Research Article **AJOERR (2020) 3:23**

American Journal of Engineering Research and Reviews
(ISSN:2637-3785)

Investigation of forced convective heat transfer in nanofluids

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ABSTRACT

The present paper concerns a theoretical study of heat transfer of the laminar two dimensional flows of various nanofluids taking into account the dissipation due to viscous term past a 2-D flat plate had a different temperatures. The steady incompressible flow equations were used and transformed to a nonlinear Ordinary Differential Equation (ODE). These equations were solved numerically using implicit finite difference method. Three types of nanoparticles in the base flow of water were considered. The symbolic software Mathematica was used in the present study. Different types of nanoparticles, different values of, nanoparticle volume fraction, Eckart and Prandtl number were tested and analyzed at different wall temperature. The effect of these parameters on the flow behaviour, the local skin friction coefficient, Nusselt number, the velocity and the temperature profiles were presented and investigated. It is concluded that these parameters affect the fluid flow behaviour and heat transfer parameters especially nanoparticle concentration. The presence of nanoparticles showed an enhancement in the heat transfer rate moreover its type has a significant effect on heat transfer enhancement.

Keywords: Nanofluid and flat plate, heat transfer; viscous dissipation, wall temperature

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How to cite this article:
Zain F. Abu Shaeer and Mofreh H. Hamed. Investigation of forced convective heat transfer in nanofluids. American Journal of Engineering Research and Reviews, 2020, 3:23

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Website: https://escipub.com/

1. Introduction

Recent researches have shown that nanofluids (dispersing some of nanometer materials in conventional flow) enhance thermal conductivities and can improve the heat transport properties of fluids, thereby enhancing energy efficiency. The size of these nanomaterials has different shape depending up on uses, while the base flow is a liquid or gas. The flow is treated as a two phase mixture. The most common materials used as nanoparticles are metal oxides (alumina, silica, titania), metal carbides (SiC) and oxide ceramics (Al_2O_3 , CuO). Nanofluid term was first introduced by Choi [1]. He concluded that the presence of nanoparticles gives a significant enhancement of their properties. Many of the published researches on nanofluids were concerned with their behavior. To enhance the thermal properties of such fluidflow, nanoscale particles are being dispersed in a base fluid [2-4]. The results showed that thermal conductivity increased by adding very small amounts of concentration (less than 1% by volume). Nield and Kuznetsov [5] studied using Buongiorno model the free boundary-layer flow of a nanofluid past a vertical plate. Xuan and Roetzel [6] were the first researchers to indicate a mechanism for heat transfer in nanofluids. Dual solutions have obtained by [7] when free stream and the plate move in the opposite directions.

Flow of nanofluid past a fixed or moving flat plate was studied numerically by Bachok et al. [8]. Three different types of metallic or nonmetallic nanoparticles were solved numerically by [9-10]. They deduced that the existence of nanoparticles into the base flow causes an increase in the skin friction and heat transfer coefficients. This paper investigates numerically 2-D steady flow of nanofluids past a horizontal flat plate embedded in the water-based nanofluid taking into account viscous term and convection of heat transfer. Eckert number is used to characterize viscous thermal dissipation of convection. If the viscous thermal dissipation is ignored then the Eckert number is regarded as zero. Flow and transfer processes can be modeled mathematically by complex systems of equations, which are often non-linear due to both the complexity of the problem and the number of physical variable. There are several ways to solve these differential equations, such as analytical and numerical methods. Mass, momentum and energy conservation equations are transformed using the similarity transformations to a nonlinear Ordinary Differential Equation (ODE), and then the resulting equations are solved using numerical method to give a complete picture of the proposed problem. Three types of nanoparticles in the water based fluid are considered. The flow parameters and heat transfer are studied for various types, values of the nanoparticle, Pr, Ec, and wall temperature. The effects of these parameters on the flow behaviour and mainly on the local skin friction and heat transfer coefficient are investigated.

2. Mathematical formulation

To provide a reasonable solution of the laminar 2-D equations the following assumptions are considered;

1- The flow is assumed as an ideal water-mixture of water and nanoparticles with zero pressure gradient.

2- The nanoparticles are spherical shape, rigid and uniformly distributed.

3- Equal velocities between the base fluid and the nanoparticles.

