Research note

CFD Study of the Turbulent Forced Convective Heat Transfer of Non-Newtonian Nanofluid

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Abstract

In this study, forced convection heat transfer of non-Newtonian nanofluids in a horizontal tube with constant wall temperature under turbulent flow conditions was investigated using computational fluid dynamics tools. For this purpose, non-Newtonian nanofluids containing three types of nanoparticles (Al_2O_3, TiO_2 and CuO) with carboxymethylcellulose aqueous solution as a liquid single phase with three average particle sizes of 10, 25 and 40 nm nanofluids were investigated. Effects of nanoparticle type and Peclet number on the convective heat transfer coefficient were investigated in fully turbulent region of a horizontal tube. A correlated equation was obtained for Nusselt number using the dimensionless numbers by applying the simulation results. Results showed that the correlated data were in very good agreement with the experimental ones obtained from the literature. The maximum error was 12%.

Keywords: *Nanofluid, Non-Newtonian, Turbulent, Convective Heat Transfer, CFD.*

1.Introduction

A fluid with high heat transfer ability has many applications in cooling systems, aerospace industries, electronics and thermal equipment design [1, 2]. Low thermal conductivity of conventional heat transfer fluids is one of the main limitations in the improvement of heat transfer equipment performance [3, 4].

The thermal conductivity of most solids is much higher than conventional heat transfer fluids. Therefore, solid particles addition into fluids leads to thermal conductivity enhancement of the fluid. Maxwell showed the possibility of thermal conductivity enhancement of a fluid–solid mixture by higher volume fraction of solid particles [3].

Choi showed that a nanoparticle suspension had higher effective thermal conductivity compared with the base liquid [5]. In fact, the nanofluids provided more uniform and stable suspensions of metallic and/or non-metallic nanoparticles [1, 6].

The nanofluids can be classified on the basis of nanoparticle materials. Metallic nanoparticles such as Cu and Fe are the first type of materials. The second type and common materials are metal oxide nanoparticles such as Al_2O_3 and CuO. The third type is carbon nanotubes (CNTs)[7].

Xuan and Li carried out an experimental study on the convection heat transfer and friction coefficient of nanofluid in laminar

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and turbulent flows [8, 9]. Their findings indicated that the flow velocity and volume fraction of nanoparticles affected the heat transfer and friction coefficients.

Teng *et al*. studied the effect of particle size, temperature, and weight fraction on the thermal conductivity ratio of alumina (Al_2O_3)/water nanofluids [10]. They measured the thermal conductivity of nanofluids with different particle sizes, weight fractions, and working temperatures.

Fotukian *et al*. experimentally studied the convective heat transfer performance and pressure drop of very dilute CuO/water nanofluid flowing through a circular tube under turbulent flow [6]. Their measurements showed that addition of small amounts of nano-sized CuO particles into a base fluid considerably increased heat transfer coefficient.

Kamali *et al*. studied a numerical investigation of heat transfer enhancement using carbon nanotube-based non-Newtonian nanofluids through a straight tube under laminar flow and constant heat flux conditions [7]. Their results showed that the numerical method coupled with the non-Newtonian model is capable of modeling the action of CNT nanofluid.

In the present study, the forced convective heat transfer in the developed region of horizontal circular tube flow containing non-Newtonian nanofluid with constant wall temperature under turbulent flow conditions was simulated using computational fluid dynamics (CFD) tools. Power-law model was used to approximate the rheological behavior of viscous non-Newtonian liquids. Three average particle sizes of 10, 25 and 40 nm and three particle concentrations of 0.2, 0.5 and 1% (v/v) were used. A correlated equation based on the dimensionless numbers for Nusselt number was obtained.

