Radiation Effect on Boundary Layer Flow of a Nanofluid over a Nonlinearly Permeable Stretching Sheet

Fazlul Kader Murshed[1] Indranil Roychowdhury[1] Arnab Chattopadhyay[1] N. Sandeep[2*]
1.M.Tech Computing Science and Engineering, VIT University, Vellore, Tamil Nadu, 632014, India
2.Assistant Professor, Fluid Dynamics Division, VIT University, Vellore, Tamil Nadu, 632014, India
Corresponding Author Email: nsreddy.dr@gmail.com

Abstract
We analyze the influence of thermal radiation on boundary layer flow of a nanofluid past a nonlinearly permeable stretching sheet. The governing partial differential equations are reduced into a system of ordinary differential equations using similarity transformation and then solved by using shooting technique. Effects of thermal radiation parameter, Brownian motion parameter, Suction parameter and Thermophoresis parameter on the flow, concentration and heat transfer characteristics are thoroughly investigated. The local Nusselt number and the local Sherwood numbers are presented and compared with existed results.
Keywords: Heat transfer, Nanofluid, Thermal radiation, Boundary layer flow, Stretching/Shrinking sheet.

1. Introduction

The fluid flow over a stretching/shrinking surface is has important industrial applications like drawing of continuous filaments through quiescent fluids, annealing and tinning of copper wires, glass blowing, manufacturing of plastic and rubber sheets, crystal growing and continuous cooling and fiber spinning, stretching of plastic films and many others. While manufacturing the sheets generally at certain temperatures there is a chance of melting the sheet due to temperature differences. So, the final output of the product is depends on the stretching rate and the rate cooling process. It is very important to understand to analyse the flow and heat transfer behavior of the process so that the output of the product is in good quality specifications along with good life period.

Choi (1995) was the first to introduce the word nanofluid that represents the fluid in which nano scale particles whose diameter is less than 100 nm. Because of the materials with nanometer sizes having unique physical and chemical properties, the can flow through very thinly channels without clotting them. Khanafer et al. (2003) explained the behavior of the liquid molecules in thinly channels. The viscosity and thermal conductivity on hydro magnetic flow over a non linear stretching sheet was discussed by Prasad et al. (2010). Kumari and Nath (2009) analyzed the flow and heat transfer of a MHD Newtonian fluid over impulsively stretched plane surface by using an analytical method namely homotophy analysis. The thermal conductivity of solid particles is several times more than that of the base or convectional fluids was discussed by Das et al. (2007) in the book nanofluids science and technology. In this book they clearly explained the thermal properties and behavior of the particles at different temperatures. Boungiorno (1996) presented different theories on enhanced heat transfer characteristics of nanofluids and he concluded that thermal dispersion phenomenon cannot explain fully about the high heat transfer coefficients in nanofluids. The researchers Kumaran and Ramanaiah (1996), Elbashbeshy (2001) proved that stretching is not necessarily being a linear and they extended their research on flow over a quadratic stretching sheet and nonlinearly stretching sheet respectively. The heat transfer characteristics of the base fluids facing major obstacle to the effectives in heat exchange was discussed by Daungthongsuk and Wongwises (2007). Oztop and Abu-Nada (2008) discussed the heat transfer characteristics on nanofluids by immersing the high conductivity nano materials in base fluids and they concluded that the effective thermal conductivity of the fluid increases appreciably and consequently enhances the heat transfer characteristics by suspending the high thermal conductivity of nano materials in to the base fluids. The two dimensional mixed convection boundary layer MHD stagnation point flow in porous medium bounded by a stretching vertical plate was studied by Hayat et al. (2010). They assumed that the stretching velocity and the surface temperature vary linearly along with the distance from stagnation point.

The flow of an electrically conducting fluid in presence of uniform magnetic field over a stretching elastic sheet was studied by Pavlov (1974). By employing Darcy model for the porous medium Cheng and Minkowycz (1977) discussed a problem of natural convection past a vertical plate. They found the effect of Brownian motion and thermophoresis parameters on the velocity and temperature profiles. The transition effect of the boundary layer flow due to suddenly imposed magnetic field on the viscous flow past a stretching sheet and sudden withdrawal of a magnetic field on the viscous flow past a stretching sheet under a magnetic field is discussed by Kumaran et al. (2010). They found that in both cases the sheet stretches linearly along the direction of the fluid flow. Sandeep et al. (2013) discussed radiation effects on unsteady natural convective flow of a nanofluid past an infinite vertical plate. Mohan Krishna et al. (2014) extended this work by considering heat source effect and different nanofluids. Sandeep et al. (2012) discussed radiation and chemical reaction effects of the MHD flow over a vertical plate. Recently the resaerchers (Ramana Reddy et al., 2014, Mohankrishna et al., 2013, Sandeep et al.2013) analyzed the heat and momentum transfer characteristics at different channels by immersing the micro or millimeter sized particles in to base fluids.

In this paper, our main objective is to extend the work of Rana and Bhargava (2012) by taking thermal radiation on boundary layer flow of a nanofluid past a nonlinearly permeable stretching sheet. To the authors' knowledge no studies have been communicated with regard to radiation effect on boundary layer flow and heat transfer of a nanofluid past a nonlinearly stretching sheet. The governing boundary layer equations have been transformed to system of ordinary differential equations using similarity transformation and these have been solved numerically. Effects of thermal radiation, thermophoresis parameter, Brownian motion parameter and suction parameter on the flow, concentration and heat transfer characteristics are thoroughly investigated. The local Nusselt number and the local Sherwood numbers are discussed through tables. It is hoped that the results obtained will not only provide useful information for applications but also serve as a complement to the previous studies.

