Korean J. Chem. Eng., **28**(12), 2230-2235 (2011)
DOI: 10.1007/s11814-011-0103-8

Turbulent convective heat transfer of nanofluids through a square channel

Mohammad Nasiri, Seyed Gholamreza Etemad[†,‡], and Rohollah Bagheri

Department of Chemical Engineering, Isfahan University of Technology, Isfahan 84154-83111, Iran
(*Received 27 January 2011 • accepted 19 April 2011*)

Abstract−This paper reports the results of experimental investigation on the heat transfer performance of Al_2O_3/H_2O and TiO_2/H_2O nanofluids through square channel with constant wall temperature boundary condition. The flow regime through channel is turbulent. The nanofluids used in this research are Al_2O_3/H_2O and TiO_2/H_2O with different nanoparticle concentrations. Based on the results of the present investigation, for specific Peclet number, convective heat transfer coefficient and Nusselt number of nanofluids are higher than those of distilled water. The enhancement increases with increasing nanoparticle concentration. The results also reveal that the convective heat transfer coefficient for Al_2O_3/H_2O nanofluid is relatively the same as that of TiO_2/H_2O nanofluid.

Key words: Nanofluid, Square Channel, Heat Transfer Coefficient, Nusselt Number, Nanoparticle

INTRODUCTION

Researchers believe that adding solid particles into an ordinary fluid like water or ethylene glycol (EG) can increase the amount of heat transfer in a heat transfer apparatus. But using micrometric size particles causes some problems such as sedimentation of particles, erosion, and pressure depreciation. The idea of using solid particles in enhancing heat transfer became practical by the possibility of creation of particles in nanometric size. Choi [1] added up the term of Nanofliud to dictionary of nanotechnology which is defined as a suspension prepared by adding nanoparticles into a base fluid. These solid nanoparticles can be in the forms of metallic particles, and nonmetallic particles like various oxides or carbonic nanotubes.

Nanofluid is prepared through two methods: one-step method and two-step method. In the one-step method using some techniques such as chemical synthesis, nanoparticles are prepared directly in a base fluid and then the nanofluid is prepared. In the two-step method which is simpler than the former method, nanoparticles are prepared separately and then are added to and mixed to base fluid.

Adding solid particles in nanometric size into a base fluid changes its thermophysical properties. Previous researches emphasize the enhancement of thermal conductivity of nanofluids. Lee et al. [2] presented 20% increase in thermal conductivity for Cu-EG nanofluid with concentration of 4% vol. While Eastman et al. [3] reported an increase up to 60% on thermal conductivity of Cu nanofluid with concentration of 5 volume percent. Types of nanoparticles and base fluid play key roles in the value of thermal conductivity of nanofluids. A review of the variation of thermal conductivity of nanofluids has been reported by Xiang et al. [4]. The most important role in thermal conductivity enhancement is related to Brownian motion which illustrates microconvection of nanoparticles [4-6].

Generally, nanoparticles tend to agglomerate in the nanofluid suspensions, which results in the sedimentation of nanoparticles, and consequently changes the thermophysical properties of the nanofluid. The agglomeration of nanoparticles results not only in the settlement and clogging of microchannels but also the decreasing of thermal conductivity of nanofluids [7].

Several studies have been conducted on the heat transfer performance of nanofluids which mainly are related to the forced convection heat transfer through a circular tube. Pak et al. [8] investigated the Al_2O_3/H_2O and TiO_2/H_2O nanofluids under turbulent flow regime in terms of heat transfer efficiency and the amount of pressure drop in a tubular heat exchanger. The size of Al_2O_3 and TiO_2 nanoparticles used in their study was 13 and 27 nm, respectively. Based on their results, the convective heat transfer coefficient of both nanofluids with concentration of 3% vol. was 12% lower than of the base fluid. Eastman et al. [9] studied the thermal efficiency of CuO/H_2O nanofluid under turbulent flow condition and found that heat transfer coefficient of nanofluids with concentration of 0.9% vol. was 15% higher than that of the base fluid. Xuan and Li [10] did an experimental study and presented an increase up to 28% in convective heat transfer coefficient for turbulent flow regime of Cu/H_2O nanofluid when the Reynolds number ranged from 10000 to 25000.