2. Mathematical modeling
2-1. Geometry and grid
The geometrical configuration is shown in Fig. 1. A circular tube with 2 m length and 10 mm internal diameter was applied. The nanofluids flow inside the tube under constant wall temperature and turbulent flow regime. The computational domain was effectively reduced by exploiting symmetric boundary along the centerline of the tube. For all cases investigated in this study, a non-structured grid was used for simulation. There are 10 meshes in the radial direction with a size ratio of 1.1 from the center to the wall. There are 2000 meshes in the axial direction.
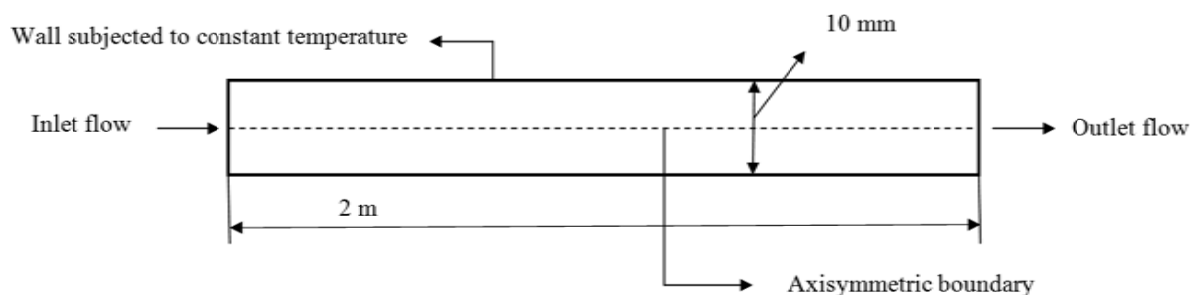

Figure 1. Computational domain of pipe**.**

2-2. Governing equations

In this study, the single phase model for numerical investigation of two dimensional symmetric steady, forced turbulence convection flow of nanofluid inside a horizontal circular tube was used. Moreover, nanofluids were assumed to be incompressible and non-Newtonian. Therefore, steady state conservation of mass, momentum, and energy equations were as follow [11]:

Continuity equation:

$$\nabla.\left(\rho_{nf}.V_m\right) = 0 \tag{1}$$

Momentum equation:

$$\nabla.\left(\rho_{nf}.V_m.V_M\right) = -\nabla P + \nabla.\left(\mu_{nf}.\nabla V_m\right) \tag{2}$$

Energy equation:

$$\nabla.\left(\rho_{nf}.C.V_m.T\right) = \nabla.\left(k_{nf}\nabla T\right) \tag{3}$$

where, ρ_{nf}, μ_{nf}, C_{nf} and k_{nf} are density, viscosity, heat capacity and thermal conductivity of nanofluid, respectively, $\vec{V}$ is the velocity vector, p is the pressure and T is the nanofluid temperature.

2-3. Thermophysical and rheological properties of nanofluids

Density and the effective heat capacitance were described by classical formulas developed for conventional solid–liquid mixtures. It was assumed that solid particles are well dispersed within the base fluid:

$$\rho_{nf} = (1 - \varphi)\rho_{bf} + \varphi\rho_p \tag{4}$$

$$\left(\rho C_p\right)_{nf} = (1 - \varphi)\left(\rho C_p\right)_{bf} + \varphi\left(\rho C_p\right)_{bf} \tag{5}$$

where, φ is the volume fraction of the solid particles, ρ and C_p are density and specific heat, respectively.

The nanofluids employed in this study were an aqueous solution of Carboxymethylcellulose(CMC) and Al_2O_3, TiO_2 and CuO nanoparticles with average particle sizes of 25, 10 and 40 nm, respectively. The rheological properties for various concentrations of non-Newtonian nano-fluids were extracted from the literature [12].

The base fluid and all nanofluids showed shear-thinning (Pseudoplastic) rheological behavior [2]. For shear thinning (Pseudo plastics) and shear thickening (Dilatant materials) non-Newtonian fluids, the apparent viscosity is generally expressed by the power law non-Newtonian model [7] as:

$$\eta = K\dot{\gamma}^{n-1} \tag{6}$$

where, η is non-Newtonian viscosity and $\dot{\gamma}$ is shear rate. K and n are the consistency index and the power law index, respectively. They can be obtained at various temperatures and solid particle concentrations from the literature [12].

