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Nanofluid Flow Past a Static Wedge with Velocity Slip Condition

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ABSTRACT

Nanofluids are known for their exceptional thermophysical properties, especially their thermal conductivity, which make them ideal for a number of heat transfer applications. In this study, the mixed convection nanofluid flow past a static wedge with the presence of velocity slip condition is investigated. The problem is governed by a system of partial differential equations which then transformed into a set of nonlinear ordinary differential equations by using an appropriate similarity transformation. The transformed governing equations are then solved numerically by using MATLAB bvp4c solver. Numerical solutions obtained are presented graphically in the form of velocity and temperature profiles for different values of nanoparticles volume fraction, wedge angle and velocity slip. It is found that the increasing values of the wedge angle parameter causes the velocity of the fluid to increase whereas the temperature profile of the nanofluid decreases, additionally it observed that velocity of the fluid increase when velocity slip is increased. The findings of this study provide valuable insights into optimizing heat transfer processes in various engineering applications by leveraging the enhanced thermal properties of nanofluids and considering factors such as wedge angle and velocity slip.

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1. Introduction

Fluid mechanics is an important discipline in physics to understand the mechanical motion of the fluid itself. In most engineering applications such as automotive manufacturing, cooling system, food processing, biomedical application, plant design, and operation, the knowledge of fluid mechanics plays a very significant role in optimizing the machine durability and also enhancing the production numbers. In fluid mechanics, there is a subdiscipline known as boundary layer flow where the fluid flow velocity is subjected to the sheering forces. This small revolutionization later contributed massively to the advancement of the aerodynamic and fluid dynamics sector. The range of the boundary layer flow velocity varies from zero at the surface of the body to the maximum velocity at the free stream. The geometrical shape, body motion, body surface characteristic, and orientation of the body surface are the factors that influence the flow behavior at the boundary layer.

Mathematics is closely related to all engineering sectors since most of the laws and principles of physics are expressed by using the language of mathematics. Navier-Stokes equation is the fundamental formula applied in describing the motion of inviscid viscous incompressible fluid. It was firstly developed by Claude-Louis Navier and then improved by Sir George Gabriel Stokes [1]. This balance differential equation was idealized from Newton’s second law of motion together with the stress tensor assumption. Most of the phenomena in science and engineering such as water flow in pipe and air flow at airplane wings are well described by using this equation.

In recent years, theoretical studies have significantly increased the rapid development in machine manufacturing, new technology, discovery of new materials and advancement in the engineering sector. The study of boundary layer flow in fluid mechanics has gained so much attention since it provides a promising result as a pioneer guideline in constructing experimental and production processes. The boundary layer flow is very important in understanding fluid behavior theoretically. Many studies have been conducted for analyzing the boundary layer flow characteristics, heat transfer properties, and also concentration distribution in fluids.

Therefore, in this research, a fundamental study is conducted to investigate the mixed convection nanofluid flow past a static wedge with the presence of velocity slip condition. The problems are mathematically formulated based on physical laws and principal and then solved numerically. The problem is then analyzed graphically in terms of profiles and physical quantities.

2. Literature Review

The term “nanofluids” refers to a relatively new category of fluids that comprise emulsions or suspensions of nanostructures such as fibers, tubes, particles, or droplets in conventional fluid media such as water, ethylene glycol etc. A nanofluid has higher thermal conductivity in comparison to conventional base fluids, such as water, kerosene oil or another solvent. These nanofluids exhibit notably heightened thermal conductivity compared to conventional base fluids such as water or kerosene oil, a phenomenon which has been significantly enhanced by the addition of a small fraction of nanoparticles [2]. Nanofluids possess several advantageous thermophysical properties including thermal conductivity, dynamic viscosity, density, and specific heat capacity, making them attractive for various heat transfer applications, including solar thermal systems, refrigeration systems, and boiling applications [3]. Notably, their exceptional thermal conductivity and enhanced reactivity as heat transfer media distinguish nanofluids among these applications.

Previously, in the discovery of the nanofluid, researchers frequently used Buongiorno nanofluid model and Tiwari-Das nanofluid model to formulate mathematical models. Researchers in [4] considered seven nanofluids criteria which are inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity that can create a relative velocity between nanoparticles and base fluid. The findings from this research indicated that among these factors, Brownian diffusion and thermophoresis emerged as the most influential in terms of their impact on heat transfer enhancement. Brownian motion is called the random motion of nanoparticles within the base fluid and results from the continuous collisions between the nanoparticles and the molecules of the base fluid. The other model proposed by Tiwari and Das [5] highlighted the behaviour of nanofluids inside a two-sided lid-driven differentially heated square cavity to gain insight into convective recirculation and flow processes of nanofluid by considering the solid nanoparticle volume fraction. They have considered two main approaches which are a two-phase model that takes into fluid and solid phase roles in the heat transfer process and a single-phase model where both the fluid phase and solid particles are in thermal equilibrium state and flow with the same local velocity. They discovered that the modified single-phase accounting for some factors is more suitable than the two-phase model for the heat transfer process.

In the discovery of nanofluids, researchers frequently used Falkner-Skan flow by focusing on a static or moving wedge. Researchers in [6] studied steady two-dimensional boundary layer flow past a static or a moving wedge immersed in nanofluid. In the paper, it stated the static or a moving wedge immersed in nanofluid with $0 \le \beta \le 1$ for wedge flow, which β is Hartree pressure gradient parameter. They consider $\beta = 0$ corresponds to a horizontal plate, while $\beta = 1$ correspond to a vertical plate. From the study, they found the effect of the solid volume fraction of nanoparticles on the fluid flow and heat transfer characteristics more pronounced compared to the type of the nanoparticles. In the examination of the Falkner-Skan problem within the context of boundary layer nanofluid flow in the presence of an induced magnetic field, it was found that larger values of magnetic parameters contributed to the reduction of the boundary layer thickness and velocity field [7]. Moreover, it was noted that the induced magnetic field diminished as the temperature profile increased, consequently leading to an expansion of the thermal boundary layer thickness caused by increment β.

