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MHD Stagnation-point Flow over a Stretching/ Shrinking Sheet in Nanofluids

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Abstract In this study, we investigated the problem of steady two-dimensional magnetohydrodynamic (MHD) stagnation-point flow over a linearly stretching/shrinking sheet in nanofluids. There are three types of metallic nanoparticles considered such as copper (Cu), alumina (Al_2O_3) and titania (TiO_2) in the base fluid of water with the Prandtl number $Pr = 6.2$ to investigate the effect of the nanoparticles volume fraction parameter φ of the nanofluids. In this problem, the governing nonlinear partial differential equations are transformed into the nonlinear ordinary differential equations by using a similarity transformation and then solved numerically using the boundary value problems solver bvp4c in Matlab software. The influence of magnetic field parameter, M on the skin friction coefficient C_f , local Nusselt number Nu and the velocity and temperature profiles are presented graphically and discussed. The results show that the velocity and temperature are influenced by the magnetic field and nanoparticles volume fraction. The dual solutions exist for shrinking sheet case and the solutions are non-unique, different from a stretching sheet. The numerical values of $C_f Re_x^{1/2}$ and $Nu_x Re_x^{-1/2}$ for $M = 0$ are also computed, which show a favourable agreement with previous work.

Keywords Magnetohydrodynamic, Stagnation-point Flow, Stretching/Shrinking Sheet, Nanofluids, Dual Solutions

1. Introduction

In the boundary layer problem, the stagnation-point flow effect has been attracted the interest of many researchers due to its applications in industry such as flows over the tips of aircraft, submarines, etc. Stagnation-point flow is the fluid motion near the stagnation region of a solid surface exists in both cases of a fixed or moving body in a fluid. Hiemenz [1] was the first researcher who studied the steady two-dimensional stagnation-point flow towards a stationary semi-infinite wall and obtained an exact solution of the governing Navier-Stokes equations. Then, the problem has been extended to the axisymmetric stagnation-point flow case by Homann [2]. Mahapatra and Gupta [3-4] have been investigated the heat transfer in the stagnation-point flow over a stretching surface through a viscoelastic fluid, respectively. Wang [5] who is the first introduced the flow past a shrinking sheet by considering both two-dimensional and axisymmetric cases of stagnation-point flow. The unique and dual solutions are obtained for shrinking parameter. Ishak et al. [6], Bhattacharyya and Layek [7], Bhattacharyya [8], Bachok et al. [9], and Lok et al. [10] have extended the work by Wang [5] by focusing different effect characteristics such as the thermal radiation, homogeneous-heterogeneous reactions and magnetic fields effect.

All the studies mentioned above are focused on stagnation-point flow towards a stretching/shrinking sheet in a viscous fluid (Newtonian fluid). Bachok et al. [11] have been investigated the problem on steady two-dimensional stagnation-point flow towards stretching/shrinking sheet in a nanofluid. They found that, the solutions are non-unique for shrinking sheet, but unique for stretching sheet. A nanofluids is a new kind of heat transfer fluids containing small quantity of nanosized particles (less than 100nm). Nanofluids solutions are obtained while dispersing in a basic fluid of the solid particles of nanometric size. The effectiveness of the transport of heat to improve had been proved by some of these solutions with very weak concentration, under certain conditions. However, the addition of nanoparticles to a basic fluid can enhance its thermal conductivity as reported by Choi et al. [12]. Choi [13] had proposed the term "nanofluid" which is to indicate the suspension of the solid nanoparticles in a basic liquid. He found that 20% increase of the effective thermal conductivity of the water- Al_2O_3 mixture for a volume fraction from 1 to 5% of Al_2O_3. Therefore, Choi [13] and Masuda et al. [14] have shown that it is possible to break down the limits of conventional solid particle suspensions by conceiving the concept of nanoparticle-fluid suspensions.

It is accepted that boundary layer flow gets influences by magnetohydrodynamic (MHD). It is described as a branch of fluid dynamics which deals the movement of an electrically conducting fluid in the presence of a magnetic field. Rashidi et al. [15], Sandeep and Sulochana [16], Soid et al. [17], Ishak et al. [18] and Mahapatra and Gupta [19] have studied the MHD flow of stagnation-point in viscous fluid over stretching and shrinking sheet. While, Hamad [20] has analysed the convective flow of heat transfer past a semi-infinite vertical stretching sheet with the magnetic field effect in nanofluid. Hsiao [21], Makinde et al. [22], Mami and Bouaziz [23], Nandy and Mahapatra [24] and Nayak et al. [25] also have investigated the effect of MHD in nanofluids with the presence of other effects such as slip and thermal radiation.

