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Research Article

Radiation Effects on MHD Stagnation-Point Flow in a Nanofluid

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Abstract: In this study, the two-dimensional Magnetohydrodynamic (MHD) boundary layer of stagnation-point flow in a nanofluid in the presence of thermal radiation is investigated. Using a similarity transform, the Navier-Stokes equations are reduced to a set of nonlinear ordinary differential equations. The similarity equations are solved numerically for three types of nanoparticles, namely copper (Cu), alumina (Al_2O_3) and titania (TiO_2) in water as the base fluid. The skin-friction coefficient and Nusselt number as well as the velocity and temperature profiles for some values of the governing parameters are presented graphically and discussed. Effects of the nanoparticle volume fraction on the flow and heat transfer characteristics are thoroughly examined.

Keywords: MHD, nanofluid nanoparticle volume fraction, stagnation-point flow, thermal radiation

INTRODUCTION

The two-dimensional flow of a fluid near a stagnation-point is a classical problem in fluid mechanics. The steady flow in the neighbourhood of a stagnation-point was first studied by Hiemenz (1911), who used a similarity transformation to reduce the Navier-Stokes equations to nonlinear ordinary differential equations. This problem has been extended by Homann (1936) to the case of axisymmetric stagnation-point flow. Later the problem of stagnation-point flow either in the two or three-dimensional cases has been extended in numerous ways to include various physical effects. The results of these studies are of great technical importance, for example in the prediction of skin friction as well as heat/mass transfer near stagnation regions of bodies in high speed flows and also in the design of thrust bearings and radial diffusers, drag reduction, transpiration cooling and thermal oil recovery. Mahapatra and Gupta (2002) and Nazar *et al*. (2004) studied the heat transfer in the steady two-dimensional stagnation-point flow of a viscous fluid by taking into account different aspects.

The effect of thermal radiation on flow and heat transfer processes is of major importance in the design of many advanced energy conversion systems operating at high temperature. Thermal radiation within such systems occur because of the emission by the hot walls and working fluid. Many researchers have investigated the radiaion effects in their studies, such as Pop *et al*. (2004), Zhu *et al*. (2011) and Bhattacharyya and Layek (2011).

Magnetohydrodynamic (MHD) boundary layer flow is of considerable interest in the technical field due to its frequent occurrence in industrial technology and geothermal application, high-temperature plasmas applicable to nuclear fusion energy conversion, liquid metal fluids and (MHD) power generation systems. Sparrow *et al*. (1961) studied the effect of magnetic field on the natural convection heat transfer. Patel and Timol (2011) studied two-dimensional MHD stagnation-point flow of a power law fluid over a stretching surface.

Low thermal conductivity of conventional fluids such as water and oil in convection heat transfer is the main problem to increase the heat transfer rate in many engineering equipments. To overcome this problem, researchers have performed considerable efforts to increase conductivity of working fluid. An innovative way to increase conductivity coefficient of the fluid is to suspend solid nanoparticles in it and make a mixture called nanofluid, having larger thermal conductivity coefficient than that of the base fluid. This higher thermal conductivity enhances the rate of heat transfer in industrial applications. Many researchers have investigated different aspects of nanofluids. Thermophysical properties of nanofluids such as thermal conductivity, thermal diffusivity and viscosity of nanofluids have been studied by Kang *et al*. (2006), Velagapudi *et al*. (2008), Turgut (2009), Rudyak *et al*. (2010), Murugesan and Sivan (2010) and Nayak *et al*. (2010). Bachok *et al*. (2010) studied the flow and heat transfer in an incompressible viscous fluid near the three-dimensional stagnation point of a body that is

