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Carboxymethyl Cellulose Based Second Grade Nanofluid around a Horizontal Circular Cylinder

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ABSTRACT

Modern challenges include improving heat transmission in a range of industries, including electronics, heat exchangers, bio and chemical reactors, etc. Innovative heat transfer fluids like nanofluids have the potential to increase energy transport effectively. This gain is attained as a result of improved effective thermal conductivity and modified fluid flow dynamics. Therefore, the topic of this paper is improving heat transmission using nanofluids. The objective is to deal with the second grade fluid model passing through a horizontal circular cylinder with mixed convection and suspended nanoparticles. The respective nanoparticles and based fluid of Copper (Cu) and carboxymethyl cellulose (CMC-water) are considered. Both non-dimensional and non-similarity transformation variables are utilized to convert the governing equations to a system of partial differential equations (PDEs). Reduction to ordinary differential equations (ODEs) is attained from the resulting PDEs at the lower stagnation area and then tackled via the Runge-Kutta Fehlberg technique (RKF45) in the Maple software. Graphs are used to illustrate the detailed description of the results of dimensionless parameters like the Biot number, mixed convection, and the second grade parameter. Results show that the fluid slows down while the temperature increases as the value of second grade parameter rises.

1. Introduction

Nanofluids are now even more crucial than they have been over the past 20 years due to the growing demands of the current day to develop effective solutions to increase the heat transfer efficiency of thermal systems. The majority of industries, including aerospace technologies, computer processors, medical drug carriers, solar collectors, and heat exchangers, use heat transfer assemblies. The nanofluids are a carefully designed mixture of conventional fluids with a negligible amount of nanosized particles that aid in enhancing the convectional fluids' capacity for heat transfer. The Choi and Eastman [1] work in 1995 at the Argonne National Laboratory is responsible for the practical

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success in this area. The physical properties of nanofluids have been the subject of extensive research, especially when dealing with flow of boundary layer and transfer of heat. An experimental investigation revealed that the thermal properties of conventional fluids are greatly impacted by the concentration, scale, shape, and composition of nanoparticles. Despite the fact that nanoparticles have increased thermal conductivity, the type of material and form of the dispersed particles determines how much and how effectively heat is transferred [2].

Exploration of conventional based fluids has turned out to be the current research interest in fluid dynamics area by reason of its numerous industrial and technical uses. Particularly in the chemical and nuclear industries, material processing, food sectors, oil reservoir engineering, and etc., such fluids are encountered. Ketchup, shampoos, paints, polymer solutions, certain oils, apple sauce, and many more substances are the examples of non-Newtonian fluids. Distinctive features of non-Newtonian fluids cannot all be recognised through a single association. As a result, a number of highly non-linear models have been put out to characterise the characteristics of conventional based fluids. The three categories of differential type, rate type, and integral type are frequently used to categorise non-Newtonian fluids. The most fundamental subclass of differential type fluids is known as the second-grade fluid model. The impacts of normal stress are described by this paradigm. Low heat conductivity, however, is a significant drawback for non-Newtonian fluid. The nanoparticles are suspended in the second-grade fluid to get around this restriction. Many researchers have recently utilised the flow of second-grade nanofluid over Riga plate [3,4], exponentially stretched surfaces [5,6], stretched cylinders [7] and stretched surfaces [8-10] under a variety of physical conditions, including nonlinear thermal radiation, activation energy, mixed convection, magnetic fields, slip boundary conditions, Soret and Dufour effects, homogeneous-heterogeneous reactions, and many more [11-14].

Since Merkin [15]'s study on combined flow of free and forced convection induced by horizontal circular cylinder, a number of articles have highlighted the flow of fluid from a horizontal circular cylinder with mixed convection. This comprises of documented studies with impacts of magnetohydrodynamics (MHD) by Aldoss *et al.,* [16] and suction and blowing by Aldos and Ali [17]. The different heating condition with non-Newtonian fluids such as viscoelastic fluid with constant wall temperature, micropolar fluid with constant heat flux and constant wall temperature, respectively was examined by Anwar *et al.,* [18], Nazar *et al.,* [19] and Nazar *et al.,* [20]. The following year, the respective impact of temperature-dependent viscosity and Newtonian heating were scrutinized by Ahmad *et al.,* [21] and Salleh *et al.,* [22]. By using the model put forward by Tiwari and Das, Nazar *et al.,* [23] examined three different types of nanoparticles with water-based fluid. The investigation was then completed by Tham *et al.,* [24], who looked at the porous medium effect. Kasim *et al.,* [25] extended the issue examined by Ahmad [21] to the constant heat flux. The viscous dissipation effect was investigated by Mohamed *et al.,* [26] and Mohamed *et al.,* [27] in the corresponding viscous and nanofluid models with constant wall temperature. The ferrofluid flow at lower stagnation point has been documented by Yasin *et al.,* [28]. The Tiwari and Das model was most recently tackled by Mahat *et al.,* [29] on the interaction between Cu/AlO and carboxymethyl cellulose (CMC) water based in a non-Newtonian model of viscoelastic.