A study investigated the properties of static-moving wedges in the context of unsteady two-dimensional Falkner-Skan flow of a cross fluid, with the added presence of nonlinear thermal radiation [8]. The approach involved the application of the Buongiorno nanofluid model to tackle the problem. Notably, the primary discovery from this research was that elevating the liquid temperature led to an increase in both the Brownian motion parameter N_f and the temperature ratio parameter θ_f. Additionally, a declining trend in the temperature field and thermal layer structures was observed as the heat sink parameters increased. Furthermore, researchers in [9] studied steady aligned MHD magnetic nanofluid flow past a static wedge. They discovered that fluid velocity increases with the increase of inclined angle, magnetic parameter and thermal buoyancy parameters while decreasing for increasing nanoparticle volume fraction. Other than that, they also noticed that magnetic parameters influence fluid velocity and temperature significantly.

Additionally, in another study focusing on the boundary layer of Falkner-Skan flow and heat transfer for MHD Cross nanofluid past a wedge surface, it was found that variations in the wedge angle parameter were associated with an increase in fluid velocity [10]. However, the temperature and concentration profiles displayed a diminishing trend. The research also highlighted that implementing Newtonian heat and mass conditions led to improvements in the fluid's temperature and nanoparticle concentration fields. Another research carried out a study for the Falkner-Skan flow in Maxwell fluids over a wedged wall [11]. Based on the result obtained, the local heat transfer rate reduces against thermophoresis parameter and smaller for the shrinking wedge while increasing for stretching wedge.

Besides that, a study on the Falkner-Skan flow for heat transfer from a source at the vertex of a wedge has also carried out [12]. They found there exists a mixing index that quantifies how well the heat or mass mixed with the convection fluid. They stated that the effect of the wedge opening angle was more complicated. Recently, another researcher studied the heat transfer in nanofluid under viscous dissipation and thermal radiation over a wedge [13]. Based on the result obtained, they concluded that the velocity field by increasing the values of mixed convection parameter, the temperature field of the nanofluid significantly results in more dissipative fluid and maximum increment is observed for opposing flow cases. They also noticed, temperature of nanofluid enhances for both assisting and opposing cases with the presence of thermal radiations.

The study of boundary layer flows has sparked considerable interest among scientists. There are studies conducted to investigated the flow of a linearly viscous fluid when the slip depends on both the shear stress and normal stress [14]. They have considered three models; slip depends only on the shear stress, slip depends only on normal stress and slip depends both on shear stress and normal stress. It is found that when the effects of normal and shear stress are incorporated into the equation governing slip, the solutions obtained are qualitatively similar to the case when the slip velocity depends only on the normal stress. The research the continue to investigated slip boundary conditions using a modified Falkner-Skan solution for laminar boundary layer flow over a wedge [15]. From the study, they concluded that with the presence of slip boundary conditions the solution showed a decrease in skin friction, boundary layer thickness, velocity thickness and momentum thickness. Besides that, studies on the problem of Falkner-Skan boundary layer flow over a static wedge with the effect of slip condition and variable thermal conductivity then conducted [16]. They observed from the numerical results obtained, it shows that with the increase of the slip parameter cause the velocity to increase. Furthermore, another study discussed flow and heat transfer of a double fractional Maxwell fluid with second order slip model [17]. They solved the fractional governing equations by using the finite difference method. It can be discovered that the fractional Maxwell fluid exhibits a stronger viscosity or elasticity for different fractional parameters and the oscillation phenomenon will gradually decrease as expected with an increase in slip parameters.

Then, it has come to researches interest to study slip condition effects on nanofluid flow. Some researcher studied the simultaneous effects of magnetic field and slippage on the stagnation point flow of nanofluid over a stretching surface [18]. They particularly analyzed the variations of Brownian motion and thermophoresis. In the study, the no-slip condition, which assumes that a liquid adheres to a solid boundary, is frequently utilized in flow problems of viscous fluids. The research then continues to investigate the influence of variable fluid properties on nanofluid flow over a wedge with the effect of surface slip [19]. They solved the resulting nonlinear ordinary differential equations by using the RK-4 method together with the shooting method. It is observed that, fluid temperature is higher in the presence of variable viscosity parameter and thermal conductivity parameter. They also observed that the wall stress decreases with the increasing value of velocity slip parameter.

A study on two dimensional magnetohydrodynamic (MHD) flow of a viscous fluid over a constant wedge immersed in a porous medium with velocity slip condition then conducted [20]. They found that velocity is an increasing function of pressure gradient. This is due to a decrease in yield stress for increasing values of pressure gradient thus causing a reduction in momentum boundary layer thickness. Then, the closed-form exact solutions for the fully developed momentum, thermal and concentration layers through a concentric annulus filled with various nanoparticle mixtures of water-based nanofluids in the presence of wall slip nanofluid velocity are obtained [21]. In this study, the researcher considered the single phase and two-phase model of Buongiorno. From the single-phase model, it is observed that the velocity profiles are decreased, so the influence of nanofluids volume fraction is to clearly reduce the momentum boundary layer thickness. In addition, by applying the same amount of velocity slip at both walls also acts to decrease the velocities by bringing the peaks down towards the inner wall.