In this paper, we extend the work of Bachok et al. [11] by including the effect of magnetic field (MHD) on the problem of steady stagnation-point flow over a stretching/shrinking sheet in nanofluids by using Tiwari and Das [26] model. Mansur et al. [27] have studied this problem in the presence of suction effect by using Buongiorno [28] model. There are two models that have been constantly used by researchers to study the behavior of nanofluids which are Buongiorno [28] and Tiwari and Das [26] models. Here the Buongiorno [28] model highlights on the Brownian motion and thermophoresis on the heat transfer characteristics, whereas Tiwari and Das [26] model focuses on the solid volume fraction of nanofluids. The effects of the magnetic field, solid volume fraction and the type of nanoparticles on characteristics of energy flow will be studied numerically and discussed further. For some particular cases of the present study, the results are compared with Bachok et al. [11] to support their validity.

2. Materials and Methods

Considering a steady, incompressible, laminar, two-dimensional magnetohydrodynamic (MHD) stagnation-point flow over a stretching/shrinking sheet in a water-based nanofluid contains different types of nanoparticles such as Cu, Al_2O_3, and TiO_2 that located at the plane $y = 0$, and confined at region $y > 0$. It is assumed that, the stretching/shrinking velocity $U_w(x) = ax$ and the ambient fluid velocity $U_\infty(x) = bx$ to vary linearly to the distance x from the stagnation point, where b is a positive constant and a is a constant with $a > 0$ and $a < 0$ corresponds to stretching and shrinking sheet respectively. Furthermore, a transverse magnetic field strength B_0 is applied normal to the sheet with constant electrical conductivity σ. The induced magnetic field is neglected due to the small value of magnetic Reynolds number. Therefore, the simplified two-dimensional MHD govern equations for the steady, laminar and incompressible nanofluid are

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_\infty \frac{dU_\infty}{dx} + \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial y^2} + \frac{\sigma B_0^2}{\rho_{nf}}(U_\infty - u)\,, \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\frac{\partial^2 T}{\partial y^2}\,, \tag{3}$$

along with the initial and boundary conditions,

$$u = U_w(x), v = 0, T = T_w \text{ at } y = 0,$$
$$u \to U_\infty(x), T \to T_w \text{ as } y \to \infty \tag{4}$$

where u and v are the velocity components along the x and y-axes, respectively. Then, $\mu_{nf}, \rho_{nf}, \alpha_{nf}$ and T are viscosity of the nanofluid, density of the nanofluid, thermal diffusivity of the nanofluid and temperature of the nanofluid, which are given by Oztop and Abu Nada [29] as

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}}\,, \rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s\,, \mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}}\,, \tag{5}$$

$$(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_s\,,$$
$$\frac{k_{nf}}{k_f} = \frac{(k_s + 2k_f) - 2\varphi(k_f - k_s)}{(k_s + 2k_f) + \varphi(k_f - k_s)}$$

where φ is the nanoparticle volume fraction parameter of the nanofluid, k_{nf} is the thermal conductivity of the fluid fraction, k_s is the thermal conductivity of the nanoparticle volume fraction, ρ_f is the reference density of the fluid fraction, ρ_s is the reference density of solid fraction, μ_f is viscosity of the fluid fraction, and $(\rho C_p)_{nf}$ is the heat capacitance of the nanofluids, where C_p is the specific heat at constant pressure. The viscosity of the nanofluid μ_{nf} has been approximated by Brinkman [30] as viscosity of the base fluid μ_f containing dilute suspension of fine spherical particles.

To obtain a similarity solution for momentum and energy equations (1) – (3), the similarity transformations (Bachok et al. [11]) are introduced:

$$\eta = \left(\frac{b}{\nu_f}\right)^{\frac{1}{2}} y, \psi = (\nu_f b)^{\frac{1}{2}} x f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \tag{6}$$

where a stream function ψ is defined as $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$ which identically satisfied with the continuity equation (1). Then, T_w is the temperature of the fluid at the stretching/shrinking sheet and T_∞ is the temperature of the fluid far away from the stretching/shrinking sheet. By substituting variables (6) into (2) and (3), the transformed ordinary differential equations are obtained:

$$\frac{1}{(1-\varphi)^{2.5}\left(1-\varphi+\frac{\varphi\rho_s}{\rho_f}\right)} f''' + ff'' - f'^2 + 1 + M(1 - f') = 0\,, \tag{7}$$

$$\frac{1}{Pr}\frac{k_{nf}/k_f}{[1-\varphi+\varphi(\rho C_p)_s/(\rho C_p)_f]}\theta'' + f\theta' = 0\,, \tag{8}$$

subjected to the boundary conditions (4) which become

$$f(0)=0\,,f'(0)=\varepsilon\,,\theta(0)=1,$$
$$f'(\eta)\longrightarrow 1\,,\theta(\eta)\longrightarrow 0 \text{ as } \eta\longrightarrow\infty. \tag{9}$$