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placed in a water-based nanofluid containing different types of nanoparticles: copper, alumina and titania. Bachok *et al*. (2011) also investigated two-dimensional stagnation-point flow of a nanofluid over a stretching/shrinking sheet. They drived the highest values of the skin friction coefficient and the local Nusselt number were obtained for the copper nanoparticles compared with the others. Two-dimensional boundary layer flow near the stagnation-point on a permeable stretching/shrinking sheet in a water-based nanofluid containing two types of nanoparticles: copper and silver, was studied by Arifin *et al*. (2011). Ahmad and Pop (2010) examined the mixed convection boundary layer flow past a vertical flat plate embedded in a porous medium filled with nanofluids. Nield and Kuznetsov (2009) conducted the classical problems of natural convective boundary layer flow in a porous medium saturated by a nanofluid, known as the Cheng-Minkowycz's problem. Kuznetsov and Nield (2010) investigated natural convective boundary layer flow of a viscous and incompressible fluid past a vertical semi-infinite flat plate with water-based nanofluids. The two-dimensional boundary layer flow of a nanofluid past a stretching sheet in the presence of magnetic field intensity and the thermal radiation was studied by Gbadeyan *et al*. (2011). Olanrewaju *et al*. (2012) examined the boundary layer flow of nanofluids over a moving surface in a flowing fluid in the presence of radiation past a moving semi-infinite flat plate in a uniform free stream. They concluded that radiation has a greater influence on both the thermal boundary layer thickness and the nanoparticle volume fraction profiles. Mirmasoumi and Behzadmehr (2008) investigated the laminar mixed convection of a nanofluid in a horizontal tube using two-phase mixture model. Abu-Nada and Chamkha (2010) conducted a numerical investigation on mixed convection flow in an inclined square enclosure filled with alumina-water nanofluid. Oztop and Abu-Nada (2008) studied natural convection in a rectangular enclosure filled with a nanofluid containing copper, alumina and titania as nanoparticles. They concluded that the highest value of heat transfer is obtained by using copper nanoparticles.

The main subject of the present study is to study the two-dimensional Magnetohydrodynamic (MHD) boundary layer of stagnation-point flow in a nanofluid in the presence of thermal radiation. Using a similarity transform the Navier-Stokes equations have been reduced to a set of nonlinear ordinary differential equations. The resulting nonlinear system has been solved numerically using the Runge-Kutta- Fehlberg method with a shooting technique. Finally, the results are reported for three different types of nanoparticles namely alumina, titania and copper with water as the base fluid.

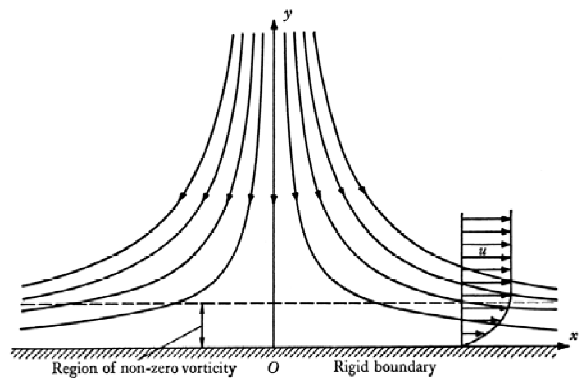

Fig. 1: Physical model and coordinate system

Mathematical formulation of problem: Consider the steady two-dimensional laminar flow of a viscous nanofluid past a plate in the presence of magnetic field and the thermal radiation (Fig. 1). The uniform magnetic field of strength B_0 is applied in the positive direction of y-axis. The ambient uniform temperature of nanofluid is T_∞, where the body surface is kept at a constant temperature T_w. The linear velocity of the flow external to the boundary layer is U(x) as U(x) =ax, where a is positive constant. Under these assumptions and following the nanofluid model proposed by Tiwari and Das (2007), the governing equations for the continuity, momentum and energy in boundary layer flow can be written as:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = U\frac{\partial U}{\partial x} + v_{nf}\frac{\partial^2 u}{\partial y^2} + \frac{\sigma_{nf}B_0^2}{\rho_{nf}}(U-u) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho c_P)_{nf}}\frac{\partial^2 T}{\partial y^2} - \frac{1}{(\rho c_P)_{nf}}\frac{\partial q_r}{\partial y} \tag{3}$$

subject to the boundary conditions:

$$u = 0, v = 0, T = T_w,\ at\ y = 0 \tag{4}$$

$$u = U(x) = ax, T = T_\infty, as\ y \longrightarrow \infty \tag{5}$$

where,

u and v = The velocity components along x and y axes, respectively

T = Temperature
σ_{nf} = The electrical conductivity of the nanofluid
q_r = The radiative heat flux
μ_{nf} = The viscosity of the nanofluid
α_{nf} = The thermal diffusivity of the nanofluid
ρ_{nf} = The density of the nanofluid, which are given by Oztop and Abu-Nada (2008):

$$\mu_{nf} = \frac{\mu_{nf}}{(1-\varphi)^{25}} (\rho)_{nf} = (1-\varphi)(\rho)_f + \varphi(\rho)_s$$
$$(\rho c_P)_{nf} = (1-\varphi)(\rho c_P)_f + \varphi(\rho c_P)_s$$
$$\frac{k_{nf}}{k_f} = \frac{(k_s+2k_f)-2\varphi(k_f-k_s)}{(k_s+2k_f)-\varphi(k_f-k_s)}, v_{nf} = \frac{\mu_{nf}}{\rho_{nf}} \tag{6}$$

where,
φ = The nanoparticle volume fraction
$(\rho c_p)_{nf}$ = The heat capacity of the nanofluid
k_{nf} = The thermal conductivity of the nanofluid
k_f and k_s = The thermal conductivities of the fluid and of the solid fractions, respectively
ρ_f and ρ_s = The densities of the fluid and of the solid fractions, respectively

The radiative heat flux q_r is described by Roseland approximation such that (Gbadeyan *et al*., 2011):

$$q_r = -\frac{4\sigma^*}{3k}\frac{\partial T^4}{\partial y}, \tag{7}$$

where,
σ^* = The Stefan-Boltzmann constant
k = The mean absorption coefficient

We assume that the temperature differences within the flow are sufficiently small so that the T^4 can be expressed as a linear function after using Taylor series to expand T^4about the free stream temperature T_∞ and neglecting higher-order terms. This result is the following approximation:

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4, \tag{8}$$

From Eq. (3), (7) and (8) one obtains:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho c_P)_{nf}}\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^* T_\infty^3}{3(\rho c_P)_{nf} k}\frac{\partial^2 T}{\partial y^2}. \tag{9}$$

To obtain similarity solutions for the system of Eq. (1)-(3), we introduce the following similarity variables:

$$\eta = \sqrt{\frac{a}{v_f}}y, \qquad \psi = \sqrt{av_f}\, xf(\eta), \qquad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \tag{10}$$

where, Ψ is the stream function defined as $u = \partial\Psi/\partial y$ and $v = -\partial\Psi/\partial x$, which identically satisfy Eq. (1). Using the non-dimensional variables in Eq. (10), Eq. (2) and (3) reduce to the following ordinary differential equations:

$$\frac{1}{(1-\varphi)^{25}\left[1-\varphi+\varphi\left(\frac{\rho_S}{\rho_f}\right)\right]} f''' ff'' - f'^2 + M^2(1-f') + 1 = 0 \tag{11}$$

$$\left[1+\frac{4}{3}R_d\right]\frac{\frac{k_{nf}}{k_f}}{\left[1-\varphi+\varphi\frac{(\rho c_P)_S}{(\rho c_P)_f}\right]}\theta'' + Prf\theta' = 0 \tag{12}$$

and the boundary conditions (4) and (5) become:

$$f(0) = 0, \quad f'(0) = 0, \quad f'(\infty) = 1,$$
$$\theta(0) = 1, \quad \theta(\infty) = 0, \tag{13}$$

where primes denote differentiation with respect to η. The Hartman number M, the Prandtl number Pr and the radiation parameter R_d are, respectively, defined as:

$$M^2 = \frac{\sigma_{nf} B_0^2}{\rho_{nf} a}, \qquad Pr = \frac{\mu c_P}{\alpha}, \qquad R_d = \frac{4\sigma^* T_\infty^3}{k_{nf} k}. \tag{14}$$