Zhou [11] evaluated the enhancement of convective heat transfer of Cu/Acetone nanofluid where the size and concentration of nanoparticles in nanofluid were 80-100 nm and 0-4 g/lit, respectively. Yang et al. [12] employed nanofluid in laminar flow through a horizontal heat exchanger to measure the heat transfer coefficient. They found enhancements of 22% and 15% for nanoparticle concentration of 2.5% wt. and 50 °C and 70 °C fluid temperatures respectively.

Results of a study by Zeinali Heris et al. [13] also emphasizes the enhancement of convective heat transfer coefficient for Al_2O_3/H_2O and CuO/H_2O nanofluids. Ding et al. [14] studied the variation of convective heat transfer coefficient of TiO_2/EG and TiO_2/H_2O nanofluids as well as nanofluids with carbonic and TiO_2 nanotubes. They illustrated a remarkable increase in convective heat transfer coefficient for the nanofluids they used in their experiments. Williams et al. [15] used the Al_2O_3/H_2O and ZrO_2/H_2O nanofluids under turbulent condition and obtained enhanced heat transfer coefficients compared to the base fluid. Duangthongsuk et al. [16] studied the

[†]To whom correspondence should be addressed.
E-mail: etemad@cc.iut.ac.ir, sgetemad@uottawa.ca
[‡]Present address: Department of Chemical and Biological Engineering, University of Ottawa, Ontario KIN 6N5, Canada

heat transfer of TiO_2/H_2O nanofluid through a heat exchanger and showed 6-11% enhancement for 0.2% wt. nanoparticle concentration.

Etemad et al. [17] investigated the turbulent flow heat transfer performance of Al_2O_3/H_2O and CuO/H_2O nanofluids through a circular channel subjected to a constant temperature. They reported 1.29 and 1.30 relative enhancement for Nusselt numbers of nanofluids at Peclet number of 55000 and with 2 vol% of γ-Al_2O_3 and CuO nanoparticles, respectively. Available papers in the literature emphasize the improvement of the thermal performance of non-Newtonian base fluids by adding nanoparticles. Hojjat et al. [18] carried out an experimental study on convective heat transfer of non-Newtonian nanofluids with CuO, TiO_2 and Al_2O_3 nanoparticles (0.1, 0.2, 0.5, 1, 1.5% vol.), and the aqueous solution CMC (0.5% wt. CMC) as the base fluid. According to their findings under laminar flow regime and constant wall heat flux condition, the nanofluids experienced an enhancement of heat transfer coefficient up to 22%. Their findings show that the enhancement of heat transfer coefficient is directly related to the increase in Peclet Number and nanoparticle concentration. Based on almost all investigations available in the literature, the enhancement of heat transfer coefficient is higher than the effect of a nanofluid's thermal conductivity. The reason can be related to some factors such as thermophoresis, nanoparticle thermal dispersion, decreasing thermal boundary layer thickness, migration of nanoparticles, and nanofluid viscosity influence on the convection heat transfer coefficient [19-21].

Heat transfer enhancement is the main concern at different industries and non-circular channels can be a good candidate for this achievement. Compact heat exchangers are generally fabricated by non-circular channels providing more compactness and high surface area/volume. The present investigation is carried out to introduce the results on the heat transfer performance of Al_2O_3/H_2O and TiO_2/H_2O nanofluids through a square channel with constant wall temperature boundary condition.

EXPERIMENTAL SET-UP

To investigate the heat transfer performance of nanofluids through square channel with constant wall temperature boundary condition, an experimental set-up was designed and constructed. Fig. 1 presents a schematic of this experimental set-up which mainly consists of two different flow circulation loops. One of these loops is the nanofluid flow loop, which includes two double pipe heat exchangers, a stainless steel pump, a nanofluid tank, a flowmeter and static mixers. In this loop the prepared nanofluid flows from tank (6) and enters to the flow loop by pump (5). The nanofluid flow rate

