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# Falkner-Skan Flow of Nanofluid with Convective Boundary Condition

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**ABSTRACT**

This study focuses on the investigation of nanofluid flow with convective boundary conditions past a static wedge by considering copper as the chosen nanoparticles and water as the conventional base fluid. The governing partial differential equations (PDE) are transformed into a set of nonlinear ordinary differential equations (ODE) by using an appropriate similarity transformation. The transformed governing equations are then solved numerically by using the Keller-box method. The significant impact of parameters included wedge angle parameter, mixed convection parameter, volume fraction of nanoparticle and Biot number are presented. The graphical analysis on velocity and temperature profiles revealed that the increasing values of all considered parameters causes the increment of velocity of the flow. Meanwhile, significant changes on the temperature profiles are clearly depicted on the increment of nanoparticle volume fraction as well as the Biot number.

## 1. Introduction

New heat transfer fluids known as nanofluids have been found to possess unique characteristics such as the thermal conductivity, thermal diffusivity and viscosity compared to those conventional fluid that make them potentially useful for a broad variety of heat transfer applications, including engine cooling, vehicle thermal management, residential refrigerators, chillers, heat exchanges, and many others. For the boundary layer flow problem, two well-known nanofluids have been used theoretically for studying the characteristic of fluid flow and heat transfer. Buongiorno model [1] demonstrated that the mobility of nanoparticle causes enhanced turbulence and thermal dispersion by assuming seven slip mechanisms including brownian diffusion, diffusiophoresis, fluid drainage, inertia, thermophoresis, magnus effects, and gravity. Among the seven slip processes in nanofluid, thermophoresis and Brownian diffusion have been identified as the most important slip mechanism. Meanwhile, Tiwari and Das model [2] focused on the effect of types of nanoparticles and base fluid as well as the nanoparticles volume fraction. Extensive studies on the convective boundary layer flow of nanofluid considering both models have been undertaken by many researchers. Noghrehabadi *et al.,* [3] performed the entropy analysis for nanofluid flow over a stretching sheet with the presence

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of heat generation/absorption and partial by taking into consideration the effect of brownian and thermophoresis. Rawi *et al.,* [4] investigated the fully developed heat transfer by mixed convection flow of nanofluid in a microgravity environment by choosing two different types of nanoparticles, which are aluminium oxide and copper. The suspended nanoparticles substantially improved the conductivity and viscosity of the conventional base fluid, and consequently enhanced the heat transfer rate of the fluid. Rawat and Kumar [5] carried out the theoretical analysis on the Cu–water nanofluid stagnation point flow past a stretching/shrinking sheet in presence of thermal radiation, heat generation/absorption, suction, slip, and activation energy. In the recent investigation of heat and mass transfer characteristics of nanofluid flow, Reddy and Sreedevi [6] scrutinized the effects chemical reaction, thermal radiation, magnetic field, thermal stratification and solutal stratification.

Nanofluid flow past wedge-shaped geometries have gained much consideration due to their existence range of applications in engineering and science. Yacob *et al.,* [7] studied the Falkner-Skan problem for a static and moving wedge with prescribed surface heat flux on nanofluid. They discovered that copper-water nanofluids have the highest skin friction coefficient and rate of heat transfer at the surface compared to the alumina–water and titania–water nanofluids. Alam *et al.,* [8] explored about the solution of Falkner-Skan unsteady MHD boundary layer flow and heat transfer past a moving porous wedge in a nanofluid. They revealed that the velocity decreases for increasing values of velocity ratio parameter but increases for magnetic parameter, unsteady parameter, permeability parameter and pressure gradient parameter. Mishra *et al.,* [9] showed by increasing of Falkner-Skan parameter, the flow of nanofluid across the wedge is accelerated. They also showed that there is an increasing trend with the Falkner-Skan coefficient for the surface shear stress coefficient, mass transfer rate, and heat transfer rate. In the following year, Waqas *et al.,* [10] examined the Falkner-Skan bioconvection flow of a cross nanofluid with melting across a moving wedge and showed that by improving the values of wedge angle parameter enhanced the velocity profile for both scenarios of a static and moving wedge. They also concluded that the bioconvection Rayleigh number, buoyancy ratio parameter, and infinite shear rate viscosity reduced the Falkner-Skan nanofluid's velocity. Recently, Akbar [11] observed that the wedge angle enhanced the surface heat flow as well as the coefficient of skin friction, and the applied external electric field changes the laminar boundary-layer separation from the static and moving wedge surface.

