Advances in Physics Theories and Applications
ISSN 2224-719X (Paper) ISSN 2225-0638 (Online)
Vol.62, 2017

Induced Magnetic Field on Williamson Fluid Past a Stretching Surface with Nonlinear Thermal Radiation and Non-Uniform Heat Source or Sink

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Abstract
In this study, we investigated the effects of induced magnetic field and nonlinear thermal radiation on Williamson nano fluid past a stretching surface in the presence of non-uniform heat source/sink. The transformed governing equations are solved numerically using Runge-Kutta based shooting technique. We acquire better accuracy of the present results by comparing with the published literature. The influence of dimensionless parameters on velocity, temperature and concentration profiles along with the friction factor coefficient, the heat transfer rate and the mass transfer rate are discussed with the help of graphs and tables. It is found that the heat transfer rate in Williamson fluid is high while compared with the Base fluid.
Keywords: Induced magnetic field, stretching sheet, nonlinear thermal radiation, non-uniform heat source/sink, Williamson fluid.

Introduction

Convection flow over stretching sheet has considerable importance in various engineering processes and industrial applications such as drawing of plastic films, polymer extrusion, heat exchangers, electrolyte paper production etc. Due to these importance Sakiadis [1] was pioneering work by flow past a stretching sheet. After that the multiple researchers are investigated with various flow characteristics like flow past a vertical, parallel stretching sheet, flow past an exponentially stretching sheet, and flow over stretched cylinders with various dimensions and effects, which are described in [2-5]. The time dependent heat source/sink effect on ferrofluid flow past a horizontal plate was numerically discussed by Raju et al. [6]. Elbashbeshy et al. [7] analyzed an unsteady MHD convection flow past permeable stretching sheet in the presence of radiation parameter.

The heat transfer characteristics of MHD non-Newtonian fluid flow past a permeable stretching sheet with heat source/sink was investigated by Tufail et al. [8]. In most of the non-Newtonian fluids have invented by depending on the viscosity nature. Viscosity is an internal property of fluids. It is a function of pressure or temperature. Most of the non-Newtonian fluids are used in coating, blood flows, printing press, micro-circulatory systems, industrial and environmental chemistry and also science and engineering technologies etc. Because of these importance most of the studies conducted in this broad area, which are presented in [9-11]. A homotopy analysis of convection flow past a radiative exponentially stretching surface was examined by Mabood et al. [12]. Sajid and Hayat [13] illustrated the flow of boundary layer over an exponentially stretching surface in the presence of radiation and found that the radiation parameter helps to improve the temperature profiles. The mass suction and heat source/sink effect on MHD flow past a stretching sheet was considered by Bhattacharyya [14].

Recently, the tremendous research is going on the heat and mass transfer analysis of the flow over a stretching sheet due to its crucial applications in the space technology, metallurgy and pharmaceutical engineering industries, such as food processing technology, various hospital treatments and polymer production and so on. Moreover, coupled heat and mass transfer problems with homogeneous-heterogeneous reaction are of importance in various engineering processes, hence it is a considerable amount of attention in modern days. Therefore the possible applications can be found in some of the systems such as drying, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damage of crops due to freezing. Some of the related applications are discussed by [15-16]. Kumar and Singh [17] were considered the induced magnetic effect on convection flow in concentric vertical heated or cooled annulus. Flow of Peristaltic couple stress fluid past a rhythmically contracting slit channel was studied analytically by Mekhemier [18] and highlighted that the high pressure was created in couple stress fluid compared to Newtonian fluids. Raju and Sandeep [19] and Raju et al. [20] illustrated the flow over cone with various nanoparticles. An unsteady boundary layer analysis of flow past a permeable stretching surface in the presence of non-uniform heat source/sink was investigated by Zheng et al. [21]. The authors [21-22] studied the flow over wedge with magnetic field and radiation effects. A convection flow of a nanofluid in a rotating frame was discussed by Das [23]. Cortell [24] examined the nonlinear flow characteristics of a flow past a stretching sheet in the presence of radiation. Recently, the authors [27-30] depicted the flow over various geometries with non-uniform heat source or sink. With that highlighted that non-uniform heat source or sink controls the thermal boundary layer.