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

$$c_f = \frac{\tau_w}{\rho_f u_w^2}, \qquad Nu_x = \frac{xq_w}{k_f(T_w - T_\infty)}, \tag{15}$$

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

$$\tau_w = \mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0}, \qquad q_w = \left.\left(\left(k_{nf} + \frac{16\sigma^* T_\infty^3}{3k}\right)\frac{\partial T}{\partial y}\right)\right|_{y=0}. \tag{16}$$

Using the non-dimensional variables (10), we get:

$$Re_x^{1/2} C_f = \frac{1}{(1-\varphi)^{2.5}} f''(0) \tag{17}$$

$$Nu_x Re_x^{-1/2} = -\left(1+\frac{4}{3}R_d\right)\frac{k_{nf}}{k_f}\theta'(0) \tag{18}$$

RESULTS AND DISCUSSION

Equation (11) and (12) subject to the boundary conditions (13) are solved numerically using the Runge-Kutta-Fehlberg method with a shooting technique for some values of the governing parameters. Three types of nanoparticles are considered, namely, copper (Cu), alumina (Al_2O_3) and titania (TiO_2). Following Oztop and Abu-Nada (2008) and Bachok *et al*. (2010), the value of the Prandtl number Pr is taken as 6.2 (for water) and the volume fraction of nano particles is from 0 to 0.2 $(0 \leq \varphi \leq 0.2)$, in which $\varphi = 0$ corresponds to the regular Newtonian fluid. The thermophysical properties of the fluid and nanoparticles are given in Table 1. (Oztob and Abu-Nada, 2008).

Figure 2 and 3, respectively show the variations of the velocity profiles $f'(\eta)$ and temperature profiles $\theta(\eta)$ for different nanoparticle volume fractions for copper-water nanofluid. It can be seen from Fig. 2 that the velocity components increase with increase in the nanoparticle volume fraction φ. From Fig. 3 the temperature $\theta(\eta)$ increases as the nanoparticle volume fraction φ increases.

Table 1: Thermophysical properties of the base fluid and the nanoparticles (Oztob and Abu-Nada, 2008)

Physical properties	Fluid phase (water)	*Cu*	*Al_2O_3*	*TiO_2*
$C_p(J/kgk)$	4179	385	765	686.2
$\rho(kg/m^3))$	997.1	8933	3970	4250
K(W/mk)	0.613	400	40	8.9538
$\alpha \times 10^{-7}(m^2/s)$	1.47	1163.1	131.7	30.7

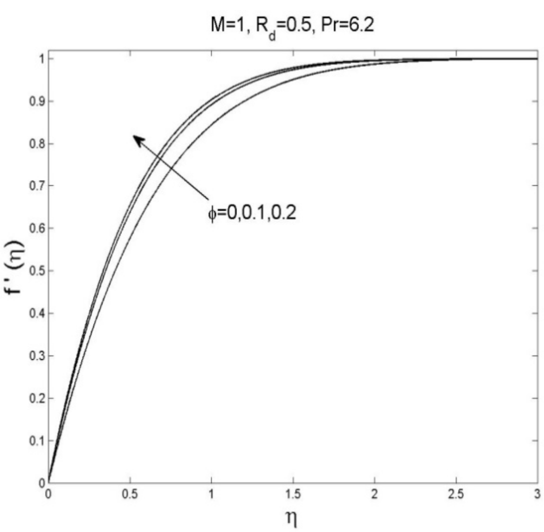

Fig. 2: The velocityprofiles $f'(\eta)$ for different nanoparticle volume fractions φ for copper-water nanofluid