Convection boundary conditions, also called Newton boundary conditions in heat transfer, are derived from surface energy balances and refer to the presence of convection heating or cooling at the surface. This condition has received tremendous attention in the nanofluid boundary layer flow due to its substantial heat transfer enhancement. Ray *et al.,* [12] explored that the behaviour of temperature and the volume percentage of nanoparticle differs depending on the thermophoresis parameter due to the influence of the convective boundary condition and Biot number which leads to an improvement in the thickness of the momentum, thermal, and concentration boundary layers. Zainal *et al.,* [13] considered the mixed convection stagnation point flow of hybrid nanofluid past a vertical flat plate. In the study, dual solutions which are upper and lower solutions have been detected and successfully proven for certain range of mixed convection parameter. On the other hand, Low *et al.,* [14] who explored the dusty nanofluid flow with the presence of magnetic field concluded that an increase in Biot number which represented the influence of convective boundary condition on the fluid flow has improved the flow temperature, consequently enhanced the heat transfer rate. They also observed that the magnetic field parameter has a tendency to create an opposing force to the flow, lowering the velocity boundary layer while increasing the heat boundary layer. Later, the free convection flow of magnetic nanofluid with aligned magnetohydrodynamics over a moving vertical plate was analyzed by Rosaidi [15].

The literature review above presents the various studies on convection nanofluid flow with various geometries including wedge-shaped with the absence or presence of convective boundary conditions. Thus, the present study aims to analyze the fluid flow behaviour and heat transfer characteristic on mixed convection nanofluid flow with convective boundary condition effect past a static wedge. The transformed governing equations are solved numerically using Keller-box method.

## 2. Problem Formulation

The two-dimensional and incompressible nanofluid flow over a static wedge in the presence of convective boundary conditions considered. The nanoparticle and conventional base fluid that have been considered in this flow is copper (Cu) and water ($H_2O$). Figure 1 shows the schematic diagram of mixed convection flow of nanofluid over a static wedge.

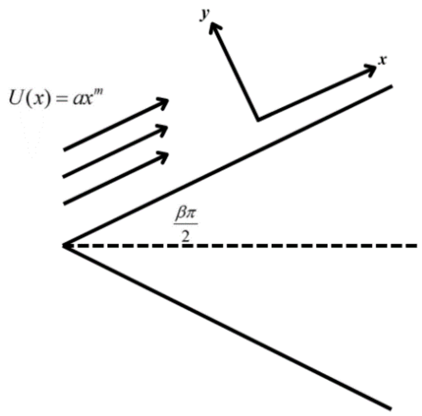


**Fig. 1.** Schematic diagram of mixed convection flow of nanofluid over a static wedge

Consider Falkner-Skan flow situation illustrated in Figure 1 where water-based nanofluids are present along a heated static wedge inclined at an angle $\frac{\beta\pi}{2}$ with respect to the horizontal where $\beta = \frac{2m}{m+1}$ is the Hatree pressure gradient. Let denote the velocities along the *x*-direction and *y*-directions as *u* and *v* respectively where $x$ -coordinate extends along the surface of the wedge, while the *y*-coordinate is perpendicular to it. This study focuses on a static wedge where a pressure gradient is employed to achieve a desired velocity profile in the free stream, denoted by

$$U(x) = ax^m \tag{1}$$

where $a > 0$ is a constant and *m* is a wedge angle parameter. While, the temperature of the wedge as follows

$$T_w = T_\infty + bx^{2m-1} \tag{2}$$

where $T_\infty$ represent the ambient temperature and $b$ is a constant [7]. The basic governing equations for this problem are given by:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=U\frac{dU}{dx}+v_{nf}\frac{\partial^2 u}{\partial y^2}+g\left(\beta_1\right)_{nf}(T-T_\infty)\sin\left(\frac{\beta\pi}{2}\right) \tag{4}$$

$$\left(\rho C_p\right)_{nf}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_{nf}\frac{\partial^2 T}{\partial y^2} \tag{5}$$

with boundary conditions,

$$\begin{gathered} u=0, v=0, -k\frac{\partial T}{\partial y}=h_f\left(T_w-T\right) \text{ at } y=0 \\ u\to U(x), T\to T_\infty \text{ as } y\to\infty \end{gathered} \tag{6}$$

