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Experimental investigation of oxide nanofluids laminar flow convective heat transfer ☆

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Abstract

In the present investigation nanofluids containing CuO and Al_2O_3 oxide nanoparticles in water as base fluid in different concentrations produced and the laminar flow convective heat transfer through circular tube with constant wall temperature boundary condition were examined. The experimental results emphasize that the single phase correlation with nanofluids properties (Homogeneous Model) is not able to predict heat transfer coefficient enhancement of nanofluids. The comparison between experimental results obtained for CuO/water and Al_2O_3/water nanofluids indicates that heat transfer coefficient ratios for nanofluid to homogeneous model in low concentration are close to each other but by increasing the volume fraction, higher heat transfer enhancement for Al_2O_3/water can be observed.

Keywords: Laminar flow; Heat transfer enhancement; Forced convection; Nanofluid; Oxide nanoparticles

1. Introduction

Fluids, such as water, ethylene glycol and engine oil have poor heat transfer performance and therefore high compactness and effectiveness of heat transfer systems are necessary to achieve the required heat transfer. Among the efforts for enhancement of heat transfer the application of additives to liquids is noticeable [1,2]. These earlier studies, however used suspensions of millimeter or micrometer sized particles, which although showed some enhancement, experienced problems such as poor suspension stability and channel clogging, extra pressure drop and erosion.

The term of nanofluids refers to a new kind of fluids by suspending nanoparticles in base fluids. This term was used by Choi (1995) [3]. Nanofluids found to possess long time stability and large efficient thermal conductivity [4]. For example Lee [5] reported that suspension of 4% volume CuO 35 nm particles in ethylene glycol shows 20% increase in thermal conductivity. Since the theoretical models such as Maxwell and Hamilton–Crosser [6–8] cannot determine exactly the thermal conductivity of nanofluids, therefore it is necessary to study about thermal conductivity enhancement mechanisms of this kind of fluids.

There are only few previous studies involved in describing fluid flow and convective heat transfer performance of the nanofluids [9–11]. Li and Xuan [9] studied convective heat transfer of 35 nm Cu/deionized water nanofluid

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Nomenclature

A	Tube cross section area (m^2)
Cp	Specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D	Tube diameter (m)
$\overline{h}_{nf}(\exp)$	Nanofluid experimentally average heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
k	Thermal conductivity ($Wm^{-2}\ K^{-1}$)
L	Tube length (m)
$\overline{Nu}_{nf}(\exp)$	Nanofluid experimentally average Nusselt number
$\overline{Nu}_{nf}(th)$	Nanofluid Nusselt number calculated form Seider–Tate equation
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
Tb_1	Inlet bulk temperature (K)
Tb_2	Exit bulk temperature (K)
$\overline{Tb}$	Average bulk temperature (K)
Tw	Tube wall temperature (K)
$\bar{U}$	Average fluid velocity ($m\ s^{-1}$)

Greek letters

μ	Viscosity (Pa s)
μ_{wnf}	Nanofluid viscosity at tube wall temperature (Pa s)
v	Nanoparticle volume fraction
ρ	Density ($kg\ m^{-3}$)

Subscripts

nf	Nanofluid
s	Solid nanoparticles
w	Water

and showed that the suspended nanoparticles remarkably enhance heat transfer process with smaller volume fraction of Cu nanoparticles.

Some other experimental or theoretical investigations indicated that the Nusselt number of the nanofluids increases with increasing volume fraction of the nanoparticles [12–14]. However Pak and Cho [15] expressed that the convective heat transfer coefficient of Al_2O_3/water and TiO_2/water nanofluids with concentration of 3.0% volume was 12.0% smaller than that of pure water. Putra [16] reported suppression of natural convection heat transfer by nanofluid of Al_2O_3/water and CuO/water and concluded that this could be due to nanoparticles settling and velocity difference between nanoparticles and main fluid. Nanofluid boiling process was investigated experimentally by several researchers [17,18]. Das et al. [17] observed nanofluids boiling performance deterioration.

The objective of this study is to compare laminar flow convective heat transfer and rheological properties of CuO/water and Al_2O_3/water nanofluids under constant wall temperature boundary condition and different concentration of nanoparticles.