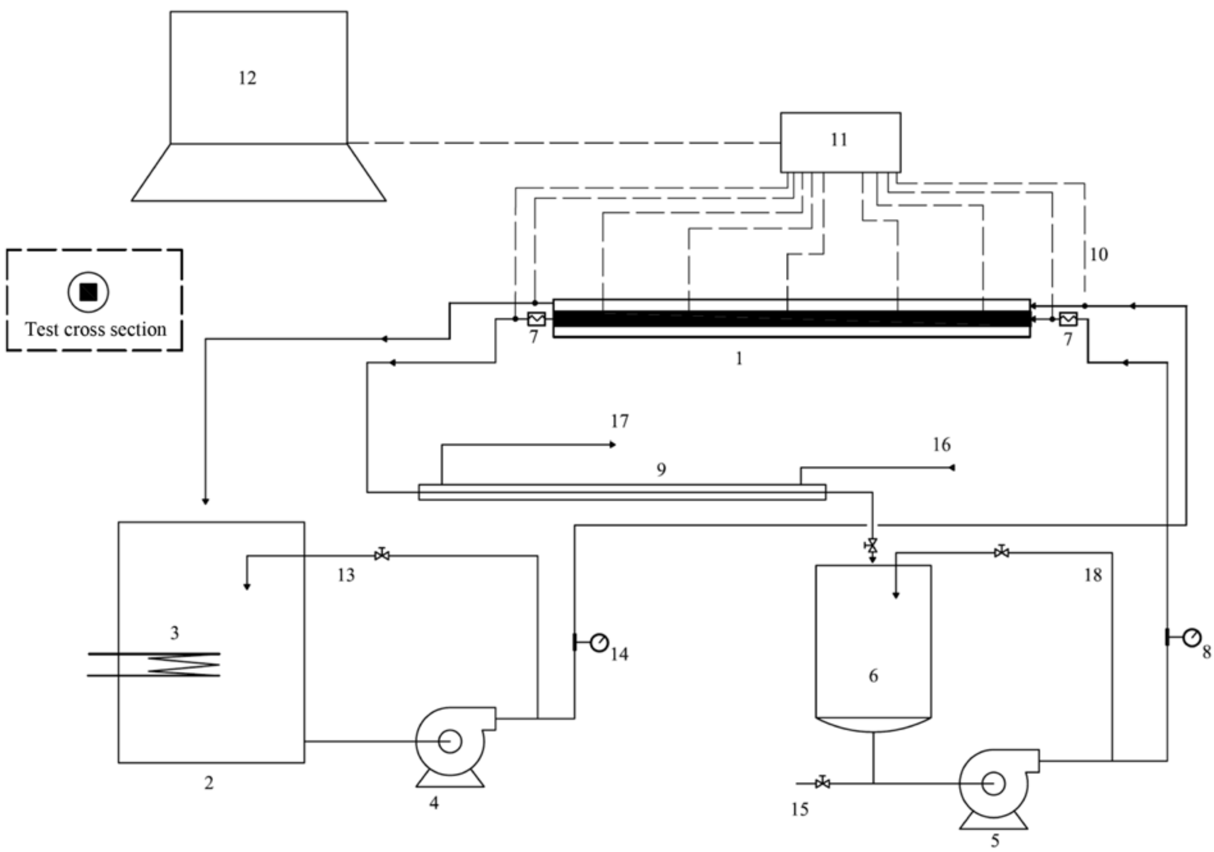

Fig. 1. Experimental set-up.

1. Nanofluid heat exchanger
2. Hot water vessel
3. Heater
4. Hot water pump
5. Nanofluid pump
6. Nanofluid vessle
7. Static mixer
8. Nanofluid flow meter
9. Cold water heat exchanger
10. Thermocuple (signal wire)
11. Data acquisition
12. Computer
13. Hot water by pass
14. Hot water flow meter
15. Nanofluid drain
16. Cold water input
17. Cold water output
18. Nanofluid by pass

is measured by magnetic flow meter (8) (Welltech copa-xe wt4300, China). Nanofluid is heated in a double pipe heat exchanger (1) (stainless steel-type 316). In this heat exchanger the nanofluid flows through a square cross section tube and water flows through the shell. The double pipe heat exchanger contains several baffles in the outer tube to intensify the turbulency of the flow. This will be helpful to provide constant wall temperature condition. To bring the temperature of the nanofluid to a certain value, another double pipe heat exchanger (9) was used. The temperature of nanofluid decreased using cold water flowing through the heat exchanger.

The second loop is a warm water circulating loop which contains a circulation pump and a tank. In this loop, water in the tank (2) is heated to 60 °C with a heater (3) with power of 4000w and then is transferred to the heat exchanger's shell (1) by a pump (4) for heating of the nanofluid.