In view of all the above studies, no study reported on the numerical analysis of the nonlinear thermal radiation and induced magnetic field effect on Williamson nano fluid past a stretching surface in the presence of homogeneous-heterogeneous reactions, non-uniform heat source/sink. In this study, we analyzed the effects of induced magnetic field and nonlinear thermal radiation on Williamson nano fluid past a stretching surface in the presence of non-uniform heat source/sink and homogeneous-heterogeneous numerically. The influence of dimensionless parameters on velocity, temperature and concentration profiles along with the friction factor and local Nusselt and Sherwood numbers are discussed with the help of graphs and tables.

Formulation of the problem

In this study we proposed a mathematical model for steady boundary layer flow of a Williamson fluid in the presence of nonlinear thermal radiation and induced magnetic field effect. Here the sheet is considered along the $x-$ axis and $y-$axis is perpendicular to it. It is assumed that the applied magnetic field is of uniform strength H_0. It is also assumed that induced magnetic field is applied in $y-$direction and the parallel component H_1 approaches the value $H_e = H_0$ in the free stream flow and normal component of the induced magnetic field H_2 vanishes near the wall. T_w and T_∞ are indicates the temperatures near and far away from the stretching sheet. $u_w = cx$ and $u_e = dx$ are the stretching and free streams velocities respectively. Where c, d are positive constants. The governing boundary layer equations are as follows

Flow Analysis:

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

$$\frac{\partial H_1}{\partial x}+\frac{\partial H_2}{\partial y}=0, \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-\frac{\mu}{4\pi\rho}\left(H_1\frac{\partial H_1}{\partial x}+H_2\frac{\partial H_1}{\partial y}\right)= \left(v_f\frac{\partial^2 u}{\partial y^2}+\sqrt{2}\nu\Gamma\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial y^2}+u_e\frac{du_e}{dx}-\frac{\mu H_e}{4\pi\rho}\frac{dH_e}{dx}\right), \tag{3}$$

$$u\frac{\partial H_1}{\partial x}+v\frac{\partial H_1}{\partial y}-H_1\frac{\partial u}{\partial x}-H_2\frac{\partial u}{\partial y}=\mu_e\frac{\partial^2 H_1}{\partial y^2}, \tag{4}$$

with the boundary conditions

$$\left.\begin{aligned}&u=u_w(x)=cx, v=0, \frac{\partial H_1}{\partial y}=H_2=0, \quad \text{at } y=0,\\ &u=u_e(x)=dx, \frac{\partial u}{\partial y}\to 0, \frac{\partial v}{\partial y}\to 0,\\ &H_1=H_e(x)=H_0x, \quad \text{as } y\to\infty,\end{aligned}\right\} \tag{5}$$

μ_e is the magnetic diffusivity of the fluid, which is given by $\mu_e=\frac{1}{4\pi\sigma}$, (6)

where u, v are the velocity components along the x, y directions respectively. H_1, H_2 are the induced magnetic components in x and y directions. H_0 is the induced magnetic component in free stream flow, v_f is the kinematic viscosity coefficient,. To convert the nonlinear partial differential equations for velocities, we now introducing the self-similarity transformations are given by:

$$\left.\begin{aligned}&u=cxf'(\eta), v=-\upsilon_f^{0.5}c^{0.5}f(\eta), \eta=\upsilon_f^{-0.5}c^{0.5}y,\\ &H_1=H_0xg'(\eta), H_2=-H_0\upsilon_f^{1/2}c^{-1/2}g(\eta),\end{aligned}\right\} \tag{7}$$

Here in Equation (7) u, v and H_1, H_2 are automatically satisfy the continuity equation, by using equation (7), the equations (1) to (3) transformed equations are given by:

$$f''' + \gamma f'' f''' + ff'' - f'^2 + \frac{d^2}{c^2} + \beta(g'^2 - gg'' - 1) = 0, \quad (8)$$

$$\varepsilon g''' + fg'' - f'' g = 0, \quad (9)$$

The transformed boundary conditions are:

$$\left.\begin{array}{l} f = 0, g = 0, f' = 1, g' = 1, \quad at \quad \eta = 0, \\ f' \to d/c, g' \to 1, \quad as \quad \eta \to \infty, \end{array}\right\} \quad (10)$$

here β is the magnetic field parameter, γ is the Williamson fluid parameter, ε and is the magnetic prandtl number.

$$\left.\beta = \frac{\mu_f H_0^2}{4\pi\rho_f c^2}, \gamma = \Gamma\sqrt{\frac{2c^3}{\nu}}, \varepsilon = \frac{1}{4\pi\sigma_f \upsilon_f},\right\} \quad (11)$$