Motivated by the ongoing research publications from the previous researchers, the current study discusses the flow of second grade fluid through a horizontal circular cylinder at lower stagnation point flow with mixed convection and convective boundary conditions.

2. Problem Formulation

A second grade fluid containing nanoparticles that flows through a horizontal circular cylinder is inspected. The presence of mixed convection flow together with convective boundary conditions is accounted.

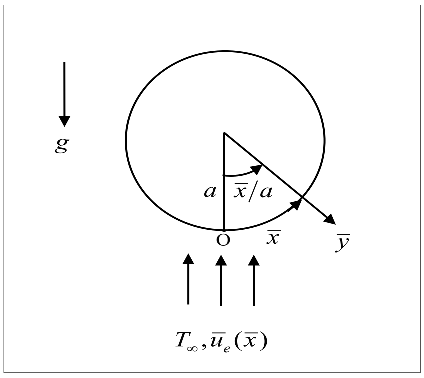

Fig. 1. Physical model

The cylinder of radius a, is heated with ambient temperature T_∞, as demonstrated in Figure 1. The coordinates of the cylinder surface, $\overline{x}$ and $\overline{y}$ are measured starting from the lower stagnation point $\overline{x}=0$ and at right angle to it, respectively. The equations that represent the fluid flow are [30, 31]:

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

$$\begin{aligned}\rho_{nf}\left(\overline{u}\frac{\partial \overline{u}}{\partial \overline{x}}+\overline{v}\frac{\partial \overline{u}}{\partial \overline{y}}\right)=\rho_{nf}\overline{u}_e\frac{d\overline{u}_e}{\partial \overline{x}}+\mu_{nf}\frac{\partial^2 \overline{u}}{\partial \overline{y}^2}+\alpha_1\left(\overline{u}\frac{\partial^3 \overline{u}}{\partial \overline{x}\partial \overline{y}^2}+\overline{v}\frac{\partial^3 \overline{u}}{\partial \overline{y}^3}+\frac{\partial \overline{u}}{\partial \overline{x}}\frac{\partial^2 \overline{u}}{\partial \overline{y}^2}+\frac{\partial \overline{u}}{\partial \overline{y}}\frac{\partial^2 \overline{u}}{\partial \overline{x}\partial \overline{y}}\right)\\ +g(\rho\beta_T)_{nf}\left(T-T_\infty\right)\sin\frac{\overline{x}}{a},\end{aligned} \tag{2}$$

$$\left(\rho C_p\right)_{nf}\left(\overline{u}\frac{\partial T}{\partial \overline{x}}+\overline{v}\frac{\partial T}{\partial \overline{y}}\right)=k_{nf}\frac{\partial^2 T}{\partial \overline{y}^2}, \tag{3}$$

The appropriate boundary conditions are

$$\begin{aligned}&\overline{u}(\overline{x},0)=0,\ \ \overline{v}(\overline{x},0)=0,\ \ -k_f\frac{\partial T}{\partial \overline{y}}=h_f\left(T_f-T\right)\quad \text{at}\quad \overline{y}=0\\ &\overline{u}(\overline{x},\infty)\to\overline{u}_e,\ \ \overline{v}(\overline{x},\infty)\to 0,\ \ T(\overline{x},\infty)\to T_\infty\quad \text{as}\quad \overline{y}\to\infty\end{aligned} \tag{4}$$