Temperature of the nanofluid at the inlet and outlet of test section and the temperature of outer surface of square channel at five different locations were measured using K-type thermocouples. All readings were stored on a computer through a data acquisition system.

There is a limited difference between the temperature of the channel's surface at the beginning and the end of the channel. For this reason the averaged value of the wall temperatures was used in all related calculations. It should be mentioned that this difference is increased by the increment of the nanofluid's flow rate. The highest created difference recorded in this research is 1.1 °C. Two static mixers (7) were included at the inlet and outlet of square channel for creating enough mixing in nanofluid flow to guarantee a uniform temperature at the cross section of the channel at these locations. The square channel test section possesses 2 meters length with an outer cross section of 1×1 cm and with 1 mm thickness.

NANOFLUIDS PREPARATION

Al_2O_3/H_2O and TiO_2/H_2O nanofluids were prepared through a double-step process. First, the required amount of Al_2O_3 nanoparticle was weighed and then gradually was added into determined distillated water. A mechanical mixer is used to disperse nanoparticles in water, then the prepared solution was sonicated by UP200S-Hielscher sonicator. Specifications of nanoparticles used in this study are available in Table 1.

To prevent possible sedimentation, for each test a new nanofluid was prepared and immediately used. Turbulent flow condition in the present investigation helps to provide a stable solution during the experiments.

DATA ANALYSIS

Heat transfer through the double pipe heat exchanger is calculated as follows:

$$Q=m^{\bullet}Cp_{nf}\Delta T \tag{1}$$

where Q is heat transfer between water and nanofluid, $m^{\bullet}$ is mass flow rate of nanofluid, Cp_{nf} is nanofluid heat capacity and ΔT is the temperature difference for nanofluid in the heat exchanger.

Convective heat transfer coefficient is obtained by the following equation:

$$U=Q/(A\Delta T_{LM}) \tag{2}$$

$$\bar{h}_{ex}=\left(U^{-1}-\frac{a_o \mathrm{Ln}\frac{a_o}{a_i}}{k}\right)^{-1}\left(\frac{a_o}{a_i}\right)$$

where $\bar{h}_{ex}$ is the average convective heat transfer coefficient, A is the surface of heat transfer, ΔT_{LM} and is logarithmic mean of temperature difference between thermal fluid and nanofluid in heat exchanger. Area of heat exchange and Logarithmic mean temperature difference are defined as the following:

$$A=4aL \tag{3}$$

Where L and a stand for the length and each side of square channel, respectively.

$$\Delta T_{LM}=\frac{(T_s-T_{nf-in})-(T_s-T_{nf-out})}{\mathrm{Ln}\left(\frac{T_s-T_{nf-in}}{T_s-T_{nf-out}}\right)} \tag{4}$$

Where T_{nf-in} and T_{nf-out} are the inflow and outflow temperatures of nanofluid in heat exchanger, respectively, and T_s is the temperature of the external surface of the square channel. Hydraulic diameter is defined by the following equation:

$$D_h=\frac{4a^2}{4a}=a \tag{5}$$

The following dimensionless numbers are used in analyzing the experimental data:

Nusselt number:

$$\overline{Nu}_{nf}=\bar{h}_{nf}D_h/K_{nf} \tag{6}$$

$\overline{Nu}_{nf}$ and K_{nf} are average Nusselt number and nanofluid thermal conductivity, respectively.

Reynolds number:

$$Re_{nf}=\frac{\rho_{nf}UD_h}{\mu_{nf}} \tag{7}$$

Re_{nf}, ρ_{nf}, U, and μ_{nf} are Reynolds number, nanofluid density, nanofluid velocity, and nanofluid viscosity, respectively.

Peclet number:

$$Pe_{nf}=\frac{\rho_{nf}Cp_{nf}UD_h}{K_{nf}} \tag{8}$$

Pe_{nf} is Peclet number.