Here, the prime notations in (7) – (9) are denoting the differentiation with respect to η. Hence, $Pr=\nu_f/\alpha_f$ is the Prandtl number, $M=\sigma B_0^2/(\rho_f b)$ is the magnetic field parameter and $\varepsilon=a/b$ is the velocity ratio parameter where $\varepsilon>0$ for stretching and $\varepsilon<0$ for shrinking.

The physical quantities of interest are the skin friction coefficient C_f and the local Nusselt number Nu_x, which are defined as

$$C_f=\frac{\tau_w}{\rho_f U_\infty^2}\,,Nu_x=\frac{xq_w}{k_f(T_w-T_\infty)}, \tag{10}$$

where the surface shear stress τ_w and the surface heat flux q_w are given by

$$\tau_w=\mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0},q_w=-k_{nf}\left(\frac{\partial T}{\partial y}\right)_{y=0}, \tag{11}$$

with μ_{nf} and k_{nf} being dynamic viscosity and thermal conductivity of the nanofluids, respectively. Using the similarity variables (6), we obtain

$$C_f Re_x^{1/2}=\frac{1}{(1-\varphi)^{2.5}}f''(0), \tag{12}$$

$$Nu_x/Re_x^{1/2}=-\frac{k_{nf}}{k_f}\theta'(0), \tag{13}$$

where $Re_x=U_\infty x/\nu_f$ is the local Reynolds number.

3. Results and Discussion

The nonlinear ordinary differential equations (7) and (8) subjected to the boundary conditions (9) have been solved numerically using the function bvp4c from Matlab due to its effectiveness in solving the boundary value problems which are much harder than initial value problems. By setting different initial guesses for the missing values for $f''(0)$ and $\theta'(0)$, the dual solutions were obtained. The guess must satisfy the boundary conditions (9) asymptotically, thus keep the behaviour of the solution. The effects of nanoparticles volume fraction of nanofluid φ, the Prandtl number *Pr* and the magnetic field parameter *M* are analysed for three different types of nanofluids which are copper (Cu), alumina (Al_2O_3) and titania (TiO_2) as the working fluids and water as the base working fluid. The Prandtl number is taken to be $Pr=6.2$ and nanoparticles volume fraction is considered from 0 to 0.2 $(0\le\varphi\le 0.2)$, where $\varphi=0$ corresponding to the regular fluid. The thermophysical properties of the base fluid and the nanoparticles are listed in Table 1. The numerical values of $C_f Re_x^{1/2}$ and $Nu_x Re_x^{-1/2}$ for $M=0$ are also computed, which show a favourable agreement with previous work by Bachok et al. [11]. The numerical computations were performed for several values of the stretching/shrinking parameter ε, magnetic field parameter *M* and nanoparticles volume fraction for further research.

Table 1 Thermophysical properties of fluid and nanoparticles (Oztop and Abu Nada [29])

Physical properties	Fluid phase (water)	Cu	Al_2O_3	TiO_2
C_p (J/kg K)	4179	385	765	686.2
ρ (kg/m^3)	997.1	8933	3970	4250
k (W/mK)	0.613	400	40	8.9538

Figures 1, 2, 3 and 4 illustrate the variation of skin friction $f''(0)$ and local Nusselt number $-\theta'(0)$ for some values of the magnetic field parameter *M* and nanoparticles volume fraction φ towards stretching/shrinking parameter. From these figures, we can observe that, the unique solutions are forms in region $\varepsilon>-1$, the dual solutions are exist in the region $\varepsilon_c<\varepsilon\le-1$ and no solutions for $<\varepsilon_c<0$, where ε_c is the critical value of ε. From this observation, Bachok et al [11] stated that, the first solution is stable and physically realizable, while second solution is not stable. The value of $f''(0)$ is zero when $\varepsilon=1$ in the Figures 1 and 3 because the friction does not occur at the fluid-solid interface when both fluid and solid boundary move with the same velocity. The positive value of $f''(0)$ when $\varepsilon<1$ means that the fluid exerts a drag force on the solid boundary and negative value when $\varepsilon>1$ means the opposite.

