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The Effects of Soret and Dufour on Mixed Convection Boundary Layer Flow of a Porous Media along a Permeable Surface filled with a Nanofluid and Radiation

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ABSTRACT

An investigation of mixed convection flow in a boundary layer saturated by a nanofluid and lodged in a porous medium with the existence of Soret and Dufour numbers, suction and thermal radiation is numerically studied. By employed a similarity transformation technique, the governing set of ordinary differential equations has been conducted from a non-linear partial differential equations system, where we apply a Runge-Kutta-Fehlberg method in order to numerically solved the final equations for a group of variety metallic and nonmetallic nanoparticles in a water base fluid consisting of copper (Cu), aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2). Numerous values of presented parameters such as thermal radiation coefficient, suction parameters, as well as Dufour and Soret numbers are graphically presented and discussed on the dimensionless velocity, temperature and concentration distributions profiles.

Keywords:
Mixed convection, porous media, nanofluid, suction, radiation, Soret number, Dufour number

1. Introduction

There has been an increasing interest in analyzing the transfer of mass and heat buoyancy-induced flow lodged in a porous medium from variety of geometries due to its important function in applications of industries, geophysical and engineering such as thermal insulation, geothermal reservoirs, oil recovery enhancement, reactors of nuclear cooling system, just to name a few. In addition, an innovative method in improving heat transfer rate known as nanofluids which is first introduced by Choi [1] is extensively used in these recent years as its ability in enhancing the performance of heat transfer in liquids. Nanofluids can elaborated as a capability of a fluid in suspending particles of nanoscale with an average size below 100nm in the base fluids such as ethylene glycol, water or engine oil. Generally, the nanoparticles are established from materials that are chemically stable, such as copper, oxides, carbides, nitrides, and similar things. The materials in

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nanofluids which are in nanometer size possess unique properties of physical and chemical behaviors. They can flow through micro-channels smoothly without clogging because of their sufficiently small to similar behaves as liquid molecules. This interesting fact of nanofluids has attracted much research in this area of heat transfer investigations. Choi [1] proved that by including a small amount of nanoparticles, the fluid thermal conductivity can be doubled. Hence, the effectiveness of nanofluids thermal conductivity is likely to happen in enhancing the rate of heat transfer compared to the conventional heat transfer liquids, and thus a number of authors such as Eastman *et al.,* [2], Ahmad and Pop [3], Bachok *et al*., [4] and Arifin *et al*., [5] had successfully analyzed the effectiveness of nanofluids in their studies.

Simultaneously, radiation of thermal can be described as electromagnetic waves in all matter emitted by the charged particles thermal motion, and it has a temperature more than absolute zero. Since radiation is one of the three fundamental methods of heat transfer, thus a continuous progress on the interpretation of flow with radiative heat transfer processing in engineering and industry sectors is highly considered. The reason behind this consideration is because any flow processing that requires high temperature are highly considered the thermal radiation effects at most of the time, because the radiation can significantly affected the participating heat transmit rate of fluids, in addition with the distribution of temperature in the boundary layer flow when temperatures are high. Hence, compared to other well-known methods, the thermal radiation concept is still in a high level of interest as it may achieve a significant control on cooling rate and also providing better results in such a way as to monitor the solidification at a slower rate. Nevertheless, a significant research in the radiation of thermal sector have been putting forward recently, and due to this interesting fact, the radiation effects over a permeable plate on the flow of boundary layer filled with a nanofluid had studied by Motsumi and Makinde [6] and other researches such as reported by Makinde [7], Sheikholeslami *et al*., [8] and Khan *et al*., [9].

Soret effect, or generally known as thermal diffusion, equals to differentiation of species happening in a homogenous mixture of initial transferred to a thermal gradient. The diffusion-thermo or widely known as Dufour effect corresponds to an energy flux generated in mixture of a binary flux by a gradient of concentration. The effects of Dufour and Soret can significantly affect the higher gradients of concentration and temperature on the fluids and these are considerably important in fluid mechanics studies. Anghel *et al*., [10] proved that these two parameters are consequently affecting the flow field in their study of Soret and Dufour influences over a vertical surface on boundary layer of free convection lodged in a porous medium. Later, Postelnicu [11] analyzed the simultaneously transfer of mass and heat on free convection lodged in a porous medium filled with electrically-conductor fluid with the existence of Soret and Dufour numbers. In addition, the study of Soret and Dufour numbers on mixed convection were also successfully reported by Ganapathirao and Ravindran [12], Raju *et al.,* [13] and Niranjan *et al.,* [14], recently.

In this present study, here we explore, and study the influences of Soret, Dufour numbers, suction and radiation of thermal on mixed convection flow lodged in a porous medium saturated by a nanofluid. Copper (Cu), alumina (Al_2O_3) and titania (TiO_2) are among the nanoparticles reviewed in this study with the base fluid as well. By performing a suitable transformation of similarity, the finalize system of ordinary differential equations has been transformed from a set of partial differential equations. Hence, the method of Runge-Kutta-Fehlberg is applied and performed in order to numerically solve the corresponding final equations. Our respected numerical results are then compared with the previous results performed by Arifin *et al*., [5] and Rosca *et al*., [15], where the results are also well presented in the form of tables and figures.

