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Simulation of Convective Heat Transfer of a Nanofluid in a Circular Cross-section

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ABSTRACT

The CFD simulation of heat transfer characteristics of a nanofluid in a circular pipe under convective heat transfer was considered using the fluent software (version 6.3.26) in the laminar flow. Al_2O_3 nano-particles in water with concentrations of 0.5, 1.0, 1.5, 2 and 2.5% were studied in the simulation. All thermo-physical properties of nanofluids were temperature independent. It was concluded that heat transfer coefficient increased with the Peclet number. Furthermore, the effect of nano-particles concentration on the convective heat transfer coefficient was theoretically investigated and the results were compared with the experimental data obtained from the literature. The maximum convective heat transfer coefficient was observed at the highest concentration of nano-particles in water (2.5%). The simulated data were in good agreement with the literature (with the discrepancy of less than 10%).

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NOMENCLATURE

D	Tube diameter (m)	**Subscript**	
k	Thermal conductivity (W/m.K)	w	Wall
Nu	Nusselt number	nf	Nanofluid
Pr	Prandtl number	bf	Base fluid
Pe	Peclet number	In	Inlet
Re	Reynolds number	p	Particle
T	Temperature (K)	Out	Outlet
X	Distance along axis (m)	∞	Bulk fluid
P	Pressure	**Greek Letters**	
L	Pipe length (m)	μ	Viscosity (Pa.s)
V	Volume (m^3)	ϕ	Volume fraction
C	Specific heat ($J/(kg.K)$)	ρ	Density (kg/m^3)

1. INTRODUCTION

Fluid heating and cooling play important role in many industrial processes such as power stations, production processes, transportation and electronics. Most of the methods for heat transfer are based on the structure variation, vibration of the heated surface, injection or suction of fluid and applying electrical or magnetic fields [1-3]. These techniques meet a great increase in heat flux. Heat transfer in the traditional fluids such as water, ethyleneglycol and oil inherently has low thermal conductivity compared to the metals and metal oxides. Therefore, fluids with suspended solid particles are expected to have better heat transfer properties [4].Due to the associated technological problems, the majority of studies on heat transfer of suspension of metal oxides in fluids were limited to suspensions with millimeter or micron-sized particles. The large particles may cause severe problems in the heat transfer equipments. In

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particular, large particles quickly tend to settle out. So, pressure drop can occur in the micro-channels [5]. Furthermore, the abrasive actions of the particles cause erosion of components and pipe lines. Small particles and their little volume fractions prevent particles clogging and pressure drop increment in the nanofluids [5, 6]. Furthermore, large surface area of nano-particles increases the stability and reduces the sedimentation of nano-particles. A more dramatic improvement in heat transfer efficiency is expected as a result of the particle size reduction in a suspension because heat transfer takes place at the particles surface [7]. Choi and Eastman [8] employed the particles in nanometer dimensions as a suspended solution. They showed that the nanofluid thermal conductivity considerably increased. Lee et al. [9] showed that the suspension of 4.0% with 35 nm CuO particles in ethylene glycol had 20% increment in the thermal conductivity. Choi et al. [10] observed 60% enhancement in the thermal conductivity of engine oil with 1.0% carbon nano-tube. Das et al. [11] investigated the temperature dependency of thermal conductivity in the nanofluids. It was observed that a 2-4 fold increase in the thermal conductivity of nanofluid can take place over a temperature range of 21-51 ºC. Alumina and copper oxide are the most ordinary and cheap nano-particles which are used in the applied processes [12]. Xuan and Li [13,14] experimentally studied the convective heat transfer and friction coefficient for the nanofluid in both laminar and turbulent flows. According to this research, the flow velocity and volume fraction of nano-particles affected the heat transfer coefficient. Wen and Ding [15] investigated the convective heat transfer characteristics in Al_2O_3-water nanofluid along the copper tubes. It was observed that heat transfer increased by increasing the Reynolds number and volumetric ratio of particles. Abu-Nada [16] investigated the effects of variable viscosity and thermal conductivity of a nanofluid (Al_2O_3-water) on the natural convective heat transfer. Sharma et al. [17] experimentally studied the convective heat transfer coefficient and pressure drop in the transient region for Al_2O_3-water nanofluid under a constant heat flux. They found that convective heat transfer increased by adding Al_2O_3 nano-particles in water. Mirmasoumi and Behzadmehr [18] numerically studied the convective heat transfer in a fully developed flow for Al_2O_3-water nanofluid. They applied two-phase mixture model. The convective heat transfer coefficient significantly increased by decreasing the nano-particles mean diameter. Since the theoretical models such as Maxwell and Hamilton-Crosser [19-21] predict the thermal conductivity of nanofluids, the mechanisms of thermal conductivity enhancement in the nanofluids should be studied. Khoddamrezaee et al. [22] simulated ethylene glycol and Al_2O_3 nanofluid through a shell and tube heat exchanger with the constant heat flux. They compared the stagnation point, separation point, heat transfer coefficient and shear stress of nanofluid with the pure fluid.