2. Mathematical formulation

Consider a steady, laminar, incompressible and two dimensional boundary layer flow and heat transfer of a nanofluid past a permeable stretching/shrinking sheet coinciding with the plane $y=0$ and the flow being confined to $y>0$. It is assumed that the pressure gradient and external forces are neglected in this problem. The flow is generated by the nonlinear stretching/shrinking sheet along the x-axis where x is the coordinate measured along the stretching/shrinking sheet. Under the boundary layer approximations, the governing equations for conservation of mass, momentum, thermal energy and nanoparticle concentration of the problem can be expressed as

$$u_x + v_y = 0 \quad (1)$$

$$uu_x + vu_y = \nu u_{yy} \quad (2)$$

$$uT_x + vT_y = \alpha T_{yy} + \tau\left[D_B C_y T_y + \frac{D_T}{T_\infty}\left(T_y\right)^2\right] - \frac{1}{\left(\rho c_p\right)_{nf}}(q_r)_y \quad (3)$$

$$uC_x + vC_y = D_B C_{yy} + \frac{D_T}{T_\infty} T_{yy} \quad (4)$$

The boundary conditions of equations (1) to (4) are

$$\begin{aligned} &u=U_w, v=v_w, T=T_w, C=C_w \ \ at\ \ y=0 \\ &u\to 0,\ \ T\to T_\infty,\ \ C\to C_\infty \ \ as\ \ y\to\infty \end{aligned} \quad (5)$$

Where u and v are the velocity components in the x and y directions respectively, T is the temperature, C is the nanoparticle volume fraction, T_w is the surface temperature, T_∞ is the ambient temperature, C_w is the nanoparticles volume fraction near the plate and C_∞ is the nanoparticles volume fraction far from the plate, v_w is the suction or injection velocity with $v_w<0$ for suction and $v_w>0$ for injection, $\tau=(\rho c)_p/(\rho c)_f$, where $(\rho c)_p$ is the effective heat capacity of the nanoparticles, $(\rho c)_f$ is the heat capacity of the base fluid, $\alpha = k_m/(\rho c)_f$ is the thermal diffusivity of the fluid, ν is the kinematic viscosity, D_B is the Brownian diffusion coefficient and D_T is the thermophoretic diffusion coefficient. The constant n is the nonlinearity parameter with $n=1$ for the linear case and $n\neq 1$ is for the nonlinear case. It is assumed that the surface is stretched or is shrunk with the velocity $U_w = ax^n$, where $a>0$ is a constant.

By using Roseland approximation, the Radiative heat flux q_r is given by

$$q_r = -\frac{4\sigma^*}{3k^*} T_y^4 \quad (6)$$

Where σ^* is the Steffen Boltzmann constant and k^* is the mean absorption coefficient. Considering the temperature differences within the flow sufficiently small such that T^4 may be expressed as the linear function of temperature. Then expanding T^4 in Taylor series about T_∞ and neglecting higher-order terms takes the form

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

In view of equations (6) & (7), equation (3) reduces to

$$uT_x + vT_y = \alpha T_{yy} + \frac{1}{(\rho c)_f}\frac{16T_\infty^3\sigma^*}{3k^*}T_{yy} + \tau\left[D_B C_y T_y + \frac{D_T}{T_\infty}\left(T_y\right)^2\right] \tag{8}$$

Further, we seek for a similarity solution of equations (1) to (4) subject to the boundary conditions (5) by introducing the following similarity transformation:

$$U = ax^n f'(\eta), v = -\sqrt{\frac{a\nu(n+1)}{2}}x^{(n-1)/2}\left[f(\eta)+\frac{n-1}{n+1}\eta f'(\eta)\right]$$

$$\theta(\eta) = (T-T_\infty)/(T_w-T_\infty), \phi(\eta) = (C-C_\infty)/(C_w-C_\infty),$$

$$\eta = y\sqrt{\frac{a(n+1)}{2\nu}}x^{(n-1)/2},\ R = \frac{16T_\infty^3\sigma^*}{(\rho c)_f 3\nu k^*} \tag{9}$$

where prime denotes differentiation with respect to η. To have similarity solutions of equations (1) to (5), we assume

$$v_w = -\sqrt{\frac{a\nu(n+1)}{2}}x^{(n-1)/2}S \tag{10}$$

where the constant parameter S corresponds to suction $(S > 0)$ and injection $(S < 0)$ or withdrawal of the fluid, respectively.

Substituting equation (8) into equations (2) to (4), where equation (1) is identically satisfied, we obtain the following ordinary differential equations:

$$f''' + ff'' - \frac{2n}{n+1}\left(f'\right)^2 = 0 \tag{11}$$

$$\left(\frac{1}{\Pr}+R\right)\theta'' + f\theta' + Nb\theta'\phi' + Nt\left(\theta'\right)^2 = 0 \tag{12}$$

$$\phi'' + \frac{1}{2}Lef\phi' + \frac{Nt}{Nb}\theta'' = 0 \tag{13}$$

The boundary conditions (5) reduce to

$$f(0)=S, f'(0)=1, \theta(0)=1, \phi(0)=1$$
$$f'(\eta)\to 0, \theta(\eta)\to 0, \phi(\eta)\to 0 \ \ as\ n\to\infty \tag{14}$$

where $\Pr = \nu/\alpha$ the Prandtl is number and $Le = \nu/D_B$ is the Lewis number. The constant dimensionless Brownian motion parameter Nb and thermophoresis parameter Nt are defined as

$$Nb = D_B\frac{\tau(C_w-C_\infty)}{\nu}, Nt = D_T\frac{\tau(T_w-T_\infty)}{\nu T_\infty} \tag{15}$$

The local Nusselt Number Nu and the Sherwood number Sh are given by

$$Nu_x = \frac{xq_w}{k(T_w-T_\infty)}, Sh_x = \frac{xq_m}{D_B(C_w-C_\infty)} \tag{16}$$

where k is the thermal conductivity of the nanofluid, and q_w and q_m are respectively the heat flux and the mass flux at the surface respectively

$$q_w = -\left(\frac{\partial T}{\partial y}\right)_{y=0} \text{ and } q_m = -D_B\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{17}$$

Substituting (9) in to (16) and (17), we obtain

$$Re_x^{-1/2} Nu = -\sqrt{\frac{n+1}{2}}\theta'(0), \; Re_x^{-1/2} Sh = -\sqrt{\frac{n+1}{2}}\phi'(0) \quad (18)$$

Where $Re_x = U_w x/\nu$ is the local Reynolds number.

