

Boundary Layer Flow of Dusty Nanofluid over Stretching Sheet with Partial Slip Effects

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ABSTRACT

In this work, the effect of dust particles and slips towards boundary layer flow of dusty nanofluid was investigated over the stretching horizontal sheet. Three types of nanoparticles; copper (Cu), aluminium oxide (Al_2O_3) and titania (TiO_2) were studied. The governing equations of flow and heat transfer were transformed into non-linear ordinary differential equations by using similarity transformation. Next, these equations were solved numerically by using the boundary value problem solver, *bvp4c* program of Matlab software. The effects of non-governing parameters including volume fraction of dust particles, volume fraction of nanoparticles, velocity slip parameter, and thermal slip parameter were computed, analysed, and discussed. Lastly, a comparison of present study with existing literature was performed and achieved excellent agreement. It is found that nanoparticles act as good thermal conductivity. Besides that, Al_2O_3 and TiO_2 show significant effect on velocity of fluid and dust phase.

1. Introduction

Studies of heat transfer and momentum in nanofluid have garnered much attention from many researchers, especially in the nanotechnology industry. According to Jama *et al.*, [1], the main objective to enhance heat transfer using nanofluid was to reduce the cost and size of heat exchangers with high heat flux. Indirectly, the energy and materials can be conserved. Industrial applications of nanofluid include radiation in automobiles, cooling of electronic devices, biomedical equipment, and solar energy system. Thus, nanofluid is widely applied in engineering and science fields.

Despite the nanofluid topic has been extensively focused by many researchers, only a few studies have been made at the early discovery. In the 21st century, the nanofluid study has been widely explored and deeply studied every year. The presence of metal nanoparticles in base fluid improves the thermal conductivity of the fluid. Bachok *et al.*, [2] found out that the fluid's effective thermal conductivity improved under the presence of the nanoparticles as both Nusselt number and skin friction increased. This is in good agreement with the findings reported by Anuar and Bachok [3]. Abd

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Rahman *et al.*, [4] studied that copper has the highest heat transfer rate while titania has the lowest as for Blasius problem. However, the Sakiadis problem showed that alumina has the highest transfer rate. Dust particles are known as impurities which can be found in the environment. Manjunatha *et al.*, [5] studied on the fluid flow with dust particles and found out that the thickness of the momentum boundary layer was reduced under the effect of magnetic. Meanwhile, the Prandtl number affected and reduced the thickness of the thermal boundary layer. As a result, the dusty fluid enhanced the heat transfer rate. Furthermore, the addition of dust particles into the nanofluid flow improved the thermal conductivity of matter due to the interaction between fluid and dust particles towards velocity and temperature. Janke's *et al.*, [6] extended the research work by embedded conducting dust particles into the nanofluid flow. Moving surfaces are commonly used in many manufacturing industries. For example, stretching sheets described as plane with the ability to elongate by velocity on plane and external flow. From the findings of Das *et al.*, [7], both momentum and concentration boundary layer became higher and thicker with the stretching parameter. Meanwhile, Jamaludin *et al.*, [8] proved that stretching sheet had better heat transfer rate than the shrinking sheet. The heat flux on the surface and the skin friction along the surface exhibited a significant effect on the stretching parameters towards the flow field. The existence of slip altered the regulation of flow field. It was also found that different outcomes were produced from the appearance of disturbance parameters towards the flow field. The research work by Nandy and Mahapatra [9] indicated that the velocity slip parameter affected the concentration of nanoparticle, the temperature of the flow field, and the velocity of the flow field. Meanwhile, Aman *et al.*, [10] performed the analysis of partial slip towards the stagnation point flow by using the shooting method. The thermal slip parameter caused a reduction in temperature profile and the thickness of the thermal boundary layer became thinner. An article from Khan *et al.*, [11] found that the slip parameter caused the heat to disperse more quickly to surrounding. Hence, the velocity accelerated while temperature fluid reduced as of shrinking sheet.

In this study, the behaviour of dusty nanofluid flow was studied over a stretching sheet with slip effects on the boundary. The effect of volume fraction of dust particles, volume fraction of nanoparticles, velocity slip parameter, and thermal slip parameter were analysed and discussed. The velocity and temperature profile were evaluated and deliberated in detailed. To the best of our knowledge, investigation of such boundary value is yet to be reported in the literature.