where $\overline{u}$ and $\overline{v}$ are the velocity components along the $\overline{x}$ and $\overline{y}$ axes, respectively. T is the fluid temperature, α_1 is the material parameter of the second grade fluid, g is the gravity acceleration, ϕ is the nanoparticle volume fraction of nanofluid, h_f is the heat transfer coefficient, T_f is the hot fluid, k_f is the thermal conductivity and $\overline{u}_e(x)=U_\infty\sin\left(\frac{\overline{x}}{a}\right)$ is the external velocity where U_∞ is the free stream velocity. The thermal expansion coefficient of nanofluid $(\rho\beta_T)_{nf}$, second grade fluid α_1, effective viscosity of nanofluid μ_{nf}, density of nanofluid ρ_{nf}, heat capacity of nanofluid $(\rho C_p)_{nf}$ and effective thermal conductivity of nanofluid k_{nf}, are defined as follows

$$\left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \phi\left(\rho C_p\right)_s, \quad \left(\rho\beta_T\right)_{nf} = (1-\phi)\left(\rho\beta_T\right)_f + \phi\left(\rho\beta_T\right)_s, \quad \rho_{nf} = (1-\phi)\rho_f + \phi\rho_s,$$
$$k_{nf} = k_f \frac{\left(k_s + 2k_f\right) - 2\phi\left(k_f - k_s\right)}{\left(k_s + 2k_f\right) + \phi\left(k_f - k_s\right)}, \ \mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}$$

Now, the following non-dimensional variables are introduced [32]:

$$x = \frac{\bar{x}}{a}, \quad y = \mathrm{Re}^{1/2}\frac{\bar{y}}{a}, \quad u = \frac{\bar{u}}{U_\infty}, \quad v = \mathrm{Re}^{1/2}\frac{\bar{v}}{U_\infty}, \quad \theta = \frac{T - T_\infty}{T_f - T_\infty}, \quad u_e = \frac{\bar{u}_e}{U_\infty} \tag{5}$$

Upon utilization of equation (5), the governing equations become

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{6}$$

$$\begin{aligned} u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} &= u_e\frac{du_e}{dx} + \frac{1}{(1-\phi)^{2.5}\left(1-\phi+\phi\left(\rho_s/\rho_f\right)\right)}\frac{\partial^2 u}{\partial y^2} \\ &+ \frac{K}{1-\phi+\phi\left(\rho_s/\rho_f\right)}\left(u\frac{\partial^3 u}{\partial x\partial y^2} + v\frac{\partial^3 u}{\partial y^3} + \frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2} + \frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}\right) \\ &+ \frac{1-\phi+\phi\left(\left(\rho\beta_T\right)_s/\left(\rho\beta_T\right)_f\right)}{1-\phi+\phi\left(\rho_s/\rho_f\right)}\gamma\theta\sin x, \end{aligned} \tag{7}$$

$$u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} = \frac{k_{nf}/k_f}{1-\phi+\phi\left(\left(\rho C_p\right)_s/\left(\rho C_p\right)_f\right)}\frac{1}{\mathrm{Pr}}\frac{\partial^2\theta}{\partial y^2}, \tag{8}$$

with the related boundary conditions

$$\begin{aligned} &u(x,0) = 0, \quad v(x,0) = 0, \quad \frac{\partial\theta}{\partial y}(x,0) = -Bi\left(1-\theta(x,0)\right) \quad \text{at} \quad y = 0 \\ &u(x,\infty) \to u_e, \quad v(x,\infty) \to 0, \quad \theta(x,\infty) \to 0 \quad \text{as} \quad y \to \infty \end{aligned} \tag{9}$$

where $\mathrm{Pr} = \left(\frac{C_p\mu}{k}\right)_f$, $K = \frac{\alpha_1 U_\infty}{\mu_f a}$, $Gr_x = \frac{g\beta_T\left(T_f - T_\infty\right)a^3}{\nu_f^2}$, $\gamma = \frac{Gr_x}{\mathrm{Re}_x^2}$ and $\mathrm{Re}_x = \frac{U_\infty a}{\nu_f}$ are the respective Prandtl number, second grade fluid parameter, Grashof number, mixed convection parameter and Reynolds number. Now, (6) is identically satisfied while (7) and (8) are as follows after substituting the non-similarity transformation variables: $\psi = xf(x,y),\ \theta = \theta(x,y)$, where ψ is the stream function, indicated by $u = \frac{\partial\psi}{\partial y}$ and $v = -\frac{\partial\psi}{\partial x}$ and θ is the fluid temperature [15].