3. Numerical method of solution

The set of equations (11) to (13) under the boundary conditions (14) have been solved numerically using shooting technique. We consider $f = x_1$, $f' = x_2$, $f'' = x_3$, $\theta = x_4$, $\theta' = x_5$, $\varphi = x_6$, $\varphi' = x_7$. Equations (11) to (13) are transformed into systems of first order differential equations. We assume the unspecified initial guesses for transformed boundary conditions and then it is then integrated numerically as an initial valued problem to a given terminal point. We can check the accuracy of the assumed missing initial condition. By comparing the calculated value of the different variable at the terminal point with the given value by the existence of the difference in improved values the missing initial conditions must be obtained. The calculations are carried out the program by using MATLAB.

4. Results and discussion

The results obtained shows the influences of the non dimensional governing parameters, namely Radiation parameter R, Suction parameter S , Lewis number Le , thermophoresis parameter Nt , Brownian motion parameter Nb and stretching/shrinking parameter λ on the velocity profile, temperature profile, nanoparticle concentration profile, and the local Nusselt Number, Sherwood number. For numerical results we used $Pr = 6.2, Nb = Nt = 0.5, Le = 2, R = 0.5, n = 2$ *and* $S = 2$ in entire study. These values kept as common except the varied values shown in figures. To validate the numerical results obtained, the present results for Nusselt Number and Sherwood Number were compared with those obtained by Rana and Bhargava (2012) for the case of a stretching surface by setting the Radiation parameter R =0, $Le = 2$ and $Pr = 2$ .The comparisons as presented Tables 1 and 2 respectively. The results showed a good agreement with existed results.