Heat Transfer analysis:

The boundary layer thermal energy equation with nonlinear thermal radiation and non-uniform heat source/sink effect is given by

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^*}{3k\rho c_p}\frac{\partial T}{\partial y}\left(T^3\frac{\partial T}{\partial y}\right) + q''', \quad (12)$$

with the convective boundary conditions are

$$T = T_w, \text{ at } y = 0, \; T \to T_\infty, \text{ as } y \to \infty, \quad (13)$$

The non-dimensional temperature is given by

$$T = T_\infty + (T_w - T_\infty)\theta, T = T_\infty(1 + (\theta_w - 1)\theta) \quad (14)$$

where T is the fluid temperature, T_w, T_∞ are the near the fluid temperature and the far away from the fluid temperature, k is the thermal conductivity of the fluid, c_p is the specific heat capacitance at constant pressure, c_s is the concentration susceptibility and σ^* is the Stefan-Boltzmann constant.

The time dependent non-uniform heat source/sink q''' defined as

$$q''' = \frac{k_f u_w(x)}{x\nu}\left(A^*(T_w - T_\infty)f' + B^*(T - T_\infty)\right), \quad (15)$$

The above equation positive values of A^*, B^* corresponds to heat generation and negative values are corresponds to heat absorption.

By using self-similarity transformations of (13), (14), equation (12) reduced to

$$\begin{array}{l} \theta'' + \Pr f\theta' + A^* f' + B^*\theta + \\ R\left(\left(1+(\theta_w-1)\theta\right)^3\theta'' + 3(\theta_w-1)\theta'^2\left(1+(\theta_w-1)\theta\right)^2\right) = 0, \end{array} \quad (16)$$

with the transformed boundary conditions

$$\theta(0) = 1, \; \theta(\infty) = 0, \quad (17)$$

where $\Pr$ is the Prandtl number, R is the thermal radiation parameter, θ_w is the ratio of temperatures which are given by

$$\Pr = \frac{k}{\mu C_p}, R = \frac{16\sigma^* T_\infty^3}{3kk^*}, \theta_w = \frac{T_\infty}{T_w}, \quad (18)$$

For physical quantities of interest the friction factor coefficients along x directions, local Nusselt and Sherwood numbers are given by

$$\begin{array}{l} C_{fx}\,\mathrm{Re}^{1/2} = -(f''(0) + \gamma f''(0)), \\ \mathrm{Re}^{1/2}\,C_{fy} = -g''(0), \end{array} \quad (30)$$

$$\mathrm{Re}^{-1/2} Nu_x = -\theta'(0). \qquad (31)$$

Where $\mathrm{Re} = \dfrac{x u_w(x)}{\nu}$ is the Reynolds number.

Results and Discussion

The set of nonlinear ordinary differential equations (6), (7) and (13) subjected to the boundary conditions (8) and (14) are solved numerically using Runge-Kutta based shooting technique. Results shows the influence of non-dimensional governing parameters on velocity, temperature and concentration profiles along with the friction factors, local Nusselt and Sherwood numbers. For numerical computations we considered the non-dimensional parameter values as $\beta = 1, \gamma = 3, \varepsilon = 0.1, R = 0.3, d/c = 3, A^* = 0.1, \theta_w = 1.1, \mathrm{Pr} = 0.7, B^* = 0.1$. These values are kept as common in entire study except the variations in respective figures and tables. In graphical results red color indicates the Williamson fluid flow over a stretching surface while green color indicates the Newtonian fluid flow over a stretching surface.

Figs. 1-2 depict the influence of induced magnetic field on velocity profiles. It is clear that for higher values of the induced magnetic field β, there is a reduction in the velocity and induced velocity fields on the flow over a stretching surface. At $d/c = 3$, these results coincide with the (Ali et al. [26]). Physically, an improved value of magnetic field parameter generates an opposite force to the flow direction. This force can be dominates the induced profiles due to this reason the velocity profiles are suppressed. In Figs. 3-5, we consider the effect of d/c on the velocity, induced velocity, temperature profiles for both the Cases. It can be examine from the figures that increasing values of d/c encourages the velocity profiles of the flow. Therefore, this results are agrees with (Ali et al. [26]). It is also important to point out that the induced velocity shows mixed profiles in the flow. Physically, enhanced values of d/c implies increases the straining motion near the stretching sheet this can leads to encourages the acceleration of the external stream. Therefore, an increase in d/c has to thinning the boundary layer structure.