4- The base fluid and the nanoparticles have the same temperature.

Using the above assumptions the basic equations can be written as follows:

where, x and y are the coordinates, while, u and v are the velocity components in these directions respectively. While, $p, T, \mu_{nf}, \rho_{nf}$ and α_{nf} are the pressure, temperature, dynamic viscosity, density and the thermal diffusivity of the nanofluid respectively, which are defined by,

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

(1)

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = \nu_{nf} \frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}\right)$$

(2)

$$u\,\frac{\partial T}{\partial x}+v\,\frac{\partial T}{\partial y}=\alpha_{nf}\,\frac{\partial^2 T}{\partial y^2}+\frac{\nu_{nf}}{C_{pnf}}\left(\frac{\partial u}{\partial y}\right)^2 \qquad (3)$$

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s\,,\quad \mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}}\,,\quad \alpha_{nf}=\frac{K_{nf}}{(\rho C_p)_{nf}}$$

$$(\rho C_\rho)_{nf}=(1-\varphi)(\rho C_\rho)_f+\varphi(\rho C_\rho)_s \qquad (4)$$

$$\frac{K_{nf}}{K_f}=\frac{(K_s+2K_f)-2\varphi(K_f-K_s)}{(K_s+2K_f)+\varphi(K_f-K_s)} \qquad (5)$$

Where, φ is the nanoparticle concentration.

- Inlet and free boundary conditions for the fluid flow are;

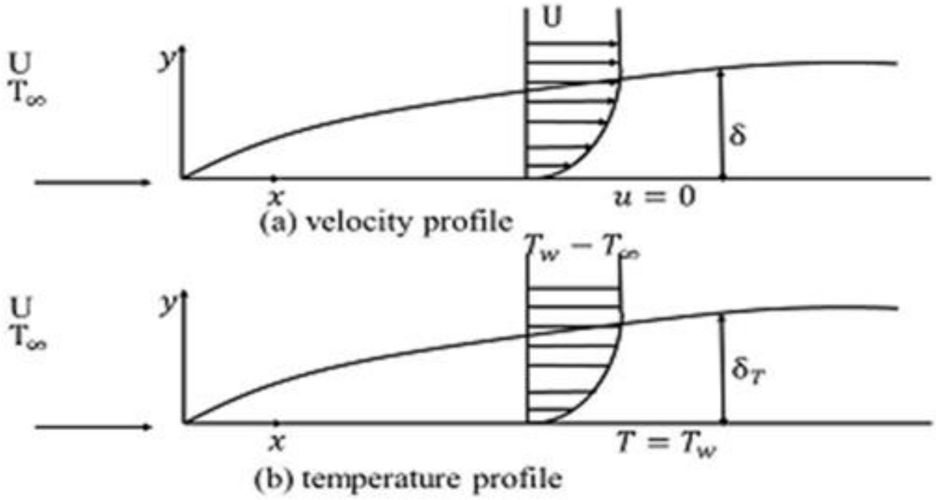


Fig. 1. Flow and convective boundary heat transfer

$$u=v=0,\ T=T_w(x),\ at\quad y=0,$$

$$u\rightarrow U\ as\ T\rightarrow T_\infty \qquad (6)$$

Assuming that the relation between ambient nanofluid and the wall surface temperatures T_∞ ,T_W respectively is,

$$T_w(x)=A\,x^n+T_\infty \qquad (7)$$

Introducing the following similarity variables in Eqs. (1–3) with the boundary conditions (6)

$$\eta=y\sqrt{(U/x\nu_f)},\ \psi(x,y)=f(\eta)\sqrt{(Ux\nu_f)},$$

$$\theta(\eta)=(T-T_\infty)/(T_w(x)-T_\infty)\,, \qquad (8)$$

Where,.is the kinematic viscosity of the fluid fraction ν_f

The stream function is common given by,

$$u = \partial\psi / \partial y, v = -\partial\psi / \partial x \quad , \tag{9}$$