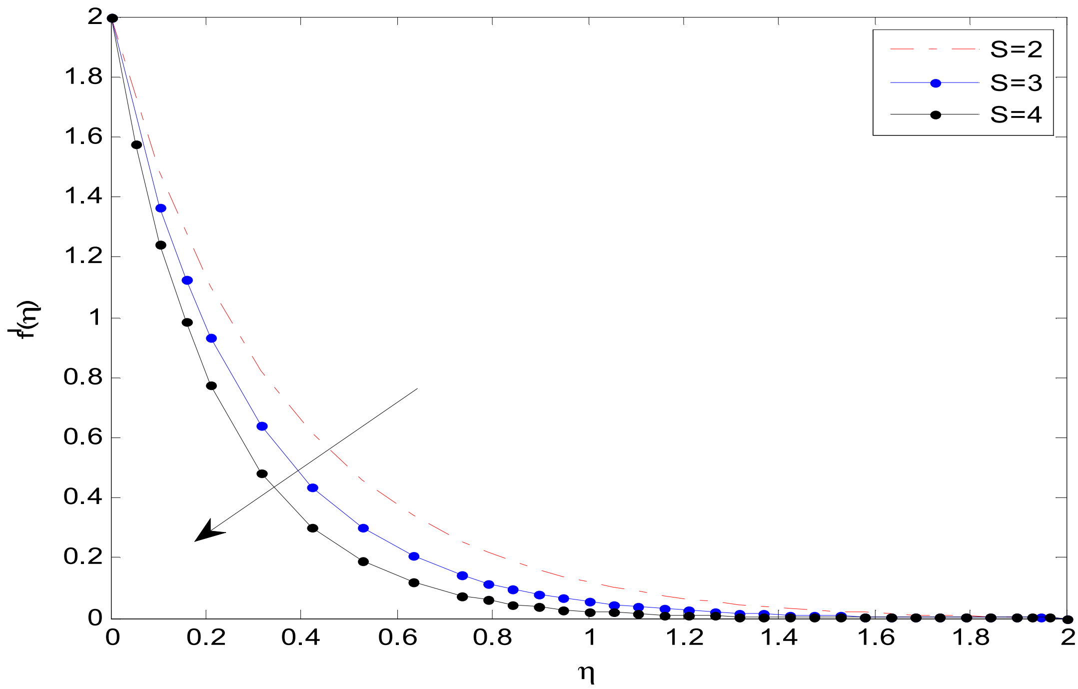

Figure 1 Velocity profiles for different values of S

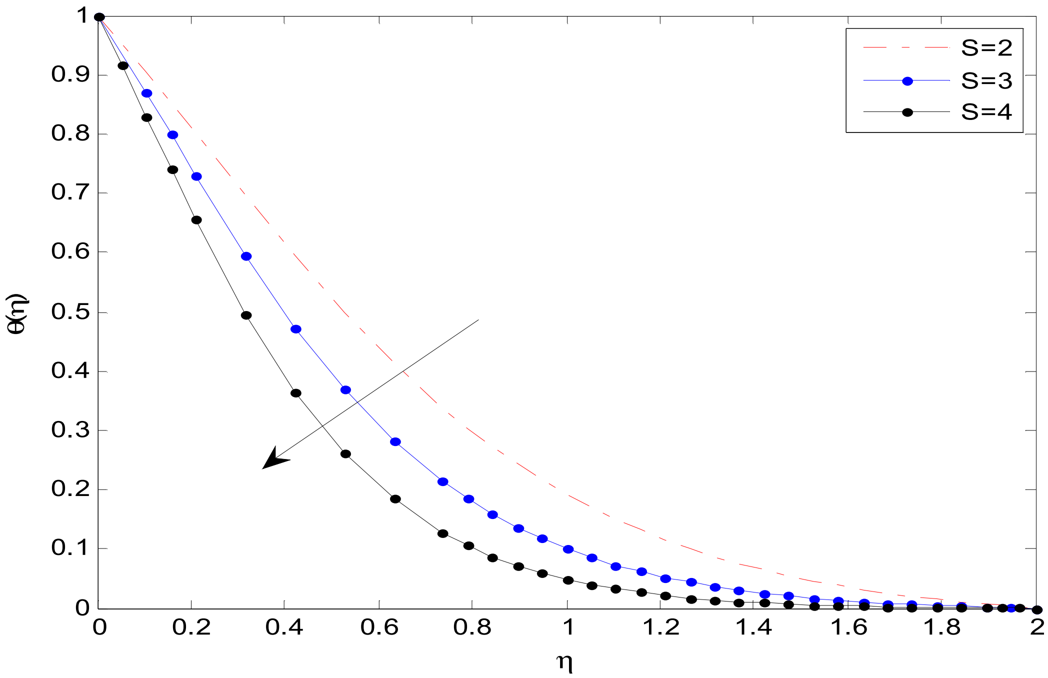

Figure 2 Temperature profiles for different values of S

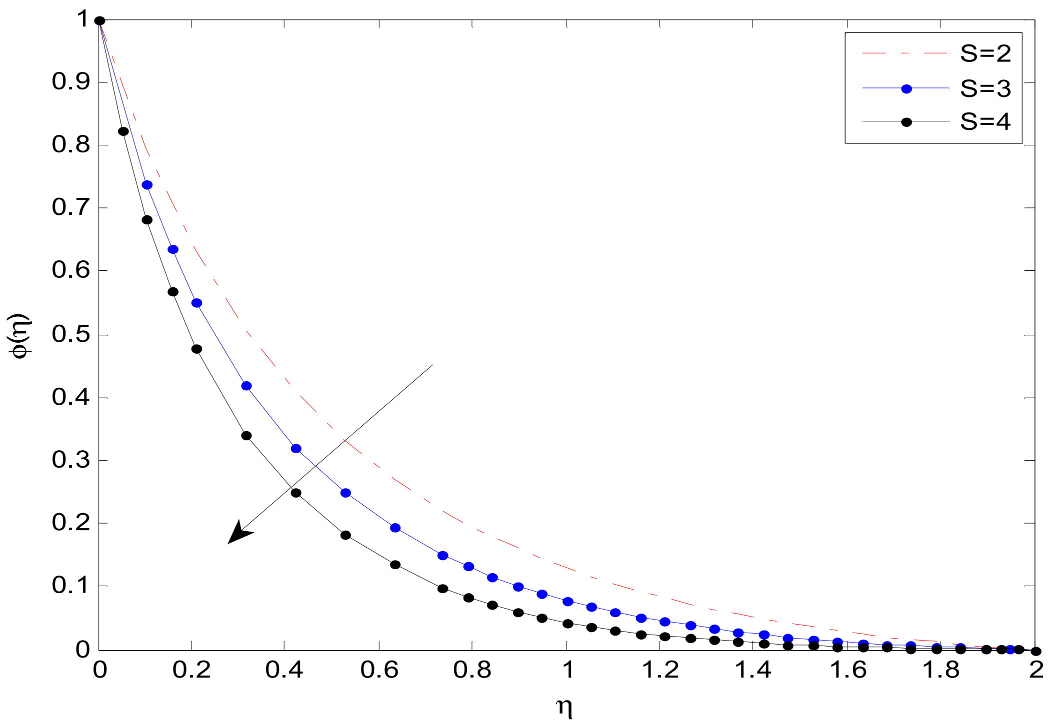

Figure 3 Concentration profiles for different values of S

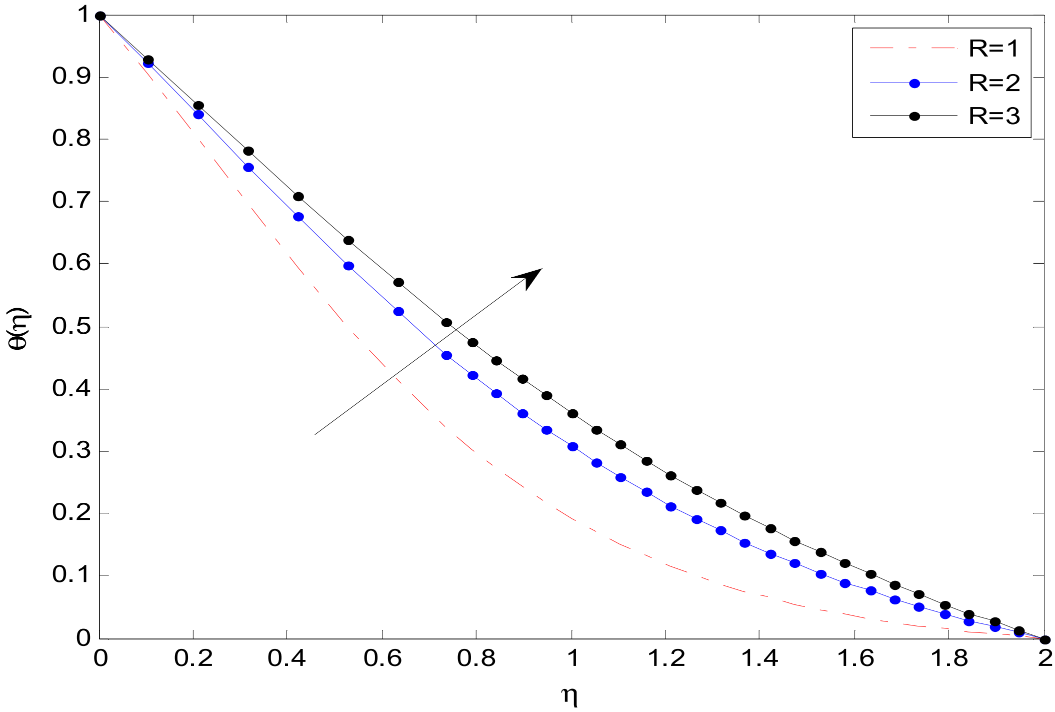

Figure 4 Temperature profiles for different values of R

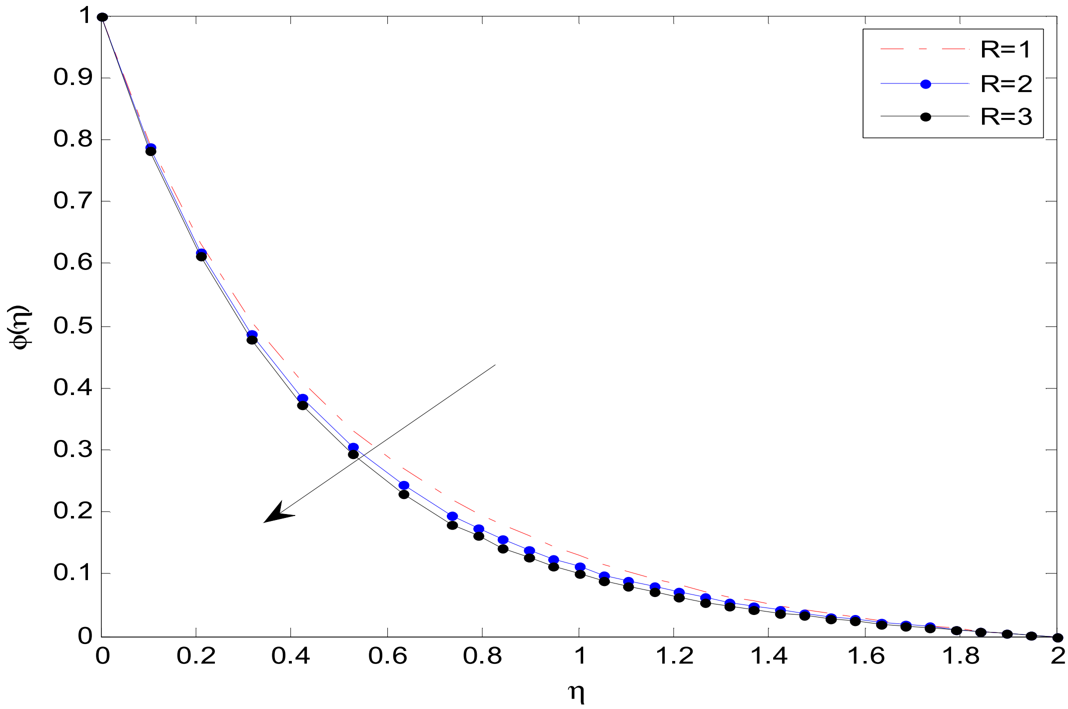

Figure 5 Concentration profiles for different values of R

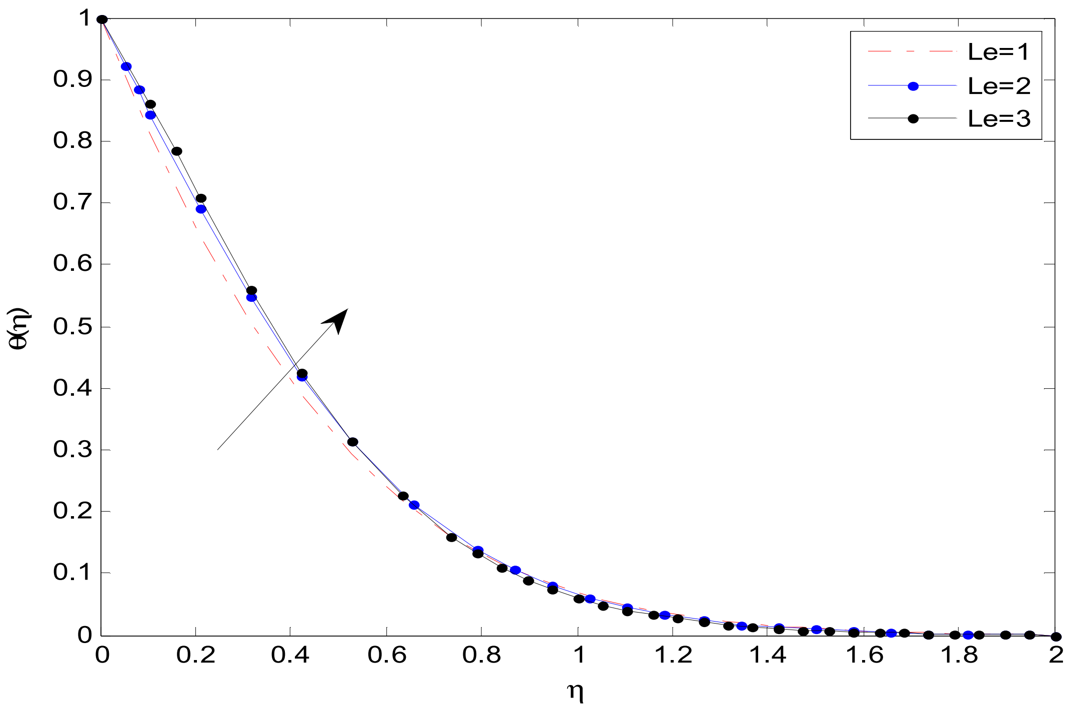

Figure 6 Temperature profiles for different values of Le

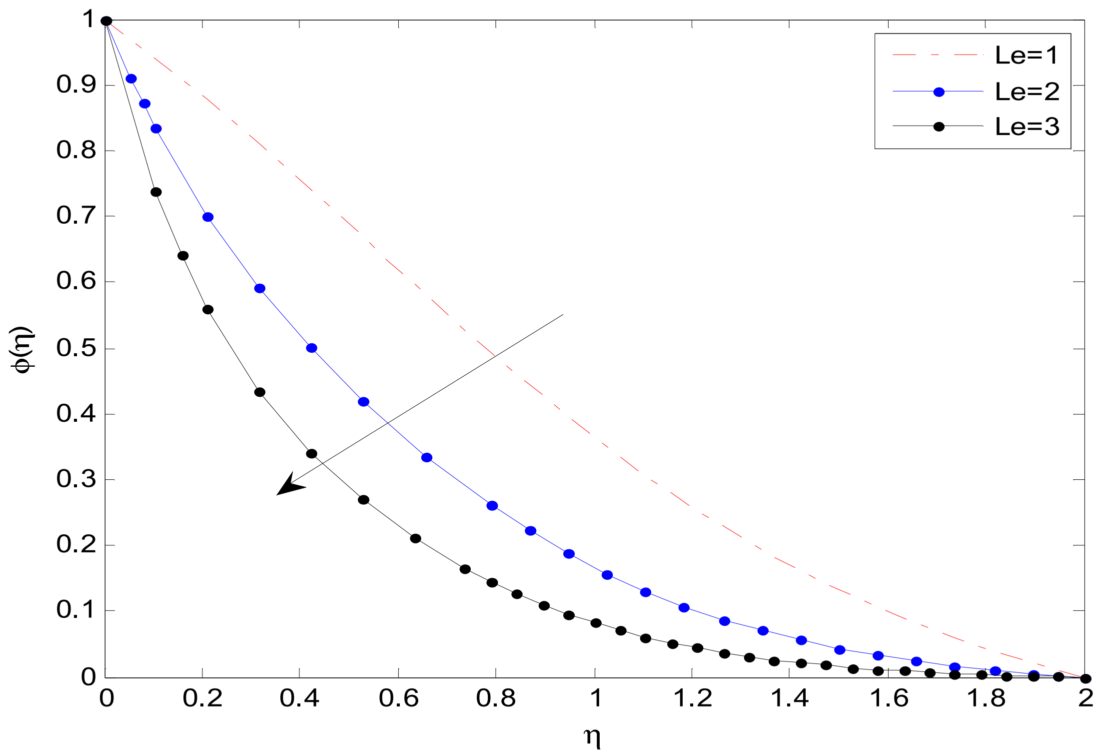