where $v_{nf}, (\rho C_p)_{nf}, k_{nf}, (\beta_1)_{nf}, g, h_f, T, T_f, T_w$ represent the effectiveness kinematic viscosity, heat capacity of nanofluid, thermal conductivity, coefficient of thermal expansion, gravity, convective heat transfer coefficient, temperature of the fluid, convective fluid temperature, and temperature of the wedge wall respectively. The expression of nanofluid constants is defined as [4,16],

$$\begin{gathered} \mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}}, \rho_{nf}=(1-\phi)\rho_f+\phi\rho_s, \\ (\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_s, (\rho\beta_1)_{nf}=(1-\phi)(\rho\beta_1)_f+\phi(\rho\beta_1)_s \\ \frac{k_{nf}}{k_f}=\frac{(k_s+2k_f)-2\phi(k_f-k_s)}{(k_s+2k_f)+\phi(k_f-k_s)} \end{gathered} \tag{7}$$

Here, $f$ is the nanoparticles volume fraction which is the concentration of the nanoparticles to be added in the chosen base fluid, where subscript *f* and *s* represent the fluid and solid component in the nanofluid mixture respectively. The thermophysical properties of copper and water are shown in Table 1 [16,17].

**Table 1**
Thermophysical properties of the base fluids (H2O) and nanoparticles (Cu)

| Physical Properties | Base Fluids ($H_2O$) | Nanoparticle (Cu) |
|---|---|---|
| $C_P$(J/kg K) | 4179 | 385 |
| $K$(W/mK) | 0.613 | 400 |
| $\rho$(kg/m$^3$) | 997.1 | 8933 |
| $\beta_1\times 10^{-5}$(mK) | 21 | 1.67 |

The following similarity transformation are adopted from studies by Bhatti *et al.,* [18], given as follows:

$$\eta = \sqrt{\frac{(m+1)U(x)}{2v_f x}}, \psi = \sqrt{\frac{2v_f x U(x)}{m+1}} f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \tag{8}$$

where $\eta$ is the similarity variable, $f$ is a dimensionless stream function, $\theta$ is the dimensionless temperature profile and $\psi$ is the stream function defined as $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$. The governing Eq. (4) and (5) are then simplified to ordinary differential equations using similarity transformation (8) as follows

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

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

where $\lambda = \frac{gb\left(\beta_1\right)_f}{a^2}$ is the mixed convection parameter, $\beta = \frac{2m}{m+1}$ is the Hartree parameter and $\Pr = \frac{v_f\left(\rho C_p\right)_f}{k_f}$ is the Prandtl number and $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ are constant given by

$$\begin{gathered} \varepsilon_1 = (1-\phi)^{2.5} + \left\{(1-\phi) + \phi\frac{\rho_s}{\rho_f}\right\}, \varepsilon_2 = (1-\phi) + \phi\frac{(\rho\beta_1)_s}{(\rho\beta_1)_f}, \\ \varepsilon_3 = (1-\phi) + \phi\frac{\rho_s}{\rho_f}, \varepsilon_4 = (1-\phi) + \phi\frac{(\rho C_p)_s}{(\rho C_p)_f}. \end{gathered} \tag{11}$$

with transformed boundary conditions given as,

$$\begin{gathered} f'(\eta) = 0,\ f(\eta) = 0, \theta'(\eta) = -Bi\left[1 - \theta(\eta)\right] \text{ at } \eta = 0 \\ f'(\eta) = 1, \theta(\eta) = 0 \text{ as } \eta \to \infty \end{gathered} \tag{12}$$

where $Bi = \frac{h_f}{k}\sqrt{\frac{2v_f x}{(m+1)U(x)}}$ is the local Biot number.