In the present work, the convective heat transfer in the developed region of a pipe (containing water and Al_2O_3 nano-particles) was simulated using the Computational Fluid Dynamics (CFD). According to the experimental work published by Zeinali Heris et al. [7], Al_2O_3 nano-particles with an average diameter of 20 nm were studied. Five different concentrations of Al_2O_3 (0.2, 1.0, 1.5, 2.0 and 2.5% volume fractions) were also chosen according to the published work. The effect of nano-particle concentrations on the convective heat transfer coefficient was theoretically investigated and the results were compared with the experimental data.

2. MATHEMATICAL MODELING

The nanofluid as a single phase fluid with different physical properties such as density, thermal conductivity and viscosity was used. The fluid phase was assumed to be a continuous phase. Flow and heat transfer are considered by the continuity, momentum and energy equations [23]. They are given as following:
Continuity equation:

$$\nabla.(\rho_{nf} V_m) = 0 \quad (1)$$

Momentum equation:

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

Energy equation:

$$\nabla.(\rho_{nf} V_m TC) = \nabla(k_{nf} \nabla T) \quad (3)$$

The physical properties for above equations can be obtained [24]:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \quad (4)$$

The effective heat capacity is calculated by [25]:

$$C_{nf} = \frac{\phi(\rho C)_p + (1-\phi)(\rho C)_{bf}}{\rho_{nf}} \quad (5)$$

The viscosity of nanofluid (20 nm) can be predicted by Einstein's equation:

$$\mu_{nf} = \mu_{bf}(1+2.5\phi) \quad (6)$$

Thermal conductivities for various concentrations of nanofluid were extracted from the literature [7]. Yu and Choi's correlation [26, 27] was applied for the nanofluid effective thermal conductivity determination:

$$k_{nf} = \left[\frac{k_p + 2k_{bf} + 2(k_p - k_{bf})(1+\beta)^3\phi}{k_p + 2k_{bf} - (k_p - k_{bf})(1+\beta)^3\phi}\right] \quad (7)$$

where, β is the ratio of the nano-layer thickness to the original particle radius; β= 0.1 was used to calculate the nanofluid effective thermal conductivity [26].The rheological and physical properties of the nanofluid were calculated at the mean temperature. As shown in Figure 1, a two- dimensional pipe (with 1m length and 6 mm inner diameter) was spotted in our simulation. The single phase approach was used for nanofluid simulation and effect of nano-particle concentration on the convective heat transfer coefficient was investigated at various Reynolds numbers (700<Re<2050).The convective heat transfer coefficient of 3000 ($W/m^2.K$) as aboundary condition at the pipe wall was applied [7].

3. CFD SIMULATION PROCEDURE

The geometry and the gird were generated using GAMBIT the preprocessing module of the FLUENT (version 6.3.26). GAMBIT is an integrated preprocessor for CFD analysis. The sequences of GAMBIT steps are shown in Figure 2(a). There were 20 meshes in the radial direction with a size ratio of 1 from the center to the wall. Further, there were 1000 meshes in the horizontal direction with an average size. Figure 2(b) demonstrates the meshes generation. The physical boundary conditions for the geometry are defined as inlet, outlet and wall of pipe. The continuum is the fluid. Then, the mesh file is successfully conducted into the FLUENT (version 6.3.26).