Figure 7 Concentration profiles for different values of Le

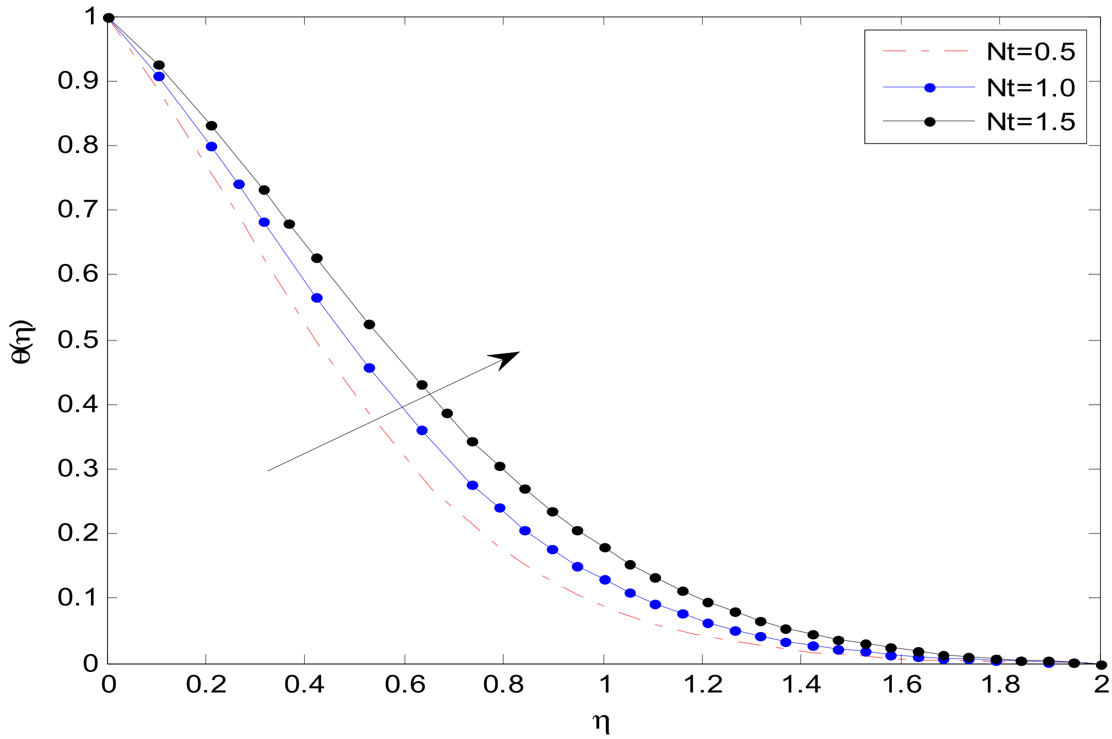

Figure 8 Temperature profiles for different values of Nt

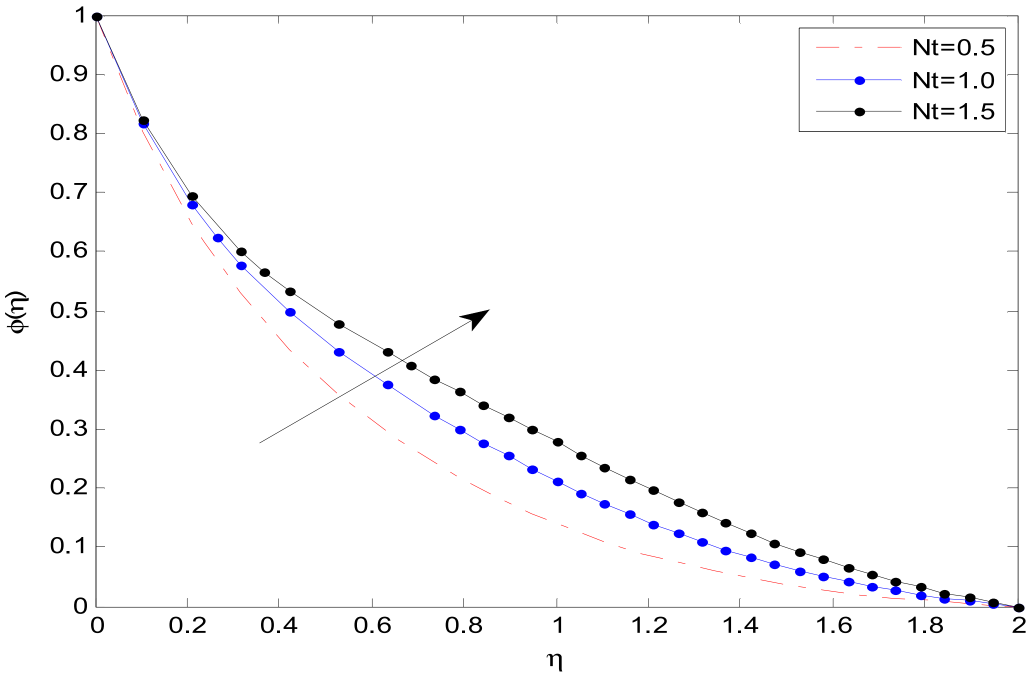

Figure 9 Concentration profiles for different values of Nt

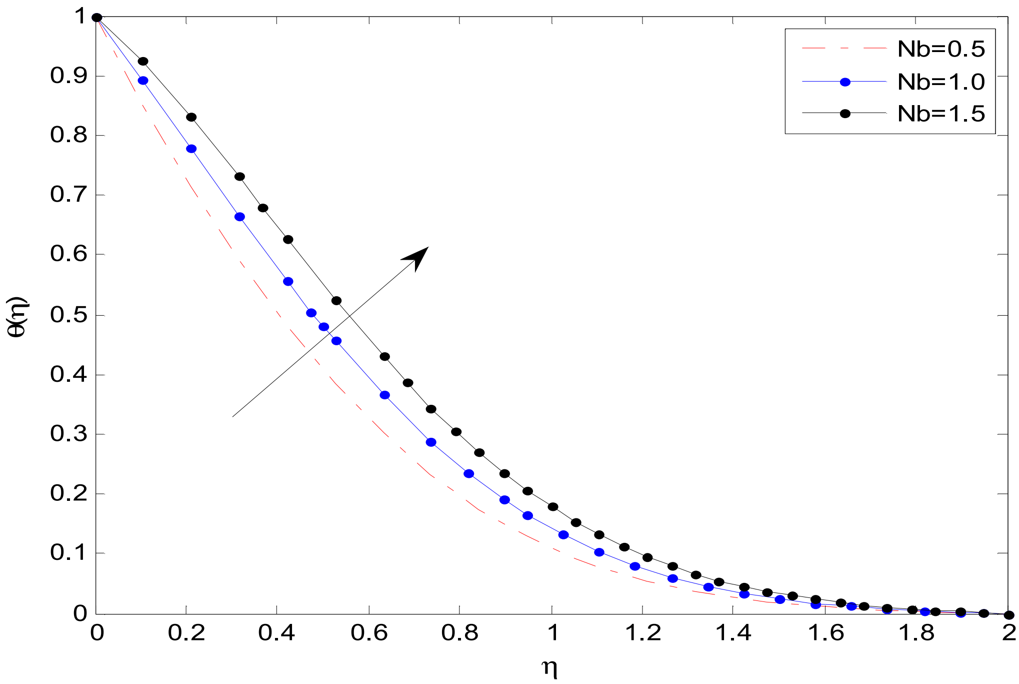

Figure 10 Temperature profiles for different values of Nb

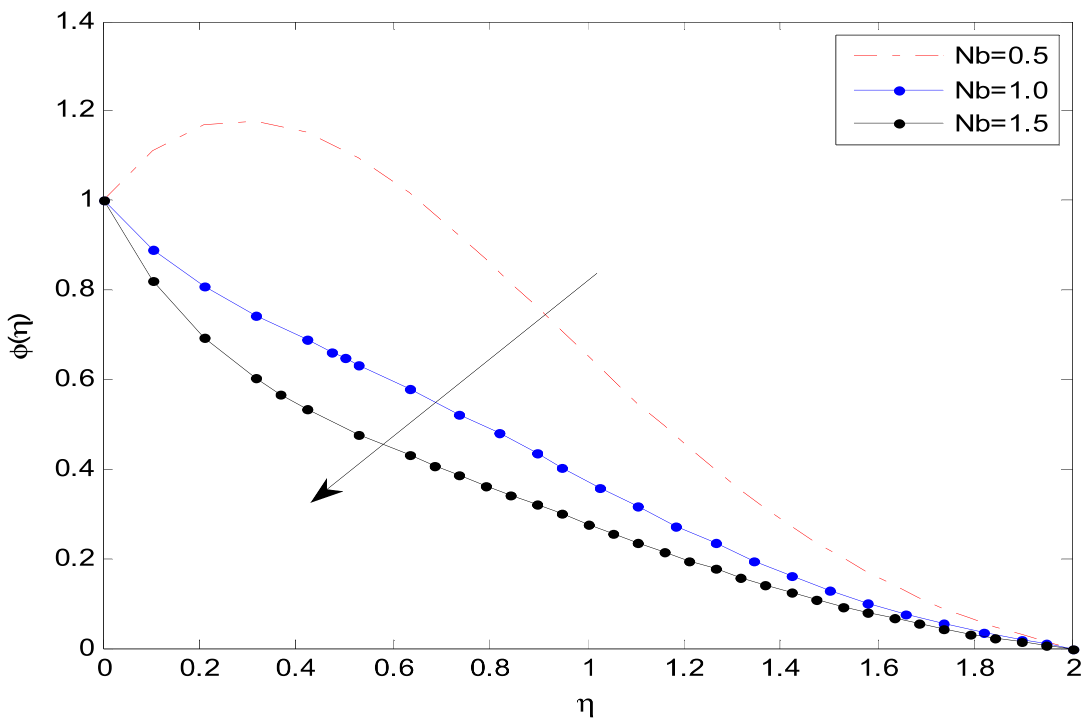

Figure 11 Concentration profiles for different values of Nb

Fig.1 depicts the effects of suction parameter S on $f'(\eta)$ representing the velocity profiles for both shrinking and stretching cases. It is observed that the velocity profiles decreases as increase in suction parameter S . It is due to the fact that the boundary layer thickness reduces by increase in suction parameter and it helps to enhance the flow near the solid surface. Fig. 2 represents the effects of suction parameter on temperature profiles. It is clear that increase in suction parameter causes the decrease in temperature profiles of the fluid. The similar type of results occurred in concentration profiles. It has been is represented in the figures 3. From these we can conclude that the suction parameter shows similar effects on temperature as well as concentration profiles. Fig. 4 illustrates the effect of Radiation parameter on temperature profiles of the fluid. It is clear from figure that increase in radiation causes increase in fluid temperature. This shows the domination of radiative heat transfer in Rosseland approximation. But radiation shows reverse action on concentration profiles. That is increase in radiation parameter causes the decrease in concentration profiles. This result can be explained by the fact that the decrease in the value of R means a decrease in the Rosseland radiation absorptivity k^* due to this reason we seen a fall in concentration profiles. We can observe these results from Fig.5.