**3. Results and Discussion**

An implicit finite difference scheme called Keller-box method is employed to numerically compute the transformed governing Eq. (9) and (10) together with the transformed boundary condition (11). Table 2 presents the comparison of the steady state numerical solutions where $(\phi = \lambda = Bi = 0)$ with those obtained by Yih *et al.,* [19], Yacob *et al.,* [7], Dinarvand *et al.,* [20] and Bhatti *et al.,* [18] for various values of wedge angle parameter, *m*. Compared to the published results, our results appear to be in close agreement, demonstrating the reliability of the numerical method. This table also clearly shows that the skin friction, $f''(0)$ increases with wedge angle parameter, *m.*

**Table 2**
The result comparison for skin friction, $f''(0)$ with $\phi=\lambda=Bi=0$ for various values of wedge angle parameter, *m*

| *m* | Yih *et al.,* [19] | Yacob *et al.,* [7] | Dinarvand *et al.,* [20] | Bhatti *et al.,* [18] | Present results |
|---|---|---|---|---|---|
| 0 | 0.46960 | 0.4696 | 0.469600 | 0.469600 | 0.469645 |
| 0.2 | 0.80213 | 0.8021 | 0.802125 | 0.802126 | 0.802129 |
| 0.5 | 1.03890 | 1.0389 | 1.038903 | 1.038900 | 1.038904 |
| 1 | - | 1.2326 | 1.232587 | 1.232590 | 1.232588 |

The values for nanoparticles volume fraction for all graphs lies in the range of $0 \le \phi \le 0.3$ as suggested by Zainal *et al*., [13]. When $\phi = 0$, it indicates the regular base fluid. Meanwhile, Prandtl number, Pr is set to be 6.2 since the base fluid used in this study is water. Figures 2 to 5 depicts the influences of wedge angle parameter *m*, mixed convection parameter $\lambda$, solid volume fraction of nanoparticles, $\phi$ and Biot number, *Bi* respectively on the variations of velocity and temperature profiles. For all graphs, the nondimensional values are fixed to $m=0.5, \lambda=1.0, \phi=0.1$ and $Bi=0.3$ except the varies values presented in the figures.

From Figure 2, it can be observed that by the increasing values of m indicate a favourable pressure gradient, which improves flow within the boundary. This also can be illustrated that boundary layer thickness is inhibited by improving the pressure gradient [18]. While temperature of the nanofluid is reduced by enhancing the magnitude of m for situations static wedge. These findings aligned closely with the outcomes reported by Yacob *et al.,* [7] that the thermal boundary layer thickness diminishes as m increases and resulting in a decrease in surface temperature. Consequently, the heat transfer rate at the surface increases progressively.

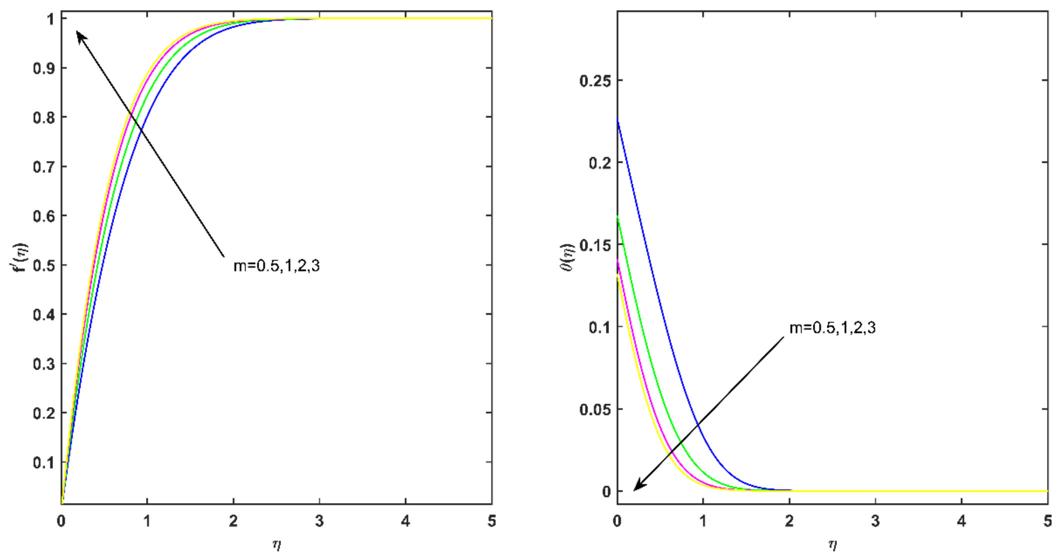


**Fig. 2.** Velocity profile $f'(\eta)$ and temperature profile $\theta(\eta)$ for various value of *m*

From Figure 3, it can be analysed that λ influenced the fluid flow over the wedge. Higher values of λ typically result in a stronger forced convection component and leading to increased fluid velocity near the wedge surface. This, in turn, affects the boundary layer thickness and heat transfer characteristics. Therefore, a thinner boundary layer implies a faster velocity near the surface. While tempearure of the nanofluid decrease as the $\lambda$ increases because the forced convection component becomes more dominant, resulting in enhanced heat transfer in the nanofluid flow on the wedge. This is because the enhanced fluid movement induced by mixed convection helps in carrying heat away from the heated surface more efficiently.