For single phase approach, solid particles with diameter less than 100 nm were spotted. Therefore, single phase approach was adopted for nanofluid modeling [28]. The convective heat transfer was assumed on the pipe wall (boundary condition). The fluid was entered the pipe with a constant velocity in each experiment. The initial temperature of fluid (at t=0) was 25 °C. The symmetric option was chosen in the software.

4. RESULTS AND DISCUSSION

Numerical simulation was carried out in various Reynolds numbers and particle concentrations (0.2, 1, 1.5, 2 and 2.5 volume fraction). Local heat transfer coefficient and local Nusselt number were calculated using the following equations:

$$Nu(x) = \frac{h(x)D}{k} \quad (8)$$

$$h_{nf}(x) = \frac{\pi L h D_{out}(T_\infty - T_w)}{\pi L D_{in}(T_w(x) - T_{nf}(x))} \quad (9)$$

where h_{nf} , k, T_W, D_{out}, D_{in} , T_{nf} and T_∞ are nanofluid heat transfer coefficient, thermal conductivity of the fluid, tube wall temperature, pipe outer diameter, inner diameter, nanofluid temperature and bulk fluid temperature, respectively. Figure 3(a) and (b) show temperature distribution at the end of pipe for velocity of 0.0634 and 0.1502 (m/s) (or Re=377 and 895.4) for nanofluid (with the particle diameter of 20 nm and concentration of 0.2 volume fraction). The nanofluid was heated by the pipe wall and its temperature increased along the pipe. The temperature of nanofluid along the pipe at Reynolds number of 377 varied sharper than that of Reynolds number of 895.4. Its reason was due to magnifying the heat transfer coefficient [24]. Figure 4 shows heat transferr coefficient of nanofluid versus Peclet number at various concentrations. As shown in this figure, there was an excellent agreement between the simulated results and the experimental data in the smaller Peclet numbers [28]. Figure 5 (a) and (b) show heat transfer coefficient in the tube versus volume fraction at various Peclet numbers. According to these figures, heat transfer coefficients (experimentally and theoretically) increased by increasing the volume fraction and Peclet number.

4. 1. Heat Transfer Correlation The convective heat transfer of nanofluid depends on various parameters such as thermal conductivity, heat capacity, viscosity, particles volumetric fraction and axial location. Nusselt number in a horizontal pipe as a function of the Reynolds number (700≤Re≤2050), Prandtl number (Pr), particles volume fraction (φ), and axial location [(x/D): pipe horizontal distance (x) per pipe diameter (D)] was correlated using the simulated data.

$$Nu = 0.18665\phi^{-0.00728}(x/D)^{0.1036}\,\mathrm{Re}^{0.368718}\,\mathrm{Pr}^{0.3992} \quad 10$$

Figure 6 shows the correlated Nusselt number data obtained from Equation (10) for the nanofluid. As shown in this figure, the correlated Nu data were in good agreement with the simulated ones. The maximum error was around 3%. As shown in Figure 7, Nusselt number data from our correlation were compared with the other data obtained from Seider-Tate's equation [29]. Comparison between the correlated Nusselt number data obtained from our correlation and the experimental data [7] showed maximum and minimum errors of 14% and 0.82%, respectively.