Fig. 6 representing to examine the effects of the Lewis number Le on the temperature profiles $\theta(\eta)$. Here the temperature profiles increases as the parameter Le is increased, which consequently reduces the local Nusselt number. However, the nanoparticle concentration profile acts in the opposite behavior with the increasing of Le as shown in Fig. 7. It is clear that the concentration decrease as Le increases. There would be a significant reduction in the concentration boundary layer thickness when Le is increased. This phenomenon occurs due to Lewis number effects which increases the concentration gradient at the surface and as a result increases the local Sherwood number. Fig. 8 gives the effects of the thermophoresis parameter Nt on the temperature profiles $\theta(\eta)$ while Fig. 9 is devoted to see the influences of Nt on the nanoparticle concentration profiles. Fig.8 elucidate that the temperature profiles as well as the boundary layer thickness of the thermal field increase with increasing in Nt. Here nano particle concentration gradient decreases by increase in Nt due to this reason the local Sherwood number decreases. Fig.10 presented to observe the effect of the Brownian motion parameter Nb on the temperature profiles $\theta(\eta)$ with the corresponding nanoparticle concentration profiles $\phi(\eta)$ being shown in Fig.11. Fig.10 indicates that by increasing the Brownian motion parameter Nb, the temperature profiles increases. This phenomenon leads to decrease the local Nusselt number. The reason behind this is different nanoparticles have different values of Nb and Nt, his leads to different rate of heat transfer and these two parameters can be used to control the heat transfer rate in a nanofluid. It is observed that the effect of Nb on the nanoparticle concentration profile $\phi(\eta)$ is in the opposite manner to that of temperature profiles $\theta(\eta)$ as illustrated in Fig. 11.

Table 1 Comparison of reduced Nusselt Number $|-\theta'(0)|$ with Rana and Bhargava (2012) by taking $R=0, Le=2, \Pr=2$

n	Nt	$\lvert-\theta'(0)\rvert$	**Rana and Bhargava(2012)**		$\lvert-\theta'(0)\rvert$	**Present Results**	
		$Nb=0.5$	1.0	2.5	$Nb=0.5$	1.0	2.5
0.2	0.1	0.5160	0.2775	0.0303	0.51620	0.27758	0.03031
	0.3	0.4533	0.2427	0.0265	0.45331	0.24269	0.02651
	0.5	0.3999	0.2135	0.0234	0.39992	0.21354	0.02335
3.0	0.1	0.4864	0.4282	0.3786	0.48641	0.42824	0.37863
	0.3	0.4282	0.2293	0.0251	0.42825	0.22933	0.02514
	0.5	0.3786	0.2020	0.0221	0.37863	0.20204	0.02211
10	0.1	0.4799	0.2581	0.0283	0.47991	0.25810	0.02830
	0.3	0.4227	0.2263	0.0247	0.42269	0.22632	0.02471
	0.5	0.3739	0.1996	0.0214	0.37394	0.19964	0.02141

Table 2 Comparison of reduced Sherwood Number $|-\phi'(0)|$ with Rana and Bhargava [26] by taking $R=0, Le=2, \Pr=2$

n	Nt	$\|-\phi'(0)\|$ Rana and Bhargava (2012)			$\|-\phi'(0)\|$ Present Results		
		$Nb=0.5$	1.0	2.5	$Nb=0.5$	1.0	2.5
0.2	0.1	0.9012	0.9413	0.9493	0.90115	0.94131	0.94932
	0.3	0.8395	0.9394	0.9571	0.83954	0.93942	0.95713
	0.5	0.8048	0.9429	0.9642	0.80481	0.94291	0.96423
3.0	0.1	0.8445	0.7785	0.7379	0.84450	0.77849	0.73792
	0.3	0.7785	0.8792	0.8997	0.77851	0.87923	0.89971
	0.5	0.7379	0.8793	0.9056	0.73790	0.87934	0.90561
10	0.1	0.8323	0.8722	0.8812	0.83232	0.87223	0.88124
	0.3	0.7654	0.8662	0.8873	0.76545	0.86616	0.88727
	0.5	0.7238	0.8656	0.8930	0.72381	0.86563	0.89301

5. Conclusions

This paper presents a similarity solution for the thermal radiation influenced boundary layer flow and heat transfer over a nonlinearly stretching sheet immersed in a nanofluid with suction effect. By means of similarity transformation, the governing mathematical equations are reduced into ordinary differential equations which are then solved numerically using shooting method. The effects of some governing parameters, such as suction parameter, radiation parameter, and thermophoresis parameter, Brownian motion parameter on the flow, concentration and heat transfer characteristics are graphically represented and discussed. The findings of the numerical results are summarized as follows

1) The temperature and concentration profiles of the flow are more influenced by radiation parameter.
2) The local Nusselt number and the local Sherwood number which respectively represent the heat transfer and mass transfer rates increase with the increase in temperature.
3) Velocity, temperature and concentration profiles of the flow are more influenced by suction parameter, radiation parameter, and thermophoresis parameter.
4) A rising value in Nb and the decreasing in Nt produce a decrease in the nanoparticle concentration, as a result increases in the Sherwood number.
5) The increase of Lewis number Le leads to an increase of the temperature but a decrease in the nanoparticle concentration.
6) With absence of radiation parameter our results have good agreement with Rana and Bhargava (2012) over stretching surface.

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