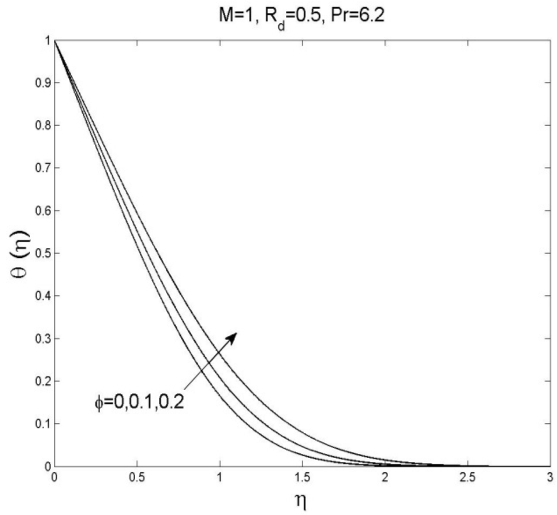

Fig. 3: The temperature profiles $\theta(\eta)$ for different nanoparticle volume fractions φ for copper-water nanofluid

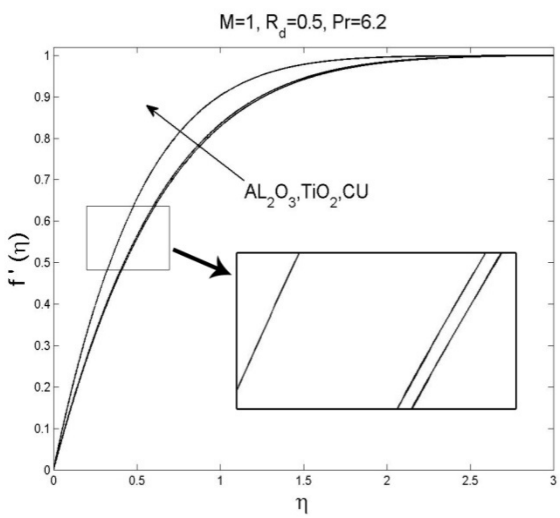

Fig. 4: The velocity profiles $f'(\eta)$ for different nanoparticles, when $\varphi = 0.2$

Figure 4 and 5 respectively illustrate the variation of $f'(\eta)$ and $\theta(\eta)$ for different nanoparticles when $\varphi = 0.2$. Figure 4 shows that the Cu nanoparticle (compared to Al_2O_3 and TiO_2) has the largest velocities. From Fig. 5 it is observed that the Al_2O_3 nanoparticles have the highest value of temperature distribution (compared to Cu and TiO_2).

Figure 6 is prepared to present the effect of the nanoparticle volume fraction φ on the skin friction coefficient $Re_x^{1/2}C_f$ for different types of nanofluids. It is observed that the magnitude of skin friction coefficient increases with the nanoparticle volume

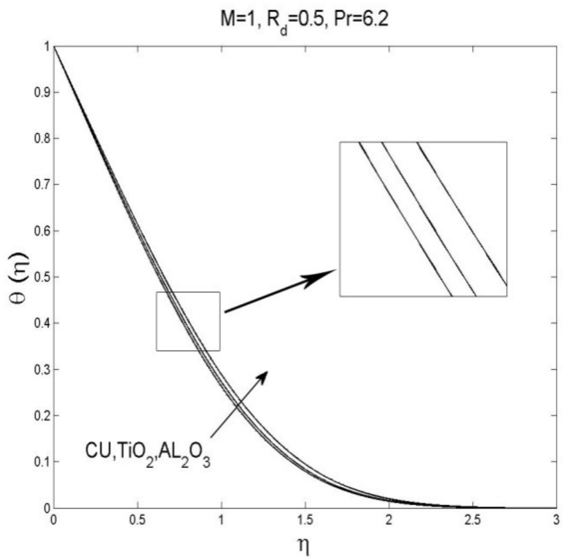

Fig. 5: The temperature profiles $\theta(\eta)$ for different nanoparticles, when $\varphi = 0.2$