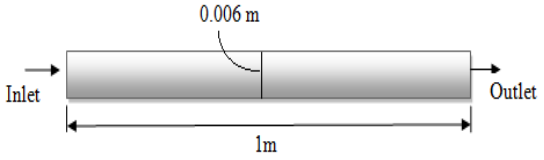


Figure 1. Pipe numerical domain

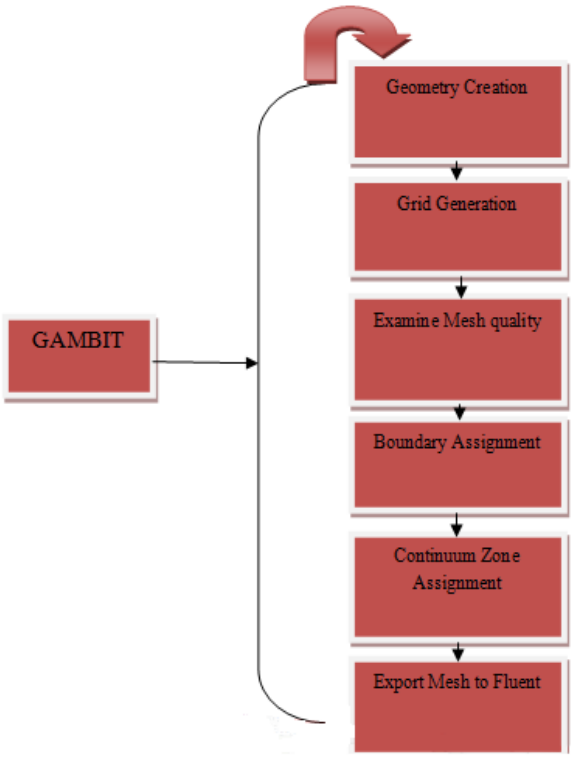


Figure 2 (a). GAMBIT steps during meshes generation

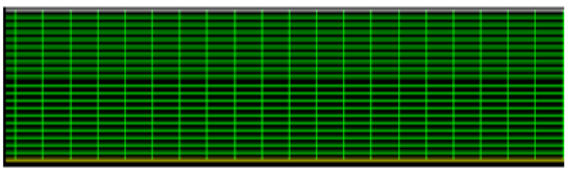
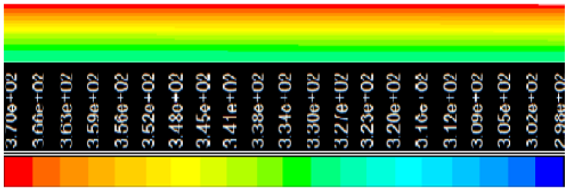
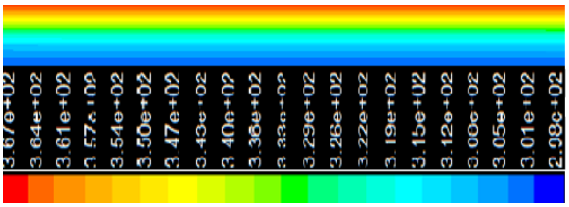


Figure 2 (b). Meshes generation obtained from CFD



(a) U=0.0634 (m/s)



(b) U=0.1502 (m/s)

Figure 3 (a) and (b). Temperature map at the end part of the pipe for the nanofluid

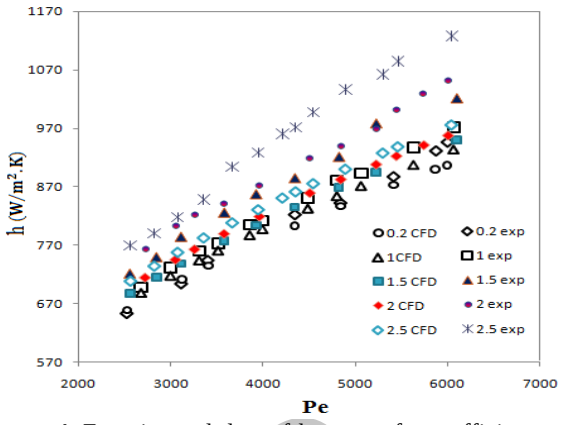
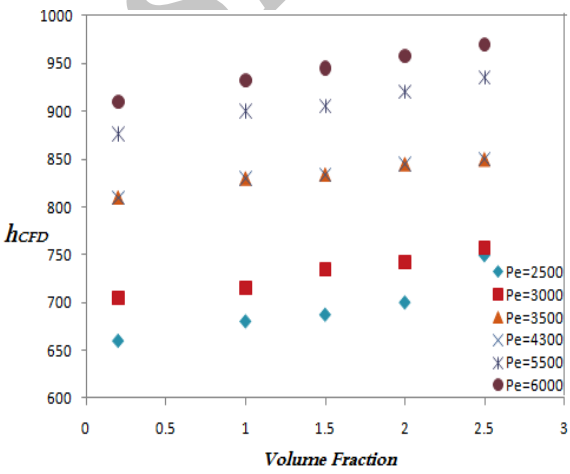
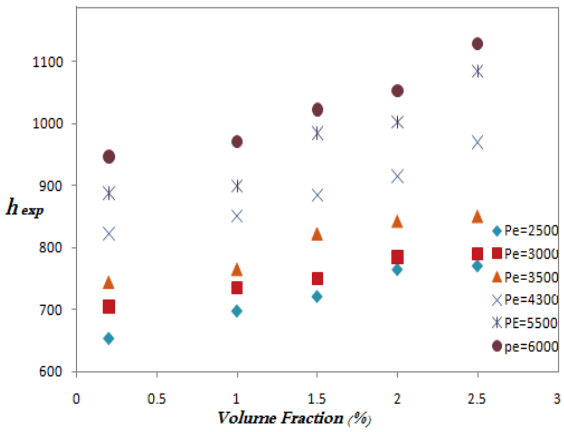