Then, the investigation on heat and mass transfer characteristics of unsteady, two-dimensional stagnation-point flow of Williamson nanofluid along a static or moving wedge with the presence of velocity slip and chemical reaction are performed [22]. They discover that the intensifying values of the temperature ratio parameter enhances the nanofluid temperature and thermal boundary-layer thickness. Recently, studies on the Falkner-Skan problem by considering the buoyancy effects in Falkner-Skan flow of water based nanofluids past a static wedge under partial slip condition was conducted [23]. They observed that with the existence of wall slip parameters, the momentum boundary layer is considerably suppressed compared with the corresponding no slip boundary case. They also found that the presence of thermal slip leads to the thinning of temperature profile which results in enhanced heat transfer from the surface. Based on the cited literature, this study is focused on the influence of velocity slip condition on nanofluid flow past a static wedge.

3. Methodology

The two-dimensional, incompressible flow of nanofluid past a static wedge in the presence of slip condition is considered. Water (H_2O) is used as the base fluid with copper (Cu) as chosen nanoparticles. Consider the Falkner-Skan flow situation in Figure 1, the flow involves water based nanofluids along a heated wedge making an angle $\frac{\beta\pi}{2}$ with the horizontal. In order to achieve a prescribed free stream velocity $U(x) = ax^m$, where $a > 0$ is a constant, pressure gradient is applied onto the case of static wedge.

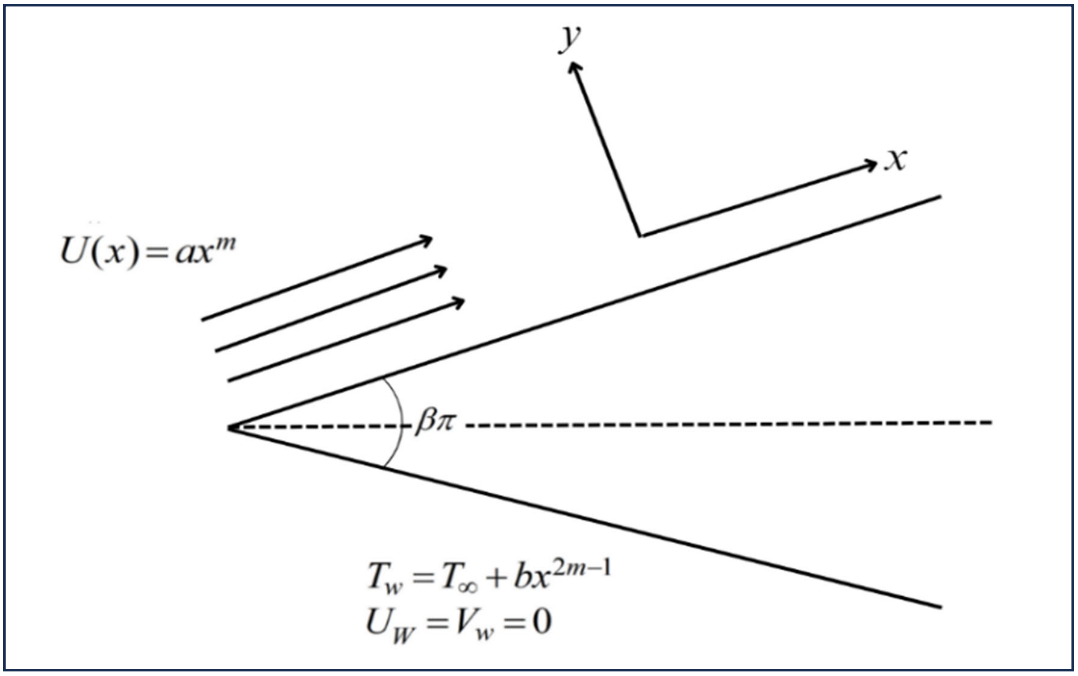

Figure 1. Falkner-Skan Flow

Then, let u and v for velocities along the x and y directions where coordinate x extends along the wedge surface and y is normal to it. By considering all the effect in the fluid flow, the governing boundary layer equations are formulated in equation (1) – (3) subjected to the boundary condition in (4) – (5).

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

$$\left(\rho C_{\rho}\right)_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=U\frac{dU}{dx}+\nu_{nf}\left(\frac{\partial^2 u}{\partial y^2}\right)+g\left(\beta_1\right)_{nf}\left(T-T_{\infty}\right)\sin\left(\frac{\beta\pi}{2}\right) \tag{2}$$

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

with boundary conditions,

$$u=U(x)+\gamma_1\frac{\partial u}{\partial y}, v=0, T=T_{w,}\text{ at } y=0 \tag{4}$$

$$u\to u(x), T\to T_{\infty}\text{ when } y\to\infty \tag{5}$$

where u, v is the component of the nanofluid's velocity in x and y axes respectively. $\left(\rho C_p\right)_{nf}$ is the heat capacity of nanofluid, $\left(\beta_1\right)_{nf}$ is the coefficient of thermal expansion, ρ is the density, ρ_{nf} is the density of the nanofluid, ν_{nf} is the kinematic viscosity and g is the gravitational force. k_{nf} is thermal conductivity of nanofluid and γ_1 is the slip parameter for velocity. T is the fluid temperature, T_w is surface temperature and T_{∞} is the ambient temperature.