2. Mathematical Analysis

Consider a two dimensional, steady surface of mixed convection flow over a permeable surface which is lodged in a porous medium and saturated with a nanofluid with the reaction of thermal radiation, Soret and Dufour numbers, as presented in Figure 1. The approximation of Boussinesq is employed, and the equilibrium of local thermal as well as the homogeneity in the porous medium is considered. The governing equations outlining the continuity, momentum, energy and concentration are as follows

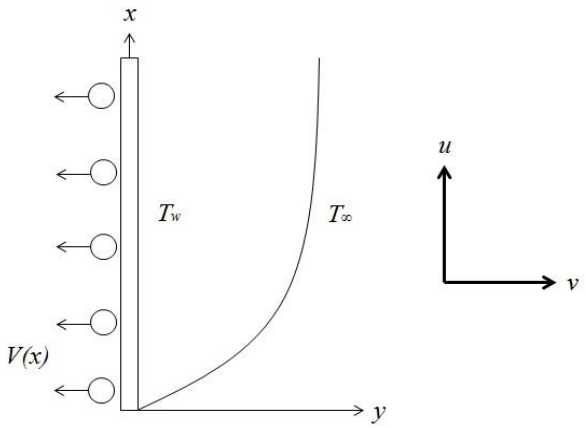


Fig. 1. Schematic of boundary layer flow and over a permeable surface and coordinate system

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

$$\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}+\frac{\rho_{nf.\infty}}{\mu_{nf}}K^{*}\left[\frac{\partial\left(u^{2}\right)}{\partial y}-\frac{\partial\left(v^{2}\right)}{\partial x}\right]=-\frac{g\rho_{nf.\infty}K\beta_{nf}}{\mu_{nf}}\frac{\partial T}{\partial x}, \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^{2}T}{\partial y^{2}}+\frac{D_{m}k_{T}}{C_{s}C_{p}}\frac{\partial^{2}C}{\partial y^{2}}-\frac{1}{\left(\rho C_{p}\right)_{nf}}\left(\frac{\partial q_{r}}{\partial y}\right), \quad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_{m}\frac{\partial^{2}C}{\partial y^{2}}+\frac{D_{m}k_{T}}{T_{m}}\frac{\partial^{2}T}{\partial y^{2}}. \quad (4)$$

Here the elements of the nanofluid velocity along the *x*- and *y*- axes are the *u* and *v*, ρ is the fluid density, μ is dynamic viscosity, α is thermal diffusivity, β is the thermal expansion coefficient, *g* is the gravity acceleration, *K* is the Darcy permeability, *K** is the inertial coefficient of the Ergun equation, *T* is the nanofluid temperature, D_m is the coefficient of mass diffusivity, k_T is the ratio of thermal diffusion, *C* is the concentration, q_r is the heat flux of radiation, C_s is the susceptibility of concentration, C_p is the constant temperature at a specific heat, T_m is the mean fluid temperature and the subscript of *nf* represents the term of nanofluid. We use the approximation of Rosseland for thermal radiation rate, which, the heat flux of radiative can be simplified as $q_r = -\frac{4\sigma}{3K^*}\frac{\partial T^4}{\partial y}$, where σ is the constant of Stefan-Boltzmann number. The differences of temperature in the flow system are significantly small where T^4 can be described as a linear function of temperature *T* by considering a truncated Taylor series about the temperature of free stream T_∞, and thus we get $T^4 \approx 4T_\infty^3 T - 3T_\infty^4$. By considering the Rosseland approximation, we can simplify Eq. 3 to

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\frac{\partial^2 T}{\partial y^2} + \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} + \frac{16\sigma T_\infty^3}{3K^*\left(\rho C_p\right)_{nf}}\frac{\partial^2 T}{\partial y^2}. \tag{5}$$

In this present problem, the respective boundary conditions are as follows

$$\begin{aligned} &u = 0, \ \ v = \pm V(x), \ \ T = T_w, \ \ C = C_w \ \text{ at } \ y = 0, \\ &u \to U_\infty, \ \ T \to T_\infty, \ \ C \to C_\infty \ \text{ as } \ y \to \infty. \end{aligned} \tag{6}$$

We will now designate $\rho_{nf,\infty}$ by ρ_{nf} for the simplicity purposes. Moreover, the nanofluid physical characteristics are given by Rosca *et al.,* [15]

$$\begin{aligned} &\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s, \ \ \alpha_{nf} = \frac{k_{nf}}{\left(\rho C_p\right)_{nf}}, \ \ \mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}}, \\ &\left(\rho C_p\right)_{nf} = (1-\varphi)\left(\rho C_p\right)_f + \varphi\left(\rho C_p\right)_s, \ \ \frac{k_{nf}}{k_f} = \frac{\left(k_s + 2k_f\right) - 2\varphi\left(k_f - k_s\right)}{\left(k_s + 2k_f\right) + \varphi\left(k_f - k_s\right)}, \end{aligned} \tag{7}$$