The influence of magnetic prandtl number on induced velocity profiles are observed in Fig. 6. It is noticed dual behavior in induced velocity. These may due to the ratio of kinematic viscosity to magnetic diffusivity is low near the stretching sheet and for away from the stretching sheet it is high. Figs. 7 depict the influence of non-uniform heat source/sink parameter on temperature profiles of the flow. It noticed that increasing values of non-uniform heat source/sink parameters enhances the temperature profiles of the flow. Generally, an improved value of the non-uniform heat source/sink parameter generates energy to the flow. The dimensionless temperature variations for various values of radiation parameter R is shown in Fig.8. It exhibit that the larger values of radiation parameter shows an improvement in the temperature profiles. Basically, the larger values of radiation parameter produce more heat to working fluid that appears an enhancement in the temperature profiles. Table 1 demonstrates the comparison of the present results with the existed literature under some limited cases. We found better agreement of the present results with the existed literature. This proves the validity of the obtained results along with the accuracy of the numerical technique we used in this study.

Tables 2 and 3 demonstrate the variations in the skin friction coefficient, the rate of heat and mass transfer for Williamson and Newtonian fluid cases for various values of non-dimensional governing parameters. It is evident that rise in the values of magnetic field parameter reduces the friction factor coefficient and heat transfer rate for both cases. The friction factor coefficient and the heat transfer rate are increased in the presence of magnetic Prandtl number and d/c. Hike in the values of non-uniform heat source/sink parameter does not influence the friction factor but it reduces the heat transfer rate. The thermal radiation parameter and temperature ratio parameters are helps to improve the rate of heat transfer.

Table.1 Validation of present results with existed studies when $\gamma = \varepsilon = R = d/c = A^* = B^* = 0$, $\theta_w = 0, \Pr = 0.72$.

β	$\frac{a}{c} = 3$				β	$\frac{a}{c} = 0.5$			
	$\mathrm{Re}_x^{1/2} C_f$ Ali et al. [26]	$\mathrm{Re}_x^{-1/2} Nu$ Ali et al. [26]	Present $\mathrm{Re}_x^{1/2} C_f$	Present $\mathrm{Re}_x^{-1/2} Nu$		$\mathrm{Re}_x^{1/2} C_f$ Ali et al. [26]	$\mathrm{Re}_x^{-1/2} Nu$ Ali et al. [26]	Present $\mathrm{Re}_x^{1/2} C$	Present $\mathrm{Re}_x^{-1/2} Nu$
0.1	4.70928	0.97902	4.70927	0.97902	0.1	-0.57595	0.59171	-0.57595	0.59171
0.5	4.62764	0.97617	4.62765	0.97617	0.15	-0.50938	0.60207	-0.50938	0.60207
1	4.52158	0.97240	4.52158	0.97240	0.2	-0.40717	0.61811	-0.40717	0.61811
2	4.29431	0.96405	4.29431	0.96404	--	--	--	--	--
5	3.43352	0.92863	3.43352	0.92862	--	--	--	--	--
8	1.87734	0.84494	1.87732	0.84493	--	--	--	--	--

Table.2 Physical parameter values of $f''(0)$, and $-\theta'(0)$ for non-Newtonian fluid

β	d/c	ε	A^*	B^*	R	θ_w	$-f''(0)$	$-\theta'(0)$
1							7.105409	1.243370
3							5.709577	1.221556
5							4.211657	1.192009
	2						6.655144	1.082776
	2.3						8.726780	1.106600
	2.6						10.24008	1.128466
		1					8.485314	1.250802
		2					8.496524	1.250949
		3					8.504279	1.251062
			0.4				7.567490	0.390587
			0.5				7.567491	-0.005537
			0.6				7.567491	-0.243420
				0			6.567490	1.283092
				0.3			6.567490	1.186196
				0.5			6.567490	1.118659
					0		12.871665	1.158946
					2		12.871665	1.279897
					4		12.871665	1.442918
						1	12.871563	1.158534
						2	12.87154	2.15950
						3	12.871563	3.653255

Table.3 Physical parameter values of $f''(0)$, and $-\theta'(0)$ for Newtonian fluid