Under the assumption that water as the base fluid and nanoparticles are in thermal equilibrium and in slip condition, the expression for nanofluid are adopted from previous studies is given as follows [22]:

$$
\begin{aligned}
\rho_{nf} &= (1-\phi)\rho_f + \phi\rho_s \\
\nu_{nf} &= \frac{\nu_f}{(1-\phi)^{2.5}\{(1-\phi)\rho_f + \phi\rho_s\}} \\
(\rho\beta_1)_{nf} &= (1-\phi)(\rho\beta_1)_f + \phi(\rho\beta_1)_s \\
(\rho C_\rho)_{nf} &= (1-\phi)(\rho C_\rho)_f + \phi(\rho C_\rho)_s \\
k_{nf} &= k_f \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f + k_s)}
\end{aligned}
\tag{6}
$$

where ϕ represents the nanoparticle volume fraction, while the subscript f, nf and s are for the base fluid, nanofluid and copper nanoparticle respectively. ρ_f is the reference density of the fluid fraction and ρ_s is the reference density of the solid fraction. ν_f is velocity of base fluid, $(\rho\beta_1)_f$ is buoyancy coefficient of base fluid and $(\rho\beta_1)_s$ is buoyancy coefficient of solid nanoparticles. $(\rho C_\rho)_f$ is heat capacity of base fluid and $(\rho C_\rho)_s$ is the heat capacity of solid nanoparticles. k_f is the thermal conductivity of the fluid fraction and k_s is the thermal conductivity of the solid volume fraction. Thermophysical properties of base fluid and nanoparticles are presented in Table 1.

Table 1. Thermophysical properties of base fluid and nanoparticles [24]

Physical Properties	**Base Fluid Water (H_2O)**	**Nanoparticles Copper (*Cu*)**
$C_p\,(J/kgK)$	4179	385
$k\,(W/mK)$	0.613	400
$\rho\,(kg/m^3)$	997.1	8933
$a \times 10^7\,(m^2/s)$	1.47	1.67

The following similarity transformation are adopted from previous studies are given as follows [23]:

$$
\eta = \sqrt{\frac{(m+1)\,U(x)}{2\nu_f x}}\,y, \quad \psi = \sqrt{\frac{2\nu_f x\,U(x)}{(m+1)}}f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}
\tag{7}
$$

where the stream function, ψ defined as

$$
u = \frac{\partial\psi}{\partial y} \text{ and } v = -\frac{\partial\psi}{\partial x}
\tag{8}
$$

where f is a dimensionless stream function, θ is the dimensionless temperature profile and η is the similarity variable. Similarities transformations equations (7) and (8) are employed in (1) – (3) and initial and boundary condition in (4) – (5) and the following governing equations is produced

$$\frac{1}{\varepsilon_1} f'''(\eta) + f(\eta) f'(\eta) + \frac{2m}{m+1}(1 - f'(\eta)^2) + \frac{2}{m+1}\frac{\varepsilon_2}{\varepsilon_3}\lambda\theta(\eta)\sin\left(\frac{\beta\pi}{2}\right) = 0 \tag{9}$$

$$\frac{1}{Pr}\cdot\frac{k_{nf}}{k_f\varepsilon_4}\theta''(\eta) + f(\eta)\theta'(\eta) - \frac{4m-2}{m+1} f'(\eta)\theta(\eta) = 0 \tag{10}$$

with boundary condition

$$\begin{aligned} & f(\eta) = 0, f'(\eta) - S_1 f''(\eta) = 0, \theta(\eta) = 1 \text{ at } \eta = 0 \\ & f'(\eta) = 1, \theta(\eta) = 0 \text{ as } \eta \to \infty \end{aligned} \tag{11}$$

where $\lambda = \frac{gb(\beta_1)_f}{a^2}$ is the mixed convection parameter, $\beta = \frac{2m}{m+1}$ is the Hartree pressure gradient parameter, m is wedge angle parameter, $Pr = \frac{v_f\left(\rho C_\rho\right)_f}{k_f}$ is the Prandtl number, where $S_1 = \gamma_1\sqrt{\frac{c}{v}}$ is the velocity slip parameter, c is a constant and ε_1, ε_2, ε_3 and ε_4 are constant being defined as,

$$\varepsilon_1 = (1-\phi)^{2.5}\left\{(1-\phi) + \phi\frac{\rho_s}{\rho_f}\right\}$$

$$\varepsilon_2 = (1-\phi) + \phi\frac{\left(\rho\beta_1\right)_s}{\left(\rho\beta_1\right)_f}$$

$$\varepsilon_3 = (1-\phi) + \phi\frac{\rho_s}{\rho_f}$$

$$\varepsilon_4 = \left(1-\phi\right) + \phi\frac{\left(\rho C_\rho\right)_s}{\left(\rho C_\rho\right)_f}$$

The governing equation in (9) – (11) then solved numerically using MATLAB and the effect of nanoparticles volume fraction, the wedge parameter and slip condition on velocity and temperature profile are graphically analyzed and discussed.

4. Results and Discussion

The mixed convection flow of *Cu*-water nanofluid flow with the presence of velocity slip condition is studied. The presented graphs for parameters of interest including wedge angle parameter m, velocity slip parameter S_1, nanoparticles volume fraction ϕ and mixed convection parameter λ are shown and discussed. Figure 2 to Figure 9 have been plotted for the physical quantities respectively. The non-dimensional values are fixed for all the graphical illustration into $m = 1.0$, $S_1 = 1.0$, $\phi = 0.01$ and $\lambda = 0.1$ except the values presented in the figures.

By comparing the present results with previous studies, the validity of the present findings is verified as shown in Table 2. The relation between the current results and the results of Watanabe [25], Yih *et al*. [26], Yacob *et al*. [6], Dinarvand [27] and Bhatti *et al.* [23] by concerning local skin friction coefficient, $f''(0)$ with different values of m are found to be excellent.

