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Numerical study on influence of a type of nanoparticles and volume fraction on turbulent heat transfer coefficient and pressure loss inside a tube

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ABSTRACT: Conventional liquids have some limitations regarding the thermal properties. The nanoparticles addition is one of the techniques which can transcend them. In this research, heat transfer coefficient (h) and pressure loss (Δp) of various nanofluids containing Al2O3, SiO2, and MgO nanoparticles dispersed in water in an annular tube with constant wall temperature is considered. According to the literature, five different nanofluid volume concentrations (1%, 2%, 3%, 4% and 5%) are selected. Two models involving the mixture and VOF are applied, and the results are compared. The average convective heat transfer coefficient and pressure loss is enhanced with volume fraction and Reynolds number (Re) increment (3000<Re<10000) although the friction factor (f) is decreased. It is concluded that the simulated data for pressure loss and heat transfer coefficient were in good agreement with the experimental ones specially for SiO2 nanoparticles (particularly in low concentrations). The SiO2 nanofluid showed the best heat transfer compared to the other nanofluids. Moreover, the simulated data obtained from the mixture method showed more agreement with the experimental ones specially the high Reynolds numbers.

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1- Introduction

A nanofluid is a fluid containing suspended solid particles with nanometer dimensions (1–100 nm) [1]. Nanofluids can be considered as a new class of solid-liquid composite materials consisting of solid nanoparticles. Typical nanoparticles in water-based nanofluids are metals and oxides such as Al_2O_3, SiO_2, MgO, etc. Normally, nanofluids have higher thermal conductivity than their base fluids [2-5].

According to a research done by Ting and Hou, the heat transfer is increased with increasing particles concentration and Peclet number [6]. In another research, the heat transfer is increased with adding nanoparticles in a fluid [7]. Furthermore, heat transfer coefficient is increased with increasing the nanoparticle concentration in a nanofluid. The natural convection of water-based nanofluid in a square cavity was numerically studied in the literature [8]. In the recent paper, the nanofluid-oriented model for calculation of the effective thermal conductivity and another model for the effective dynamic viscosity calculation were applied.

The friction factor and forced convection heat transfer of TiO_2 nanoparticles dispersed in water of a car's radiator were numerically determined. The Reynolds number (from 10000 to 100000) and inlet temperature (from 60 to 90 °C) were studied in this research. The results showed that the friction factor is decreased with increasing the Reynolds number and concentration. The TiO_2 nanoparticles at low concentrations can increase the heat transfer efficiency up to 20% compared with the pure water [9]. According to a research done by Davarnejad and Jamshidzadeh, the Nusselt number is increased with increasing the volume fraction of nanofluid [10].

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In another research, the thermal conductivity, viscosity and turbulent heat transfer behavior of Magnesium Oxide-water nanofluid in a circular pipe (when volume fraction of nanoparticle in the base fluid was less than 1%) were experimentally investigated [11]. The most of the conventional models were unable to predict the thermal conductivity and dynamic viscosity of MgO-water nanofluid.

In the current research, a new correlation for the dynamic viscosity prediction was applied. The simulation was carried out in a fully developed turbulent regime. The conditions were exactly extracted from the experimental work [12]. The simulated data (obtained from two models: mixture and VOF model) were compared with each other and the experimental ones.

2- Simulation

A heat exchanger applied in the literature [12, 13] was simulated by Fluent software (version: 6.3.26). It was an annular tube with constant wall temperature (78 °C). Its length and diameter of tube were 1.5 m and 0.64 cm, respectively. The initial temperature of nanofluid was 25 °C.

Gambit was applied under the Fluent software [14]. The tube was meshed with an interval count option. The mesh number in the vertical and horizontal directions were respectively found at 0.001067 and 0.03 according to the tube dimensions and interval count amount.

In Computational Fluid Dynamics (CFD), the Volume of Fluid (VOF) method is a numerical technique for tracking and locating the free surface (or fluid-fluid interface). In fact, it is a numerical recipe which allows the programmer to track the shape and position of interfaces. The Navier-Stokes equations are also solved to analyze the flow motion [15].