β	d/c	ε	A^*	B^*	R	θ_w	$-f''(0)$	$-\theta'(0)$
1							4.369221	1.297262
3							3.788377	1.259931
5							3.158422	1.222766
	2						1.909444	1.129353
	2.3						2.755920	1.198634
	2.6						3.420977	1.226009
		1					4.689125	1.306632
		2					4.694339	1.313842
		3					4.697612	1.326992
			0.4				4.678620	0.257504
			0.5				4.678620	0.135972
			0.6				4.678620	-0.128988
				0			4.678620	1.307351
				0.3			4.678620	1.213349
				0.5			4.678620	1.128473
					0		4.678620	1.268770
					2		4.678620	1.420326
					4		4.678620	1.603999
						1	4.678620	1.283281
						2	4.678620	1.525017
						3	4.678620	1.552344

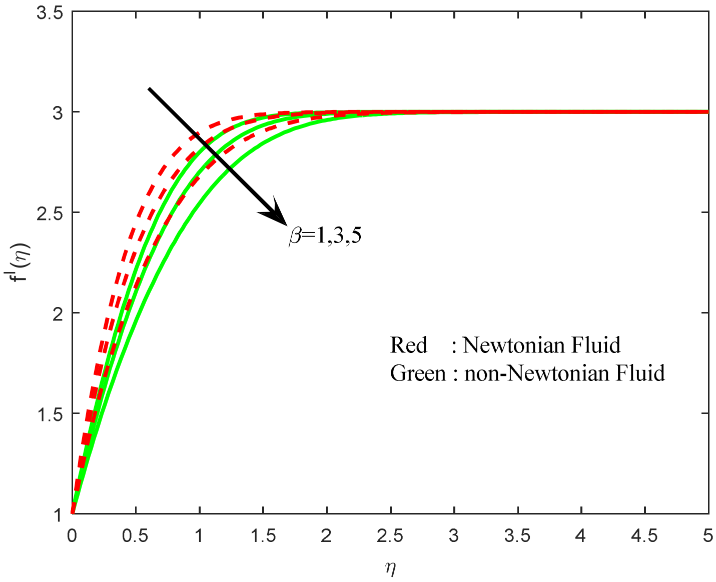

Fig.1 Velocity profile for different values of magnetic field parameter

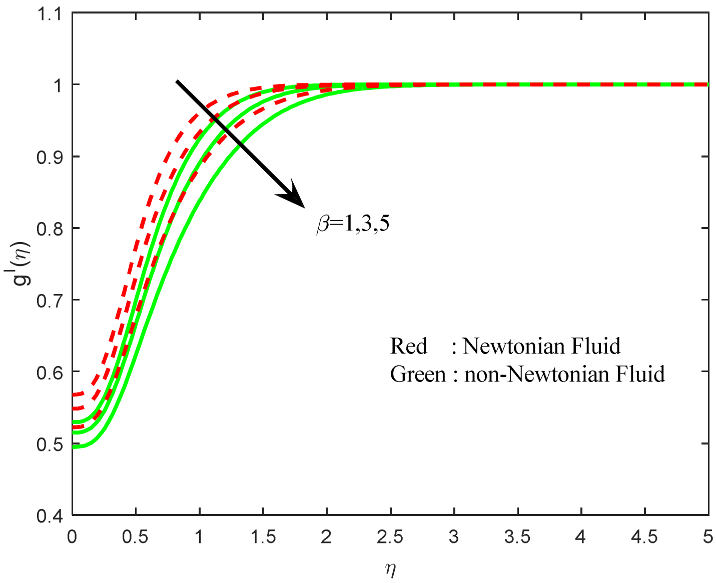

Fig.2 Induced velocity profiles for different values of magnetic field parameter