The variations of the skin friction coefficient and the local Nusselt number with different nanoparticles; namely copper (Cu), alumina (Al_2O_3) and titania (TiO_2) with different values of magnetic field parameter M $(M=0,0.1,0.2)$ are shown in Figures 5 and 6. These quantities increase almost linearly with φ. From these figures, we can state that, the increasing of the magnetic field parameter *M* will increase the both value of skin friction and Nusselt number coefficient. These figures show that Al_2O_3 has the lowest skin friction coefficient and the difference values between TiO_2 and Al_2O_3 are very small. However, TiO_2 has the lowest heat transfer rate compared to Cu and Al_2O_3 due to the domination of conduction mode of heat transfer. Table 1 clearly shows that TiO_2 has the lowest value of thermal conductivity compared to Cu and Al_2O_3.

Further, Figures 7–12 physically show the velocity and temperature profiles for different values of φ, M and nanoparticles which support the existence of dual solution in Figures 1–4 for certain values of ε. Figure 7 indicates that, the increasing of M, increase the velocity profiles at any point η except at the sheet where the boundary conditions confine it to value 1.0. Figure 9 shows that the momentum boundary layer increases as φ increase. However, Figure 10 shows that the thermal boundary layer thickness increases with a decrease in the parameter φ. Cu has the highest momentum boundary layer and lowest thermal boundary layer thickness compared to the Al_2O_3 and TiO_2 as shown in the Figures 11 and 12. As we observed, the boundary layer thickness for the first solution is thicker than the second solution. It can be seen that all these profiles are asymptotically satisfied all boundary conditions (9) thus support the validity of the numerical results as well as existence of the dual solutions.

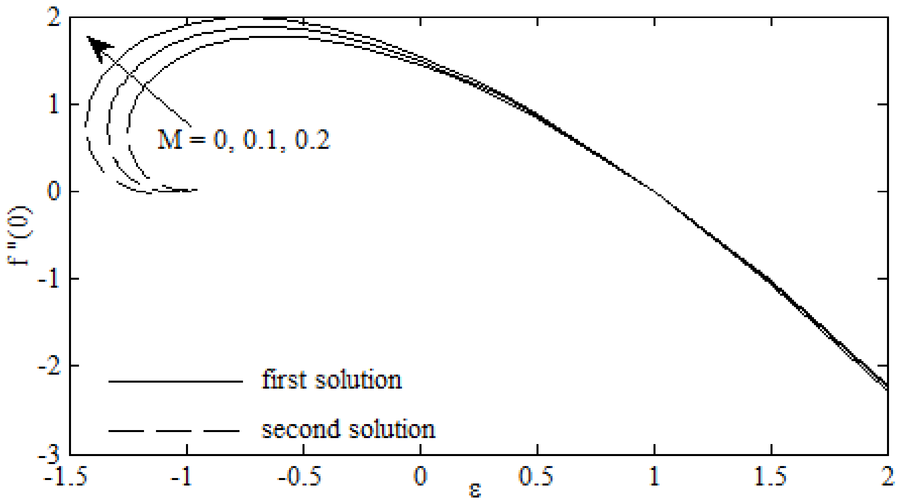

Figure 1. Variation of $f''(0)$ with ε for some values of M for Cu-water working fluid, $Pr = 6.2$ and $\varphi = 0.1$

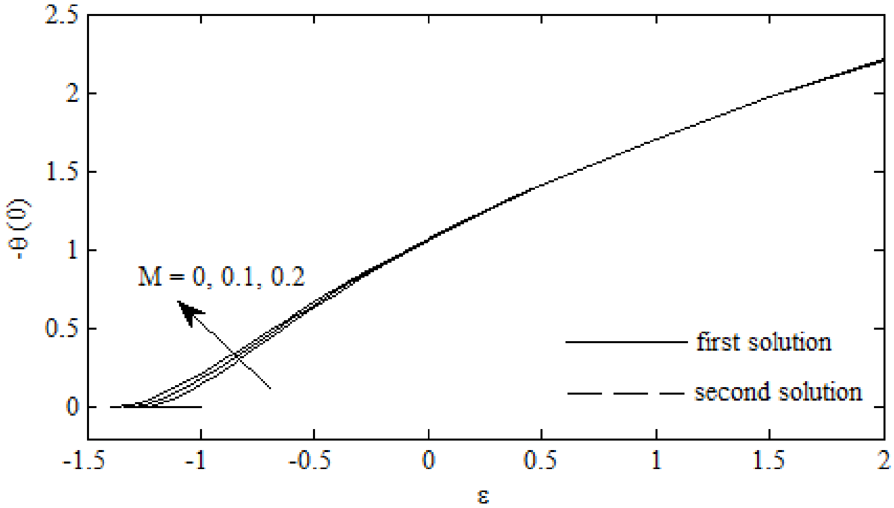

Figure 2. Variation of $-\theta'(0)$ with ε for some values of M for Cu-water working fluid, $Pr = 6.2$ and $\varphi = 0.1$