where k is the conductivity of thermal and φ is the volume fraction of nanoparticle parameter. In addition, the subscripts of *s* and *f* indicate the terms of solid and fluid, as well. Next, we defined the variables of dimensionless as follows

$$\begin{aligned} &\psi = \left(\alpha_f U_\infty x\right)^{1/2} f(\eta), \ \ \ T = T_\infty + \left(T_w - T_\infty\right)\theta(\eta), \ \ \ C = C_\infty + \left(C_w - C_\infty\right)\phi(\eta), \\ &\eta = \left(\frac{U_\infty x}{\alpha_f}\right)^{1/2}\left(\frac{y}{x}\right), \end{aligned} \tag{8}$$

where η is variable of similarity. Hence, the following equations are finally obtained once we substitute Eq. 8 into Eqs. 2, 4 and 5

$$f'' + (1-\varphi)^{2.5} G\left(1 - \varphi + \varphi\frac{\rho_s}{\rho_f}\right)\left(f'\right)^2 - \frac{1}{2}(1-\varphi)^{2.5}\left(1 - \varphi + \varphi\frac{\rho_s\beta_s}{\rho_f\beta_f}\right)(\eta\theta' - \theta)\lambda = 0, \tag{9}$$

$$\frac{k_{nf}/k_f}{(1-\varphi)\left(\rho C_p\right)_f + \varphi\left(\rho C_p\right)_s}\left(1 + \frac{4}{3}Rd\right)\theta'' - \frac{1}{2}\left(f'\theta - f\theta'\right) + Du\ \phi'' = 0, \tag{10}$$

$$Le^{-1}\phi'' - \frac{1}{2}\left(f'\phi - f\phi' \right) + Sr\ \theta'' = 0, \tag{11}$$

where prime corresponds to the differentiation with respect to η, *G* is the inertial or non-Darcy parameter, λ is the parameter of constant mixed convection, Pe_x is the local Péclet numbet, Ra_x is the local Rayleigh number for the porous media, *Rd* is the radiation parameter, *Du, Le* and *Sr* are the Dufour, Lewis and Soret numbers, respectively, which described as

$$\begin{aligned} &G = \frac{K^* U_\infty}{\nu_f},\ \lambda = \frac{Ra_x}{Pe_x^{3/2}},\ Ra_x = \frac{gK\beta_f Ax^{1/2}}{\alpha_f \nu_f},\ Pe_x = \frac{U_\infty x}{\alpha_f},\ Rd = \frac{\kappa K^*}{4\sigma T_\infty^3}, \\ &Du = \frac{D_m k_T \left(C_w - C_\infty\right)}{\alpha_f C_s C_p \left(T_w - T_\infty\right)},\ Le = \frac{\alpha_f}{D_m},\ Sr = \frac{D_m k_T \left(T_w - T_\infty\right)}{T_m \alpha_f \left(C_w - C_\infty\right)}. \end{aligned} \tag{12}$$

The boundary conditions in Eq. 7 now become

$$\begin{aligned} &f(0) = S,\quad \theta(0) = 1,\quad \phi(0) = 1 \ \text{at} \ \eta = 0, \\ &f'(\eta) \to 1,\quad \theta(\eta) \to 0,\quad \phi(\eta) \to 0 \ \text{as} \ \eta \to \infty, \end{aligned} \tag{13}$$

where $S = -v_w / \left(U_\infty \alpha_f\right)^{0.5}$ representing the suction rate at the surface where $S > 0$.

In addition, the practical interest of physical quantities are the coefficient of skin friction C_f, the number of local Nusselt Nu_x, and the number of local Sherwood Sh_x, which are interpreted as follows

$$C_f = \frac{\tau_w}{\rho_f U_\infty},\ Nu_x = \frac{xq_w}{k_f\left(T_w - T_\infty\right)},\ Sh_x = \frac{xq_m}{D_m\left(C_w - C_\infty\right)}. \tag{14}$$

Here τ_w is the shear stress at the plate surface or the coefficient of skin friction, q_w is the heat transfer from the plate and q_m is the mass transfer from the plate, which can be interpreted by

$$C_f = \frac{\tau_w}{\rho_f U_\infty},\ Nu_x = \frac{xq_w}{k_f\left(T_w - T_\infty\right)},\ Sh_x = \frac{xq_m}{D_m\left(C_w - C_\infty\right)}. \tag{15}$$

By considering the non-dimensionless variables in Eq. 8 into Eqs. 14 and 15, we finally obtained

$$\mathrm{Re}_x^{1/2} C_f = \frac{1}{(1-\varphi)^{2.5}} f''(0),\quad \mathrm{Re}_x^{1/2} Nu_x = -\left(\frac{k_{nf}}{k_f} + \frac{4}{3}Rd\right)\theta'(0),\quad \mathrm{Re}_x^{1/2} Sh_x = -\phi'(0). \tag{16}$$

3. Results and Discussions

In this section, we examine a couple systems of water as the working fluids and a group of nanoparticles consisting of copper (Cu), aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2), while the physical features of these nanofluids are stated in Table 1. By using a Runge-Kutta-Fehlberg method, Eqs. 9, 10 and 11 subjected to the boundary conditions in Eq. 13 have been numerically solved. We have considered the range of radiation, suction parameters and Soret and Dufour numbers because these parameters are the key to analyze the implications on the characteristics of heat transfer and flow fields. Before we proceed to our numerical results, we have to verify our numerical method by comparing our present $f''(0)$ results with those reported by Arifin *et al.*, [5] and Rosca *et al.*, [15] for regular fluid ($\varphi = 0.0$) as listed in Table 2. We can clearly confirmed that the present results are accurate by a good agreement as shown in the comparison list in Table 2, and hence, we are now confident to proceed into our respective numerical results.