$$\frac{1}{(1-\phi)^{2.5}}\frac{\partial^3 f}{\partial y^3}+K\left(2\frac{\partial f}{\partial y}\frac{\partial^3 f}{\partial y^3}-f\frac{\partial^4 f}{\partial y^4}+\left(\frac{\partial^2 f}{\partial y^2}\right)^2\right)+C_1\left(f\frac{\partial^2 f}{\partial y^2}-\left(\frac{\partial f}{\partial y}\right)^2\right)+C_2\frac{\sin x}{x}\gamma\theta$$
$$+C_1\frac{\sin x\cos x}{x}=xC_1\left[\begin{array}{l}\dfrac{\partial f}{\partial y}\dfrac{\partial^2 f}{\partial x\partial y}-\dfrac{\partial f}{\partial x}\dfrac{\partial^2 f}{\partial y^2}\\ +\dfrac{K}{C_1(1-\phi)^{2.5}}\left(\dfrac{\partial f}{\partial x}\dfrac{\partial^4 f}{\partial y^4}-\dfrac{\partial f}{\partial y}\dfrac{\partial^4 f}{\partial x\partial y^3}+\dfrac{\partial^2 f}{\partial x\partial y}\dfrac{\partial^3 f}{\partial y^3}+\dfrac{\partial^2 f}{\partial y^2}\dfrac{\partial^3 f}{\partial x\partial y^2}\right)\end{array}\right], \tag{10}$$

$$\frac{1}{\Pr}\frac{k_{nf}}{k_f}\frac{\partial^2\theta}{\partial y^2}+C_3 f\frac{\partial\theta}{\partial y}=xC_3\left(\frac{\partial f}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial f}{\partial x}\frac{\partial\theta}{\partial y}\right), \tag{11}$$

with C_1, C_2 and C_3 are constants and be defined as

$$C_1=1-\phi+\phi\frac{\rho_s}{\rho_f},\quad C_2=1-\phi+\phi\frac{(\rho\beta_T)_s}{(\rho\beta_T)_f},\quad C_3=1-\phi+\phi\frac{(\rho C_p)_s}{(\rho C_p)_f}$$

and the boundary conditions (9) become

$$\begin{gathered}f(x,0)=0,\ \ \frac{\partial f}{\partial y}(x,0)=0,\ \ \frac{\partial\theta}{\partial y}(x,0)=-Bi\left(1-\theta(x,0)\right)\ \text{ at }\ y=0\\ \frac{\partial f}{\partial y}(x,\infty)\to\frac{\sin x}{x},\ \ \frac{\partial^2 f}{\partial y^2}(x,\infty)\to 0,\ \ \theta(x,\infty)\to 0\ \text{ as }\ y\to\infty\end{gathered} \tag{12}$$

Equations (10) and (11) are reduced to ordinary differential equations when $x\approx 0$

$$\frac{1}{(1-\phi)^{2.5}}\frac{\partial^3 f}{\partial y^3}+K\left(2\frac{\partial f}{\partial y}\frac{\partial^3 f}{\partial y^3}-f\frac{\partial^4 f}{\partial y^4}+\left(\frac{\partial^2 f}{\partial y^2}\right)^2\right)+C_1\left(f\frac{\partial^2 f}{\partial y^2}-\left(\frac{\partial f}{\partial y}\right)^2\right)+C_2\gamma\theta+C_1=0, \tag{13}$$

$$\frac{1}{\Pr}\frac{k_{nf}}{k_f}\frac{\partial^2\theta}{\partial y^2}+C_3 f\frac{\partial\theta}{\partial y}=0, \tag{14}$$

with the boundary conditions

$$\begin{gathered}f(0)=0,\ \ \frac{\partial f}{\partial y}(0)=0,\ \ \frac{\partial\theta}{\partial y}(0)=-Bi\left(1-\theta(0)\right)\\ \frac{\partial f}{\partial y}(\infty)\to 1,\ \ \frac{\partial^2 f}{\partial y^2}(\infty)\to 0,\ \ \theta(\infty)\to 0\end{gathered} \tag{15}$$

where $Bi=-\dfrac{h_f a}{k_f \operatorname{Re}_x^{1/2}}$ is the Biot number

2. Results and Discussion

The Runge-Kutta Fehlberg technique (RKF 45) is applied to tackle the ODEs (13) and (14) and their related boundary conditions (15), leading to numerical solutions for fluid flow and heat transfer. The base fluid and nanoparticles' thermophysical characteristics are shown in Table 1. According to Lin *et al.,* [33], the non-Newtonian base fluid is carboxymethyl cellulose (CMC-water). One of the typical forms of time-independent non-Newtonian fluids, CMC-water has been experimentally demonstrated and unveils shear thinning or pseudoplastic rheological behaviour [34].