In the current research the dimensionless numbers for non-Newtonian power-law behavior of nanofluids were:

$$Re = \frac{\rho.u^{2-n}.D^n}{K} \tag{7}$$

Prandtl number:

$$Pr = \frac{C_p.K.(u/D)^{n-1}}{k} \tag{8}$$

Peclet number:

$$Pe = \frac{\rho.C_p.u.D}{k} \tag{9}$$

2-4. Boundary conditions

At the tube inlet, axial velocity and temperature profiles were assumed, uniformly. Turbulent flow condition was applied for liquid phase. No-slip boundary condition was also applied at the walls. The fluid velocity at the wall boundary was set at zero. At the tube outlet, flow field is assumed to be fully developed. The tube wall temperature was maintained at a constant temperature. Flow and thermal fields were assumed symmetrical with respect to the axial plane.

2-5. Numerical method

In this research, two-dimensional computational fluid dynamics (CFD) was developed based on a single phase fluid system. The nanofluid (as a single phase fluid) with quite different physical properties such as density, thermal conductivity and viscosity was used. The fluid phase was assumed to be as a continuous phase. The numerical solutions for the governing equations were obtained using the finite volume method. The solver specifications for the discretization of the domain were the first-order upwind for momentum and energy, and SIMPLE algorithm for pressure–velocity coupling. In all cases, the residual terms for all of the equations were less than 10^{-6}.

In order to ensure that the calculated results are grid independent, three different grid distributions were tested. Fig.2 shows the results. As shown in this Figure, the convective heat transfer coefficient did not remarkably change for the grid numbers more than10×2000.

3. Results and discussion

Numerical simulation was carried out using the single phase model and in a wide range of Peclet number ($190000<Pe< 360000$), nanoparticle concentrations (0.2, 0.5 and 1% (V/V)) and particle sizes (10, 25 and 40 nm).Overall heat transfer coefficient and Nusselt number were calculated using the following equations:

$$h_{nf} = \frac{C_{p_{nf}} \cdot \rho_{nf} \cdot u \cdot A \cdot (T_{b2}-T_{b1})}{\pi \cdot D \cdot L \cdot LMTD} \tag{10}$$

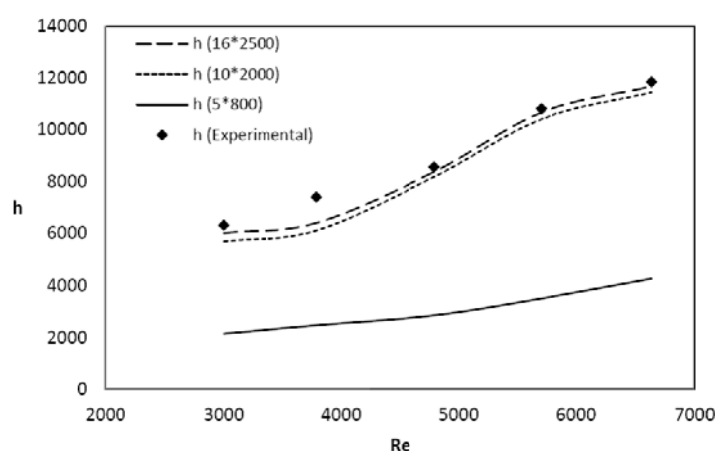$$Nu_{nf} = \frac{h_{nf} \cdot D}{k_{nf}} \tag{11}$$

Figure 2. Grids independency.

where T_{b1} and T_{b2} are inlet and outlet fluid bulk temperatures, respectively. LMTD is the logarithmic mean temperature difference and are calculated by:

$$LMTD = \frac{(T_w - T_{b1}) - (T_w - T_{b2})}{ln\left((T_w - T_{b1})/(T_w - T_{b2})\right)} \qquad (12)$$

T_w is wall temperature.