Thermophysical properties of nanofluids are calculated through the following equations:

Table 1. Specifications of nanoparticles

Particle	Size (nm)	ρ (kg/m^3)	k (W/m·K)	Cp (j/kg·°C)	Company
γ-Al_2O_3	25	3970	46	750	Nanostructured & Amorphous Materials Inc. USA
TiO_2	10	3840	11.7	710	Nanostructured & Amorphous Materials Inc. USA

$$K_{nf}=\frac{k_p+2k_{bf}-2(k_{bf}-k_b)\phi}{k_p+2k_{bf}+2(k_{bf}-k_b)\phi} \qquad [1](9)$$

$$Cp_{nf}=\frac{\phi(\rho_p Cp_p)+(1-\phi)(\rho_{bf}Cp_{bf})}{\rho_{nf}} \qquad [2](10)$$

$$\rho_{nf}=\phi\rho_p+(1-\phi)\rho_{bf} \qquad [3](11)$$

$$\mu_{nf}=\mu_{bf}(1+2.5\phi) \qquad [4](12)$$

where, μ_{bf}, Cp_{nf}, Cp_{bf}, Cp_p, ρ_p, k_{bf}, k_p, and ϕ are nanofluid viscosity, nanofluid heat capacity, base fluid heat capacity, nanoparticles heat capacity, nanoparticles density, thermal conductivity of base fluid, thermal conductivity of nanoparticles, and volume fraction of nanoparticles, respectively.

RESULTS AND DISCUSSION

The experiments were primarily performed with distillated water for which the accurate correlations exist in the literature. Nusselt number calculated through the experimental result is compared with the Dittus and Boelter correlation [26]:

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

The hydraulic diameter has been used for calculation of Re in the above equation.

Based on the comparison presented through Fig. 2, very good agreement with a maximum difference of 7% exists between the experimental data and the results of Eq. (13).

The present investigation was done for Al_2O_3/H_2O and TiO_2/H_2O nanofluids under turbulent flow regime. The range of Reynolds number was 4,000 to 35,000 and both nanoparticles were employed with concentrations of 0.1, 0.5, 1.0 and 1.5% vol.

1. The Convective Heat Transfer Coefficient of Nanofluids

Heat transfer coefficient of Al_2O_3/H_2O nanofluid versus Peclet number for different nanoparticle concentration is presented in Fig. 3. Based on the results, for a constant Peclet number, the nanofluid possesses a higher heat transfer coefficient than that of the base fluid.

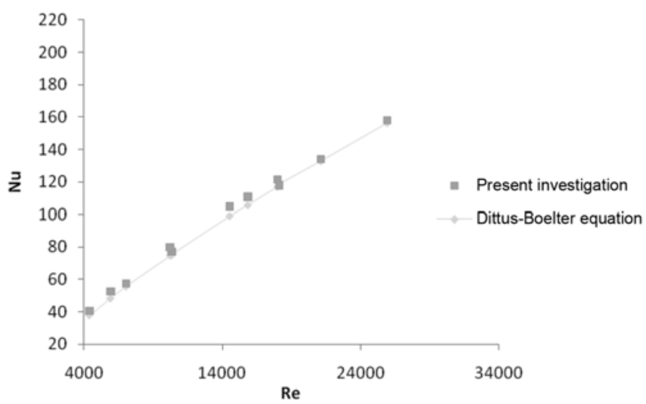

Fig. 2. Comparison of the Nusselt number for distilled water obtained from present investigation with the results of Eq. (13).

[1]Maxwell, [22]
[2]Zhou et al., [23]
[3]Izadi et al., [24]
[4]Einsten et al., [25]

This enhancement is strongly dependent on the concentration of nanoparticles so that nanofluid with higher concentration possesses higher heat transfer coefficient. For example, at Peclet number about 59000, the heat transfer coefficients are 16% and 24% greater than those of the base fluid when the nanoparticle concentration is 0.5% and 1.5% vol., respectively.

The heat transfer enhancement of nanofluids has been reported for circular channel. Etemad et al. [17] presented the results for Al_2O_3/H_2O nanofluid in circular tube with nanoparticle concentration of 0.5% at Peclet number about 59000 under turbulent regime, and the enhancement of heat transfer coefficient was about 13%. The corresponding result for the square channel at the same Peclet number and nanoparticle concentration is 16%.

Results of the experiments on TiO_2/H_2O nanofluid with concentration ranging from 0.1% to 1.5% vol. are demonstrated in Fig. 4. The results show that adding TiO_2 nanoparticle into water causes a relative enhancement of heat transfer coefficient, concluding that higher enhancement belongs to the nanofluid with higher concentration. Based on the results of Figs. 3 and 4, similar heat transfer performances are available for both employed nanofluids. For example, at a Peclet number of about 59000 the enhancements of heat transfer coefficient for TiO_2/H_2O nanofluid are about 15% and 28% for nanoparticle concentrations of 0.5% and 1.5% vol., respectively.

