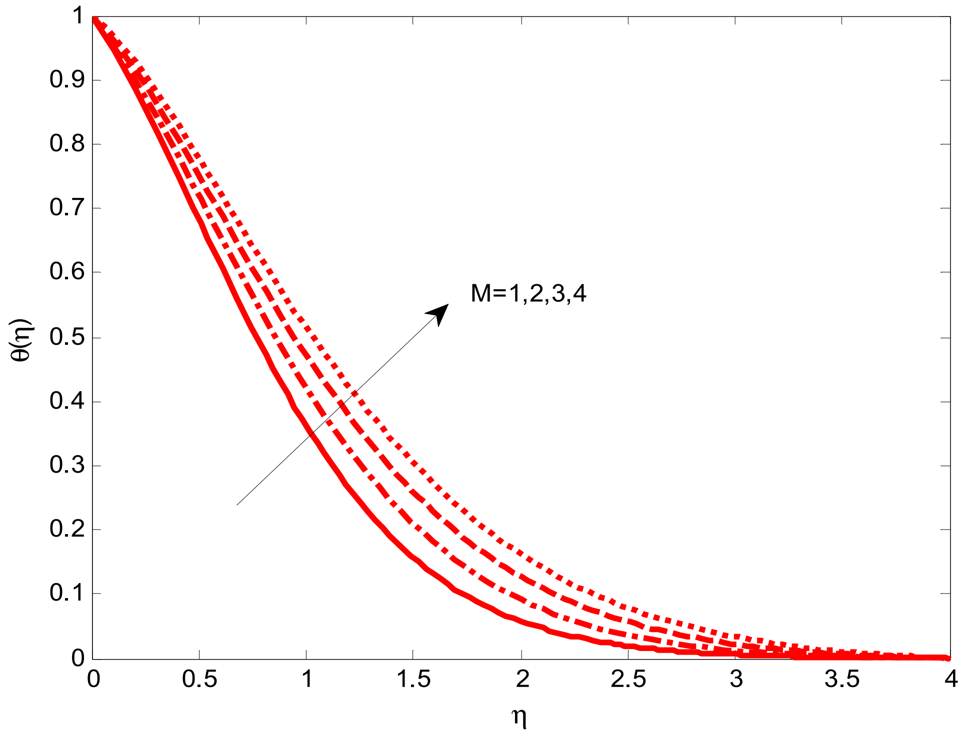

Fig.2 Temperature profiles for various values of *M*

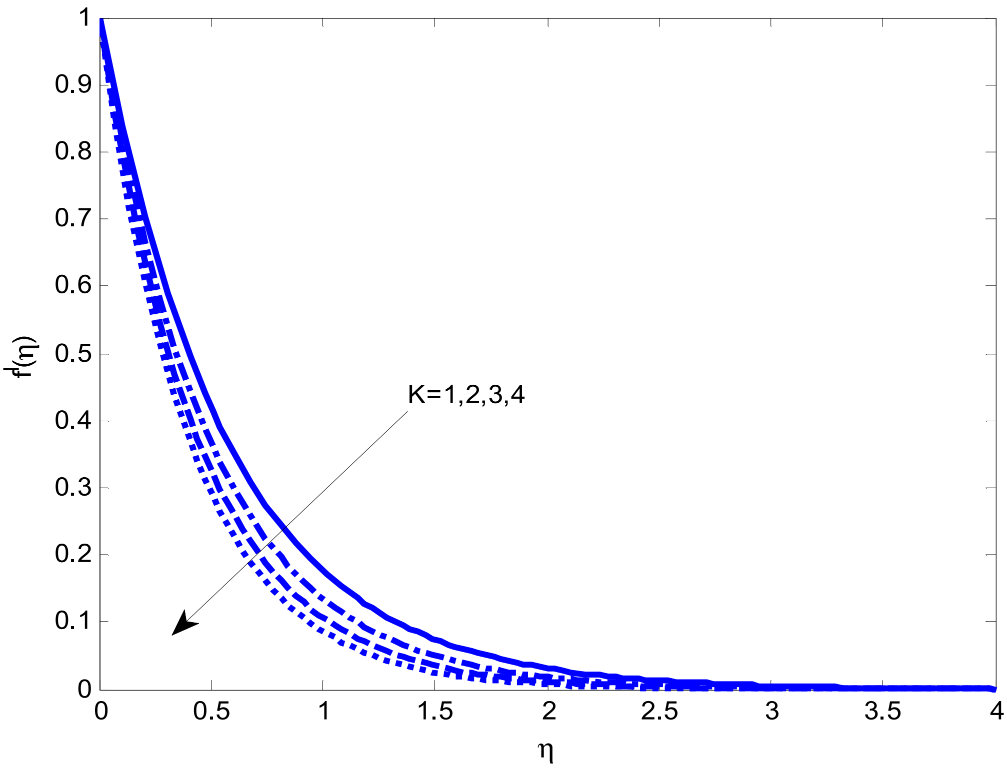

Fig.3 Velocity profiles for various values of *K*

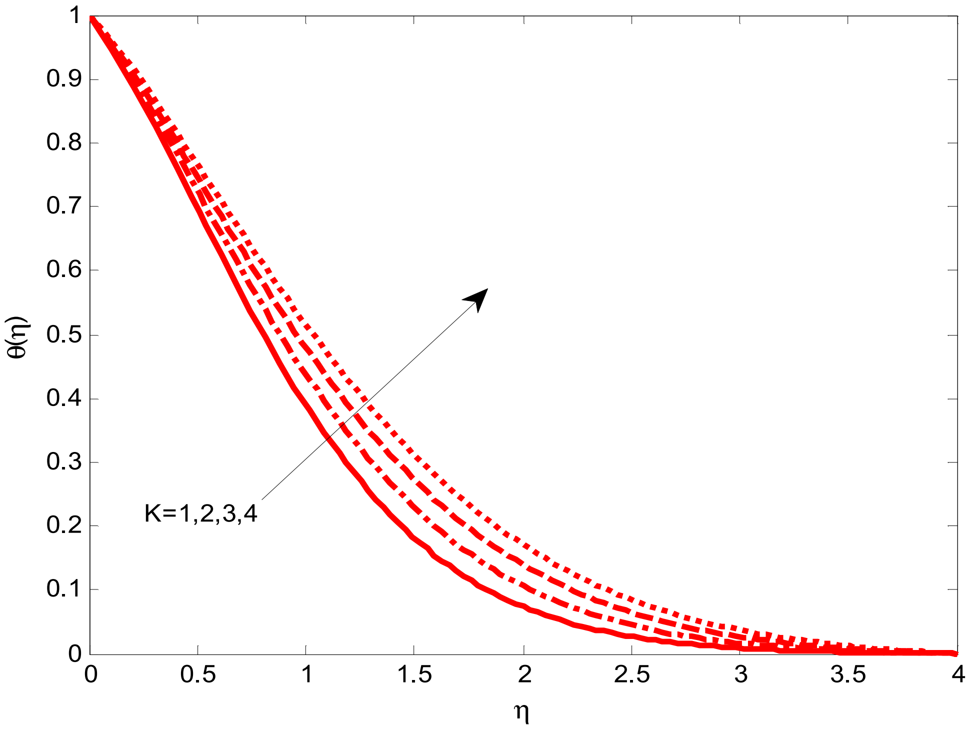

Fig.4 Temperature profiles for various values of *K*

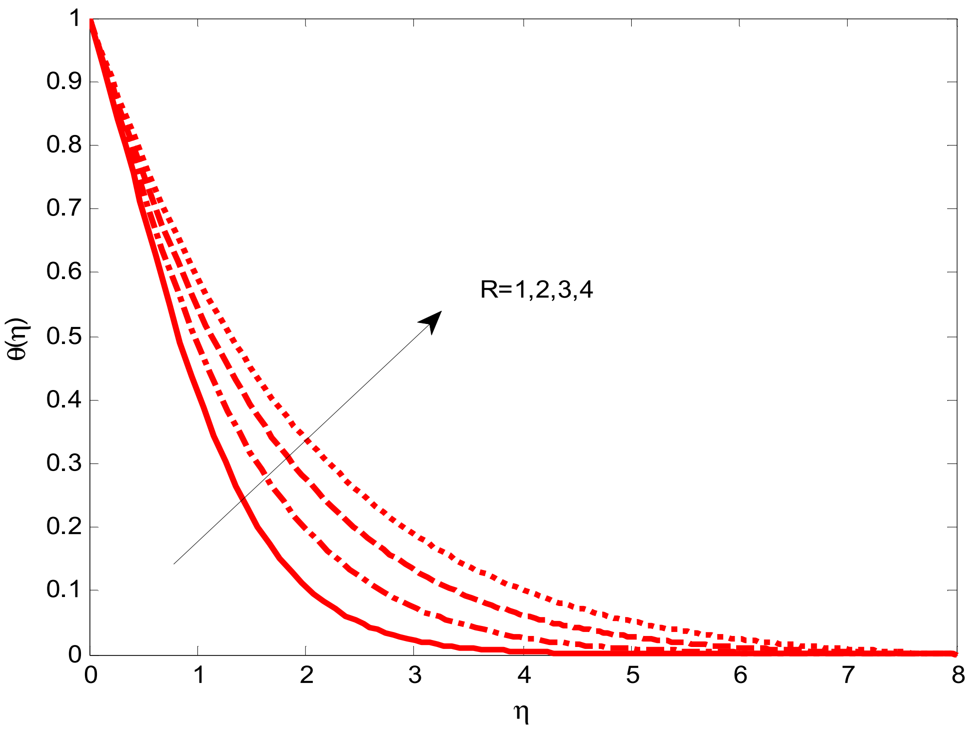