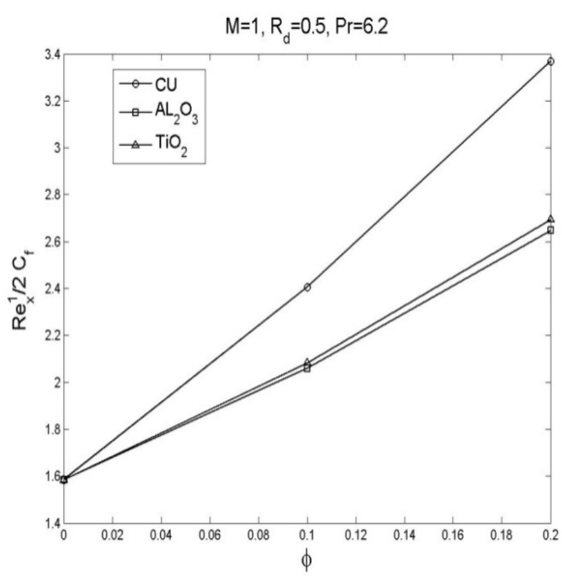

Fig. 6: The effect of the nanoparticle volume fraction φ on the skin friction coefficient for different types of nanofluids

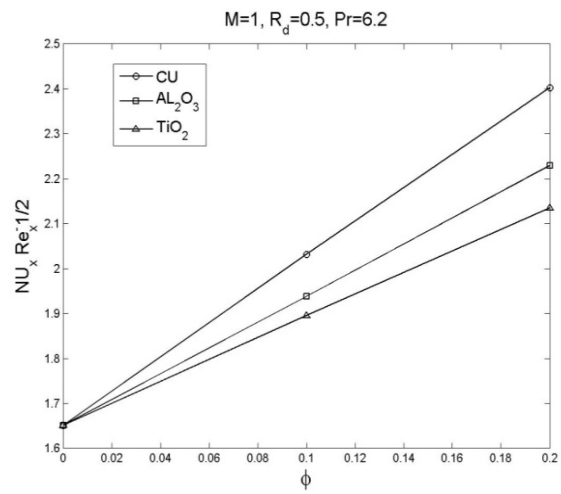

Fig. 7: The effect of the nanoparticle volume fraction φ on the local Nusselt number for different types of nanofluids

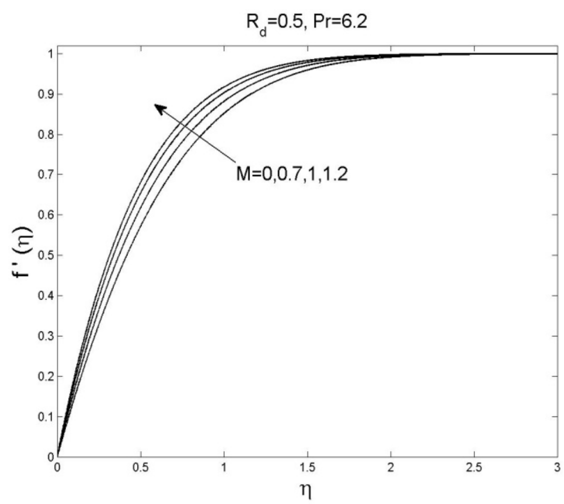

Fig. 8: The effect of the Hartman number M on the velocity profiles $f'(\eta)$ for copper-water nanofluid, when $\varphi = 0.2$

fraction φ. In addition, it is noted that the highest skin friction coefficient is obtained for the Cu nanoparticle.

The infuence of the nanoparticle volume fraction φ on the local Nusselt number $Nu_x Re_x^{-1/2}$ for different types of nanofluids are shown in Fig. 7. It is observed that the local Nusselt number increases with the nanoparticle volume fraction φ. Moreover, it is noted that the lowest heat transfer rate is obtained for the nanoparticles TiO_2 due to domination of conduction mode of heat transfer. This is because TiO_2 has the lowest value of thermal conductivity compared to Cu and Al_2O_3, as seen in Table 1. This behaviour of the local Nusselt number is similar to that reported by Bachok *et al*. (2010). However, the difference in the values of Cu and $Al_2O_3$is negligible. The thermal conductivity of Al_2O_3 is approximately one-tenth of that of Cu, as given in Table 1. A unique property of Al_2O_3 is its slow thermal diffusivity. The reduced value of thermal diffusivity leads to higher temperature gradients and, therefore, higher enhancement in heat