Table 1
Base fluid and selected nanoparticle physical properties

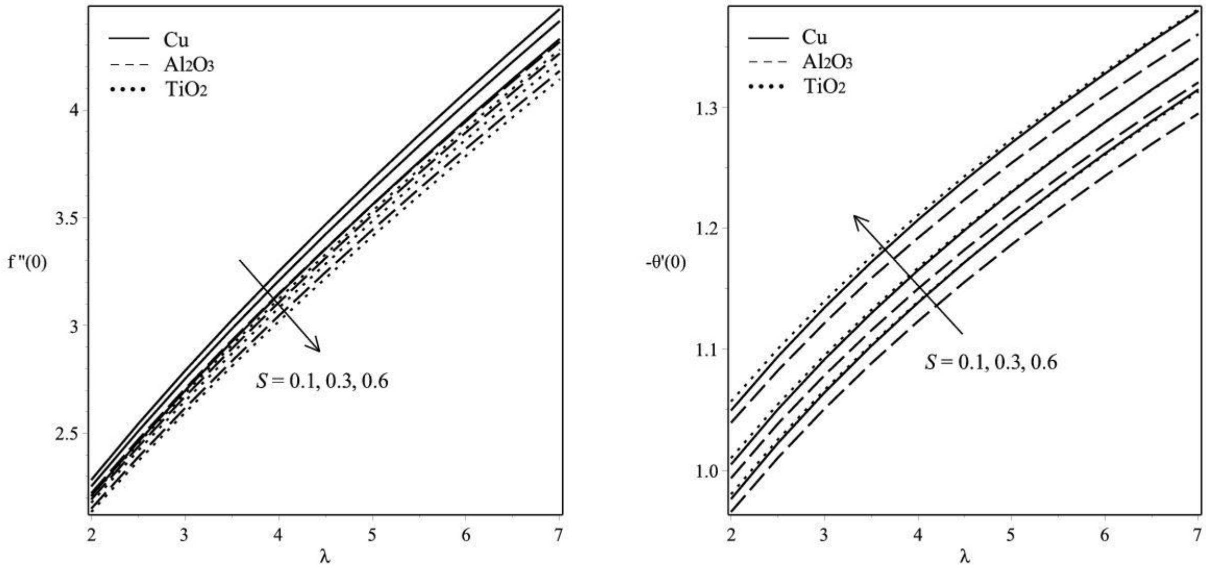
Property	Cu	Al_2O_3	TiO_2	Water
$C_p\,(J/kg\ \mathrm{K})$	385	765	686.2	4179
$k\,(W/m\ \mathrm{K})$	400	40	8.9538	0.613
$\rho\,(kg/m^3)$	8933	3970	4250	997.1
$\alpha \times 10^7\,(m^2/s)$	1163.1	131.7	30.7	1.47
$\beta \times 10^{-5}\,(1/K)$	1.67	0.85	0.9	21

Table 2
Comparison of $f''(0)$ and $-\theta'(0)$ for various values of λ when $\varphi = S = Rd = Sr = Du = Le = 0.0$ in the case of Cu-water

λ	Present		Rosca *et al.*, [15]		Arifin *et al.*, [5]	
	$f''(0)$	$-\theta'(0)$	$f''(0)$	$-\theta'(0)$	$f''(0)$	$-\theta'(0)$
0.6	1.474115	1.028150	1.4741	1.0281	1.4741	1.0282
2.0	2.348029	1.249548	2.3480	1.2495	2.3471	1.2493
5.0	3.799588	1.550303	3.7995	1.5503	3.7992	1.5502
8.0	4.998608	1.760941	4.9986	1.7609	4.9984	1.7609
15.0	7.344659	2.113750	7.3446	2.1137	7.3422	2.1133