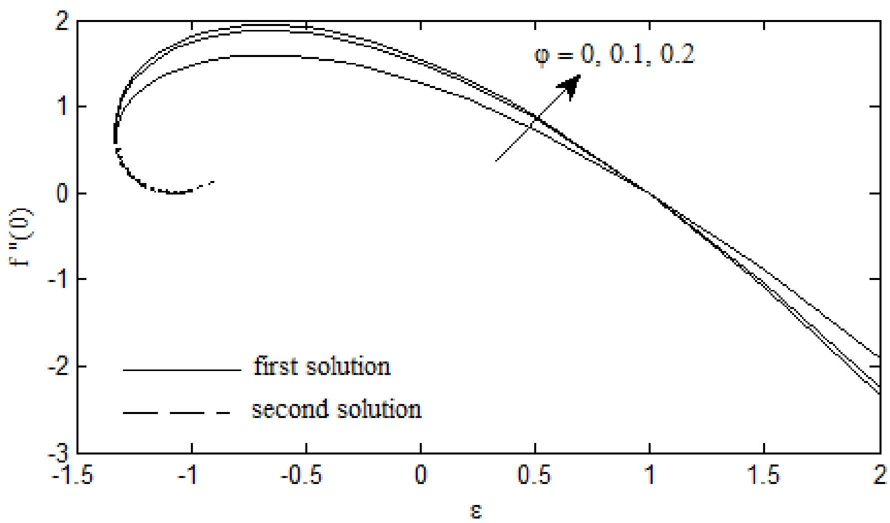

Figure 3. Variation of $f''(0)$ with ε for some values of φ $(0 \leq \varphi \leq 0.2)$ for Cu-water working fluid, $Pr = 6.2$ and $M = 0.1$

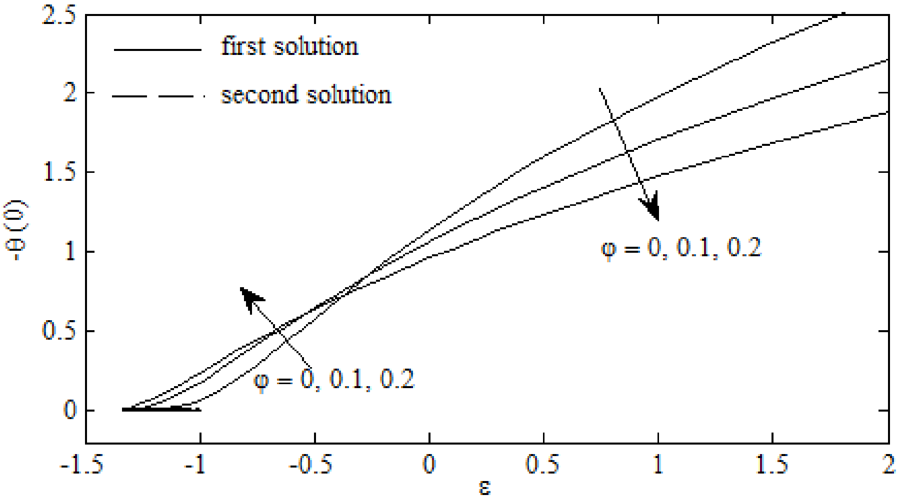

Figure 4. Variation of $-\theta'(0)$ with ε for some values of φ $(0 \leq \varphi \leq 0.2)$ for Cu-water working fluid, $Pr = 6.2, M = 0.1$