Table 2. Effect of m on $f''(0)$

m	Watanabe [25]	Yih *et al.* [26]	Yacob *et al.* [6]	Dinarvand [27]	Bhatti *et al.* [23]	Present Study
0	0.46960	0.469600	0.4696	0.469600	0.469600	0.469645
0.2	0.80213	0.802125	0.8021	0.802125	0.802126	0.802129
0.5	1.03890	-	1.0389	1.038903	1.038900	1.038904
1.0	-	1.232588	1.2326	1.232587	1.232590	1.232588

Figure 2 and Figure 3 depict the influence of the wedge angle parameter m, on velocity and temperature profile. The velocity profile shows an increasing behavior with increasing values of m. In other words, when m is increasing, the boundary layer thickness is suppressed, which resulted a rapid rate of velocity near the surface. On the other hand, an increase in m decreases the thermal boundary layer thickness and generally, decreases the temperature profile.

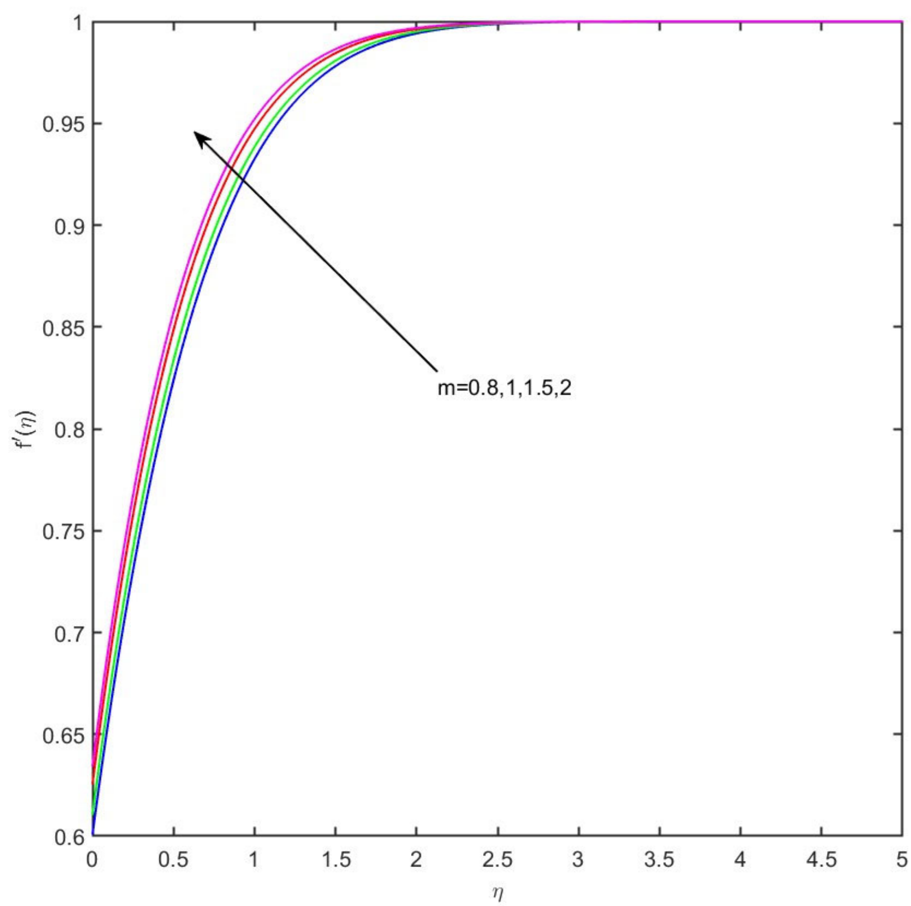

Figure 2. Velocity profile $f'(\eta)$ for different values of m

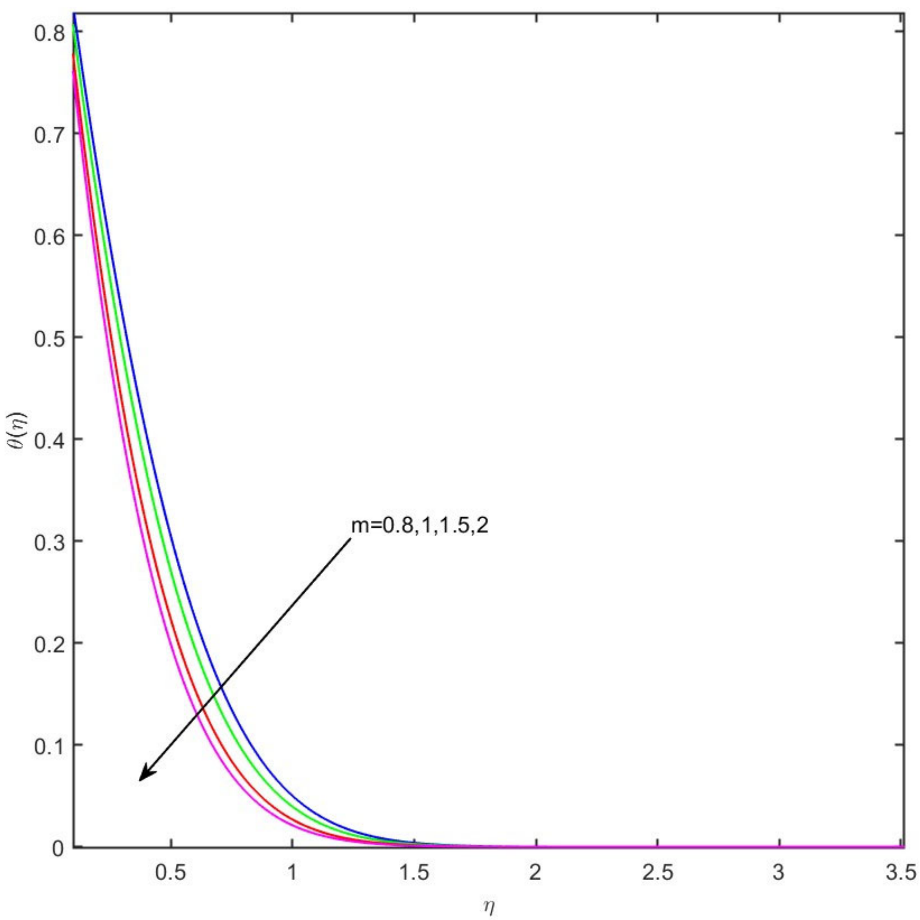

Figure 3. Temperature profile $\theta(\eta)$ for different values of m

From Figure 4, it can be examined that with the increase of velocity slip parameter cause the velocity profile to increase as well. The obtained results exhibit similarities with the findings previous study [23]. In Figure 5, on the other hand, shows that