Nanofluids containing Al_2O_3 or TiO_2 nanoparticles possess higher thermal conductivity than that of the distilled water. Generally, the

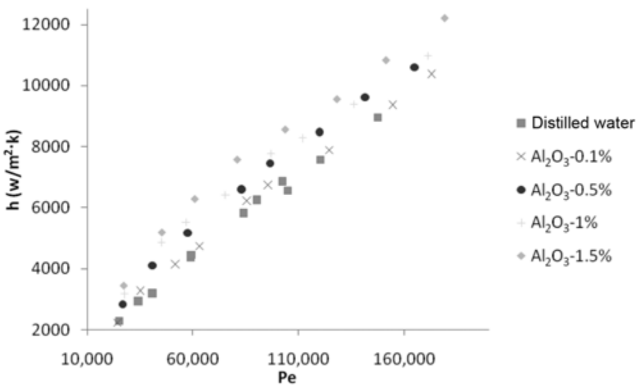

Fig. 3. Convective heat transfer coefficient versus Peclet number for Al_2O_3/H_2O nanofluid.

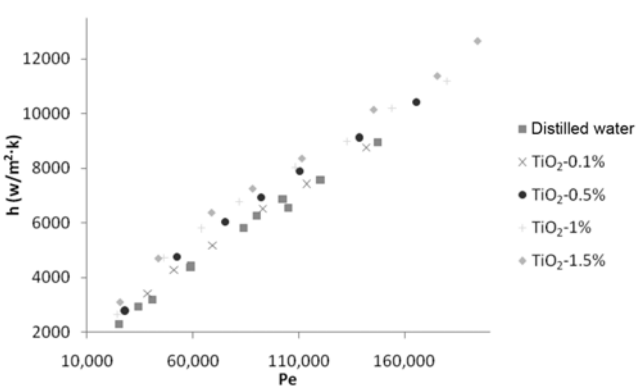

Fig. 4. Convective heat transfer coefficient versus Peclet number for TiO_2/H_2O nanofluid.

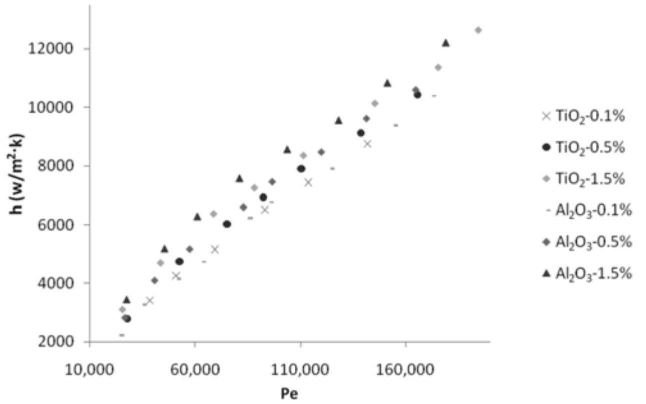

Fig. 5. Convective heat transfer coefficient versus Peclet number for TiO_2/H_2O and Al_2O_3/H_2O nanofluids.

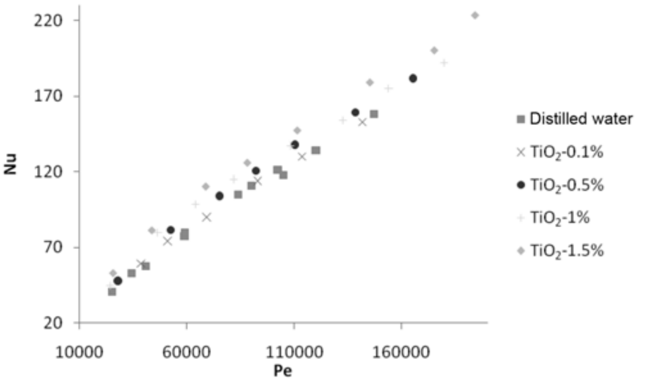

Fig. 7. Nusselt number versus Peclet number for TiO_2/H_2O nanofluid.

higher heat transfer coefficient of nanofluids can be related to the higher thermal conductivity of these fluids, migration of nanoparticles in the solution, possible slip velocity on the walls, Brownian motion of nanoparticles, and decreasing hydrodynamical and thermal boundary layers thickness.