Fig.5 Temperature profiles for various values of *R*

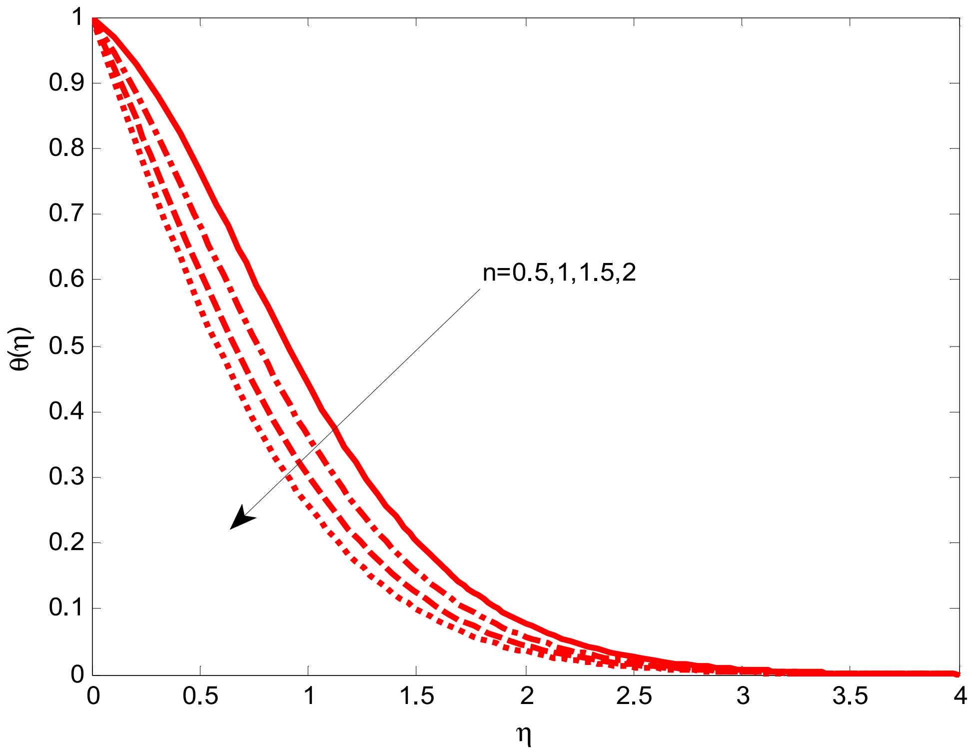

Fig.6 Temperature profiles for various values of n

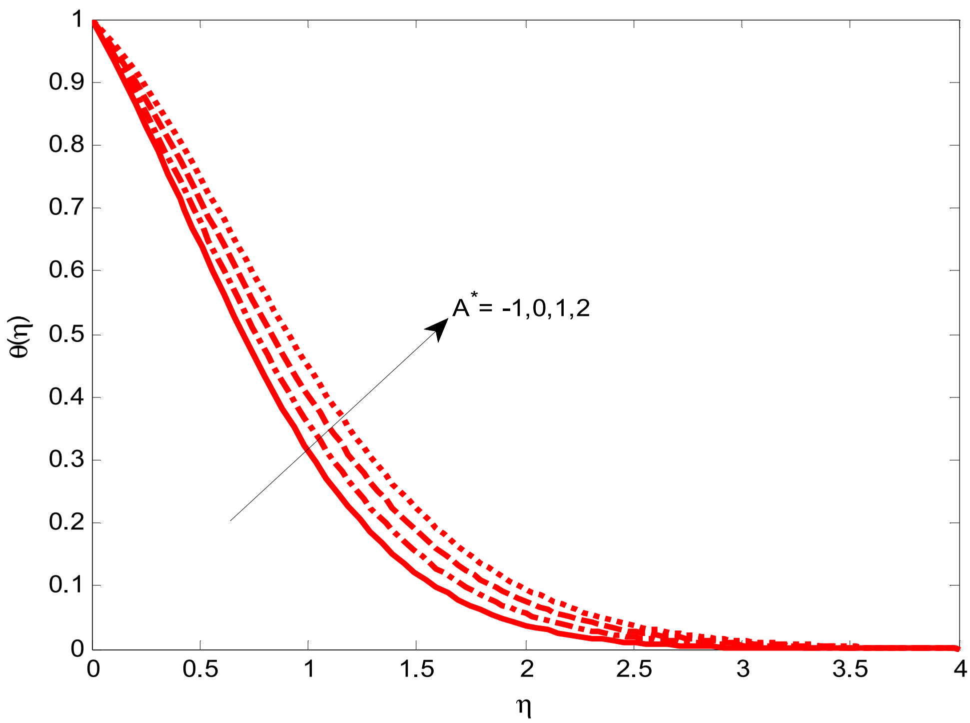

Fig.7 Temperature profiles for various values of A^*

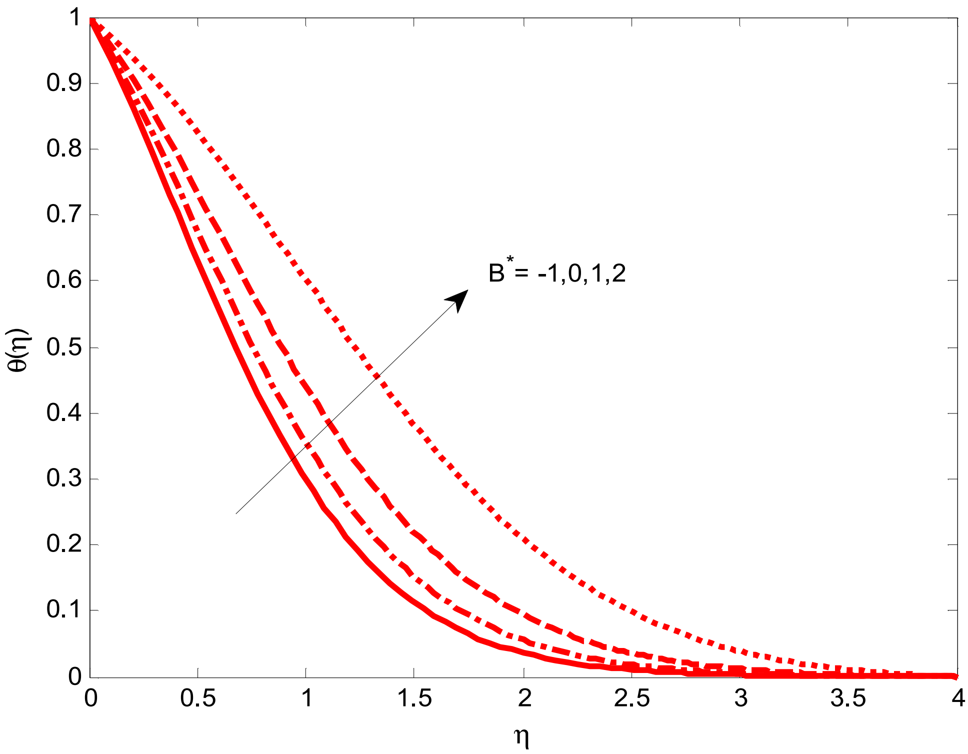