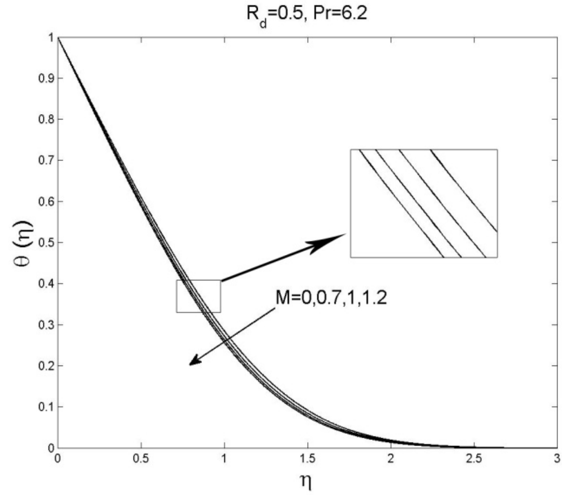

Fig. 9: The effect of the Hartman number M on the temperature profiles $\theta(\eta)$ for copper-water nanofluid, when $\varphi = 0.2$

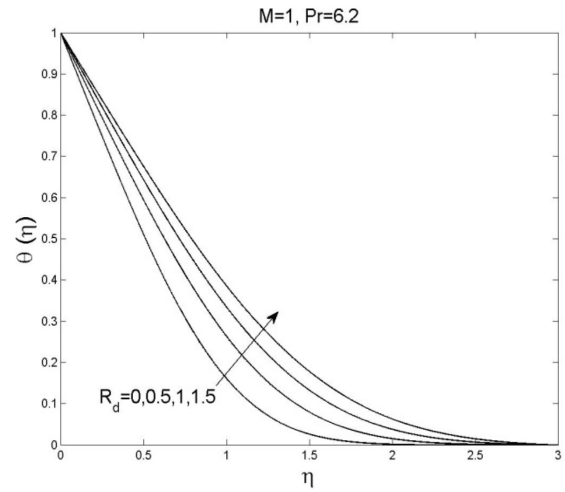

Fig. 10: The effect of the radiation parameter R_d on the temperature profiles $\theta(\eta)$ for copper-water nanofluid, when $\varphi = 0.2$

transfer. The Cu nanoparticles have high values of thermal diffusivity and, therefore, this reduces the temperature gradients, which will affect the performance of Cu nanoparticles.

The effect of M on the velocity profiles $f'(\eta)$ and temperature profiles $\theta(\eta)$ for copper-water nanofluid (φ = 0.2) are illustrated in Fig. 8 and 9 respectively. Figure 8 displays that the velocity $f'(\eta)$ increases as M increases. Moreover, The boundary layer thickness is increased by increasing M. From Fig. 9, we can see that the temperature profiles $\theta(\eta)$ decreases as M increases. Figure 10 and 11 respectively show the influence of R_d and Pr on the temperature profiles $\theta(\eta)$ for copper-water nanofluid ($\varphi = 0.2$). It can be seen from Fig. 10 that the temperature profiles $\theta(\eta)$increases by increasing R_d, therefore, the thermal boundary layer increases when R_d increases. From Fig. 11, it is noted that the temperature $\theta(\eta)$ increases as the Prandtl number Pr decreases.

Table 2 shows the values of the skin friction coefficient $Re_x^{1/2}C_f$ and the local Nusselt number $Nu_x Re_x^{-1/2}$ for some values of the nanoparticle volume fraction φ using different nanoparticles. It is observed that, the large values of average Nusselt number can be obtained by adding copper.