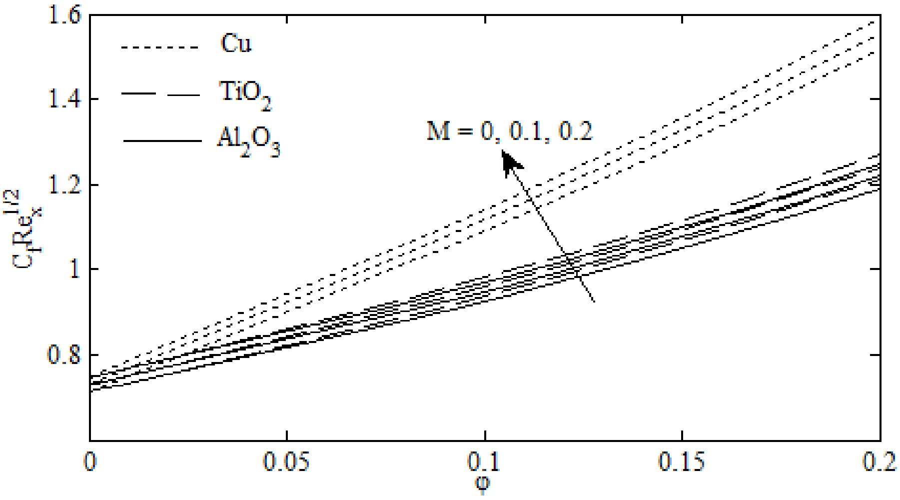

Figure 5. Variation of the skin friction coefficient $C_f Re_x^{1/2}$ with φ for different nanoparticles and magnetic field *M* with $\varepsilon = 0.5$ and $Pr = 6.2$

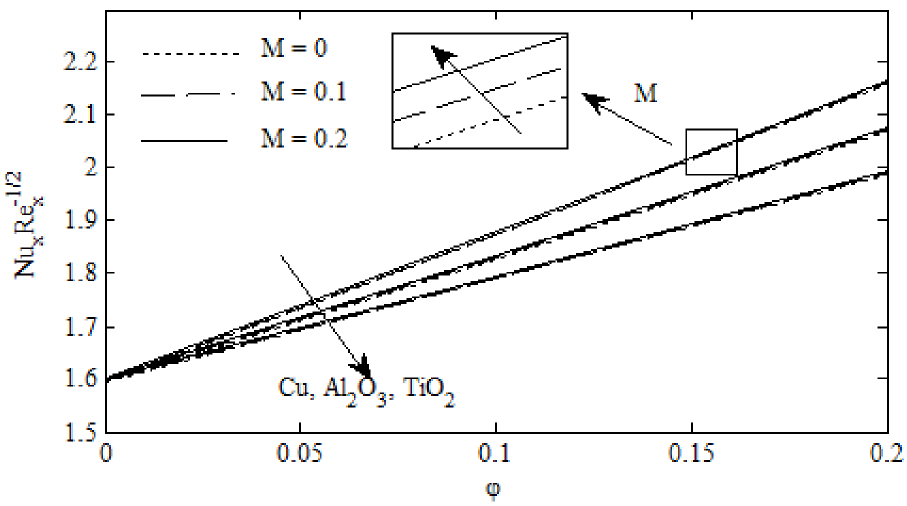

Figure 6. Variation of the local Nusselt number $Nu_x Re_x^{-1/2}$ with φ for different nanoparticles and magnetic field *M* with $\varepsilon = 0.5, Pr = 6.2$

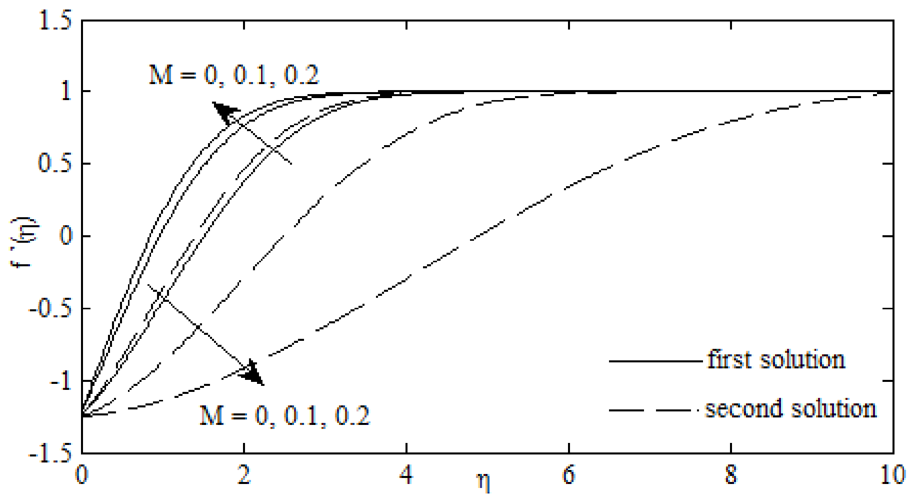

Figure 7. Velocity profiles for different M for Cu-water working fluid with $\varphi = 0.1, \varepsilon = -1.25$ and $Pr = 6.2$