In order to evaluate the accuracy of the numerical method, the initial simulation was carried out on the pure water. The Nusselt number obtained from the initial simulation was compared with the experimental data [2]. The predicted Nusselt numbers obtained from the Dittus–Boelter equation for the turbulent flow (equation (13)) [13] were in good agreement with the experimental data.

$$Nu = 0.023 \, Re^{0.8} Pr^{0.4} \qquad (13)$$

Fig. 3 shows the results of the comparison. As shown in this Figure, the theoretical results obtained from the initial simulation(for pure water) were in good agreement with the experimental ones [2].

The mean errors between the experimental data [2] and the data calculated by Dittus–Boelter equation [13] and the initial simulation results (for pure water) were around 9 and 6%, respectively.

Fig. 4 represents the convective heat transfer coefficient versus Peclet number for various nanoparticle types and concentrations. The theoretical heat transfer coefficients were in good agreement with the experimental ones at various nanoparticle concentrations and Peclet numbers for all of the nanofluids. The results clearly show that nanoparticles addition remarkably increased the heat transfer coefficient. The heat transfer coefficient increased with nanoparticle concentration and Peclet number. The good agreement between simulated results and experimental data confirmed that the single phase model could satisfactorily predict the heat transfer coefficient for various types of nanofluids (nanoparticles with diameters less than 100 nm as considered in the current research).
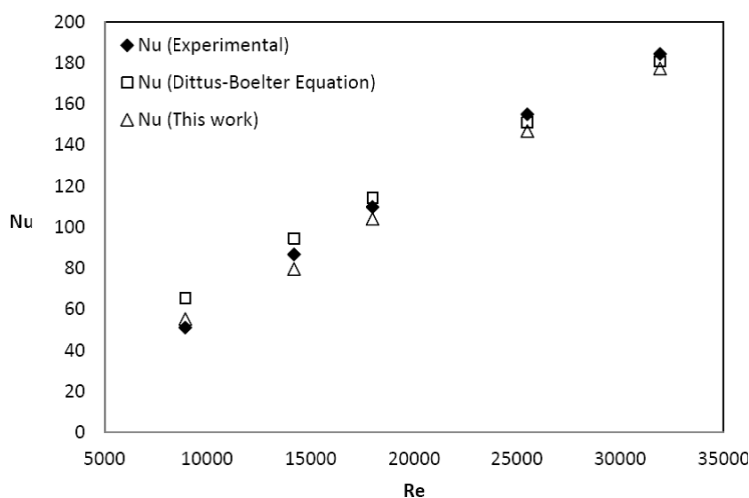
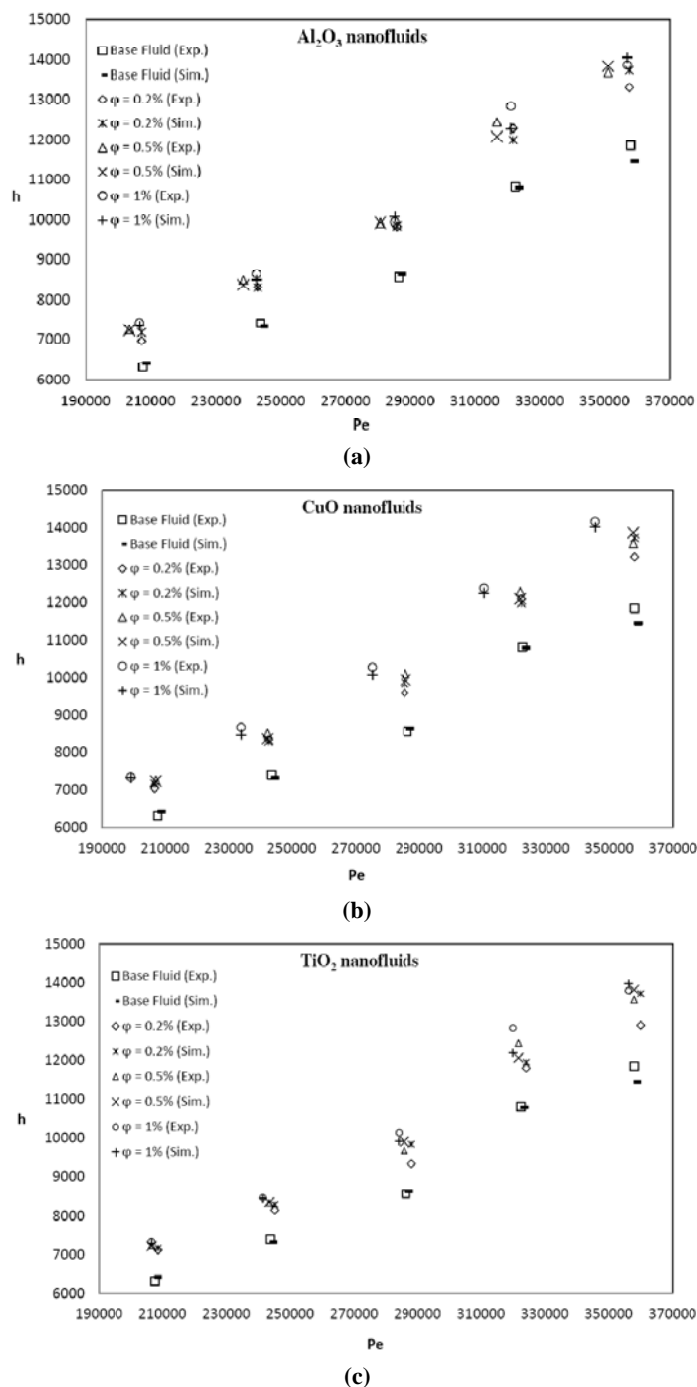**Figure 3.** Nusselt number of pure water versus Reynolds number.

