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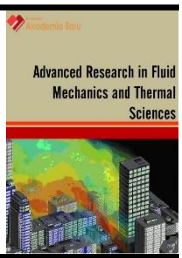

MHD Micropolar Nanofluid Flow over an Exponentially Stretching/Shrinking Surface: Triple Solutions

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Sumera Dero[1,2], Azizah Mohd Rohni[1,*], Azizan Saaban[1]

[1] School of Quantitative Sciences, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[2] University of Sindh, Jamshoro, Pakistan

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ABSTRACT

In this study, the problem of MHD micropolar nanofluid boundary layer flows over an exponentially stretching/shrinking sheet with radiation and suction effect is considered. The Buongiorno's nanofluid model is applied to the problem. The governing equations are first transformed to the coupled nonlinear similarity equations by using similarity transformations. The resulting equations which is in ordinary differential equations form are then solved numerically by using shooting method. Triple solutions are observed to exist for the flows. A comparison with existing solutions in literature for specific case are made to assess the accuracy of the present results. Further, the flows profiles are examined, and it is found that the presence of suction parameter will contribute the occurrences of triple solutions.

Keywords:
MHD, Micropolar Nanofluid, Stretching/Shrinking Sheet, Buongiorno's model, Radiation, Suction

1. Introduction

Micropolar fluids are fluids which combine the macroscopic velocity field and the particles rotational motion. It belongs to the classes of fluids with nonsymmetrical stress tensor and is a kind of non-Newtonian fluid consisting of a suspension of small body fluids and colloidal fluid elements such as large dumbbell molecules [1]. In general, micropolar fluids has greater resistance to the fluid motion compared to Newtonian fluid. This phenomenon also shows that the higher micropolar parameter enhances the total viscosity in the fluid flow. So, the micropolar fluid is a very effective fluid medium in boundary layer for monitoring the laminar flow [2]. Physically, micropolar fluids signify fluids comprising of rigid, arbitrarily situated particles suspended in a viscid medium, where particles deformation is disregarded [3]. Micropolar fluids are often used in industrial applications such as polymer solutions, lubricant fluids, and biological structures [1]. This kind of fluid was first introduced by Eringen [4] and has numerous industrial and engineering application, hence attracted many researchers to study the flow characteristic of these fluids with various situations [5-14], to mention just a few.

[*] *Corresponding author.*
E-mail address: azizahrohni@yahoo.com (Azizah Mohd Rohni)

On the other hand, nanofluids is a mixture consisting of nano-sized particles dispersed in a base fluid and has high thermal conductivity which can increase the heat transfer performance of the base fluids [15]. Choi [16] made the first attempt to introduce this innovative fluid resulting from the mixture of nanoparticles and the base fluid. The mixture of a base fluid and nanoparticles has unique physical and chemical properties substantially enhances the heat transfer characteristics of the nanofluid [17]. This field of study gets attention from many researches to study the behavior of this fluid towards various scenarios [18-30]. As reported by Buongiorno [18], nanoparticles can carry slip velocity with base fluid molecules and give rise to the possibility of translation and microrotation. In fluid mechanics, micropolar theory considers the effect of microrotation. So, application of this theory in the presence of nanoparticles gives an important insight to control the thermal conductivity of nanofluids. Ahuja [19] examined that the nanoparticle rotation has an important factor in heat transfer enhancement of the base fluid.

Recently, the problem of magneto hydrodynamic micropolar nanofluid boundary layer flows has attracted attention by several authors [31-36]. It is a study related to magnetic properties of electrically conducting fluid and shortly called MHD (Magneto hydrodynamic). These applications are used in the geothermal energy extractions, plastic sheets, cooling of nuclear reactor, blood flow problems, plasma studies, cooling of underground electric cables and artificial fibers. However, as reported in [31-36], they found only one solution exist in the problems they considered. Motivated by the mentioned studies, in this paper, we consider an MHD micropolar nanofluid boundary layer flows over exponentially shrinking/stretching surfaces with thermal radiation and suction effect whereas to our present knowledge, this problem has not been considered before. Due to the nonlinearities that appears in the problem, we attempt to notice all the possible solutions that might exist because multiplicity of solutions is important but difficult to visualize [37, 38].