To compare the performances of two employed nanofluids, heat transfer coefficients of both nanofluids with concentrations of 0.1%, 0.5% and 1.5% vol. are presented through Fig. 5. Based on the results, the heat transfer performances of both nanofluids are very close together. The thermal conductivity of Al_2O_3 nanoparticle is higher than that of TiO_2 while the size of TiO_2 is smaller. Higher thermal conductivity and smaller nanoparticle size both result in higher heat transfer coefficient [27]. Compromising between two parameters results in very close thermal behavior for two mentioned nanofluids.

Based on error analysis, the maximal error in calculation of the nanofluid's heat transfer coefficient is about 3.47%.

2. Nusselt Number of Nanofluids

Examining the relative change of Nusselt number for nanofluid is of importance, since the effects of relative changes in convective heat transfer and thermal conductivity of nanofluid are simultaneously included in the Nusselt Number. Figs. 6 and 7 present the Nusselt number versus Peclet number for both TiO_2/H_2O and Al_2O_3/H_2O nanofluids with different nanoparticle concentrations. The results

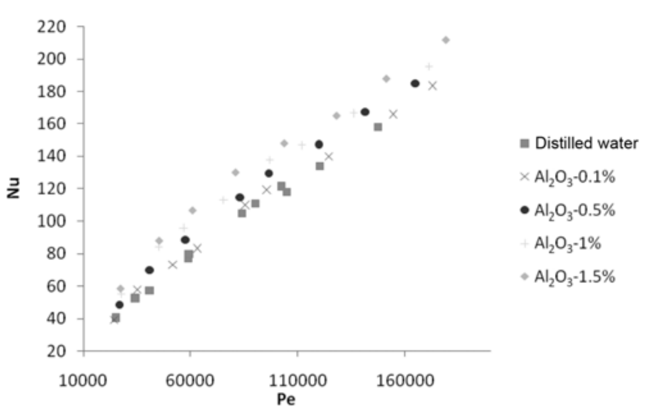

Fig. 6. Nusselt number versus Peclet number for Al_2O_3/H_2O nanofluid.

of these figures reveal that the Nusselt number of both nanofluids is higher than that of the base fluid and the enhancement increases by increasing the concentrations of nanoparticles.

CONCLUSION

This research is related to the measurement of convective heat transfer performance of Al_2O_3/H_2O and TiO_2/H_2O nanofluids. The experiments were conducted in square channel with constant wall temperature boundary condition under turbulent flow regime. The experimental results reveal findings as below:

- Al_2O_3/H_2O and TiO_2/H_2O nanofluids have better heat transfer performance than the base fluid.
- Comparison of thermal performances of both nanofluids reveals that the relative increments of heat transfer coefficient as well as the Nusselt number of Al_2O_3/H_2O nanofluid are very close to that of TiO_2/H_2O nanofluid.
- In both nanofluids the relative enhancements of heat transfer coefficient and the Nusselt number increase by increasing the concentrations of nanoparticles. This can be explained by increasing thermal conductivity of nanofluid in comparison to the base fluid. Studies show that the presence of Brownian motion and nanoparticle migration in nanofluid are among other reasons for this issue [4-6].

ACKNOWLEDGEMENTS

The financial support of Iranian Nanotechnology Initiative is gratefully acknowledged.

NOMENCLATURE

A : surface area of the square cross-section duct [m^2]
a : each side of square channel [m]
m^o : mass flow rate [kg/s]
Cp : specific heat [J kg^{-1} K^{-1}]
D_h : hydraulic diameter [m]
h : peripherally average heat transfer coefficient [W m^{-2} K^{-1}]
k : thermal conductivity [W m^{-1} K^{-1}]
L : duct length [m]
Nu : peripherally average Nusselt number [dimensionless]

Pe : peclet number [dimensionless]
Pr : prandtl number [dimensionless]
Q : heat flux [W/m^2]
Re : reynolds number [dimensionless]
T_s : duct wall temperature [K]
ΔT_{LM} : logarithmic mean temperature difference [K]
U : average fluid velocity [m s^{-1}]