Figure 4. Experimental data of heat transfer coefficient and simulated ones for Al_2O_3-water nanofluid versus Peclet number at various volume concentrations



(a)



(b)

Figure 5 (a) and (b). Heat transfer coefficients from CFD (a) and experiment (b) for Al_2O_3-water nanofluid versus volume fraction (%) at various Peclet numbers

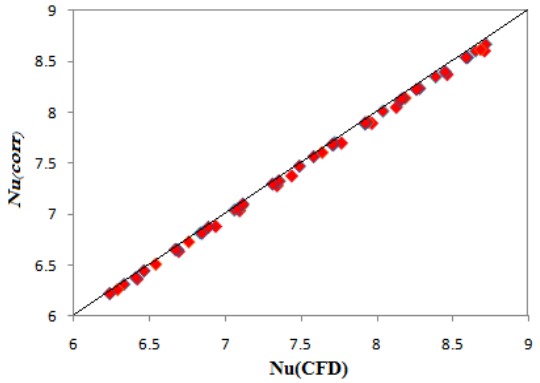


Figure 6. Prediction of simulated and correlated data for the Nusselt number

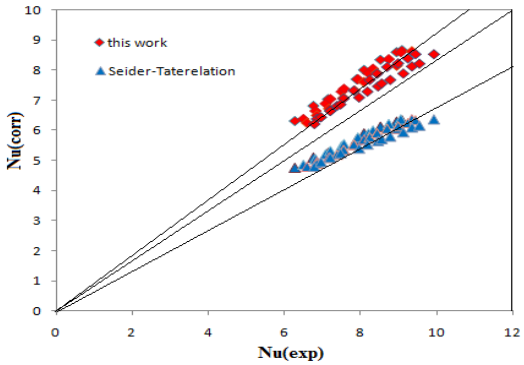


Figure 7. Nusselt number comparison for the nanofluid

5. CONCLUSIONS

In this article, the heat transfer coefficient in the developed region of pipe flow containing Al_2O_3-water nanofluid during the convective heat transfer was simulated using CFD. The results showed that the heat transfer coefficient enhanced by increasing the nano-particle concentration and Peclet number. A good agreement between the results obtained from the simulation and experiment was observed in the smaller Pe numbers. A correlation based on the CFD was developed for the Nusselt number. An excellent agreement between the correlation and experimental data obtained from the literature was found. According to this research, the CFD is dramatically able to simulate heat transfer in a pipe with a nanofluid.

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چکیده

ویژگی های انتقال حرارت نانو فلوئید در یک لوله مدورتحت انتقال حرارت جابه جایی با استفاده از نرم افزار فلوئنت (نسخه ۶.۳.۲۶) در جریان آرام شبیه سازی شده است. نانو ذرات در آب با غلظت های ۰.۵ , ۱ , ۱.۵, ۲ و ۲.۵ در شبیه سازی استفاده شده است .وهمه ی خاصیت های ترموفیزیکی نانو فلوئید مستقل از دما می باشد.در این کار نتیجه گرفته شد که ضریب انتقال حرارت با افزایش عدد پکلت افزایش می یابد .و همچنین اثر غلظت نانو ذرات بر روی ضریب انتقال حرارت جابجایی بطور تئوری بررسی شد و نتایج با داده های آزمایشگاهی بدست آمده از مقاله چاپ شده مقایسه شد. حداکثر ضریب انتقال حرارت جابجایی در بالاترین غلظت نانو ذرات در آب (٪۲.۵) مشاهده شد. داده های شبیه سازی شده هماهنگی خوبی با داده های مقاله منتشرشده اصلی داشتند (با خطایی کمتر از ٪۱۰).

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