2. Methodology

2.1 Mathematical Formulation

We consider a two - dimensional incompressible MHD micropolar nanofluid with radiation and suction effect over an exponentially horizontal stretching/shrinking. A uniform body force is imposed normal to the flow over the sheet. A schematic representation of this problem is shown in Figure 1. Temperature and concentration flux at the wall of exponentially surface respectively are T_w and C_w while T_∞ is the temperature of the ambient fluid and C_∞ is the concentration of the ambient fluid. Under these assumptions, the governing equations of this problem are:

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

$$u\,\frac{\partial u}{\partial x}+v\,\frac{\partial u}{\partial y}=\left(\vartheta+\frac{K_1}{\rho}\right)\frac{\partial^2 u}{\partial y^2}+\frac{K_1}{\rho}\frac{\partial N}{\partial y}-\frac{\sigma B^2 u}{\rho} \tag{2}$$

$$\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}=\frac{\gamma}{\rho j}\frac{\partial^2 N}{\partial y^2}-K_1\left(2N+\frac{\partial u}{\partial y}\right) \tag{3}$$

$$u\,\frac{\partial T}{\partial x}+v\,\frac{\partial T}{\partial y}=\alpha\,\frac{\partial^2 T}{\partial y^2}+\tau_w\left[D_B\,\frac{\partial C}{\partial y}\,\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]-\frac{16\sigma T_\infty^3}{3K^*\rho c_p}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

$$u\,\frac{\partial C}{\partial x}+v\,\frac{\partial C}{\partial y}=D_B\,\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\,\frac{\partial^2 T}{\partial y^2} \tag{5}$$

along with initial and boundary conditions

$$v = -v_w(x); \quad u = u_w(x); \quad N = -m\frac{\partial u}{\partial y}; \quad T = T_w(x); \quad C = C_w(x) \quad at \quad y = 0$$

$$u \to 0; \; N \to 0; \; T \to T_\infty; \; C \to C_\infty \quad as \;\; y \to \infty \tag{6}$$

where *u* and *v* are components of the velocity in the directions of *x* and *y* respectively, $v_w(x) = \sqrt{\frac{\vartheta U_w}{2l}}\, e^{x/2l} S$ is suction/injection variable, $u_w(x) = ce^{\frac{2x}{\ell}}$ is the velocity of sheet with $c > 0$ and $c < 0$ are respectively stretching and shrinking constant, $T_w(x) = T_\infty + T_0 e^{\frac{2x}{\ell}}$ is variable temperature at sheet, $C_w(x) = C_\infty + C_0 e^{\frac{2x}{\ell}}$ is variable concentration flux, K_1 is vortex viscosity, N is the micro rotation, γ indicates spin gradient viscosity and j is ratio of micro inertia and unit mass, α stands for thermal diffusivity, K^* indicates thermal conductivity of fluid and *m* is constant within the range $0 \le m \le 1$.

In the case of $m = 0$, we have $N = 0$ which indicates a strong concentration and micro-elements are near to the wall, which are not rotatable. Furthermore, when $m = {}^1/_2$, this value shows a weak concentration, may vanish the anti-symmetric part of stress tensor. For $m = 1$, this value indicates a turbulent boundary layer flows modeling as reported by Ishak *et al.,* [39] and Jena and Mathur [40]. Furthermore, many authors considered $\gamma = \left(\mu + \frac{K_1}{2}\right) j = \mu\left(1 + \frac{K}{2}\right) j$ where $K_1 = \mu K$ is the material parameter and $j = \frac{2LVe^{-x/l}}{U_w}$ as found in Uddin *et al.,* [13]. The magnetic field $B(x)$ in an exponential sheet is defined as $B = B_0 e^{x/l}$ where, B_0 is a constant of magnetic field. The stream function ψ is written as $= \frac{\partial \psi}{\partial y}$, $v = -\frac{\partial \psi}{\partial x}$.