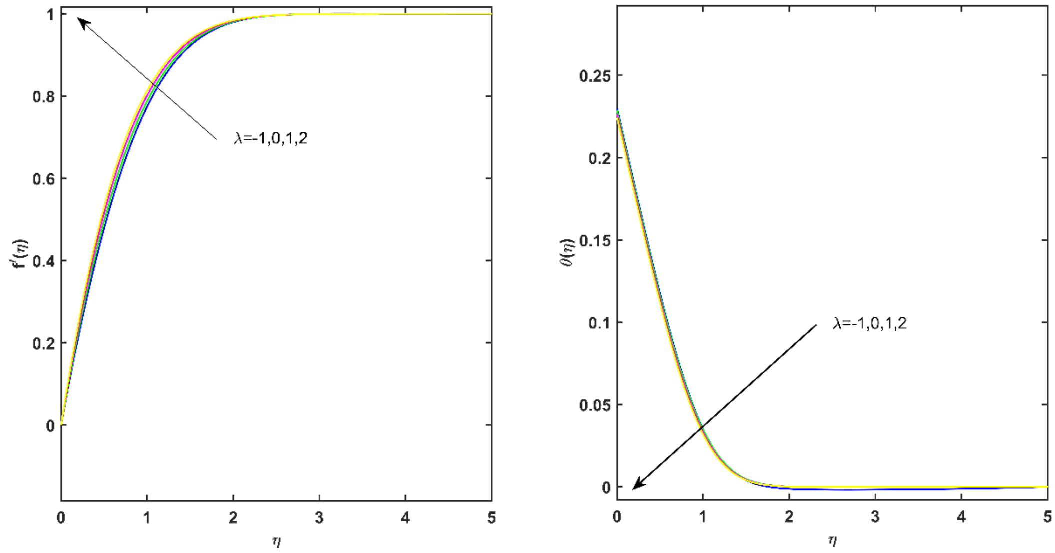


**Fig. 3.** Velocity profile $f'(\eta)$ and temperature profile $\theta(\eta)$ for various value of $\lambda$

From Figure 4, the addition of copper nanoparticles increases the velocity of the fluid. On the other hand, temperature inside the boundary layer exhibits an upward trend as $\phi$ rises. These findings aligned closely with the outcomes reported by Zainal *et al.,* [13]. In accordance with their study, it can be inferred that increasing of $\phi$ in the fluid results in an increment of the boundary layer thickness. Therefore, the thermal conductivity of the nanofluid rises and leading to the growth of temperature of the fluid.