2. Methodology

2.1 Flow Analysis

In this work, a steady-state boundary layer of viscous and incompressible dusty nanofluid flow was assumed. As shown in Figure 1, the horizontal stretching surface located at $y = 0$ was driven by the region of $y > 0$. The flow was generated by the stretching of the sheet from the application of two equal and opposites forces along the x -axis. The fluid flow was assumed to be under ambient fluid velocity and the stretching velocity was in forms of $U_w(x) = ax$ with constant $a > 0$, which corresponded to the stretching rate. The velocities were varied linearly. The size of the dust particle was assumed uniform. Spherical shaped dust particles were considered. The number density of dust particles, along with the individual volume fraction of dust and nanoparticles, were considered.

The boundary layer equations that governed the present flow are listed as below

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\rho_{nf}(1 - \phi_d) \left[u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right] = (1 - \phi_d) \mu_{nf} \frac{\partial^2 u}{\partial y^2} + KN(u_p - u) \quad (2)$$

$$u_p \frac{\partial u_p}{\partial x} + v_p \frac{\partial u_p}{\partial y} = \frac{K}{m} (u - u_p) \quad (3)$$

$$\frac{\partial u_p}{\partial x} + \frac{\partial v_p}{\partial y} = 0 \quad (4)$$

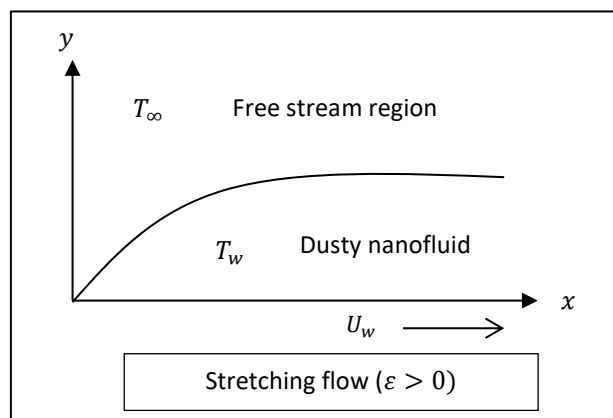


Fig. 1. Physical model and coordinate system

Corresponding to its boundary conditions,

$$\begin{aligned} u &= U_w(x) + L(\partial u / \partial y), v = 0, \text{ at } y = 0, \\ u &\rightarrow 0, u_p \rightarrow 0, v_p \rightarrow v \text{ as } y \rightarrow \infty, \end{aligned} \quad (5)$$

where (u, v) and (u_p, v_p) are the velocity components of nanofluid and dust phases along the x - and y -axes respectively, μ_{nf} is the viscosity of nanofluid, ϕ_d is the volume fraction of dust particles, L is the slip length, K is the Stokes resistance, N is the number density of dust particles, m is the mass of dust particles, and ρ_{nf} is the density of nanofluid. The nanofluid constants are adapted from Oztop and Abu-Nada [12],

$$\begin{aligned} \rho_{nf} &= (1 - \phi) \rho_f + \phi \rho_s, \\ (\rho c_p)_{nf} &= (1 - \phi) (\rho c_p)_f + \phi (\rho c_p)_s, \\ \frac{k_{nf}}{k_f} &= \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f - k_s)}, \mu_{nf} = \frac{\mu_f}{(1 - \phi)^{2.5}} \end{aligned} \quad (6)$$

where the subscript f and s refer to fluid and solid properties, respectively. Besides, ϕ is the volume fraction of nanoparticles, $(\rho c_p)_{nf}$ is the heat capacity of nanofluid, ρ_f and ρ_s are the density of the fluid and solid fractions respectively, k_{nf} is the effective thermal conductivity of nanofluid, k_f and k_s are the thermal conductivities of fluid and solid fractions respectively. According to Abu-Nada [13], the expression k_{nf} is restricted to spherical nanoparticles where it did not account for other shapes of nanoparticles.