temperature profile decreases with the increasing values of S_1. In other words, when S_1 is increasing, the thickness of thermal and momentum of boundary layers is decreased which tend to decrease the temperature profile. In addition, based on the equation of velocity slip S_1, when S_1 is enlarging the slip parameters for velocity also increase, however the momentum diffusivity ν, which also is the kinematic viscosity of the fluid will decrease. Thus, it leads to lower the temperature of the fluid.

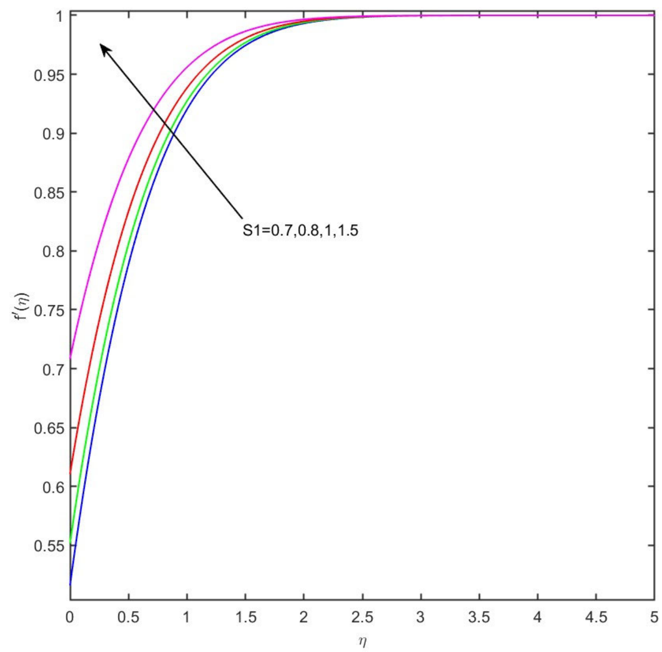

Figure 4. Velocity profile $f'(\eta)$ for different values of S_1

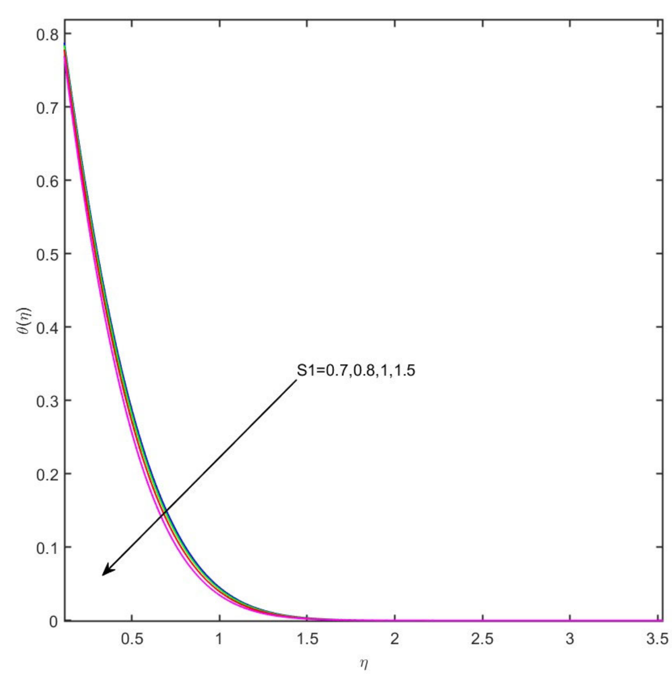

Figure 5. Temperature profile $\theta(\eta)$ for different values of S_1

Figure 6 and Figure 7 show the influence of nanoparticles volume fraction ϕ, on velocity and temperature profile. It shows that with the increasing of ϕ, velocity profile increase, similarly apply to the temperature profile. These findings align closely with the results reported before [23]. According to their study, whenever nanoparticles are considered the thermal boundary layer thickness will be upraised. At the same time, the increment of ϕ cause the improvement of thermal conductivity of the fluid, therefore causing fluid temperature to rise.