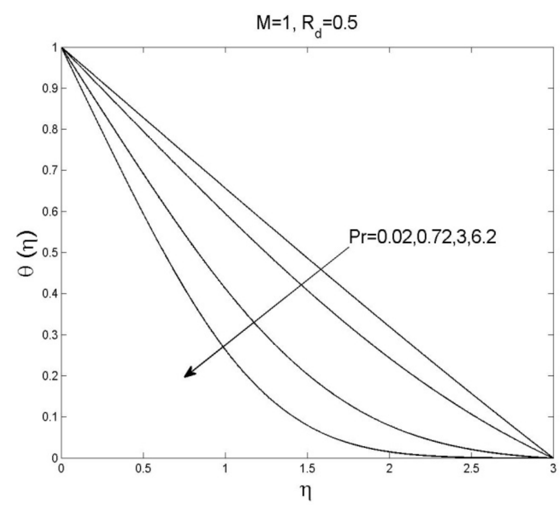

Fig. 11: The effect of the Prandtl number P_r on the temperature profiles $\theta(\eta)$ for copper-water nanofluid, when $\varphi = 0.2$

Table 2: The effect of the various nanoparticle volume fractions on the skin friction coefficient and local Nusselt number for the different nanoparticles, when M = 1 and R_d = 0.5

	Cu		*Al_2O_3*		*TiO_2*	
φ	$Re_x^{1/2}C_f$	$Nu_x Re_x^{-1/2}$	$Re_x^{1/2}C_f$	$Nu_x Re_x^{-1/2}$	$Re_x^{1/2}C_f$	$Nu_x Re_x^{-1/2}$
0.00	1.585400	1.650833	1.585400	1.650833	1.585400	1.650833
0.05	1.997958	1.847150	1.811292	1.794396	1.822888	1.774156
0.10	2.405934	2.031578	2.060035	1.938243	2.082549	1.895634
0.15	2.875792	2.218840	2.336844	2.083274	2.370472	2.014743
0.20	3.369125	2.402679	2.647819	2.229723	2.693763	2.134747

Table 3: The effect of the various values of M and R_d on the skin friction coefficient and the local Nusselt number for copper-water nanofluid, when $\varphi = 0.2$

M	R_d	$Re_x^{1/2} C_f$	$Nu_x Re_x^{-1/2}$
0.0	0.5	2.619519	2.295027
0.7		3.017294	2.355254
1.0		3.369125	2.402679
1.2		3.650730	2.437593
1.0	0.0	3.369125	2.928719
	0.5	3.369125	2.402679
	1.0	3.369125	2.105617
	1.5	3.369125	1.908934

Table 3 is made to give the values of the skin friction coefficient and the local Nusselt number for different values of M and R_d for copper-water nanofluid. The values of the skin friction coefficient and the local Nusselt number increases when M increases. From this table, the magnitude of the local Nusselt number decreases when R_d increases.

CONCLUSION

Here, the steady two-dimensional laminar flow of a viscous nanofluid past a plate in the presence of magnetic field and the thermal radiation was investigated. The governing partial differential equations were converted to ordinary differential equations by using a suitable similarity transformation and were then solved numerically using the Runge-Kutta-Fehlberg method with a shooting technique. In this study, three types of nanoparticles, namely copper (Cu), alumina (Al_2O_3) and titania (TiO_2) with water as the base fluid were considered to investigate the effect of the nanoparticle volume fraction φ, the Hartman number M the Prandtl number Pr and the radiation parameter R_d on the flow and heat transfer characteristics. Finally, from the presented analysis, the following observations are noted.

- For all three nonoparticles, the magnitude of the skin friction coefficient and local Nusselt number increases with the nanoparticle volume fraction φ .
- For a fixed value of the nanoparticle volume fraction φ, the velocity of fluid increases by increasing M
- For a fixed value of the nanoparticle volume fraction φ, the temperature increases by decreasing M and Pr. A similar effect on the temperature is observed when R_d increases.
- The highest values of the skin friction coefficient and the local Nusselt number were obtained for the Cu nanoparticles compared to Al_2O_3 and TiO_2
- The type of nanofluid is a key factor for heat transfer enhancement. The highest values are obtained when using Cu nanoparticles

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