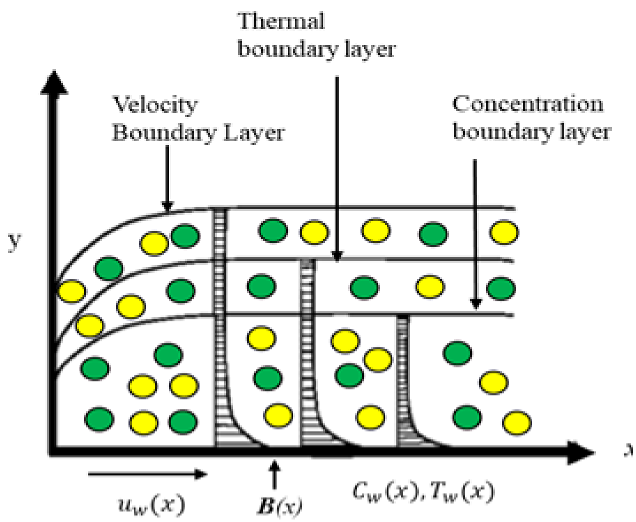

Fig. 1. Geometry of flow problem and coordinate system

The following similarity variables are used to transform Eq. (1)-(6) to similarity equations

$$\psi = \sqrt{2\vartheta l U_w} e^{x/2l} f(\eta);\ \ N = U_w e^{3x/2l} \sqrt{\frac{U_w}{2\vartheta l}}\, g(\eta);\ \ \ \theta(\eta) = {(T - T_\infty)}\big/{(T_w - T_\infty)};$$
$$\emptyset(\eta) = {(C - C_\infty)}\big/{(C_w - C_\infty)};\qquad \eta = y\sqrt{\frac{U_w}{2\vartheta l}}\, e^{x/2l} \tag{7}$$

By using similarity variables in Eq. (7), Eq. (1)-(6) are reduced to the following ordinary differential equations

$$(1 + K)f''' + ff'' - 2f'^2 + Kg' - Mf' = 0 \tag{8}$$

$$\left(1 + \frac{K}{2}\right) g'' + fg' - 3gf' - 2Kg - Kf'' = 0 \tag{9}$$

$$\frac{1}{Pr}\left(1 - \frac{4}{3}Rd\right)\theta'' + f\theta' + Nb\emptyset'\theta' + Nt(\theta')^2 - 4f'\theta = 0 \tag{10}$$

$$\emptyset'' + Sc(f\emptyset' - 4f'\emptyset) + \frac{Nt}{Nb}\theta'' = 0 \tag{11}$$

with boundary conditions

$$f(0) = S;\ \ f'(0) = \lambda;\ \ g(0) = -mf''(0);\ \ \theta(0) = 1;\ \ \emptyset(0) = 1$$
$$f'(\eta) \to 0;\ g(\eta) \to 0;\ \theta(\eta) \to 0;\ \emptyset(\eta) \to 0 \qquad as\ \eta \to \infty \tag{12}$$

where prime denote the differentiation with respect to the new independent variable η, and $K = \frac{K_1}{\mu}$ is micropolar parameter, $M = \frac{2l\sigma(B_0)^2}{\rho U_w}$ is magnetic field, $Rd = \frac{4\sigma T_\infty^3}{kK^*}$ is thermal radiation, $Pr = \frac{\vartheta}{\alpha}$ is Prandtl number, $Nt = \frac{\tau_w D_T(T_w - T_\infty)}{\nu T_\infty}$ is thermophoresis parameter, $Nb = \frac{\tau_w D_B(C_w - C_\infty)}{\nu}$ is parameter of Brownian motion, $Sc = \frac{\vartheta}{D_B}$ is Schmidt number, $\lambda = \frac{c}{U_w}$ where $c < 0$ is shrinking surface and $c > 0$ is stretching surface and $S < 0$ and $S > 0$ are mass injection and suction parameter respectively. The important physical quantities of skin friction coefficient, the local Nusselt number number and local Sherwood number are given as

$$C_f = \frac{\left[(\mu + K)\frac{\partial u}{\partial y} + KN\right]_{y=0}}{\rho U_w^2};\qquad N_u = \frac{-x\left(\frac{\partial T}{\partial y}\right)_{y=0}}{(T_w - T_\infty)};\qquad S_h = \frac{-x\left(\frac{\partial C}{\partial y}\right)_{y=0}}{(C_w - C_\infty)};$$

$$C_f(Re_x)^{\frac{1}{2}}\sqrt{\frac{2l}{x}} = (1 + (1 - m)K)f''(0);\qquad N_u(Re_x)^{-\frac{1}{2}} = -\theta'(0);\qquad S_h(Re_x)^{-\frac{1}{2}} = -\emptyset'(0) \tag{13}$$