A nanofluid contains small particles without phase separation

Table 1. Nanoparticles properties

Nanoparticle	Density (kg/m3)	Specific heat capacity (J/ kg. K)	Molecular weight (kg/ kgmole)	Conductivity [kg/(m. s)]
Al_2O_3	4100	880	101.963	35
MgO	3580	960	40.312	45
SiO_2	2200	733	60	1.38

Table 2. Friction factor compared with the base fluid (Re = 3000-10000)

	Nanoparticle volume fraction percentage				
Nanoparticle type	0.005	0.01	0.02	0.03	0.04
Al_2O_3 (experiment)	-1%	-0.2%-0.9%	-1.6%-(-0.9%)	-1.9%-0.1%	-1%
Al_2O_3 (mixture)	-0.003٪	-0.11٪	-0.15٪	-0.18٪	-0.25٪
Al_2O_3 (VOF)	≅0	-0.07٪	-0.12٪	-0.15٪	-0.25٪
MgO (experiment)	0.2%-7%	1%-2.9%	-0.1%-5.2%		
MgO (mixture)	-0.032٪	-0.11٪	-0.16٪		
MgO (VOF)	≅0	-0.07٪	-0.12٪		
SiO_2 (experiment)	(-4.6%)-(+0.6%)	(-4.9%)-(-2%)	-8.1%-(-1.1%)	(-8.2%)-(-0.6)٪	-2.2%-7.6%
SiO_2 (mixture)	-2.2%	-4.58%	-10.54%	-12.31%	-16.32%
SiO_2 (VOF)	0.02%	-3.69%	-7.78%	-10.3%	-14.79%

and sedimentation. It also shows a dramatic new property [16]. Table 1 shows nanoparticles data. The particles were assumed to be in a spherical shape. Therefore, ψ and n are 3 and 1, respectively [17]. The nanofluids characteristics can be obtained from the following equations [18,19]:

$$c_{p,nf} = \frac{\varphi c_{p,p} \rho_p + (1-\varphi)\rho_{bf} c_{p,nf}}{\rho_{nf}} \quad (1)$$

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_f \quad (2)$$

$$\frac{k_{nf}}{k_f} = \frac{k_p + (n-1)k_f + (n-1)\varphi(k_p - k_f)}{k_p + (n-1)k_f - \varphi(k_p - k_f)} \quad (3)$$

Furthermore, a model which predicts the nanofluid viscosity is presented as [20]:

$$\mu_{nf;wang} = \left(1 + 7.3\varphi + 123\varphi^2\right)\mu_f \quad (4)$$

where, μ and μ_f are nanofluid and water viscosity, respectively.

The friction factor (f) is determined by [21]:

$$f = 2\Delta p d / \rho v^2 l \quad (5)$$

where Δp denotes the pressure loss.

3- Results and Discussion

The convective heat transfer and pressure losses grow by adding nanoparticles to the base fluid. According to the literature, pressure loss is increased with Reynolds number and volume fraction increment [13].

Table 2 shows friction factor (f) for nanofluids and base fluid (water) in the turbulent region. The friction factor is increased with increasing the pressure loss and nanoparticles volume fraction in the pipe [12, 22]. As shown in equation (5), there is a direct relation between the friction factor and the pressure loss. A sharper difference was also observed between SiO_2 nanofluid and the base fluid. Its reason may be due to having smaller size of SiO_2 nanoparticles compared with the other ones.

Fig. 1 shows the enhancement of simulated data for pressure loss at various nanoparticles concentration versus Reynolds number. As shown in Fig. 1, simulated data (for pressure loss) are in good agreement with the experimental ones in specially for SiO_2 (Maximum error is 18% and minimum error is 1.02%). Furthermore, the simulated data obtained from the mixture method is in more agreement with the experimental ones in the higher Reynolds numbers. It also needs a shorter convergence time. Its reason may be due to having more homogenous solution in the high Reynolds numbers [13, 21]. The heat transfer coefficient of all nanofluids is significantly higher than that of the base fluid. The experimental results illustrate that addition of flow value of nanoparticles to pure water (around 0.0625%) improved the heat transfer performance significantly [13].