(a)

(b)

(c)

Figure 4 (a-c). Comparison of the simulation results and experimental data [2].

Fig. 5 shows the ratio of convective heat transfer coefficient for various nanofluids to the non-Newtonian base fluid (h_{nf}/h_{bf}) versus Peclet number. It increased with the Peclet number. Furthermore, the shear thinning fluids viscosity decreased with the shear rate enhancement [14]. Since the average velocity and consequently the shear rate became larger at higher Peclet numbers, the apparent viscosity of the non-Newtonian nanofluids reduced. It caused the boundary layer thickness reduction and the heat transfer rate increment [15].
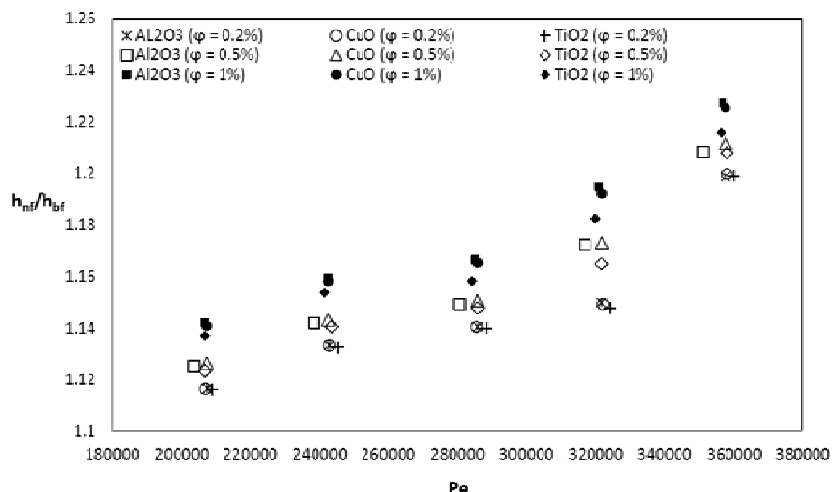
Figure 5. Ratio of computed heat transfer coefficient of nanofluids to the non-Newtonian base fluid versus Peclet number at various concentrations of nanoparticle.