2. Experimental setup

The experimental apparatus with constant wall temperature boundary condition is shown schematically in Fig. 1. The test chamber constructed of 1 m annular tube with 6 mm diameter inner copper tube and with 0.5 mm thickness and 32 mm diameter outer stainless steel tube. Nanofluid flows inside the inner tube while saturated steam enters annular section, which creates constant wall temperature boundary condition. The fluid after passing through the test section enters heat exchanger in which water is used as cooling fluid, and then enters the flow measuring section. Flow measuring section consisted of 300 cm^3 glass vessel with a valve at the bottom. To record temperature at the outer surface of copper tube, ten (k-type) thermocouples were welded on inner tube wall at equally spaced 10 cm apart distances. Two (k-type) thermocouples have inserted into the flow at inlet and outlet of test section for measuring bulk temperatures of nanofluid. The thermocouples have a maximum precision of 0.1 °C and were calibrated before tests. A 2 l glass vessel equipped by drain valve is used as fluid reservoir. After injection of nanofluid with specified concentration in reservoir tank, it is circulated toward the heat exchanger using a centrifugal pump. Then the steam line is opened to increase the tube wall temperature. After 20–30 min the system reaches steady state condition. There is a valve in reflux line and the flow rate is regulated by using this valve.

3. Problem formulation

The experimental data was used for calculation the convective heat transfer coefficient and Nusselt number as follows:

$$\bar{h}_{\mathrm{nf}}(\exp) = \frac{\mathrm{Cp}_{\mathrm{nf}} \cdot \rho_{\mathrm{nf}} \cdot \bar{U} \cdot A \cdot (\mathrm{Tb}_2 - \mathrm{Tb}_1)}{\pi \cdot D \cdot L \cdot (\mathrm{Tw} - \overline{\mathrm{Tb}})} \tag{1}$$

$$\overline{\mathrm{Nu}}_{\mathrm{nf}}(\exp) = \frac{\bar{h}_{\mathrm{nf}}(\exp) \cdot D}{k_{\mathrm{nf}}}. \tag{2}$$

The heat transfer coefficient of laminar fluid flow through circular tube can be calculated from Seider–Tate equation [19] in the following form:

$$\overline{\mathrm{Nu}}_{\mathrm{nf}}(\mathrm{th}) = 1.86\left(Re_{\mathrm{nf}} \cdot Pr_{\mathrm{nf}} \cdot \frac{D}{L}\right)^{1/3}\left(\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{wnf}}}\right)^{0.14} \tag{3}$$

Re_{nf} and Pr_{nf} are defined as follow:

$$Re_{\mathrm{nf}} = \frac{\rho_{\mathrm{nf}} \cdot \bar{U} \cdot D}{\mu_{\mathrm{nf}}} \tag{4}$$

$$Pr_{\mathrm{nf}} = \frac{\mathrm{Cp}_{\mathrm{nf}} \cdot \mu_{\mathrm{nf}}}{k_{\mathrm{nf}}}. \tag{5}$$

The properties of nanofluid in the Eqs. (1)–(5) were calculated from nanoparticle and water properties using the following correlations at the mean bulk temperature [4,8,10,20]:

$$\rho_{\mathrm{nf}} = v \cdot \rho_{\mathrm{s}} + (1 - v) \cdot \rho_{\mathrm{w}} \tag{6}$$

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{w}} \cdot (1 + 2.5v) \tag{7}$$

$$\mathrm{Cp}_{\mathrm{nf}} = \frac{v \cdot (\rho_{\mathrm{s}} \cdot \mathrm{Cp}_{\mathrm{s}}) + (1 - v) \cdot (\rho_{\mathrm{w}} \cdot \mathrm{Cp}_{\mathrm{w}})}{\rho_{\mathrm{nf}}} \tag{8}$$

$$k_{\mathrm{nf}} = \frac{k_{\mathrm{s}} + 2k_{\mathrm{w}} - 2 \cdot v \cdot (k_{\mathrm{w}} - k_{\mathrm{s}})}{\frac{k_{\mathrm{s}}}{k_{\mathrm{w}}} + 2 + v \cdot \left(\frac{k_{\mathrm{w}} - k_{\mathrm{s}}}{k_{\mathrm{w}}}\right)}. \tag{9}$$