The governing Eq. (1) to Eq. (4) were subjected to the boundary condition (5) can be simplified further by introducing similarity transformation,

$$u = cx f'(\eta), v = -v_f^2 c^{\frac{1}{2}} f(\eta), u_p = cx F'(\eta), v_p = -v_f^2 c^{\frac{1}{2}} F(\eta), \eta = v_f^2 c^{\frac{1}{2}} \quad (7)$$

where η is the similarity variable. Eq. (7) identically satisfied Eq. (1) and Eq. (4). Then, Eq. (2) and Eq. (3) becomes

$$\frac{1-\phi_d}{(1-\phi)^{2.5}} f'''' - (1-\phi_d) \left[1 - \phi + \phi \left(\frac{\rho_s}{\rho_f} \right) \right] (f'^2 - f f'') + \alpha \beta (F' - f') = 0 \quad (8)$$

$$F'^2 - F F'' - \beta (f' - F') = 0 \quad (9)$$

Subject to boundary conditions (5),

$$\begin{aligned} f'(0) &= \varepsilon + \delta f''(0), f(0) = 0, \\ f'(\eta) &= 0, F'(\eta) = 0, F(\eta) = f(\eta) \text{ as } \eta \rightarrow \infty \end{aligned} \quad (10)$$

From the equations above, the primes denoted differentiation with respect to η . Meanwhile, $\alpha = Nm/\rho_f$ is the mass concentration of dust particles and $\beta = K/cm$ is the fluid-particle interaction for the velocity. The velocity ratio parameter is $\varepsilon = a/c$ with $\varepsilon > 0$, and $\delta = L \left(\frac{b}{v} \right)^{\frac{1}{2}}$ is the velocity slip parameter.

2.2 Heat Transfer Analysis

The boundary layer heat transport of dusty nanofluid flow can be shown as,

$$(\rho c_p)_{nf} \left[u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right] = k_{nf} \frac{\partial^2 T}{\partial y^2} + \frac{N_1 (c_p)_f}{\tau_t} (T_p - T) + \frac{N_1}{\tau_v} (u_p - u)^2 \quad (11)$$

$$N_1 c_m \left[u_p \frac{\partial T_p}{\partial x} + v_p \frac{\partial T_p}{\partial y} \right] = - \frac{N_1 (c_p)_f}{\tau_t} (T_p - T) \quad (12)$$

where T and T_p are the temperature of nanofluid and dust particles, respectively, $(c_p)_f$ and c_m are the specific heat of fluid and dust particles, respectively, $N_1 = Nm$ is the density of particle phase, τ_t is the thermal equilibrium time, and τ_v is the dust particle relaxation time.

The temperature boundary conditions are listed below

$$\begin{aligned} T &= T_w + S \left(\frac{\partial T}{\partial y} \right) \text{ at } y = 0, \\ T &\rightarrow T_\infty, T_p \rightarrow T_\infty \text{ as } y \rightarrow \infty, \end{aligned} \quad (13)$$

where T_∞ is the ambient temperature, T_w is the temperature near the surface meanwhile S is a proportionality constant. To get the similarity solution, below similarity transformation will be applied to transform Eq. (11), Eq. (12) and Eq. (13)

$$\theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty}, \theta_p(\eta) = \frac{T_p-T_\infty}{T_w-T_\infty} \quad (14)$$

$$T - T_\infty = A \left(\frac{x}{\ell}\right)^2 \theta(\eta), A > 0$$

By using Eq. (14), the transformed of ordinary differential equations for Eq. (11), Eq. (12) and Eq. (13) are as below

$$\frac{1}{Pr} \left(\frac{k_{nf}}{k_f}\right) \left(\frac{1}{1-\phi+\phi\left(\frac{(\rho C_p)_s}{(\rho C_p)_f}\right)}\right) \theta'' - (2f'\theta - f\theta') + \left(\frac{1}{1-\phi+\phi\left(\frac{(\rho C_p)_s}{(\rho C_p)_f}\right)}\right) \left[\alpha\beta_T(\theta_p - \theta) + \frac{\alpha Ec}{\tau_v}(F' - f')^2\right] = 0 \quad (15)$$

$$2F'\theta_p - F\theta'_p + \gamma\beta_T(\theta_p - \theta) = 0 \quad (16)$$

along with the transformed boundary condition

$$\begin{aligned} \theta(0) &= 1 + \omega\theta'(0) \\ \theta(\eta) &= 0, \theta_p(\eta) = 0 \text{ as } \eta \rightarrow \infty \end{aligned} \quad (17)$$

where,

$$Pr = \frac{v_f(\rho C_p)_f}{k_f}, \beta_T = \frac{1}{c\tau_T}, Ec = \frac{cl^2}{A(c_p)_f}, \gamma = \frac{(c_p)_f}{c_m}, \omega = S \left(\frac{c}{v_f}\right)^{\frac{1}{2}}, \ell = v_f^{\frac{1}{2}} c^{\frac{1}{2}}$$

as $Pr, \beta_T, Ec, \gamma, \omega$ and ℓ are Prandtl number, fluid-particle interaction parameter for temperature, Eckert number, ratio of specific heat of fluid to dust particles, thermal slip parameter, and characteristic length, respectively.