Substituting Eqs. (8-9) into Eqs. (2-3) and using the transform [11] to obtain the following uncoupled equations,

$$f''' + 0.5(1-\varphi)^{2.5}(1-\varphi+\varphi\rho_s/\rho_f)\, f\, f'' = 0, \tag{10}$$

$$\theta'' + P_r / (K_{nf} / K_f)(1-\phi+\phi(\rho C_p)_s / (\rho C_p)_f)$$

$$\times(0.5f\,\theta' + Ec(f'')^2 - nf'\theta) = 0, \tag{11}$$

Eqns. (10-11) are subjected to,

$$f(0) = f'(0) = 0,\ \theta(0) = 1, f'(\infty) = 1, \theta(\infty) = 0 \tag{12}$$

The local skin friction coefficient is defined by,

$$C_f = \tau_w /(U^2 \rho_f) \tag{13}$$

While the plate surface shear stress is defined by,

$$\tau_w = \mu_{nf}(\partial u / \partial y)_{y=0}$$

Pr , *Nu* are the Prandtl number and the local Nusselt number which are defined as,

$$Pr = \nu_f / \alpha_f, Nu = xq_w / k_f(T_w - T_\infty), \tag{14}$$

Where, q_w is the heat flux from the plate,

$$q_w = -K_{nf}(\partial T / \partial y)_{y=0}, \tag{15}$$

Substituting Eqn. (8 and 15) into Eqs. (13 , 14) gives,

$$R_{ex}{}^{1/2} C_f = f''(0)/(1-\varphi)^{2.5}, \qquad R_{ex}{}^{-1/2} Nu = -\theta'(0) K_{nf} / K_f \tag{16}$$

Where, Re_x [illegible]x / ν_{nf} is the local Reynolds number.

The Eckert number is defined as the ratio of a flow's kinetic energy to the boundary layer enthalpy difference.

$$E_c = U^2 / C_p(T_w - T_\infty), \tag{17}$$

The Eckert number is regarded as zero when the viscous thermal dissipation is neglected.

3 . Mathematical Solutions

A set of coupled equations is the transformation of the governing nonlinear PDE using a similarity variable. This set of equations is solved numerically using the method reported in [12] in which the partial derivatives are replaced by appropriate central differences patterns and using Newton's method to linearize the resulting algebraic equations. Finally, the block-tridiagonal-elimination technique is used to solve that linear system.

4 . Mathematical Validation

Tables 1 to 3, show the values of temperature gradient at wall the – θ' (0). These values are compared with that obtained by [13]. To validate the numerical results the same boundary conditions are used. Therefore a flow without any nanoparticles is tested. In Table 1, the values of –θ'(0) are calculated at Pr = 0.7 for various values of Ec for variable values of wall temperature index (n =1, 2, 3 and 4).

In Table 2, the values of – θ'(0) are calculated for Ec = 0.5 for various values of Pr. In Table 3, the values of – θ (0) are calculated for n = 3 for various values of Pr with various values of Ec. From Table 1, it is seen that the values of –θ'(0) decrease when Ec increases for all tested values of n, the results obtained show a good agreement with the published data.

Table 1. Values of –θ' (0) for Pr = 0.7 and variable temperature index, n.

Method	Present	Keller [13]	Present	Keller [13]	Present	Keller[13]
n	Ec = 0.1		Ec = 0.5		Ec = 0.7	
1	0.471658	0.471081	0.436675	0.433778	0.419183	0.415127
2	0.576926	0.576896	0.546819	0.544484	0.531765	0.528278
3	0.654004	0.654579	0.626875	0.625153	0.611444	0.610440
4	0.716296	0.717506	0.691264	0.690181	0.67489	0.676519

Table 2. Values of – θ' (0) for Ec = 0.5 for temperature index, n.

Method	Present	Keller [13]	Present	Keller[13]	Present	Keller[13]
n	Pr = 0.7		Pr = 3		Pr = 5	
1	0.436675	0.433778	0.660545	0.645443	0.746864	0.729576
2	0.546819	0.544484	0.841009	0.837255	0.977085	0.964844
3	0.626875	0.625153	0.979378	0.974597	1.13878	1.13158
4	0.691264	0.690181	1.08606	1.084292	0.67489	0.676519

Table 3. Values of – θ' (0) for n = 3 for variable Ec nd Pr.