Fig. 2 shows simulated data for turbulent heat transfer coefficient of nanofluid for various nanoparticles concentration versus Reynolds number. As shown in Fig. 2, the simulated data for heat transfer coefficient is increased with increasing the Reynolds number and the nanoparticle concentration.

The simulated data for turbulent heat transfer coefficient are in good agreement with the experimental ones specially for SiO_2 (the maximum error is 14% and minimum error is 3.8%). The simulated data more agree with the experimental ones in low velocities.

The MgO-water nanofluids at five different volumetric concentrations (1%, 0.5%, 0.25%, 0.125% and 0.0625%) were examined. The Reynolds number varied from 3200 to

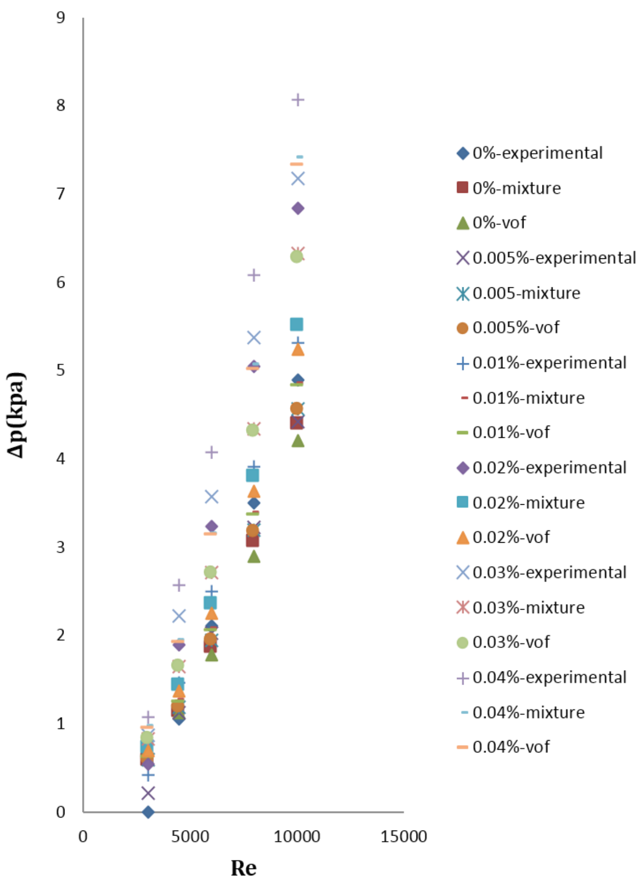

Fig 1. Pressure loss of SiO2 nanofluids versus Reynolds number

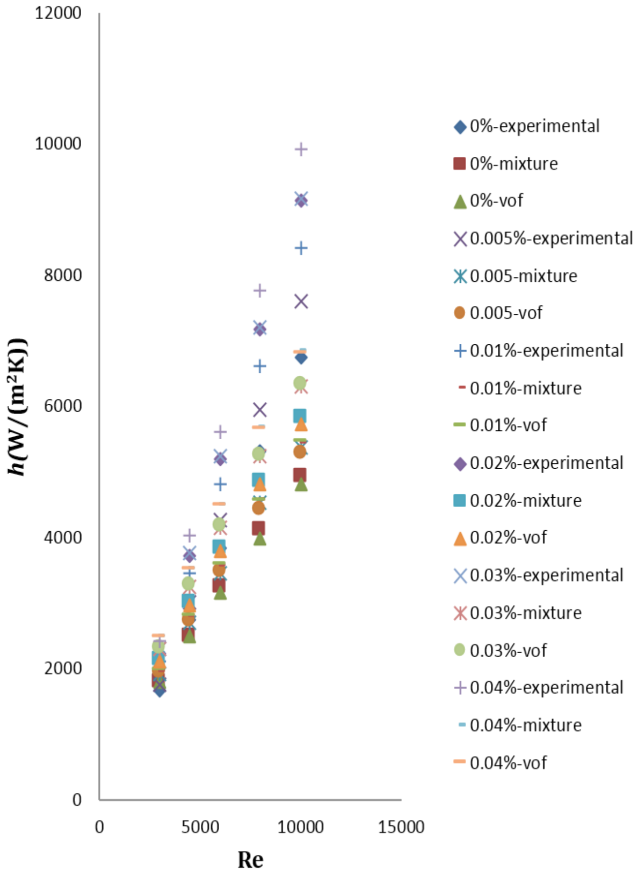

Fig 2. Turbulent heat transfer coefficient of SiO2 nanofluids versus Reynolds number

19000. It was observed that the heat transfer coefficient of all nanofluids is significantly higher than that of the base fluid. The experimental results illustrate that adding low value of nanoparticles to pure water improves the heat transfer performance significantly [11].

Table 3 shows nanofluid turbulent heat transfer coefficient compared with the base fluid (3000<Re<10000). It was obtained that the heat transfer coefficient increases for all of nanofluids (compared with the base fluid) by the volume fraction increment [12]. According to a research carried out with applying a two-phase mixture model, finite volume method, and second-order upstream difference scheme, the convective heat transfer coefficient increases and the surface friction coefficient of an inclined tube decreases with increasing the Reynolds number. Furthermore, the convection heat transfer coefficient increases with increasing the volume fraction of nanoparticles [23]. According to another simulation work on Al_2O_3, TiO_2 and SiO_2 nanofluids, the friction factor and Nusselt number increases with increasing the volume concentration [24].