3. Results and Discussion

The nonlinear ordinary differential Eq. (8), Eq. (9), Eq. (15), and Eq. (16) with respect to the boundary conditions (10) and (17) were solved numerically by using the `bvp4c` program in Matlab software. By using the numerical calculation, these values were kept as constant throughout the entire study except the different values as displayed in respective figures. The values were $\phi = \phi_d = 0.1, \delta = \beta = \varepsilon = \tau_v = 0.5, \omega = 1.5, \beta_T = \alpha = 0.2, Ec = 3$, and $\gamma = 2$. The non-dimensional governing parameters were volume fraction of dust particles (ϕ_d), volume fraction of nanoparticles (ϕ), velocity slip parameter (δ), and thermal slip parameter (ω) as presented on both velocity and temperature profiles.

In accordance to Oztop and Abu-Nada [12] and Mahanthesh *et al.*, [14], Prandtl number (Pr) of water was 6.2 and the volume fraction of nanoparticles was found in between 0 and 0.2 ($0 \leq \phi \leq 0.2$). This study also focused on three types of nanoparticles including copper (Cu), aluminium oxide (Al_2O_3) and titania (TiO_2). Table 1 shows the thermo-physical of nanoparticles and base fluid. Several values of Prandtl number in the existing literatures were compared with current results of viscous fluid. From Table 2, one can conclude that the temperature gradient ($-\theta'(0)$) in this work are relatively similar to that of reported in previous studies.

Table 1
 Thermophysical properties of nanoparticles and base fluid

Physical properties		Density, ρ ($Kg\ m^{-3}$)	Specific heat, c_p ($J\ Kg^{-1}K^{-1}$)	Thermal conductivity, k ($Wm^{-1}K^{-1}$)
Base fluid	H ₂ O	997.1	4179	0.613
Nano-particles	Cu	8933	385	400
	TiO ₂	4250	686.2	8.9538
	Al ₂ O ₃	3970	765	40

Table 2

Comparison results for the dimensionless temperature gradient $-\theta'(0)$ in the case of $\varepsilon = 1, \phi = \phi_d = \delta = \omega = \beta_T = \alpha = \beta = 0$

Pr	Grubka and Bobba [15]	Chen [16]	Abel and Mahesha [17]	Gireesha <i>et al.</i> , [18]	Present results
0.72	1.0885	1.0885	1.0885	1.0885	1.0886
1.0	1.3333	1.3333	1.3333	1.3333	1.3333
3.0	2.5097	2.5097	-	2.5097	2.5097
10.0	4.7969	4.7969	4.7969	4.7969	4.7969

Figure 2 and Figure 3 show the effect of volume fraction of nanoparticles (ϕ) towards velocity and temperature, respectively. The velocity of fluid increased for both Al₂O₃-water nanofluid and TiO₂-water nanofluid. On the contrary, the velocity of Cu-water nanofluid reduced as the ϕ value increased. Meanwhile, the temperature of all three nanofluids in fluid and dust phase increased. The presence of nanoparticles was found to enhance the heat transfer rate due to its desired size and ability. As the nanoparticles were derived from solid metal, a higher value of density and thermal conductivity were exhibited as compared to the base fluid. Besides density and thermal conductivity, the nano size of particles was found to inhibit clogging, sedimentation, and obstruction phenomena. Thus, a higher volume fraction of nanoparticles in nanofluid improved the heat transfer characteristics.

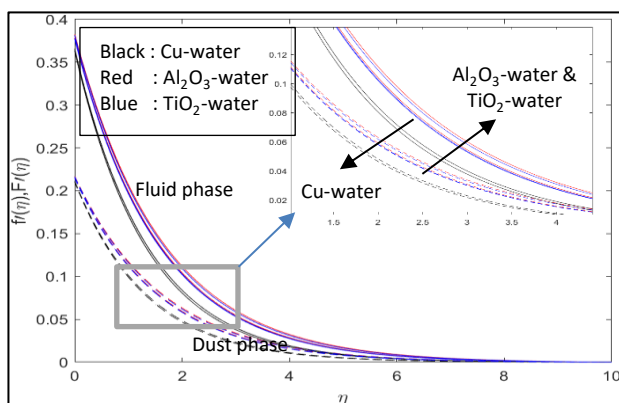


Fig. 2. Velocity profile of fluid and dust phase for different values of ϕ (volume fraction of nanoparticles) on 3 types of nanofluid for $\phi = 0, 0.1, 0.2$