3. Results and Discussion

The governing nonlinear Eq. (8)-(11) subjected to boundary conditions Eq. (12) were solved numerically by using shooting method from *shootlib* function in Maple software. The case without MHD effect (M = 0), weak concentration (m = 0.5) and shrinking parameter = -1 has been considered to assess the accuracy of the present results. A comparison with Uddin *et al.,* [13] for this specific case is shown in Figure 2 and it is found that the present results are in a good agreement with those reported by Uddin *et al.,* [13] and possess the same turning points $S = 2.3221$ for $K = 0.1$ and $S = 2.3769$ for $K = 0.2$. Therefore, we believe that our results are accurate and hence, this give confidence to further study the problem.

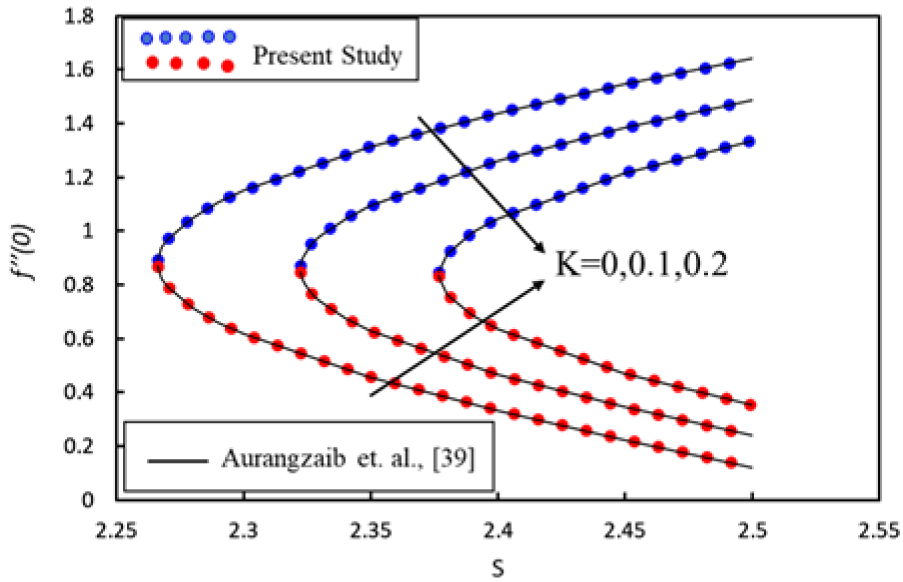

Fig. 2. Comparison of present results with Aurangzaib *et al.,* [13]

Further, we plotted new results in Figure 3 to 9. For all cases considered in this study, the values of Prandtl and Scmidth number are taken equal to 1 and m = 0.5 for weak concentration only. As can be seen from these figures, there occurs triple solutions for the problem considered. The variations of the skin friction coefficient, the coefficient of the couple stress, heat transfer coefficient and concentration of nanoparticle transfer versus stretching/shrinking parameter λ for several values of micropoplar/material parameter (K) and thermal radiation (Rd) are shown in Figure 3 to 6. Figure 3 displays the variation of the coefficient of skin friction $f''(0)$ with K for various values of λ.