Table 1
Thermophysical properties of nanoparticles and base fluid

Physical properties	ρ (kg m^{-3})	C_p (J kg^{-1} K^{-1})	k (W m^{-1} K^{-1})	$\beta_T \times 10^5 \left(\text{K}^{-1}\right)$
Base fluid (CMC-water)	997.1	4179	0.613	21
Nanoparticle (Cu)	8933	385	401	1.67

Through contrasting values of physical characteristics, such as the second grade parameter K, mixed convection parameter γ and Biot number Bi over profiles of velocity and temperature, the current physical issue may be clearly visualised. All of the study outcomes have been reported with confidence because there is a strong agreement between the current and earlier documented numerical values for rising values of γ as presented in Table 2. Unless otherwise specified, the thickness of boundary layer is exploited from 3 to 10 and the subsequent fixed values of parameter are: $K = 0.2,\ \phi = 0.02,\ \Pr = 6.2$ and $Bi = 0.5.$

Table 2
Comparison of $-\theta'(0)$ with former studies for various values of γ when $\lambda = \phi = 0, \Pr = 1$ and $\lambda_2 \to 0$ (very small)

	$-\theta'(0)$					
γ	Merkin [15]	Nazar [19]	Rashad *et al.,* [36]	Zokri *et al.,* [37]	Zokri [30]	Present
-1	0.5067	0.5080	0.5068	0.506679	0.506678	0.506661
-0.5	0.5420	0.5430	0.5421	0.542072	0.542065	0.542057
0	0.5705	0.5710	0.5706	0.570484	0.570470	0.570465
0.5	0.5943	0.5949	0.5947	0.594546	0.594534	0.594531
0.88	0.6096	0.6112	0.6111	0.610775	0.610762	0.610759
0.89	0.6110	0.6116	0.6114	0.611182	0.611169	0.611167
1	0.6158	0.6160	0.6160	0.615601	0.615587	0.615585
2	0.6497	0.6518	0.6518	0.651507	0.651492	0.651491
5	0.7315	0.7320	0.7319	0.731529	0.731510	0.731510

The physical impact of second-grade fluid on the profiles of velocity and temperature are illustrated through Figures 2 and 3. As K is raised, the temperature field in the flow zone rises while there is a noticeable decrease in the velocity field. The reason is because the nearby particles are compelled to move quickly, which gives rise to a significant augmentation in boundary layer thickness resulting from the greater normal stress.

The distribution of velocity caused by the increasing mixed convection parameter, γ is shown in Figure 4. Regardless of whether there is an assisting or opposing flow, the velocity profile has an increasing effect on rising γ. The cause is that a high value of γ results in strong buoyancy forces, which sap kinetic energy. The momentum has been lost as a result of this situation. Anwar [18]'s paper concentrating on the mixed convection flow of a viscoelastic fluid from a horizontal circular cylinder has highlighted a similar trend of graph.

As depicted in Figure 5, $Bi < 0.1$ indicates a thermally thin material, $Bi > 0.1$ indicates a thermally thick material, and $Bi > 1$ indicates a non-uniform thermal field inside the boundary layer [35]. Increasing the Bi values in this section to raise the temperature profile. At the sheet surface, this escalation is noticeably variable; however, when the boundary layer thickness approaches the freestream, the temperature approaches zero. The expression of Bi in Equation (17), which describes a direct relationship of Bi to the heat transfer coefficient and an inverse relationship of Bi to the thermal resistance, really clarifies such an outcome. The thermal resistance becomes reduced as Bi increases, augmenting the thermal boundary layer thickness.