Method	Present	Keller[13]	Present	Keller[13]	Present	Keller[13]
Ec	Pr = 0.7		Pr = 3		Pr = 5	
0.1	0.654004	0.654579	1.05296	1.057992	1.24108	1.250237
0.3	0.64044	0.639866	1.01617	1.016295	1.18993	1.190909
0.5	0.626875	0.625153	0.979378	0.974597	1.13878	1.13158
0.7	0.613311	0.61044	0.942587	0.9329	1.08763	1.072252

5. Results and Discussion

Solution of the system of equations (10 and 11) with the help of (12) is obtained. The effect of the nanoparticles volume fraction φ , Prandtl number Pr , Eckart number Ec and wall temperature index n on the flow characteristics are discussed and analyzed for three different types of nanofluids Cu-water, Al2O3-water, and TiO2 -water as working fluid. The effect of solid concentration φ is investigated in the range of $0 \le \varphi \le 0.2$, Prandtl number number range $0.004 \le Pr \le 6.2$, Eckart number range $0 \le Ec \le 1$ and n = 0,1,2, 3, 4 and 5 is investigated in details for Cu-water nanofluids.

Figure (2) shows the temperature variation past flat plate for different values of Pr. From the figure it is observed that increasing Pr, the temperature profile decreases for different values of nanoparticles concentration for fixed Pr, Ec. Also the figure shows that increasing the values of φ the temperature increases as a result of heat gained from the nanoparticles. In case of zero nanoparticle concentration Fig. 2.a the predicted results are exactly the same as data reported in [13].

Figure 3 shows that the temperature decreases as η increases for specific wall temperature (n = constant) and also decreases as n increases. Also the figure shows the effect of the presence of nanoparticles, it is observed that by increasing the values of φ, the temperature profile increases for variable flat plate temperature index (n = 0,1,2,3,4,5) for fixed Pr and Ec.

The results obtained for temperature variation for various values of the Eckert number at constant values of Pr, n and φ are shown in Fig. 4. It is clear from the figure that as Ec increases the temperature distribution increases. In the case of zero Ec, this means that viscous thermal dissipation is ignored.

Figures 5-6 present the variation of skin friction coefficient ($Rex^{1/2}. C_f$) and the Nusselt number ($Rex^{-1/2}. Nu$) in case of the presence of nanoparticle for the three tested working fluids. It is noticed from the figures that both numbers of C_f and Nu increase when increasing the values of φ. Hence, more particles are suspended and thermal conductivity of nanoparticles increases. On the other side, figures indicate that more fluid is heated for higher values of φ. Also the figures show that the lowest skin friction coefficient is obtained for Al_2O_3, on the other side the lowest value of the Nusselt number is obtained for TiO_2 this is because TiO_2 has the lowest thermal conductivity compared with Cu and Al_2O_3.