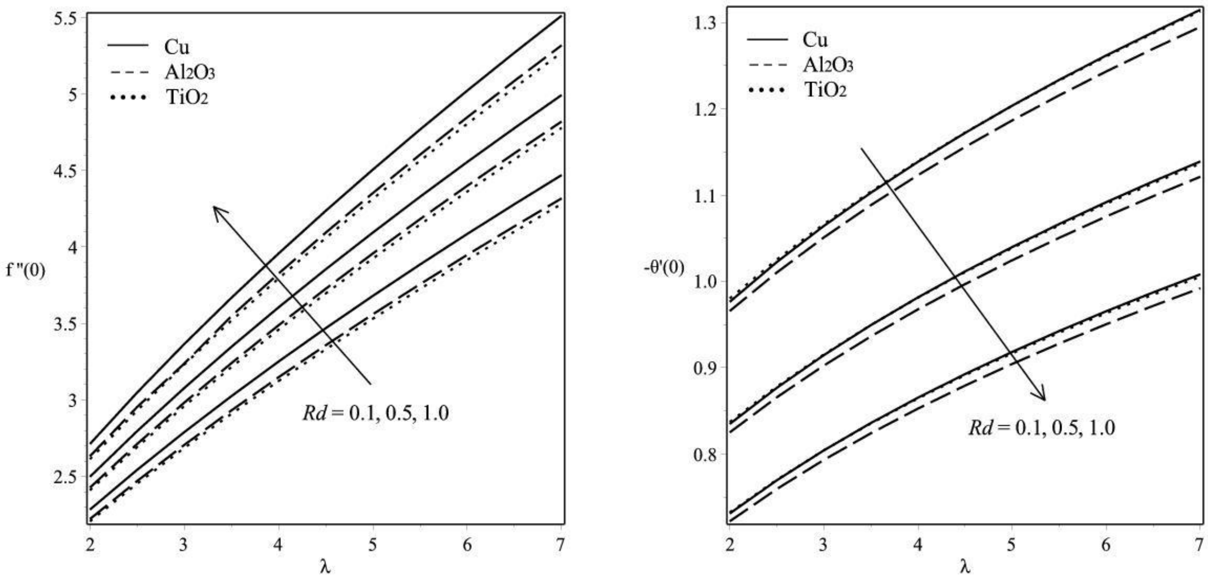
Figures 2(a) and 2(b) are prepared to illustrate the skin friction coefficient $f''(0)$, and thermal gradient $-\theta'(0)$, with suction parameter *S* against mixed convection parameter λ, for three kinds of nanoparticles, respectively, while Figures 3(a) and 3(b) represent the numbers of $f''(0)$ and $-\theta'(0)$ for selected numbers of radiation parameter *Rd* against mixed convection parameter λ, by considering three types of nanoparticles. From Figures 2(a) and 2(b), we observed a decreasing pattern of skin friction coefficient while thermal gradient is increasing alongside the growing value of *S*, and on the other hand, the enhancement value of *Rd* parameter leads to a conversely behaviour than *S* parameter. The reason behind these increasing/decreasing patterns is because the force of buoyancy behaves like a pressure gradient which causes the fluid to decelerate or accelerate within the boundary layer.

We then pay attention on how suction parameter, *S*, affects velocity profiles $f'(\eta)$, temperature profiles $\theta(\eta)$ and concentration profiles $\phi(\eta)$ for Cu-nanoparticles as shown in Figures 4(a), 4(b) and 4(c), respectively. From these three figures, we noticed that an expansion in wall fluid suction results in reduction of velocity profiles, but conversely increasing in temperature and concentration profiles. The main reason of this behaviour is that the flow in velocity profiles of boundary layer is reducing by suction effect, while the temperature and concentration profiles are taken up by suction, and thus sparks an enhancing energy on the same matter.



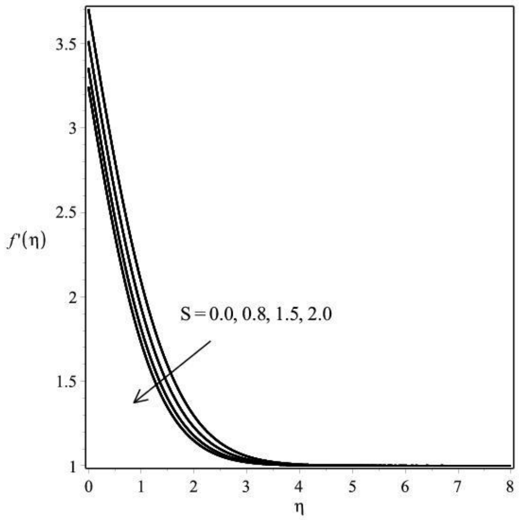
(a) Skin friction coefficient $f''(0)$ (b) Thermal gradient $-\theta'(0)$

Fig. 2. $f''(0)$ and $-\theta'(0)$ for various values of *S* against λ when $\varphi = G = Rd = Du = 0.1$, $Sr = 0.4$ and $Le = 1.0$ for three types of nanoparticles