4- Conclusions

It was concluded that the convective heat transfer coefficient increases with the nanoparticle volume fraction increment up to 4% in the turbulent regime. The applied Reynolds number varies in the interval [3000 10000]. The data were obtained from the two models (involving VOF and mixture) and compared. According to the experimental work [10] and out simulation, the heat transfer coefficient and the pressure loss increases with increasing volume fraction of nanofluids, although friction factor (f) was decreased. The simulated data for pressure loss and heat transfer coefficient are in good agreement with the experimental ones specially for nano-SiO_2 (particularly in low concentrations). Furthermore, the SiO_2 nanoparticles showed the best heat transfer. The simulated data obtained from the mixture method showed more agreement with the experimental ones [13] specially in high Reynolds numbers.

Nomenclature

C_p	specific heat, J/kg K
μ	viscosity, pa.s
ρ	density, kg/m^3
f	friction factor
φ	nanoparticles volume fraction
Δp	pressure drop, kpa
ψ	particle sphericity
d	tube diameter, m
K	thermal conductivity, W/m
K_n	empirical shape factor
v	mean velocity, m/s
l	tube length, m

Subscripts

bf	base fluid
nf	nanofluid
p	particle

Table 3. Nanofluid turbulent heat transfer coefficient compared with the base fluid (Re = 3000-10000)

	Nanoparticle volume fraction percentage				
Nanoparticle type	0.005	0.01	0.02	0.03	0.04
Al_2O_3 (experiment)	10.50%	6.6%-28.4%	15.3%-32.5%	33.5%-40.2%	46.3%
Al_2O_3 (mixture)	12.55%	21.83%	34.11%	44.9%	53.76%
Al_2O_3 (VOF)	11.77%	32.08%	33.38%	43.15%	49.73%
MgO (experiment)	(-2.8%)-(+9.9%)	6.3%-24.6%			
MgO (mixture)	16.53%	24.81%			
MgO (VOF)	15.64%	24.19%			
SiO_2 (experiment)	10.4%-15.5%	23.2%-28.2%	23%-32.6%	23.7%-35.1%	26.4%-46.7%
SiO_2 (mixture)	8.03%	10.73%	18.65%	27.94%	39.26%
SiO_2 (VOF)	9.90%	13.54%	19.20%	31.11%	41.32%

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