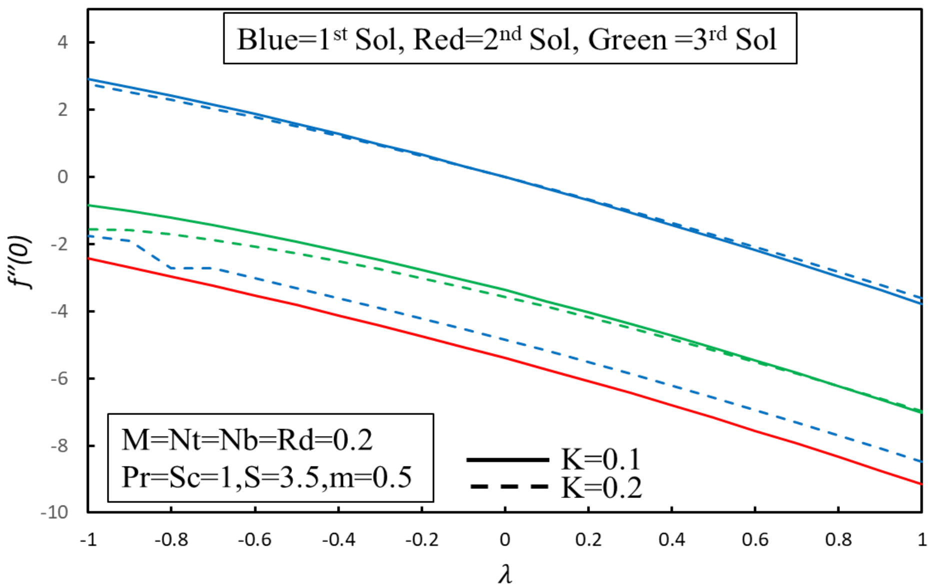

Fig. 3. Variation of skin friction at various values of λ and K

It is noticed that for the stretching as well as shrinking surfaces the triple solutions exist and the skin friction decreases monotonically for higher values of λ in all solutions. Figure 4 shows the couple stress coefficient $g'(0)$ reduces with enhancing the values of λ in the first as well as in the second solution. However, an opposite behavior is observed in the third solution for both value of $K = 0.1$ and $K = 0.2$.

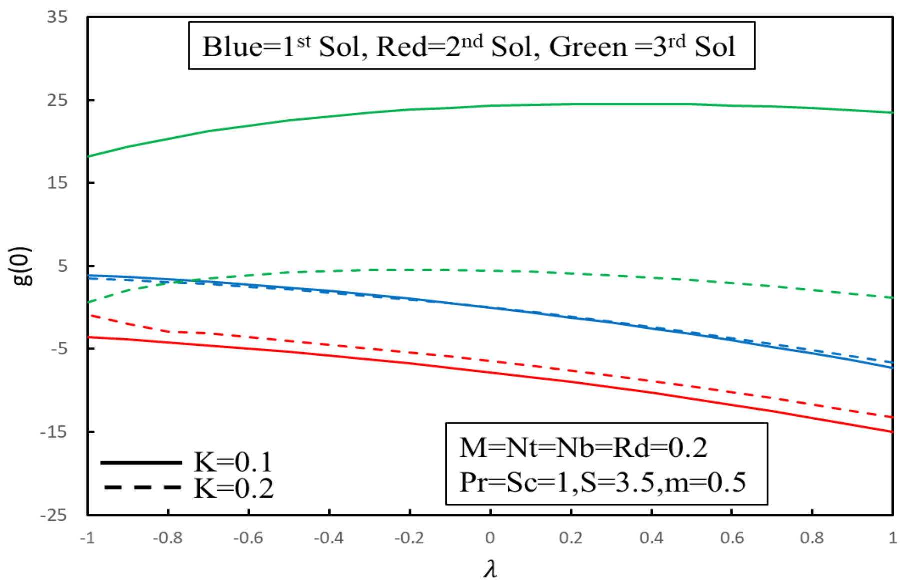

Fig. 4. Variation of couple stress coefficient at various values of λ and K

In Figure 5, The skin friction increases monotonically for higher values of λ in all solutions with and without the effect of thermal radiation Rd.