Greek Letters

μ : viscosity [Pa s]
ϕ : nanoparticle volume fraction [dimensionless]
ρ : density [kg m^{-3}]

Subscripts

nf : nanofluid
p : manoparticles
bf : base fluid
nf-in : nanofluid input
nf-out : nanofluid output
i, o : Inner, outer

REFERENCES

1. S. U. S. Choi, in American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED, **231**, 99 (1995).
2. S. Lee, S. U. S. Choi, S. Li and J. A. Eastman, *J. Heat Transf.*, **121**, 280 (1999).
3. J. A. Eastman, S. U. S. Choi, S. Li, W. Yu and L. J. Thompson, *Appl. Phys. Lett*., **78**(6), 718 (2001).
4. Q. Xiang, X. Q. Wang and A. S. Mujumdar, *Brazilian J. Chem. Eng.*, **25**(4), 631 (2008).
5. A. K. Santra, S. Sen and N. Chakraborty, *Int. J. Therm. Sci.*, **48**, 391 (2009).
6. M. Shahi, A. H. Mahmoodi and F. Talebi, *Int. J. Heat Mass Transf.*, Article Under Press (2011).
7. L. Yanjiao, J. Zhou, S. Tung, E. Schneider and S. Xi, *Powder Technol.*, **196**, 89 (2009).
8. B. Pak and Y. I. Cho, *Exp. Heat Transf.*, **11**(2), 151 (1998).
9. J. A. Eastman, S. U. S. Choi, S. Li, G. Soyez, L. J. Thompson and R. J. DiMelfi, *Material Sci. Forum*, **312**, 629 (1999).
10. Y. Xuan and Q. Li, *J. Heat Transf.*, **125**(1), 151 (2003).
11. D. W. Zhou, *Int. J. Heat Mass Transf.*, **47**(20) (2004).
12. Y. Yang, Z. G. Zhang, E. A. Grulke, W. B. Anderson and G. Wu, *Int. J. Heat Mass Transf.*, **48** (2005).
13. S. Zeinali Heris, S. Gh., Etemad and M. Nasr Esfahany, *Int. Commun. Heat Mass Transf.*, **33**, 526 (2006).
14. Y. Ding, H. Chen, Y. He, A. Lapkin, M. Yeganeh, L. Siller and Y. V. Butenko, *Adv. Powder Technol.*, **18**(6) (2007).
15. W. Williams, J. Buongiorno and L. W. Hu, *ASME J. Heat Transf.*, **130**(1), 42412 (2008).
16. W. Duangthongsuk and S. Wongwises, *Int. J. Heat Mass Transf.*, **52**(71) (2009).
17. S. Gh. Etemad, B. Farajollahi, M. Hajipour and J. Thibault, Accepted for publication at *J. Enhanced Heat Transf.*
18. M. Hojjat, S. Gh. Etemad and S. G. R. Bagheri, *Korean J. Chem. Eng.*, **27**(5), 1391 (2010).
19. S. V. Ravikanth, D. K. Das and D. P. Kulkarni, *Int. J. Heat Mass Transf.*, **53**, 4607 (2010).
20. A. Zamzamian, Sh. N. Oskouie, A. Doosthoseini, A Joneidi and M. Pazouki, *Exp. Therm. Fluid Sci.*, **35**, 495 (2011).
21. S. Heris, M. Esfahany and S. Gh. Etemad, *Int. J. Heat. Fluid Flow*, **28**(2), 203 (2007).
22. J. C. Maxwell, *A treatise on electricity and magnetism*, 2nd Ed., Clarendon Press, Oxford, U.K. (1881).
23. S. Q. Zhou and R. Ni, *Appl. Phys. Lett.*, **92**, 93 (2008).
24. M. Izadi, A. Behzadmehr and D. Jalali-Vahida, *Int. J. Therm. Sci.*, **48**(11), 2119 (2009).
25. A. Einstein, *Annalen der Physik*, **19**(2), 289 (1906).
26. F. W. Dittus and L. M. K. Boelter, Univ. Calif. Publ. Eng., **2**(13), 443 (1930).
27. S. Mirmasoumi and A. Behzadmehr, *Int. J. Heat. Fluid Flow*, **29**, 566 (2008).