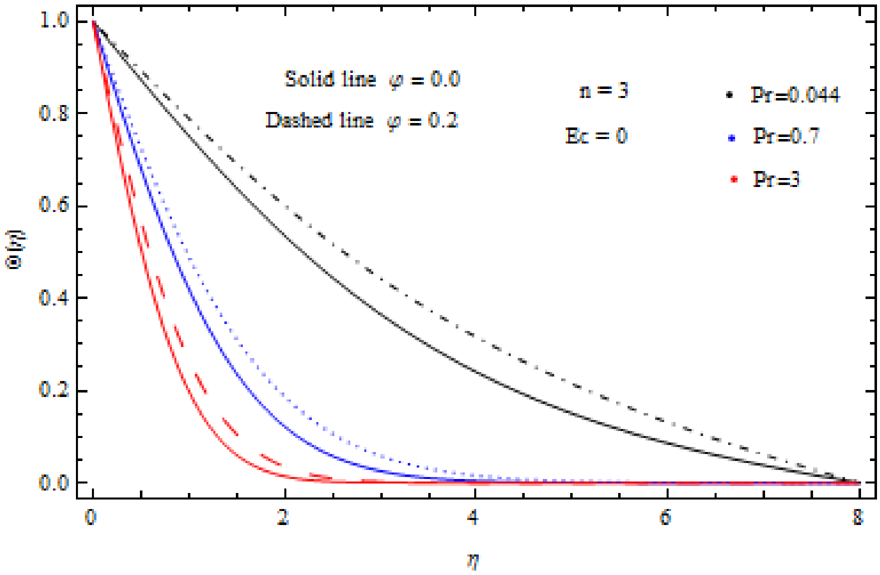
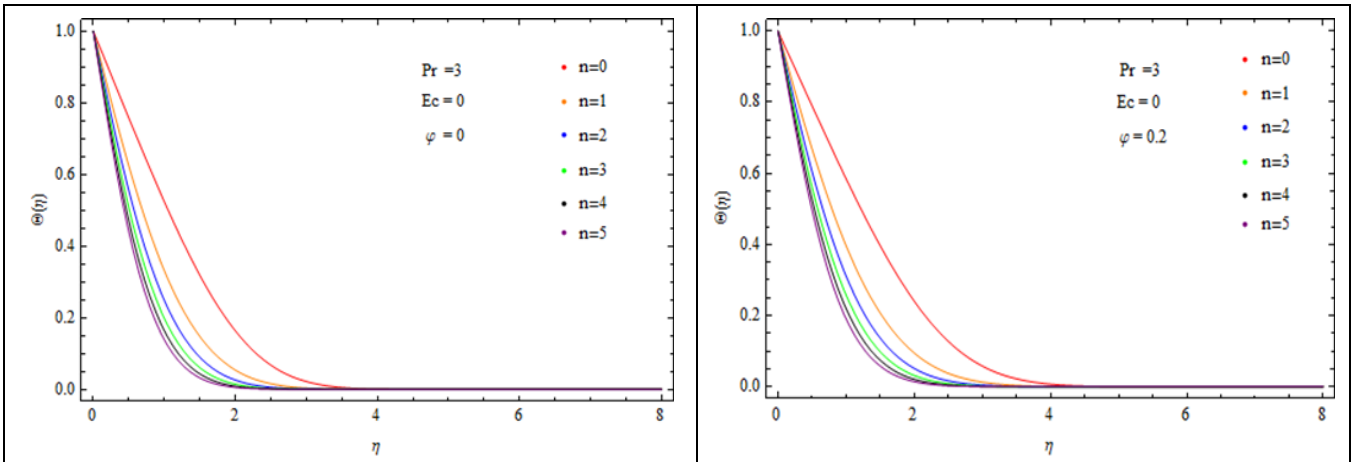


Fig. 2 Effect of nanoparticles concentration on temperature distribution



a-φ = 0.0 b- φ = 0.0

Fig.3.Temperature variation for for different values of *n*.

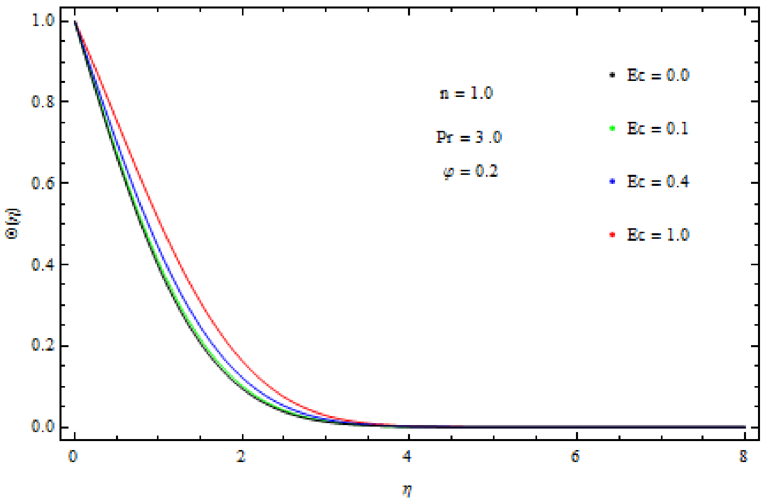


Fig.4. Temperature distribution for different values of Ec.