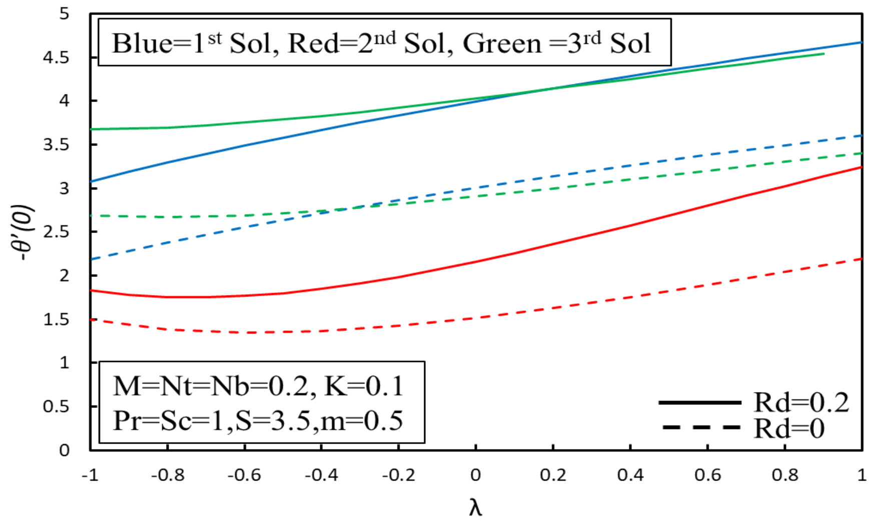

Fig. 5. Variation of heat transfer rate at various values of λ and Rd

The variation of concentration rate versus λ with $Rd = 0$ and $Rd = 0.2$ is demonstrated in Figure 6. It can be observed that rate of concentration increases when λ increases at $Rd = 0.2$ in the first and third solution, but it decreases in second solution. For $Rd = 0$, the first and the second solutions decrease with increment in λ, however, the rate increases in the third solution.

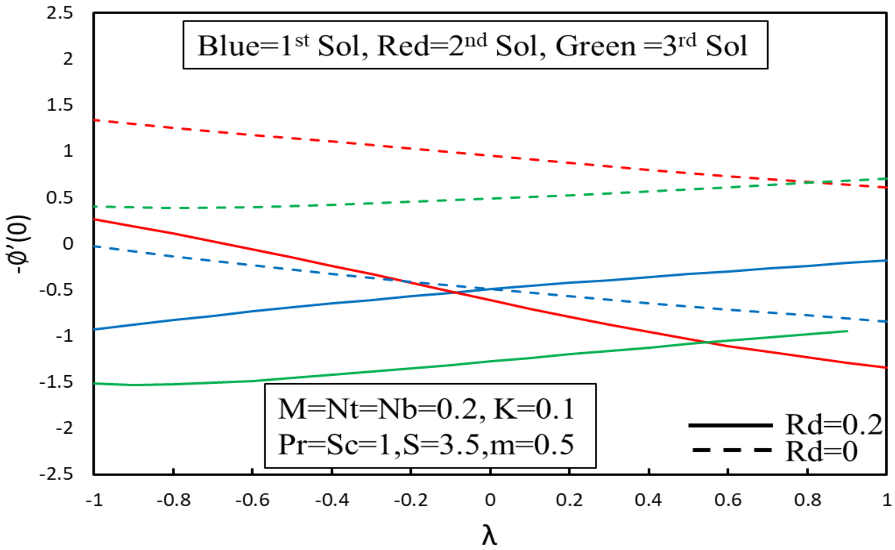

Fig. 6. Variation of the concentration rate at various values of λ and Rd

The temperature profiles variation with different values of thermal radiation (Rd), Thermophoresis (Nt) and Brownian motion (Nb) parameters are plotted in Figures 7, 8 and 9 respectively. Increment in radiation shows the retraction of both temperature and thermal layer thickness in first and second solutions as shown in Figure 7. Profile of temperature and thermal layer thickness rises when R_d increases in third solution but it is observed that only dual solutions exist at $Rd = 0.4$.