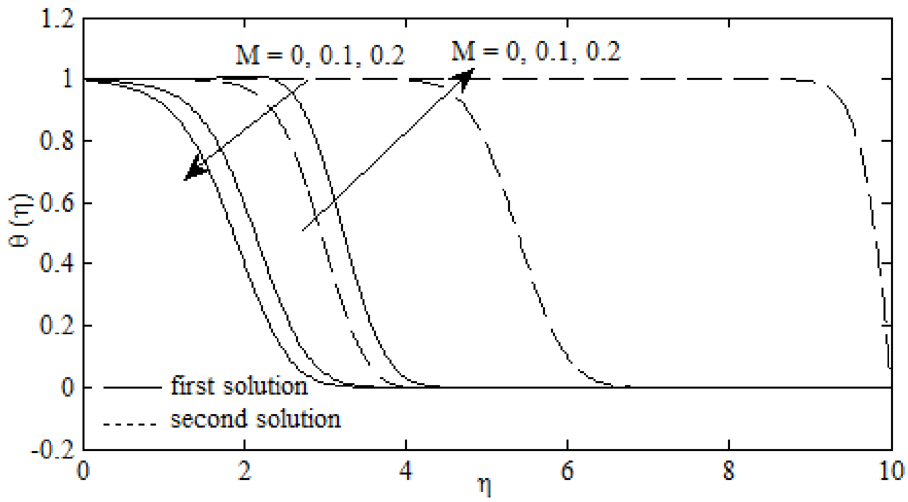

Figure 8. Temperature profiles for different M for Cu-water working fluid with $\varphi = 0.1, \varepsilon = -1.25$ and $Pr = 6.2$

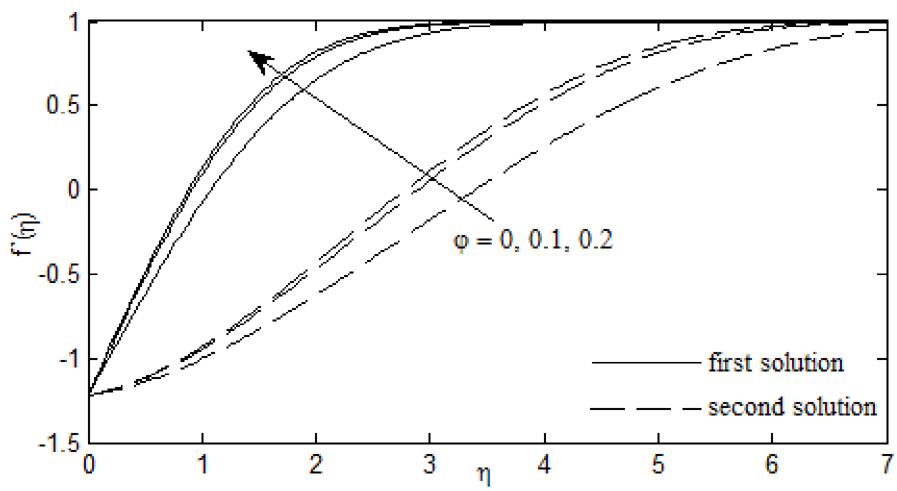

Figure 9. Velocity profiles for some values of φ $(0 \leq \varphi \leq 0.2)$ for Cu-water working fluid with $\varepsilon = -1.22, Pr = 6.2$ and $M = 0.1$

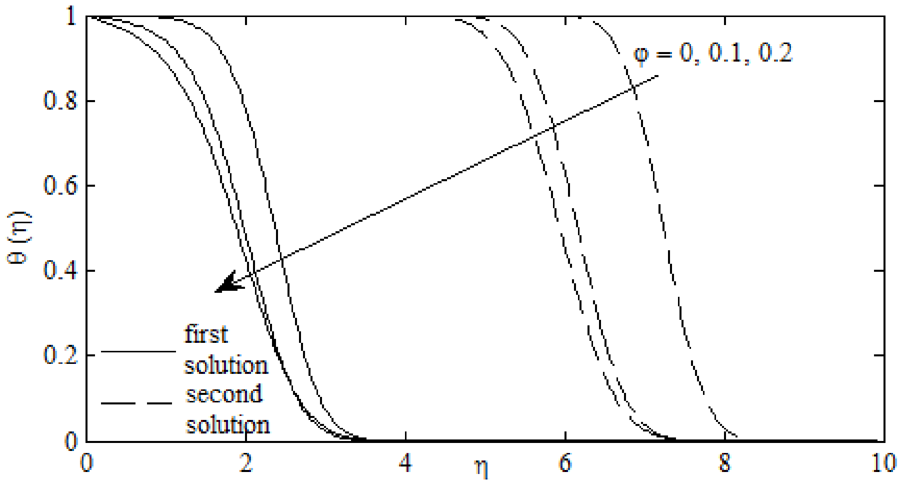

Figure 10. Temperature profiles for some values of φ $(0 \le \varphi \le 0.2)$ for Cu-water working fluid with $\varepsilon = -1.22, Pr = 6.2$ and $M = 0.1$