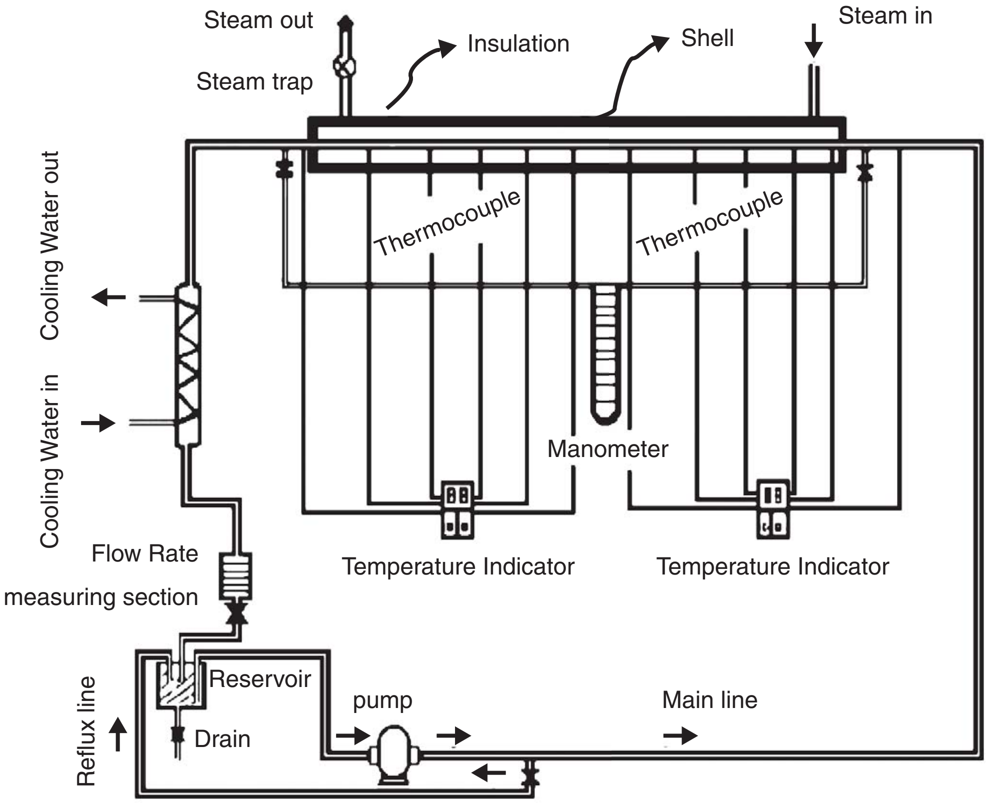

Fig. 1. Schematic of experimental circuit.

The Einstein model (Eq. (7)) is applied for dilute suspension viscosity and Eq. (9) (Hamilton–Crosser [8]) is used for determination of nanofluids thermal conductivity in absence of experimental data.

4. Production of nanofluid suspension

In this study two series of oxide nanofluid including Al_2O_3 nanoparticles with 20 nm average diameter and 50–60 nm CuO nanoparticles in water as base fluid with different concentrations (0.2–3.0% volume fraction) were prepared.

To prepare the proper volume for each suspension, nanoparticles were mixed with distilled water in a flask and then kept under ultrasonic (Model Parsonic 3600S) vibration for 8–16 h. No sedimentation was observed for produced nanofluids suspension after 24 h.

5. Rheological measurement

The viscosity of nanofluids was measured using cylindrical rheometer at 24 °C and compared with theoretical correlation (Eq. (7)).

The viscosities of nanofluid against shear rate are shown in Fig. 2. From this figure the viscosities of CuO/water nanofluids increase more significantly with volume fraction compared with Al_2O_3/water. It may result from large particle size of CuO nanoparticles. Also as shown from Fig. 2 both nanofluids systems are treated as Newtonian fluid at concentration to 3.0% nanoparticles.