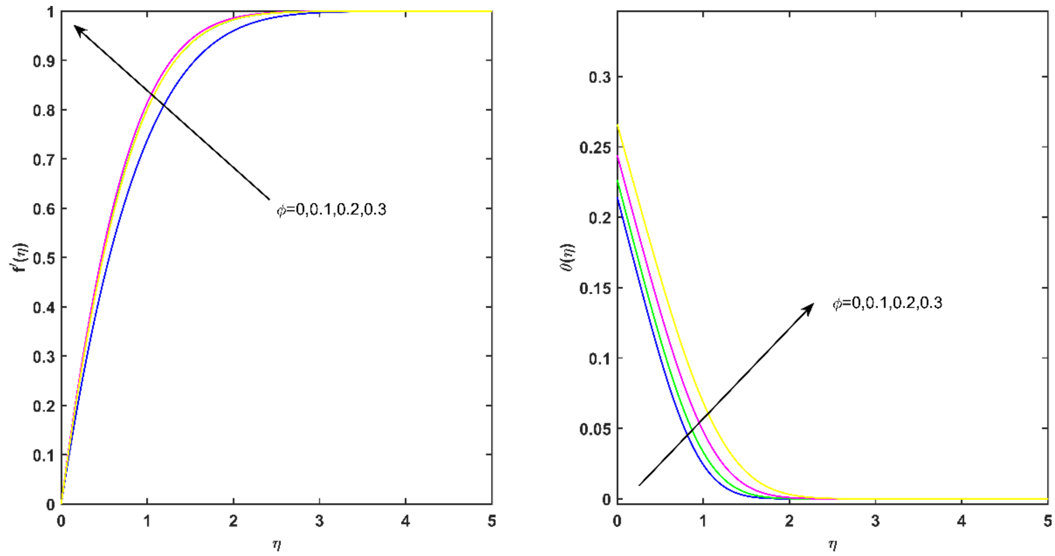


**Fig. 4.** Velocity profile $f'(\eta)$ and temperature profile $\theta(\eta)$ for various value of $\phi$

From Figure 5, it is clear that the temperature distribution show increases as *Bi* increases. Referring to the Khan *et al.,* [21], they stated that when $Bi = 0$, the surface of the wedge is completely isolated, indicating a remarkably high internal thermal resistance. Consequently, there is no convective heat transfer taking place from the surface of the wedge to the fluid located far away from the wedge. However, as predicted, by enhancing the values of *Bi,* corresponds to a stronger convective heat transfer (the temperature inside the boundary layer increase) and leading to a thinner thermal boundary layer. As a result, thinner boundary layer typically associated with higher velocities near the surface of the wedge.

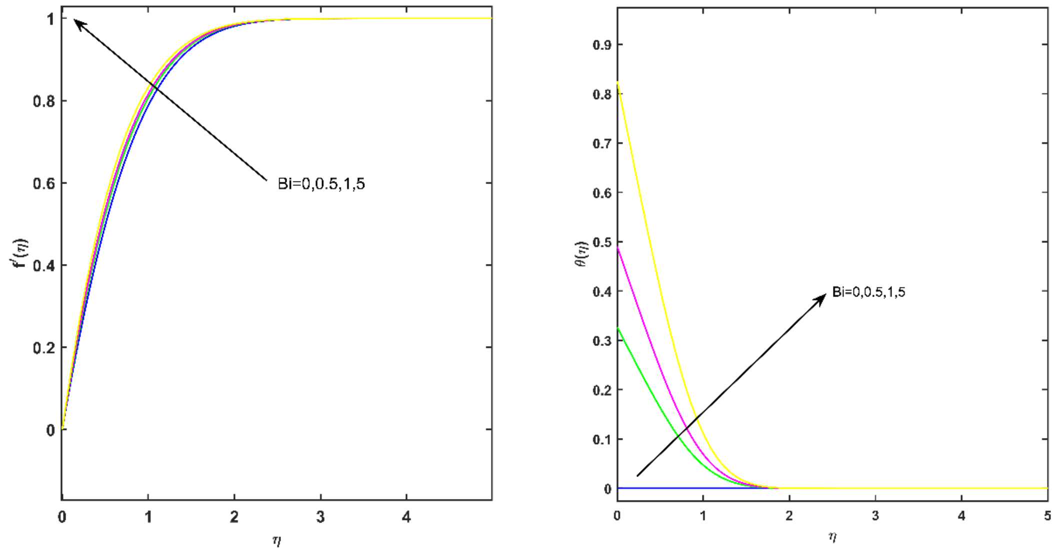


**Fig. 5.** Velocity profile $f'(\eta)$ and temperature profile $\theta(\eta)$ for various value of *Bi*

## 4. Conclusions

The Falkner-Skan flow of nanofluid with convective boundary condition is investigated. The numerical results are plotted to explore the significant impact of wedge angle parameter *m*, mixed convection parameter *λ*, volume fraction of nanoparticle, *ϕ* and Biot number, *Bi* on velocity and temperature profiles. Main outcomes of the graphical analysis are listed via the following points:

i. Larger values of wedge angle, mixed convection, nanoparticle volume fraction and Biot number enhance the velocity of nanofluid.
ii. Temperature declines by the increment of *m* and *λ* but rises in the increment of *ϕ* and *Bi*.
iii. Boundary layer thickness are increase as the velocity of the nanofluid are decrease and temperature of nanofluid are increase.
iv. Enhancing the values of *m* and *λ* are leading to a thinner thermal boundary layer.
v. Increasing of *ϕ* and *Bi* in nanofluids results in an increment of the boundary layer thickness.
vi. Increasing *ϕ*, the viscosity of the fluid is enhanced and leading to increased resistance to flow in the presence of shear stress

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