Fig.8 Temperature profiles for various values of B^*

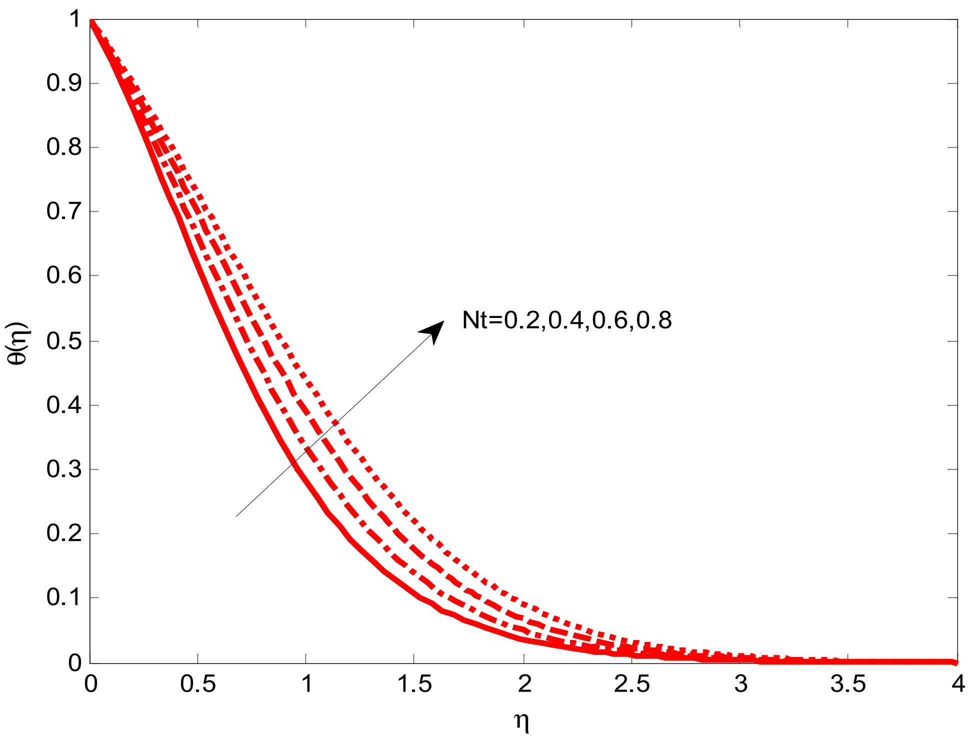

Fig.9 Temperature profiles for various values of Nt

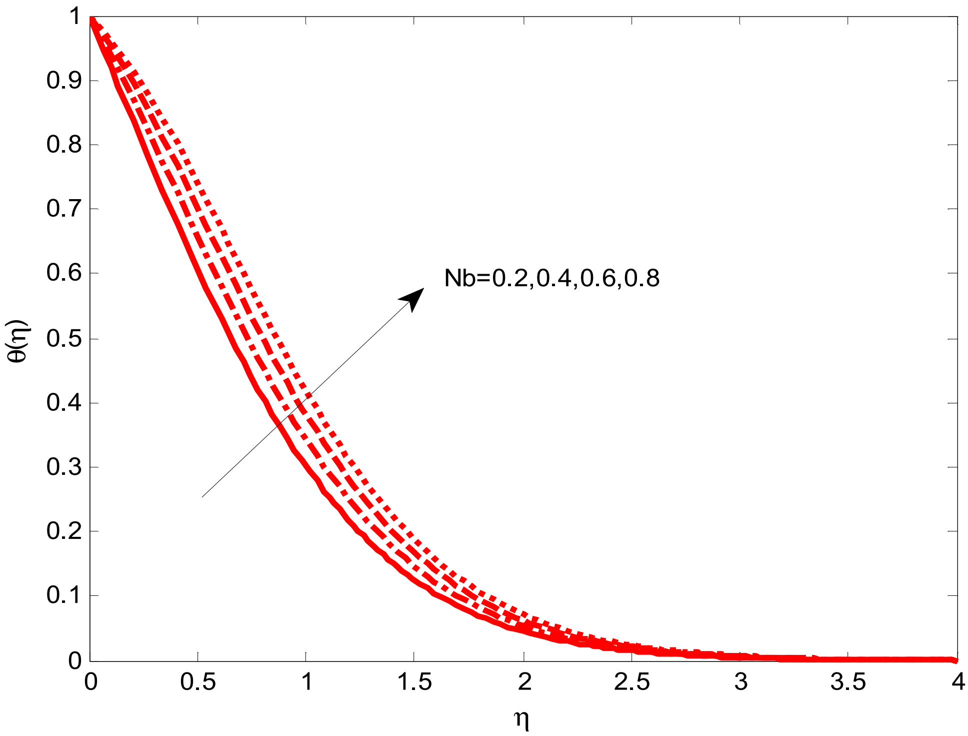

Fig.10 Temperature profiles for various values of *Nb*

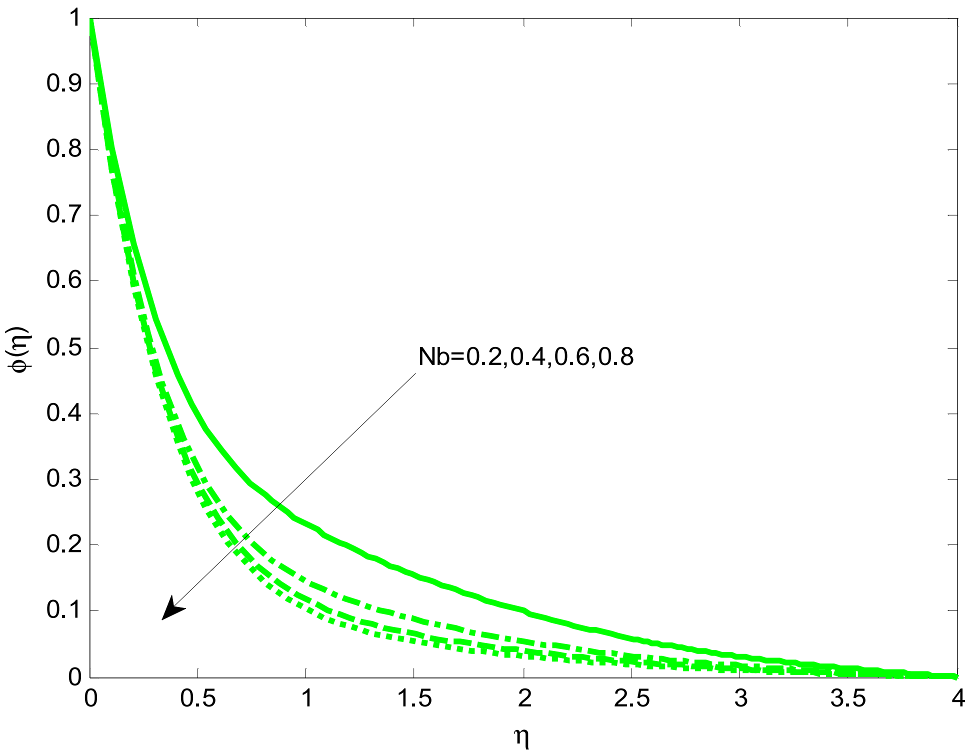

Fig.11 Concentration profiles for various values of *Nb*