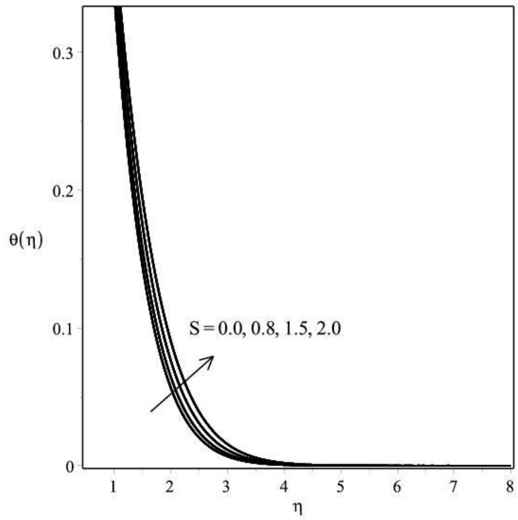


(a) Skin friction coefficient $f''(0)$ (b) Thermal gradient $-\theta'(0)$

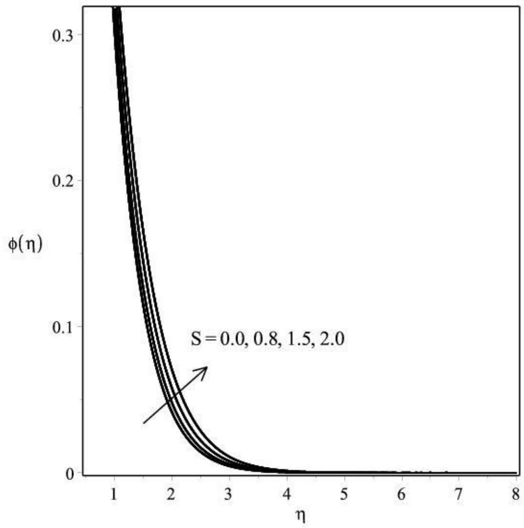
Fig. 3. $f''(0)$ and $-\theta'(0)$ for various values of *Rd* against λ when $\varphi = G = S = Du = 0.1$, $Sr = 0.4$ and $Le = 1.0$ for three types of nanoparticles



(a) Velocity profiles $f'(\eta)$



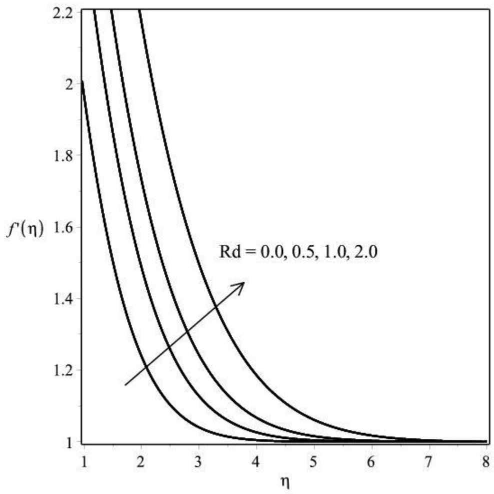
(b) Temperature profiles $\theta(\eta)$



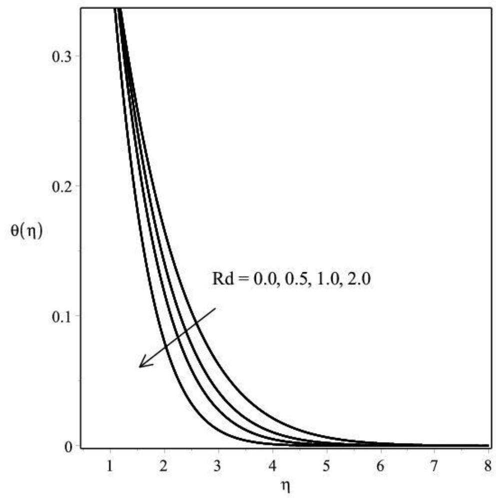
(c) Concentration profiles $\phi(\eta)$

Fig. 4. Profiles for several values of *S* when $\varphi = G = Rd = Du = 0.1$, $Sr = 0.4$, $\lambda = 5.0$ and $Le = 1.0$ for Cu-water

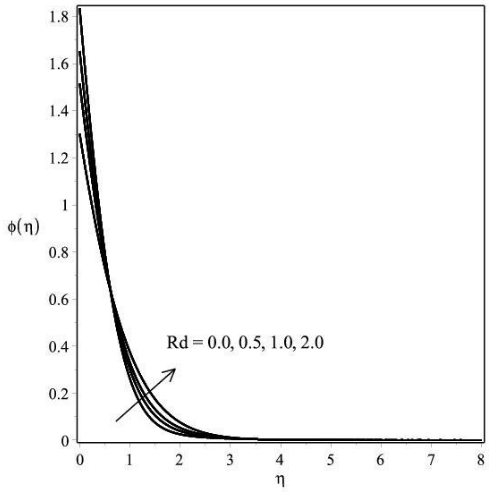
Next, Figures 5(a), 5(b) and 5(c) represent the radiation parameter *Rd*, effects on velocity, temperature and concentration profiles, respectively, when other parameters are kept fixed in the Cu-nanoparticles case. We can observed that the velocity and concentration profiles enhance while temperature layer thickness decreases when *Rd* increases from 0.0 to 2.0 as can be seen in these three figures. It is worth to know that the heat transfer rate can be elevated by the radiation effect, thus, in this study, the radiation effect should be at its maximum value (in this case is $Rd = 2.0$) in order to ease the cooling process of velocity and concentration profiles, or else the process of heat transfer might become slower with a lower value of radiation. On the contrary, the minimum value of radiation parameter should be considered in the case of temperature profiles as in Figure 5(b) since we noticed that the increasing value of radiation will reduce the boundary layer of temperature thickness.