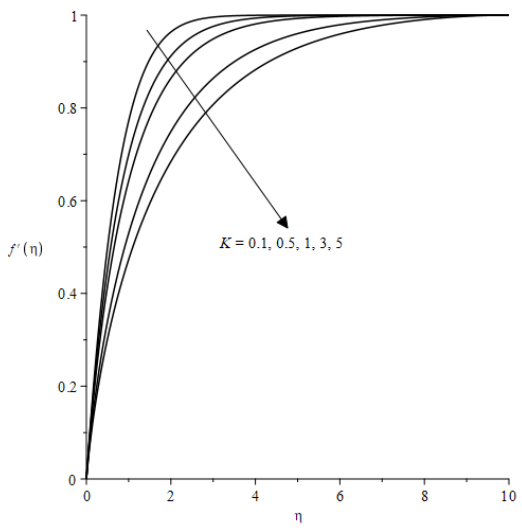

Fig. 2. Variation of $f'(y)$ due to K

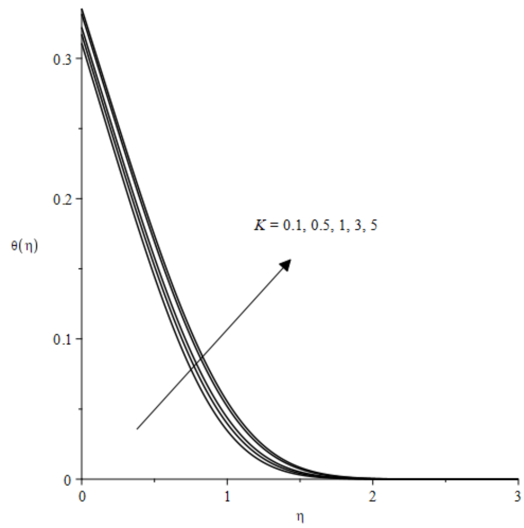

Fig. 3. Variation of $\theta(y)$ due to K

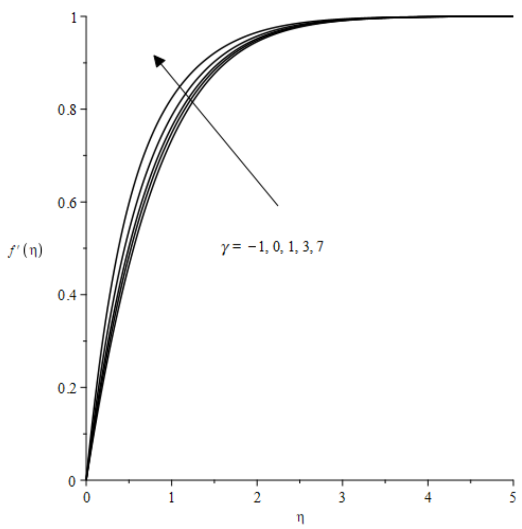

Fig. 4. Variation of $f'(y)$ due to γ

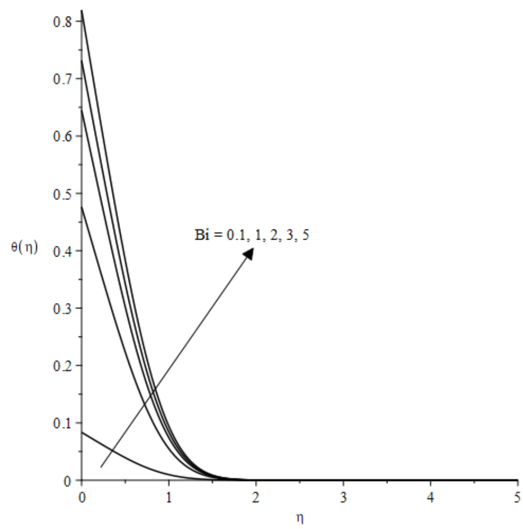

Fig. 5. Variation of $\theta(y)$ due to Bi

3. Conclusions

With the aid of Maple software and the RKF 45 method, a numerical solution on the lower stagnation point of a second-grade nanofluid flow from a horizontal circular cylinder has been carried out. Copper (Cu) nanoparticles are combined with the base fluid carboxymethyl cellulose solution (CMC-water). The accuracy of the current data has been established by verification of the numerical results by comparison with earlier investigations. The following is a summary of the current findings:

- The temperature has increased while the velocity has decreased as the second grade parameter has risen.
- The velocity has increased due to a mixed convection parameter increase.
- Increasing the amount of Biot results in an increase in temperature.

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