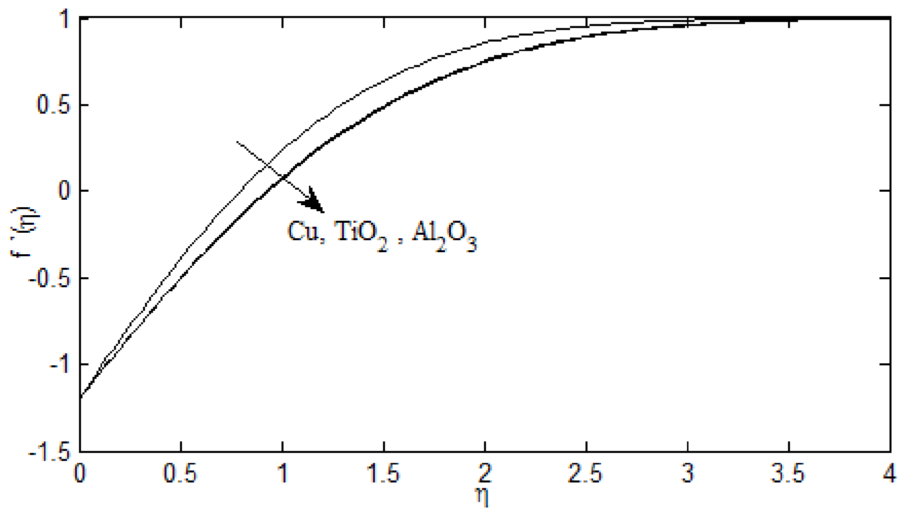

Figure 11. Velocity profiles for different nanoparticles with $\varphi = 0.1, \varepsilon = -1.2, M = 0.2$ and $Pr = 6.2$

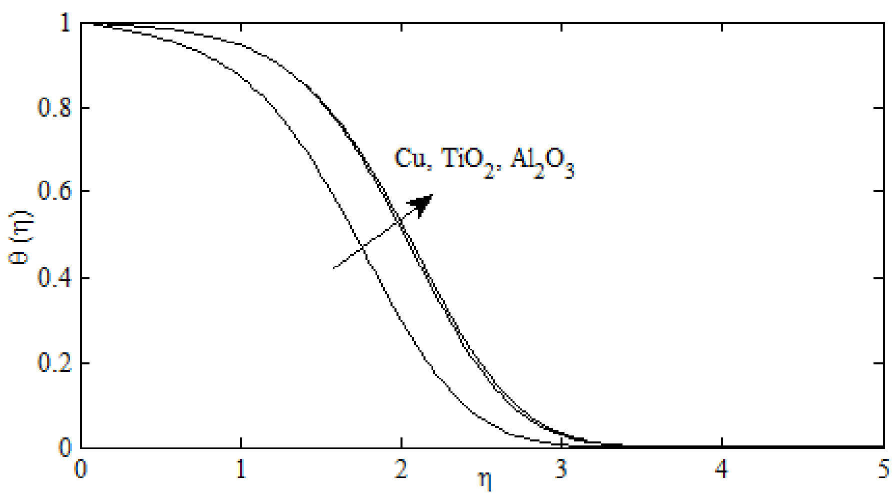

Figure 12. Temperature profiles for different nanoparticles with $\varphi = 0.1, \varepsilon = -1.2, M = 0.2$ and $Pr = 6.2$

4. Conclusions

We have numerically analysed how magnetic field parameter M affects the flow of stagnation-point over stretching/shrinking sheet in nanofluids. From the stagnation-point distance, the stretching/shrinking and the ambient fluid velocities are assumed to vary linearly. The analysis effect of nanoparticles volume fraction parameter φ and heat transfer characteristics for three types of nanoparticles which are copper (Cu), alumina (Al_2O_3) and titania (TiO_2) were solved numerically in water-based fluid with Prandtl number $Pr = 6.2$. As the magnetic field parameter M increases, the skin friction coefficient and heat transfer rate increase. The dual solutions are found for the shrinking sheet while only unique solution for the stretching sheet. With the increment of the magnetohydrodynamic, the range of solutions is widely expanded.

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