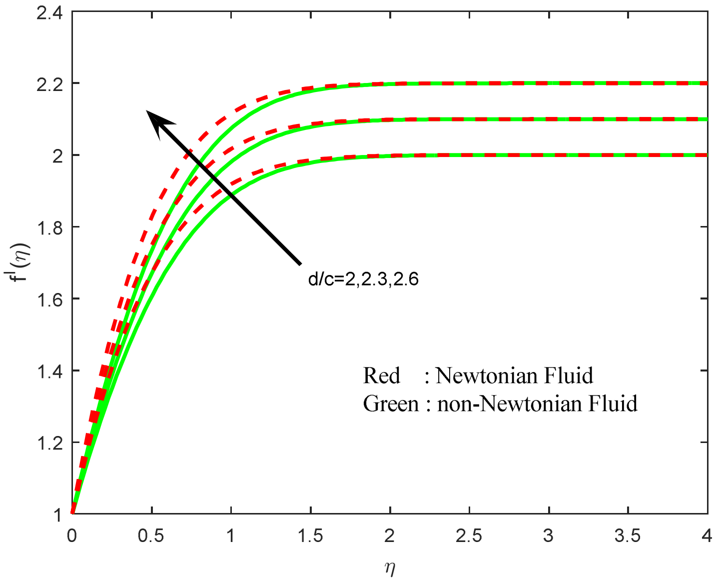

Fig.3 Velocity profiles for different values of the d/c

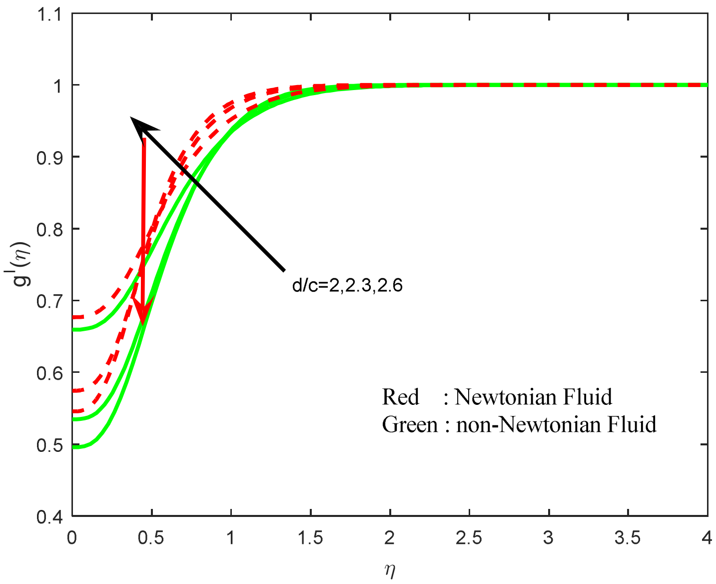

Fig.4 Induced velocity profile for different values of the d/c

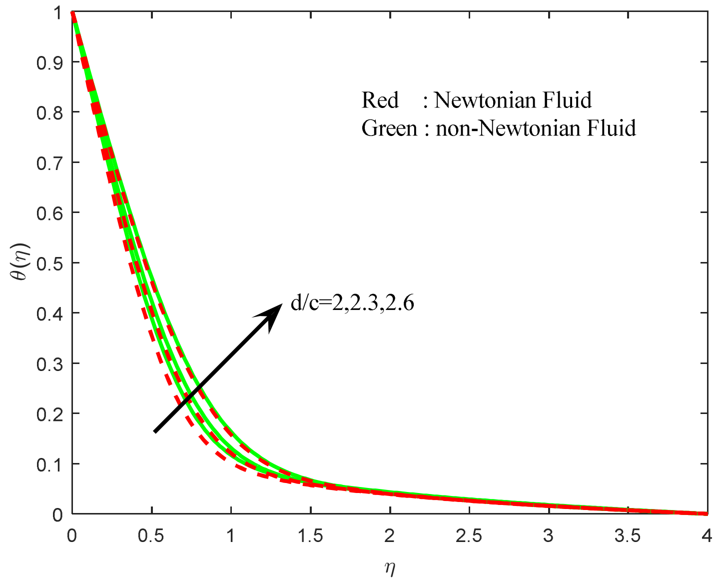

Fig.5 Temperature profiles for different values of d/c

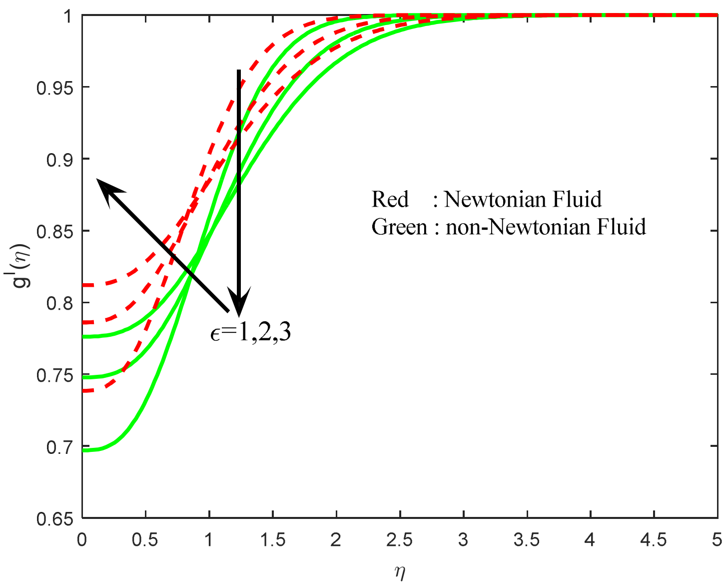

Fig.6 Induced velocity profiles for different values of reciprocal magnetic prandtl parameter

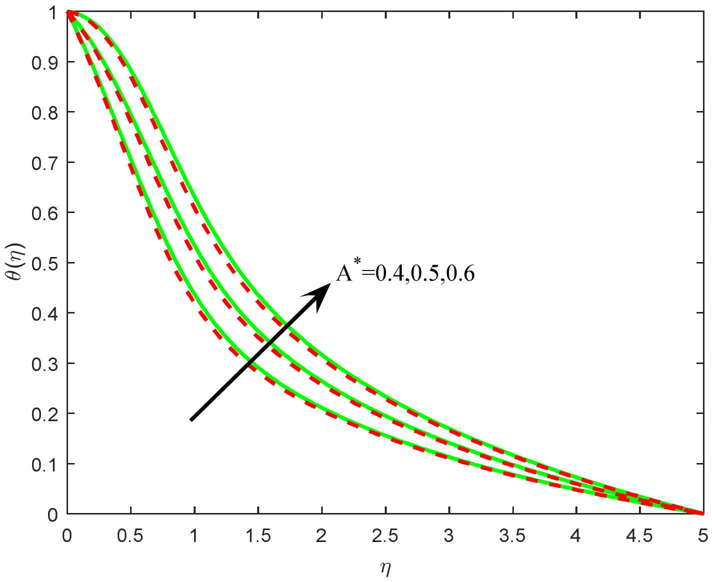

Fig.7 Temperature profiles for different values of non-uniform heat source/sink parameter

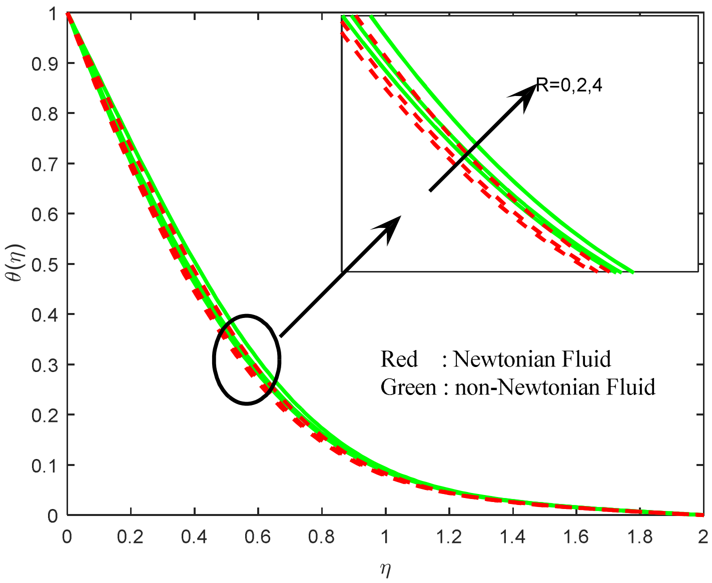

Fig.8 Temperature profiles for different values of radiation parameter

4. Conclusions

In this study, we discussed the effects of induced magnetic field and nonlinear thermal radiation on Williamson fluid flow past a stretching/shrinking surface in the non-uniform heat source/sink. The influence of dimensionless parameters on velocity and temperature profiles along with the friction factors and local Nusselt numbers are depicted with the help of graphs and tables. The conclusions are as follows:

- For controlling of heat transfer rate Williamson fluid is very helpful while compared with the Newtonian fluid.
- The radiation and non-uniform heat source/sink parameters help to enhance the temperature profiles of the flow.
- Induced magnetic field have tendency to reduce the momentum boundary layer along with the friction factor.
- Heat and mass transfer rate in Newtonian fluid is high while compared with the Williamson fluid.

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