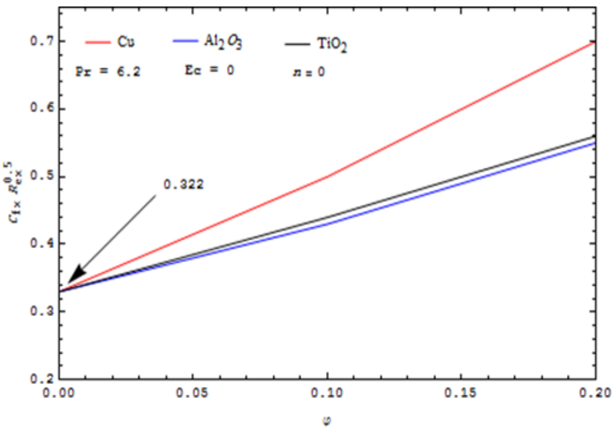


Fig.5 Variation of, C_f, with φ for different types of nanoparticles

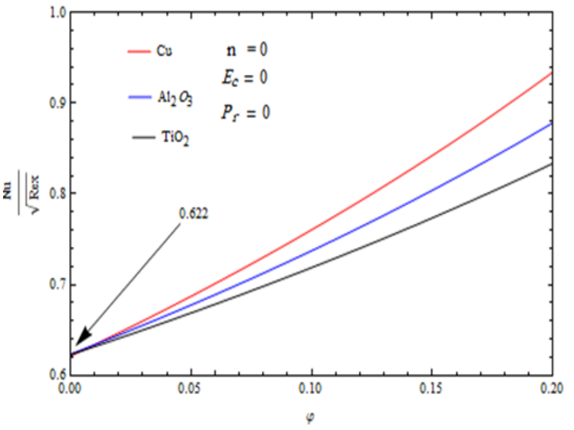


Fig.6 Variation of the Nu, with φ for different types of nanoparticles

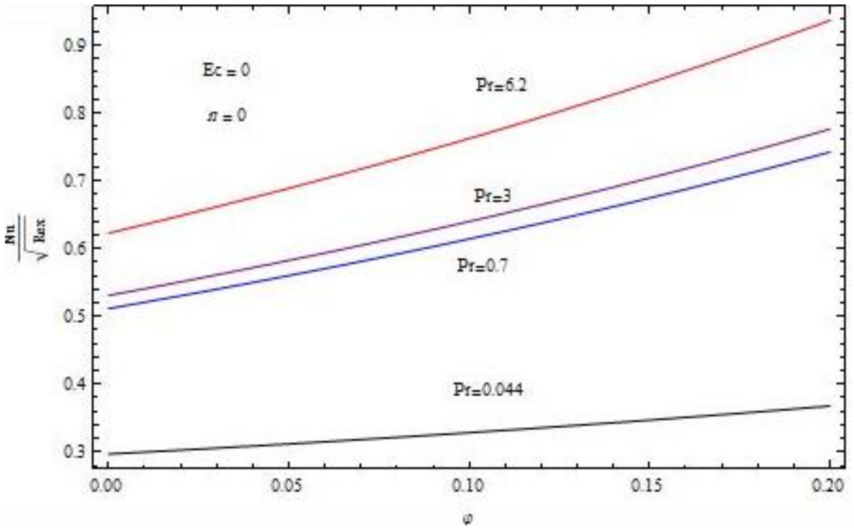


Fig.7 Effect of Pr on Nu number at constant values of Ec and n.