It can also be seen that CuO and Al₂O₃ nanofluids in all of the nanoparticle concentrations, had almost an identical enhancement to the convective heat transfer coefficient while TiO₂ nanofluids had a slight heat transfer coefficient augmentation at high concentrations. This output is supported by literature [2].

Based on the simulation results, a new correlation for the Nusselt number of non-Newtonian nanofluids in a horizontal tube was developed by fitting the simulation results to a correlation equation:

$$Nu = C_1 (Re_{MR})^{C_2} Pr^{C_3} (1 + \varphi^{C_4}) \qquad (14)$$

where, Re_{MR} is the Metzner–Reid Reynolds number and is defined as [16]:

$$Re_{MR} = \frac{\rho u^{2-n} D^n}{8^{n-1} K \left(\frac{3n+1}{4n}\right)^n} \qquad (15)$$

By fitting the simulation results to equation (14):

$$Nu = 0.0176(Re_{MR})^{0.8723} Pr^{0.2246} (1 +$$
$$\varphi^{0.4366} \qquad 100 < ReMR < 16400 \quad 49 < Pr < 81 \qquad (16)$$

Fig. 6 shows a comparison between the correlated heat transfer coefficient predicted by equation (16), the experimental data [2] and the results obtained from the literature [17] for heat transfer of purely viscous fluids in the turbulent region:

$$St = \frac{h}{\rho u C_p} = 0.0152(Re_{MR})^{-0.155} Pr^{-2/3}$$

$$(17)$$

Re_{MR} is the Metzner–Reid Reynolds number[16].

As shown in these Figures, the correlated heat transfer coefficients were in good agreement with the experimental data. Furthermore, it is clear that the equation for heat transfer of single phase and non-Newtonian fluids is not able to predict accurate results for the heat transfer of non-Newtonian nanofluids.

Fig. 7 shows the correlated Nusselt number data obtained from equation (16) for the nanofluids. The correlated data were in good agreement with the simulated ones. The average and maximum errors were 4.4 and 8.9%, respectively.
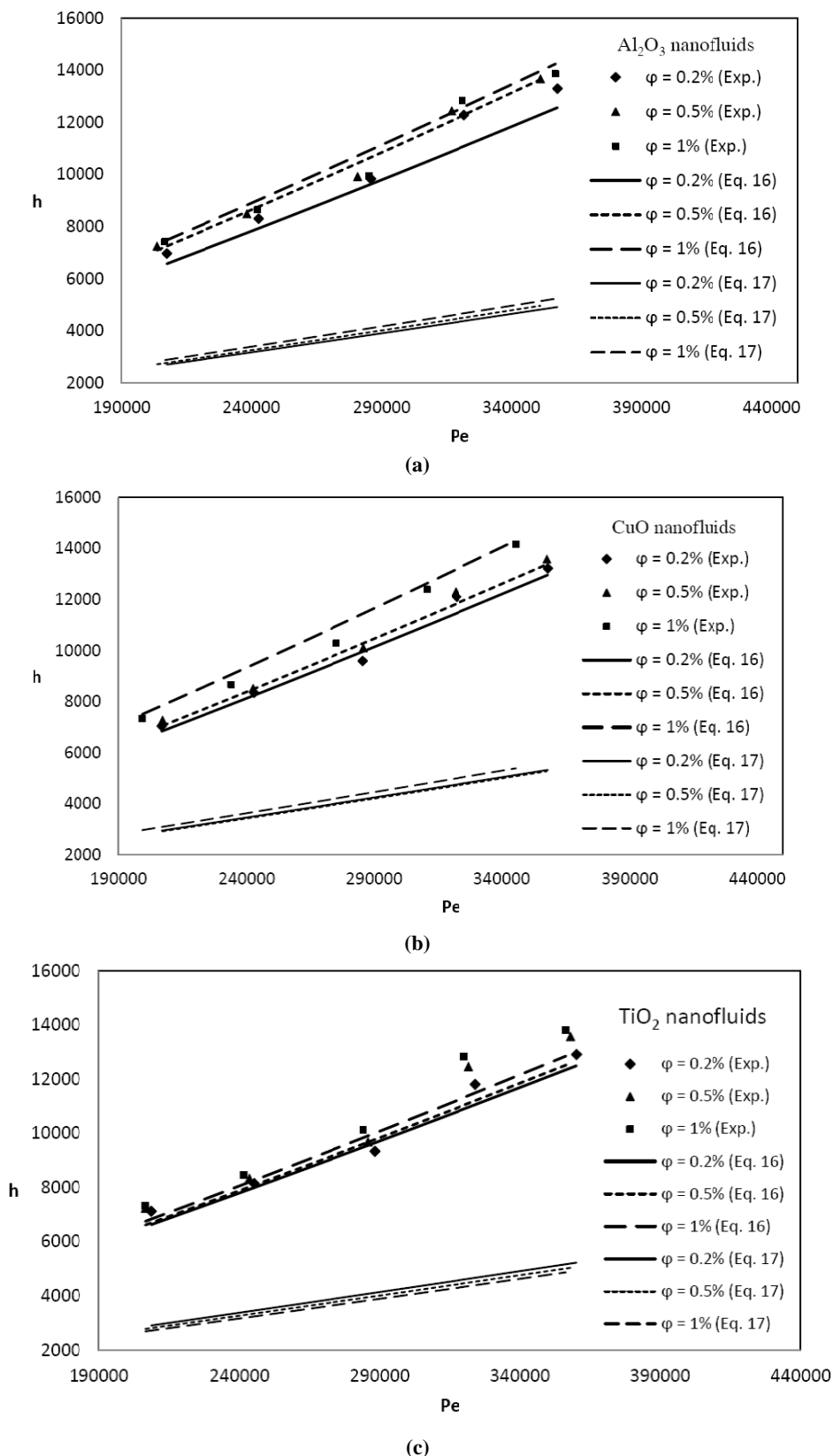
(a)