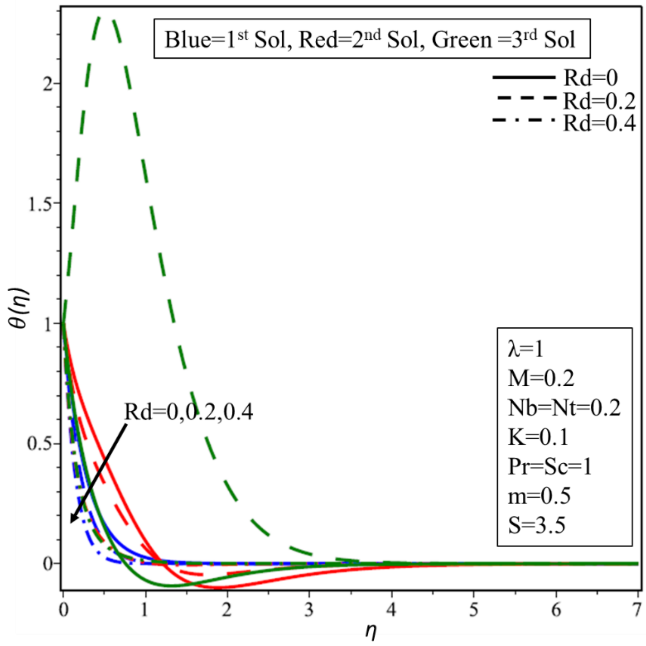

Fig. 7. Variation of the temperature profile at various values of Rd

From Figure 8 and 9, it can be analyzed that temperature and thickness of boundary layer increases when Nt and Nb increase in the first solution as expected, because the definition of thermophoresis is as the relocation of a colloidal molecule or vast atom in a solution in light of a macroscopic temperature slope, and thicker thermal boundary layer for large values of N_b which rise the temperature of liquid. On the other hand, opposite behavior has been noticed for temperature profiles in the second and the third solutions in Figure 8 and 9. Initially, temperature increases with enhancement in Nt and Nb but after $\eta \sim 0.5$ it starts to decrease in the third solution. The second solution is noticed to decrease after $\eta \sim 1$.

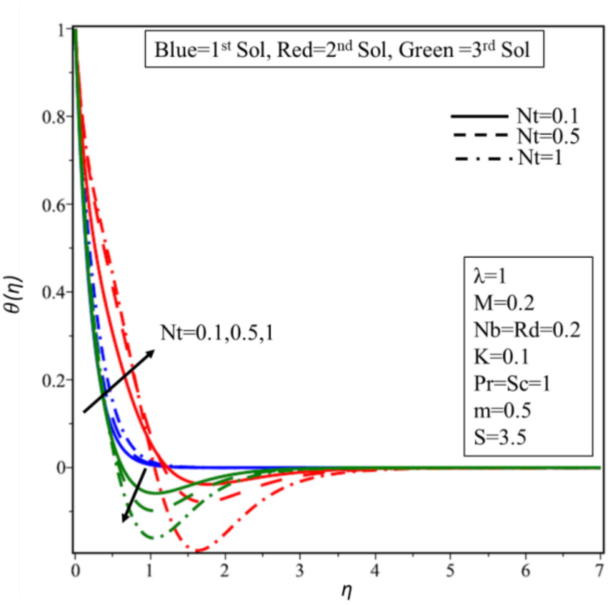

Fig. 8. Variation of temperature profile at various values of Nt

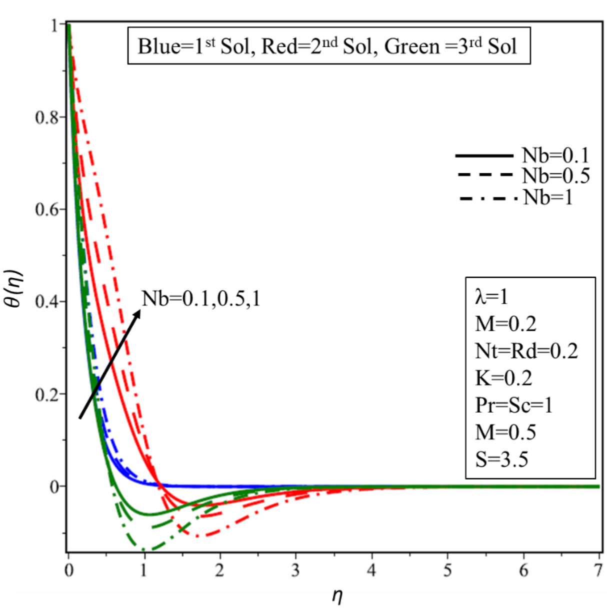

Fig. 9. Variation of temperature profile at various values of Nb

4. Conclusions

In this study, we attempt to examine the multiplicity of solutions that might occur in the problem of MHD micropolar nanofluid boundary layer flows over an exponentially stretching/shrinking sheet with radiation and suction effect. The governing equations are first transformed to similarity equations which are then solved numerically by shooting techniques. From this study, the following main remarks are concluded:

(i) Triple solutions exist for lower value of the magnetic parameter, thermophoresis and the material parameter with high suction S.
(ii) Triple solutions exist in both cases namely shrinking and stretching surfaces.
(iii) The range parameter K for the occurrences of triple solutions is $0 \leq K \leq 0.2$, while for $K = 0.3$ dual solution exists in the stretching as well as shrinking surfaces.
(iv) Increment of parameter K, require more suction for solutions to exist.

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