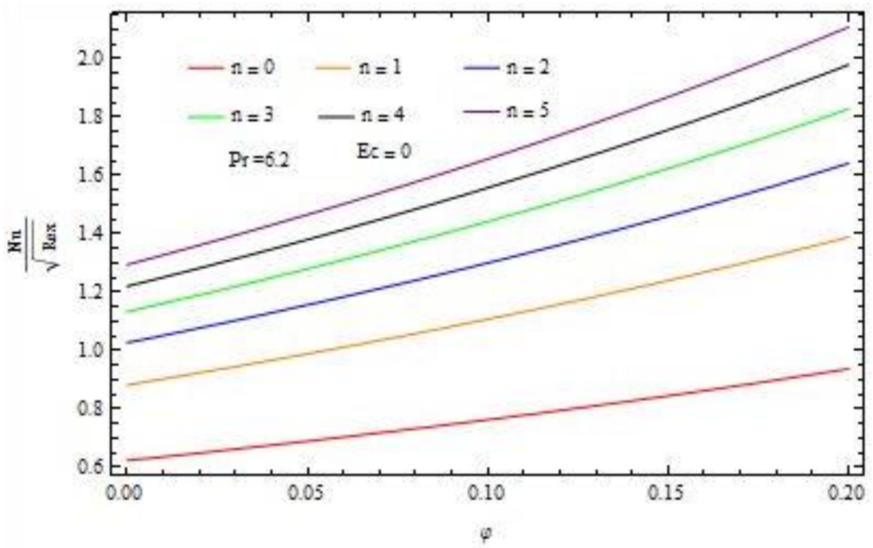


Fig.8 Effect of n on Nu number at constant values of Ec and Pr

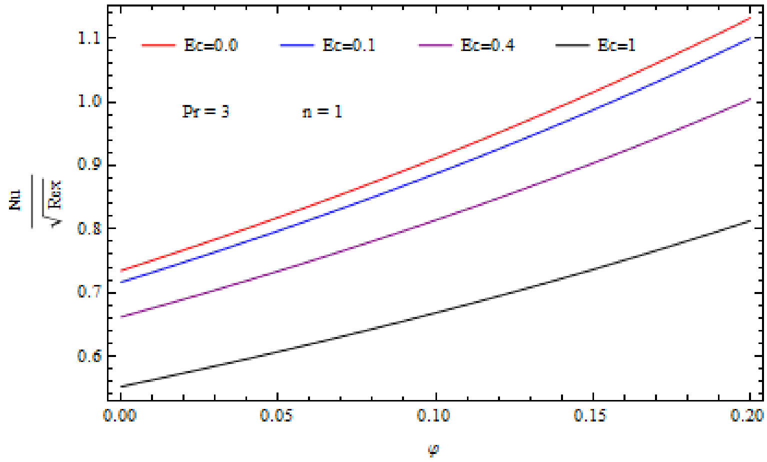


Fig.9 Effect of Ec on Nu number at constant values of Pr and n

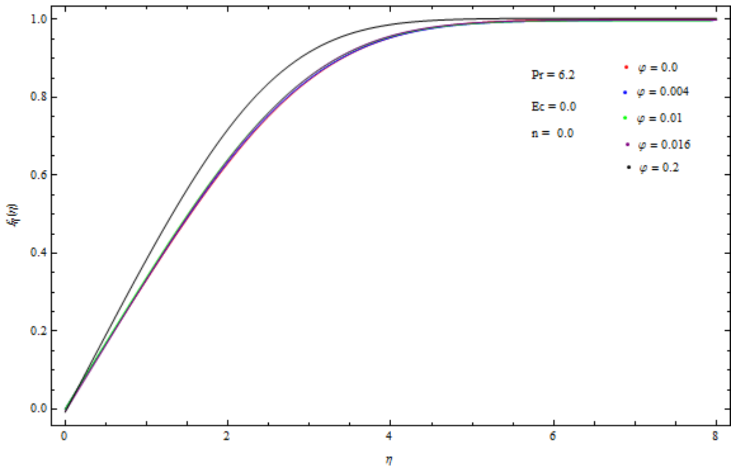


Fig.10 Effect ofφ on velocity variation past flat plate at constant values of Pr, Ec and n.

While Figures (7-9) show the variation of Nusselt number in case of using Cu-water as working fluid for different values of Pr, n and Ec respectively. It is noticed that Nusselt number increases as Pr and n increases and decreases as Ec increases. The transverse component of the flow velocity is shown in Fig. 10. The results show that small values of φ has a small effects on transverse component of the velocity.

6. Conclusions

In the present study predicted results for various different parameters are obtained and discussed. The following conclusions can be drawn:

-The presence of nanoparticles in the base fluid gives an increase in both numbers of C_f and Nu, which increases as nanoparticle volume fraction increase.

-The increase of nanoparticles showed an enhancement in the heat transfer rate;

-The type of nanofluid has a significant effect on heat transfer enhancement;

-The highest values for both numbers of **C_f and Nu** are obtained when using Cu nanoparticles in the base fluid of water with the Prandtl number $Pr = 6.2$.

-The effect of *Ec*, wall temperature and *Pr* number is a great effect on the thermal boundary layer and heat transfer..

Nomenclature

nf : Nanofluid

Re : local Reynolds number

Ec : Ecart number

f : dimensionless stream-function

S : Solid

W : Wall

φ : nanoparticle volume fraction

ψ : Stream function

τ : Wall shear stress

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