(b)

(c)

Figure 6 (a-c). Comparison between predicted data and the experimental data of convective heat transfer coefficient of nanofluids.
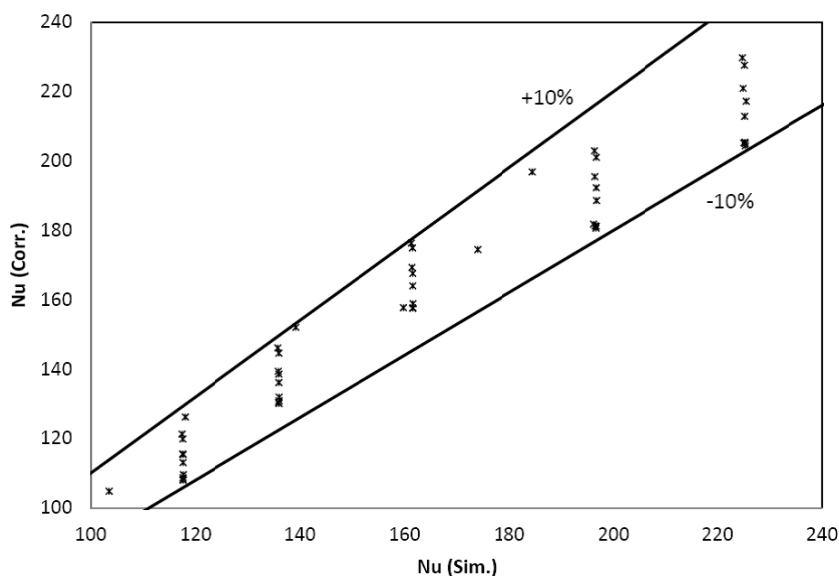
Figure 7. Comparison between predicted data and simulated results.