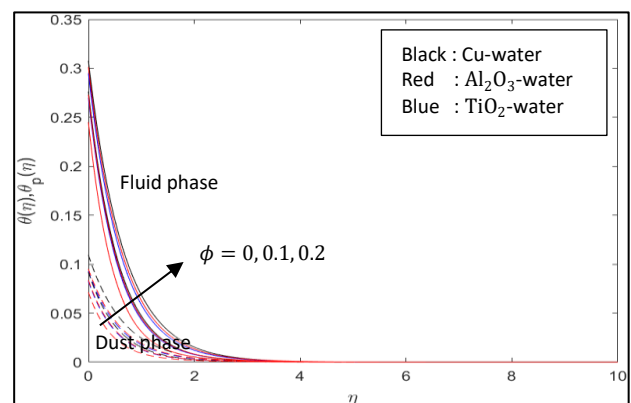


Fig. 3. Temperature profile of fluid and dust phase for different values of ϕ (volume fraction of nanoparticles) on 3 types of nanofluid

Figure 4 shows the velocity profile for the volume fraction of dust particles parameter (ϕ_d) on dusty nanofluid with Cu-water, Al₂O₃-water and TiO₂-water. From Figure 4, the velocity was found to be reduced for both fluid and dust phases. This is because the mass concentration of dust particles reduced the pressure inside the boundary layer. Besides that, the presence of dust particles increase

the shear stress near the wall hence slow down the velocity of fluid. Meanwhile from Figure 5, one can notice that the presence of dust particles could improve thermal conductivity of fluid, evidenced from the increase of ϕ_d .

From the temperature profile, both parameters ϕ and ϕ_d improved the thermal boundary layer. However, there is small increment difference between the parameters can be seen in Figure 3 and Figure 5. This is because the presence of nanoparticles increased the thermal conductivity of fluid due to good interaction with the base fluid. Meanwhile, the dust particles in micro/millimeter size need more interacting mean time as compared to fluid and nanoparticles. This proved that the nanoparticles have better thermal conductivity than dust particles.

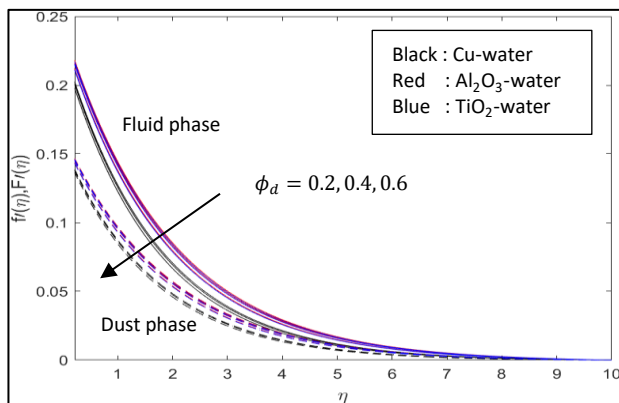


Fig. 4. Velocity profile of fluid and dust phase for different values of ϕ_d (volume fraction of dust particles) on 3 types of nanofluid

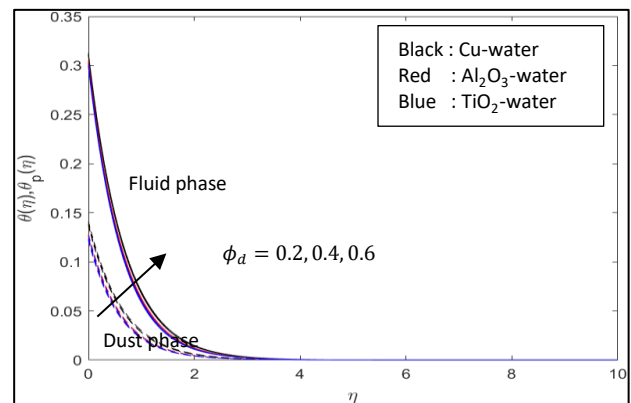


Fig. 5. Temperature profile of fluid and dust phase for different values of ϕ_d (volume fraction of dust particles) on 3 types of nanofluid

Figure 6 shows the effects of velocity slip parameter (δ) on the velocity of fluid and dust phases. From Figure 6, the velocity of both fluid and dust phases was initially in a decreasing trend. As it approached the boundary layer, the velocity of both phases increased. The same trend can be observed in all three nanofluids. Thus, the thickness of the momentum boundary layer became thinner by δ . When the slip occurred, the velocity flow near the sheet was no longer equal to the stretching velocity at the sheet. Hence, the pulling of the stretching sheet partly transmitted to the fluid and caused the fluid velocity declined [9].