(a) Velocity profiles $f'(\eta)$



(b) Temperature profiles $\theta(\eta)$



(c) Concentration profiles $\phi(\eta)$

Fig. 5. Profiles for several values of *Rd* when $\varphi = G = S = Du = 0.1$, $Sr = 0.4$, $\lambda = 5.0$ and $Le = 1.0$ for Cu-water

In addition, Figures 6(a), 6(b) and 6(c) illustrate temperature profiles $\theta(\eta)$, with the effects of Dufour numbers *Du*, for three types of nanoparticles, respectively, and in a contrary, Figures 7(a), 7(b) and 7(c) display the concentration profiles $\phi(\eta)$, for selected numbers of Soret effects *Sr*, in the case of copper (Cu), alumina (Al_2O_3) and titania (TiO_2) while other parameters are remain unchanged. We now discovered that the growing values of *Du* and *Sr* will lead the temperature and concentration layer thicknesses to decrease. In these cases, velocity profiles are not included in this matter since the act of *Du* and *Sr* is to affect the temperature and solute concentration thicknesses of boundary layer.

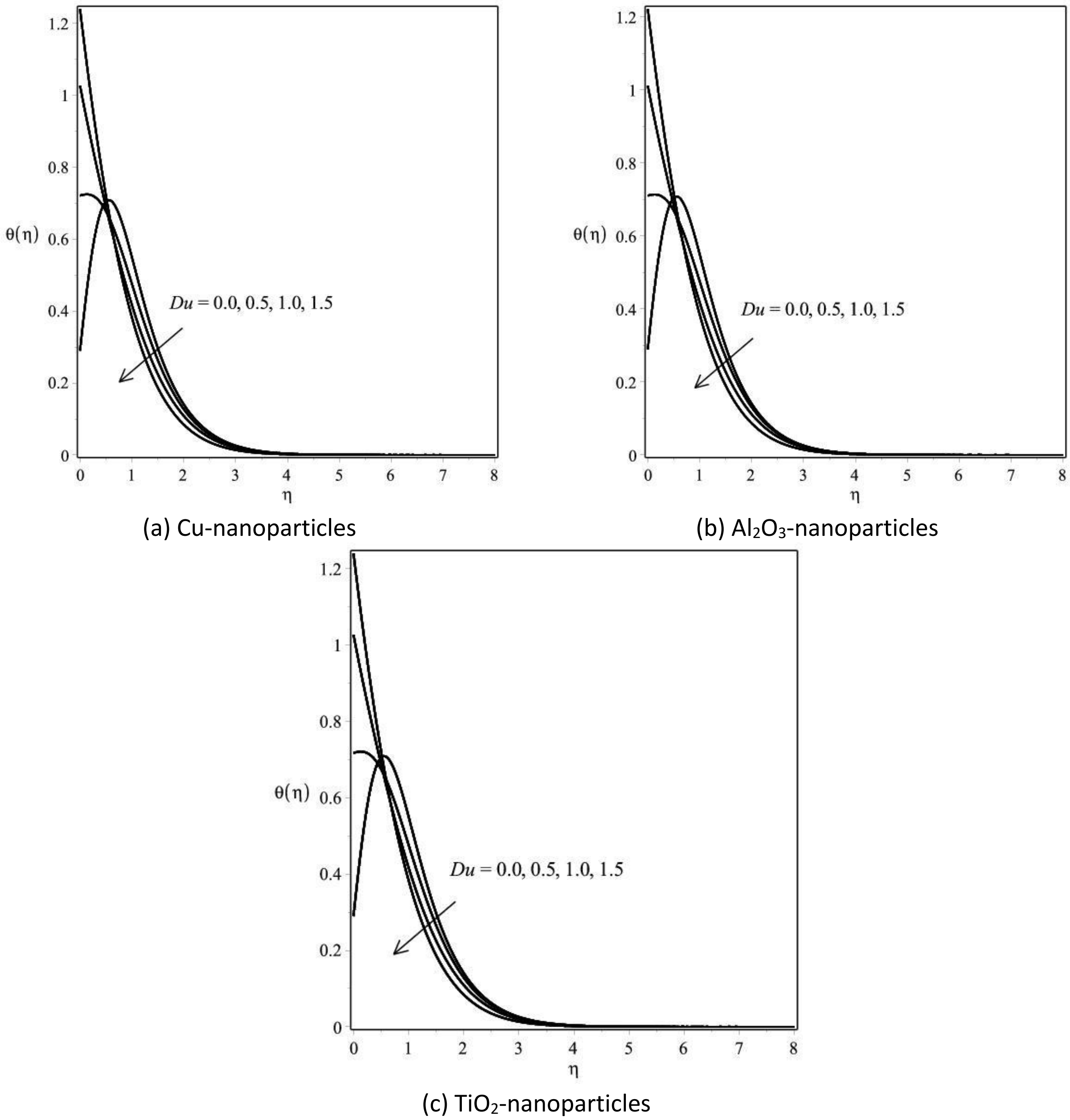
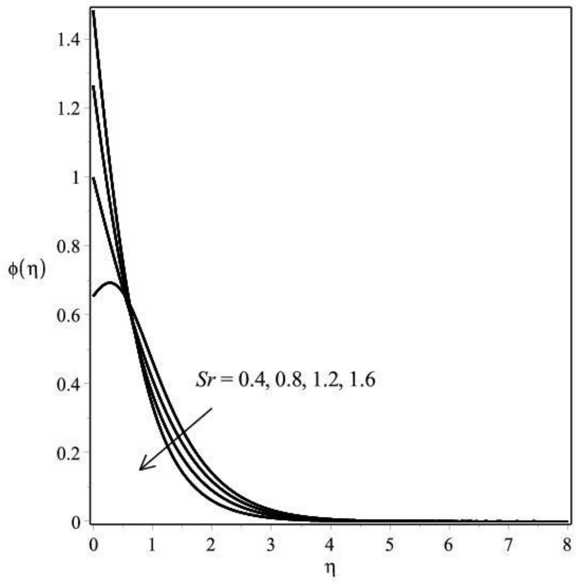
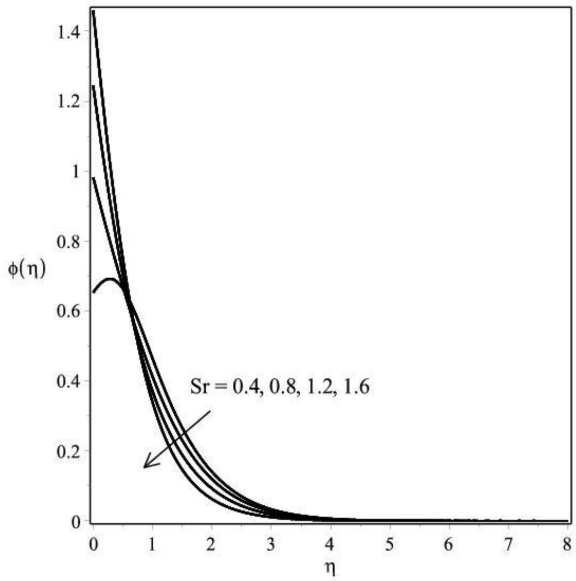