Fig. 8 illustrates the heat transfer coefficient obtained from equation (16), Dittus-Boelter's equation [13], and Pak and Cho's equation (equation (18)) [18].

$$Nu = 0.021\, Re^{0.8} Pr^{0.5} \qquad (18)$$

The comparison between the correlated Nusselt number obtained from equation (16) and the experimental data [2] showed average and maximum errors of 4% and 11.7%, respectively.
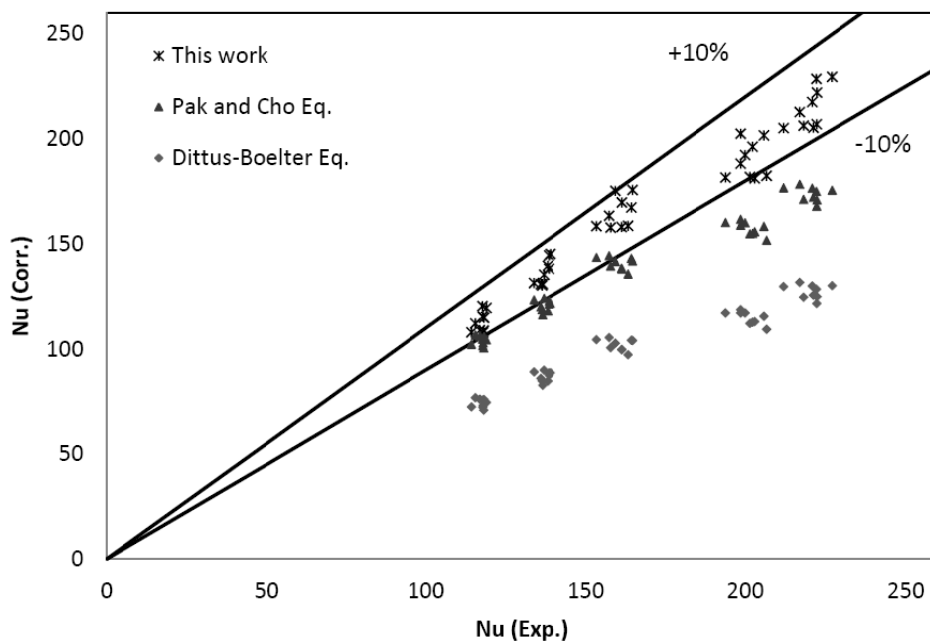

Figure 8. Nusselt number comparison for the nanofluids.

4. Conclusions

In this paper, the convective heat transfer coefficient in the turbulent flow regime under constant wall temperature conditions for non-Newtonian nanofluids consisting of Al_2O_3, CuO, and TiO_2 suspensions in an aqueous solution of CMC were simulated using CFD. Simulated results showed that increasing in the nanoparticle concentration and Peclet number led to an enhancement in the heat transfer coefficient of the nanofluids. There was a good concurrence between the results obtained from the simulation and the experimental data in various ranges of Peclet number for nanofluids. A good agreement between the predicted results and experimental data confirmed the accuracy of the numerical prediction presented in this research. The maximum error was less than 12%.

Nomenclature

A   Heat transfer area (m^2)

C   Specific heat (kJ/kg.K)

D   Tube internal diameter (m)

d_p Particle diameter (m)

h   Heat transfer coefficient (W/m^2 K)

k   Thermal conductivity (W/m K)

K   Consistency index (Pa s^n)

L   Tube length (m)

LMTD   Logarithmic mean temperature difference (K)

N   Power law index

Nu   Nusselt number: $Nu = \frac{hD}{k}$

P   Pressure (Pa)

Pr   Prandtl number: $Pr = \frac{C_p.K.(u/D)^{n-1}}{k}$

Re   Reynolds number: $Re = \frac{\rho.u^{2-n}.D^n}{K}$

T   Temperature (K)

T_{b1} Inlet bulk temperature of fluid (K)

T_{b2} Outlet bulk temperature of fluid (K)

T_w Wall temperature (K)

u   Fluid average velocity (m/s)

Greek symbols

α Thermal diffusivity

φ Particle volume concentration

$\dot{\gamma}$ Shear rate (1/s)

ρ Density (kg/m^3)

Subscripts

bf   Base fluid

nf   Nanofluid

p   Particle

w   Wall

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