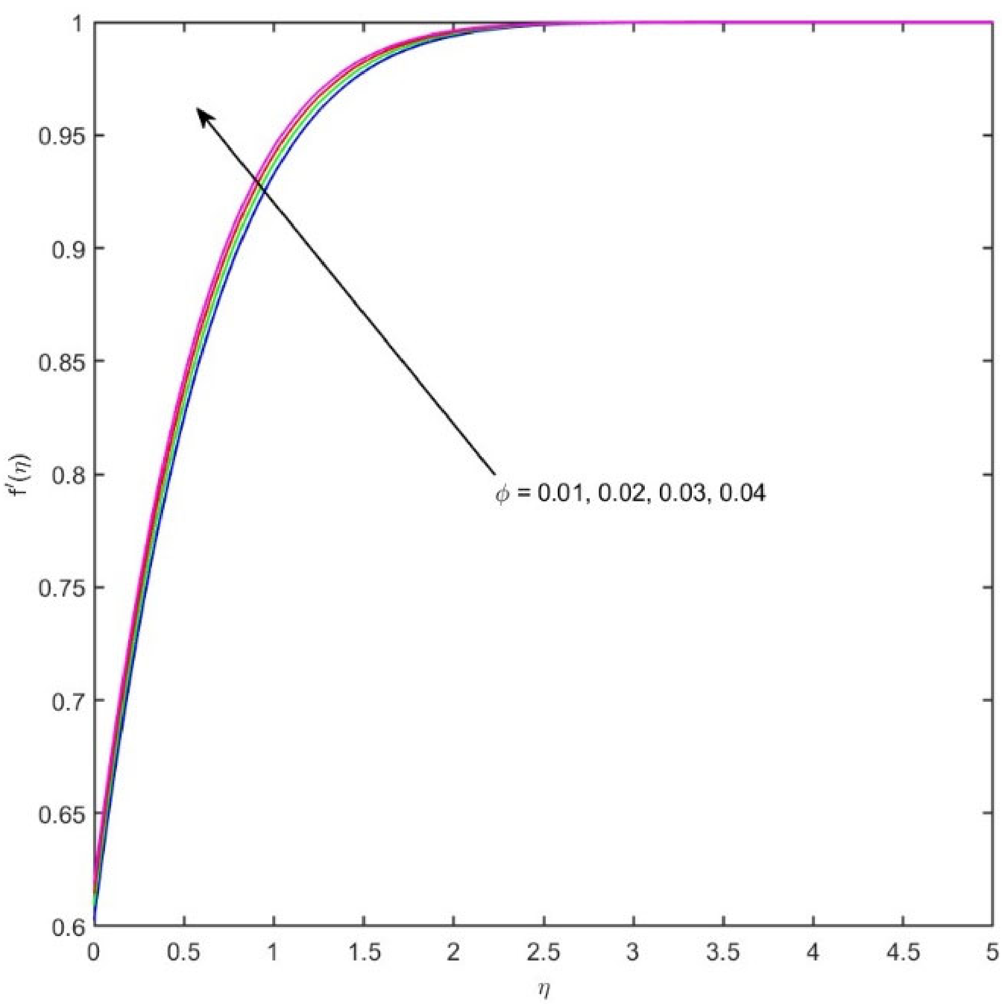

Figure 6. Velocity profile $f'(\eta)$ for different values of ϕ

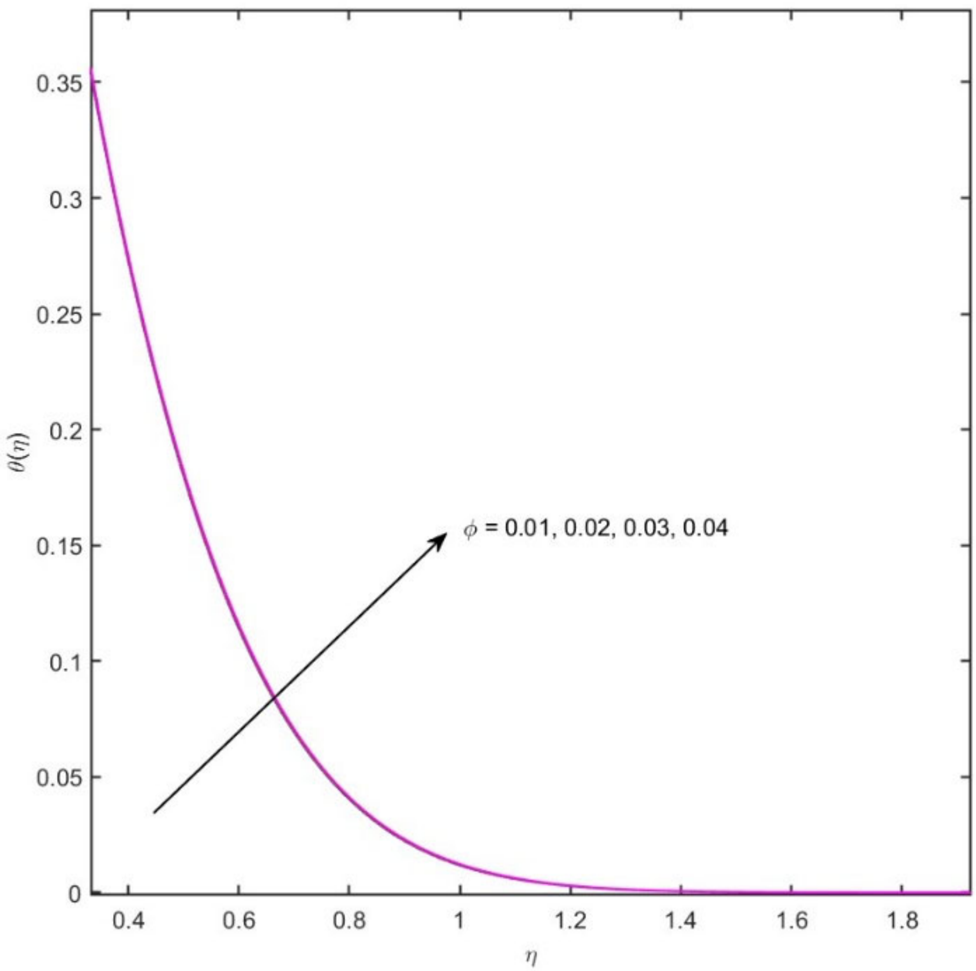

Figure 7. Temperature profile $\theta(\eta)$ for different values of ϕ

Figure 8 and 9 shows the velocity and temperature profiles with different values of mixed convection parameter, λ. From the graphical illustration, it shows that velocity profile increasing with the increase value of λ, while temperature profile on the other hand is decreasing. Based on the previous study, they stated that the higher values of λ increase the velocity due to higher amount of cold fluid is being drawn towards the hot edge surface [18]. Then, it causes thinning of thermal boundary layer.

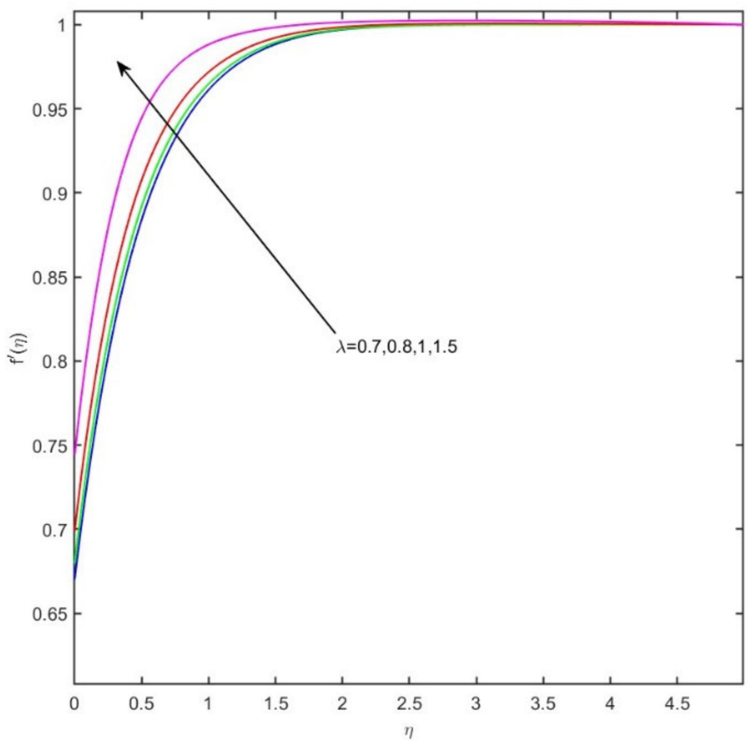

Figure 8. Velocity profile $f'(\eta)$ for different values of λ

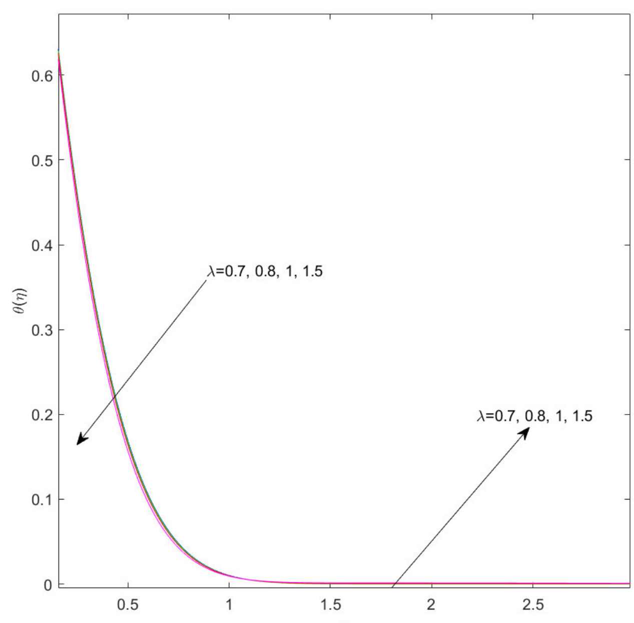

Figure 9. Temperature profile $\theta(\eta)$ for different values of λ

5. Conclusion

In this study, the flow of nanofluid past a static wedge with the presence of velocity slip condition is studied. The solutions are illustrated in the different figures to analyse the influence parameters of interest. The major key points extracted from this study are:

- The increment in wedge angle parameter, m causes the velocity of the fluid to increase whereas the temperature profile of the nanofluid flow to decrease.
- Bigger values of S_1 corresponds to a lower average temperature of the nanofluid and higher average velocity.
- Increasing value of ϕ will enhance both the fluid velocity and temperature profile.
- By increasing values of λ, velocity profile shows an increase value while temperature profile shows a decreasing pattern.

There are quite a few interesting opportunities for future studies. For the purpose of ensuring the efficiency of heat transfer equipment, the study on the nanofluid flow past a static wedge with the presence of velocity slip condition can be explored to different parameter. As this paper is focused on Newtonian fluid, then non-Newtonian fluid in heat transfer is also suggested topics to study on. On top of that, it will be a potential area of investigation to see the effects of nanofluid flow with the presence of heat generation in the future study. Furthermore, it would be interesting to include other relevant effects such as thermal slip and concentration slip effects, magnetic field, thermal radiation, electric field and more in order to expand the possibilities of this studies. In conclusion, based on the preview studies there are still quite a few of related research that can be done in the future.

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Conflict of Interest

The authors declare no conflict of interest in the subject matter or materials discussed in this manuscript.

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