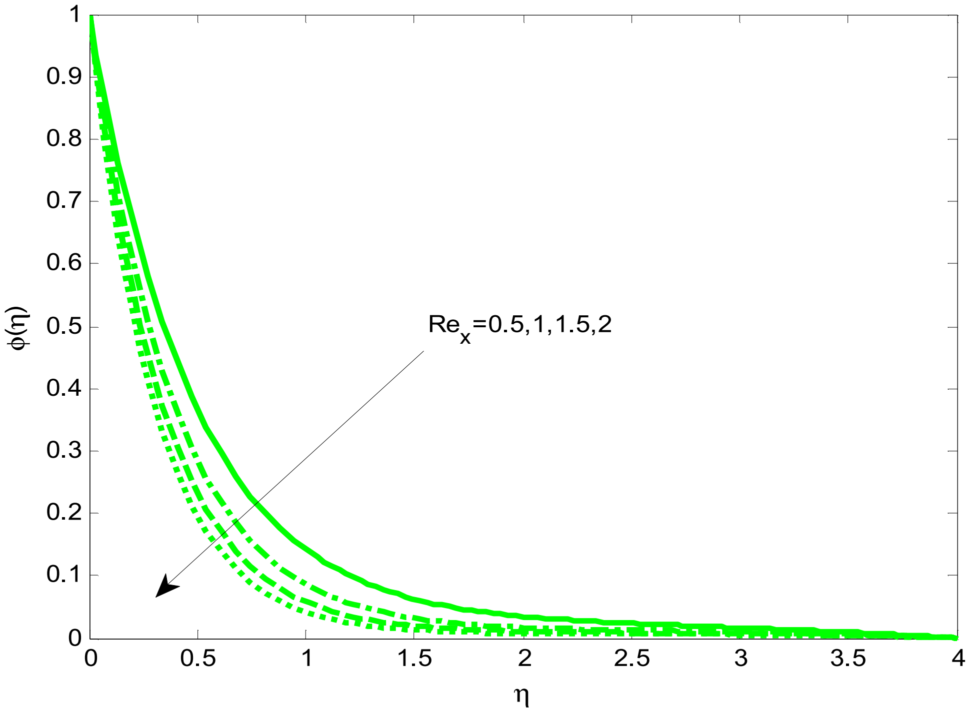

Fig.12 Concentration profiles for various values of Re_x

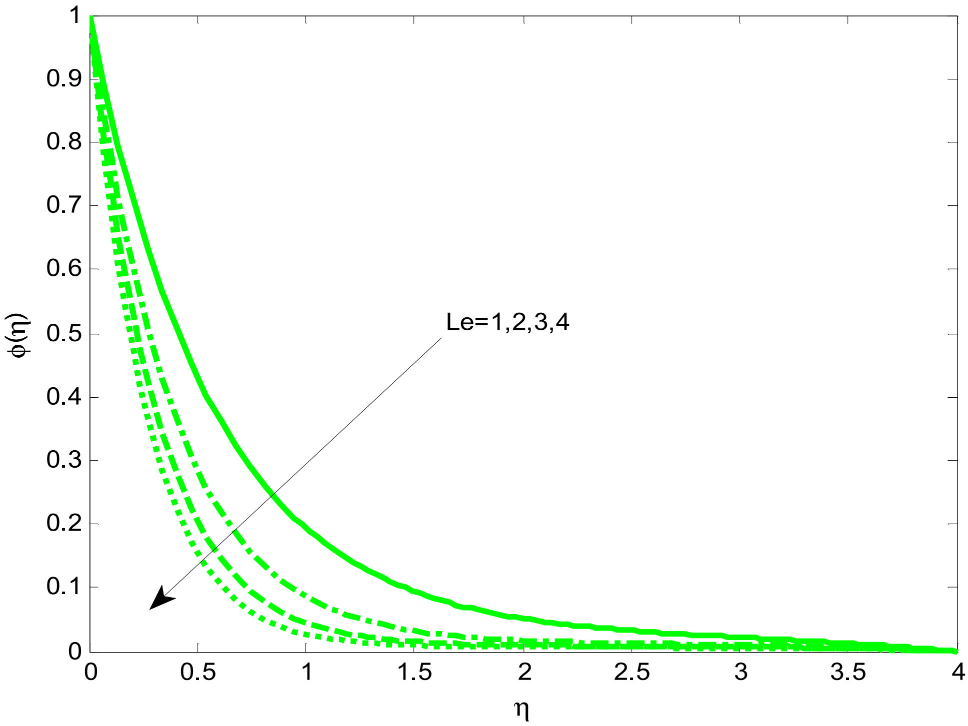

Fig.13 Concentration profiles for various values of *Le*

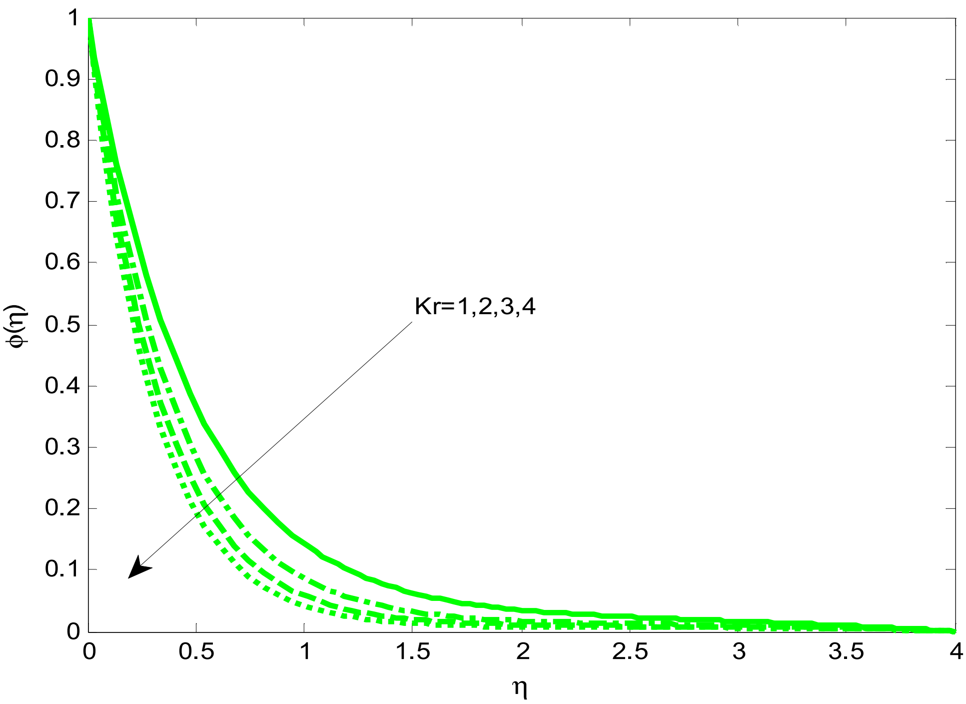

Fig.14 Concentration profiles for various values of *Kr*

4. Conclusions

This paper presents the influence of radiation and chemical reaction on MHD nanofluid flow over a continuously moving surface in porous medium in presence of non-uniform heat source/sink. The governing equations are transformed into system of nonlinear ordinary differential equations by using similarity transformation and solved numerically. The effects of non-dimensional governing parameters on velocity, temperature and concentration profiles are discussed and presented with help graphs. Also, friction factor, local Nusselt and Sherwood numbers are calculated and presented through tables. The conclusions of the present study are made as follows:

- A raise in the value of exponent parameter enhances the heat and mass transfer rate.
- An increase in the value of radiation parameter depreciates the Nusselt and Sherwood numbers.
- A raise in magneticfield parameter depreciates the friction factor, Nusselt number and enhances the mass transfer rate.
- The enhancement in porosity parameter declines the heat and mass transfer rate and skin friction coefficient.
- An increase in non-uniform heat source/sink parameters enhances the temperature profiles of the flow.

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