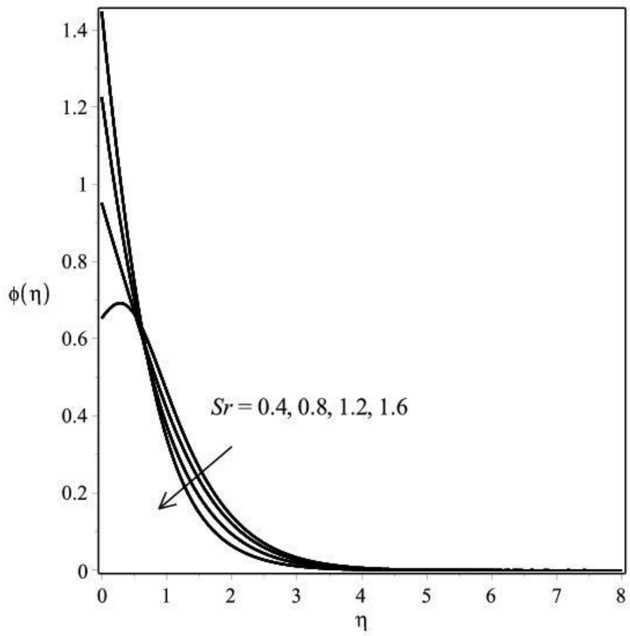
Fig. 6. Temperature profiles $\theta(\eta)$ for several values of *Du* when $\varphi = G = S = Rd = 0.1$, $Sr = 0.4$, $\lambda = 5.0$ and $Le = 1.0$ for Cu-water



(a) Cu-nanoparticles



(b) Al_2O_3-nanoparticles



(c) TiO_2-nanoparticles

Fig. 7. Concentration profiles $\phi(\eta)$ for several values of *Sr* when $\varphi = G = S = Rd = 0.1$, $Du = 0.5$, $\lambda = 5.0$ and $Le = 1.0$ for Cu-water

4. Conclusions

The boundary layer flow of mixed convection lodged in a porous medium with the influences of Dufour and Soret numbers, as well as thermal radiation effect, filled with a nanofluid over a permeable surface is numerically studied. Copper (Cu), aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2) are among of nanoparticles that is considered in our system together with water-based fluid, where we solved the similarity equations numerically by performing the method of Runge-Kutta-Fehlberg. The flow characteristics and heat transfer with the involving of governing parameters, such as Dufour number *Du,* Soret number *Sr,* radiation parameter *Rd*, as well as suction parameter *S*, are analyzed and explored in details. The addition of these parameters and corresponding nanoparticles used in this investigation are found to improve or reduce the boundary layer thicknesses, and therefore significantly affected the heat transfer rate from the surface. Hence, we also can finally conclude that the particular category of nanofluid is a main element in enhancing the heat transfer rate.

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