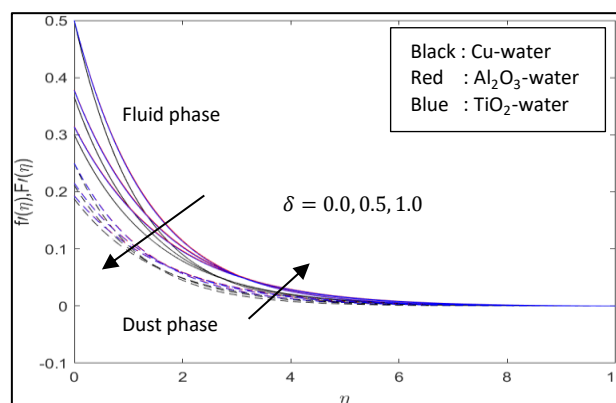


Fig. 6. Velocity profile of fluid and dust phase for different values of δ (velocity slip) on 3 types of nanofluid

From Figure 7, the δ parameter was found to be increased the temperature as the thickness of the thermal boundary layer became thicker. Hence, one can conclude that the δ parameter improved the heat transfer rate. Figure 8 displays the temperature of the fluid by the parameter of thermal slip (ω) and it showed a reduction in the thermal conductivity.

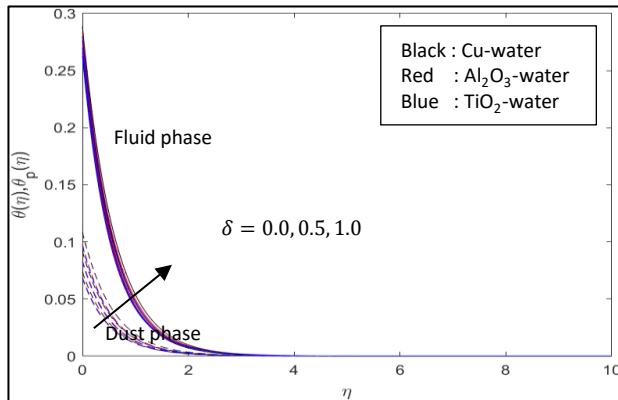


Fig. 7. Temperature profile of fluid and dust phase for different values of δ (velocity slip) on 3 types of nanofluid

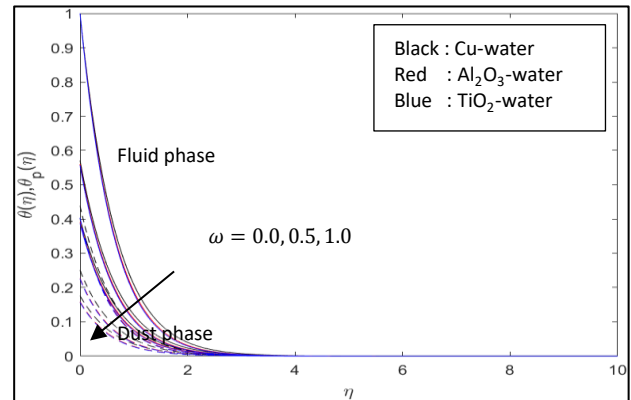


Fig. 8. Temperature profile of fluid and dust phase for different values of ω (thermal slip) on 3 types of nanofluid

4. Conclusions

The current study investigated the boundary layer flow of dust and three type of nanoparticles, namely copper (Cu), aluminium oxide (Al_2O_3) and titania (TiO_2). Besides, the velocity slip and thermal slip effects towards the flow were studied as well. To analyse the momentum and heat transfer characteristics, the parameters have been discussed through velocity and temperature profiles.

The present study concluded as follow

- i. Nanoparticles have better thermal conductivity than dust particles.
- ii. Both ϕ_d and δ parameter have positive effects on the momentum boundary layer.
- iii. ϕ and δ increased the thickness of the thermal boundary layer, but ϕ_d and ω reduced the thickness of the thermal boundary layer.
- iv. The velocity of fluid had significant effect towards both Al_2O_3 and TiO_2 by ϕ .

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