6. Results and discussion

Before initiating systematic experiments on nanofluids, the reliability and accuracy of experimental measurements, were tested using distilled water. Experimental results were compared with the prediction of Seider–Tate correlation (Eq. (3)) for laminar flow

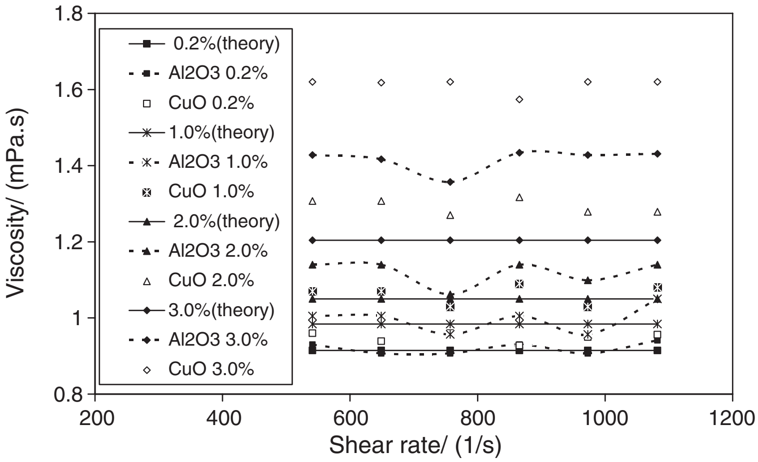

Fig. 2. Viscosity of Al_2O_3/water and CuO/water nanofluids versus shear rate at different concentrations.

under the constant wall temperature condition. As shown from Fig. 3 there is very good agreement between experimental data and the results of Seider–Tate equation which emphasize on the accuracy and reliability of the experimental data.

The experiments were performed for a wide range of (650–2050) Reynolds number and for various concentrations of Al_2O_3 and CuO nanoparticles (0.2–3.0% vol.%).

Fig. 4 demonstrates the Nusselt number for nanofluids versus Peclet number for different concentrations. The results clearly show the enhancement of Nusselt number for both nanofluids with nanoparticles concentrations as well as Peclet number, and the Al_2O_3/water nanofluid shows more enhancement compared with CuO/water nanofluid.

The ratio of the experimental heat transfer coefficients to the results obtained from Seider–Tate equation are shown through Fig. 5. From this figure the ratio increases with Peclet number and nanoparticle concentrations. Also it can be found the Al_2O_3 nanoparticles show better heat transfer enhancement compared with *CuO* nanoparticles at the same Peclet number. For example at Peclet number 5000 as the Al_2O_3/water nanofluid concentration changes from 0.2% to 2.5% the ratio increases from 1.05 to 1.29 while for CuO/water at same Peclet number this ratio increases from 1.06 to 1.23.

Overall, from the experimental results, convective heat transfer coefficient of Al_2O_3/water is higher than CuO/water, in contrast to high thermal conductivity of CuO nanoparticles. This is related to the large CuO particle size and high viscosity of CuO/water which affect on heat transfer coefficient. Therefore, increasing thermal conductivity is not the only mechanism responsible for heat transfer enhancement and other factors such as dispersion and chaotic movement of nanoparticles, Brownian motion, particle migration and nanofluid viscosity must be considered in the interpretation of the experimental results. As the viscosity of nanofluids

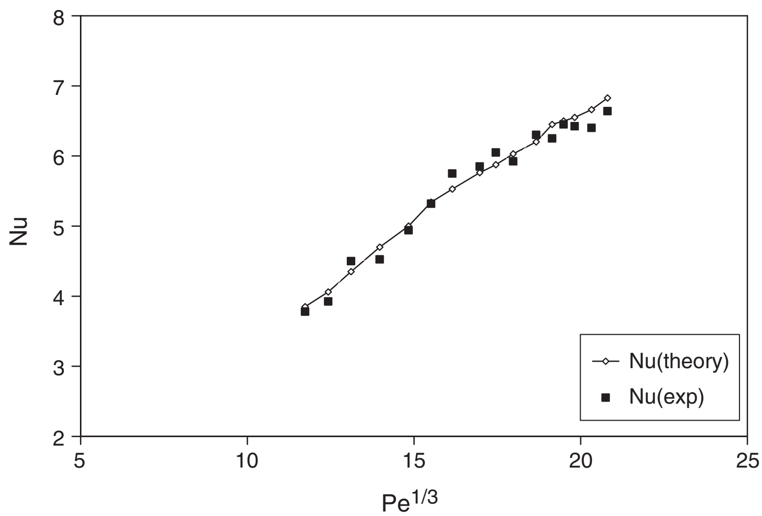

Fig. 3. Comparison between the heat transfer results of experimental investigation and Seider–Tate equation for distilled water.

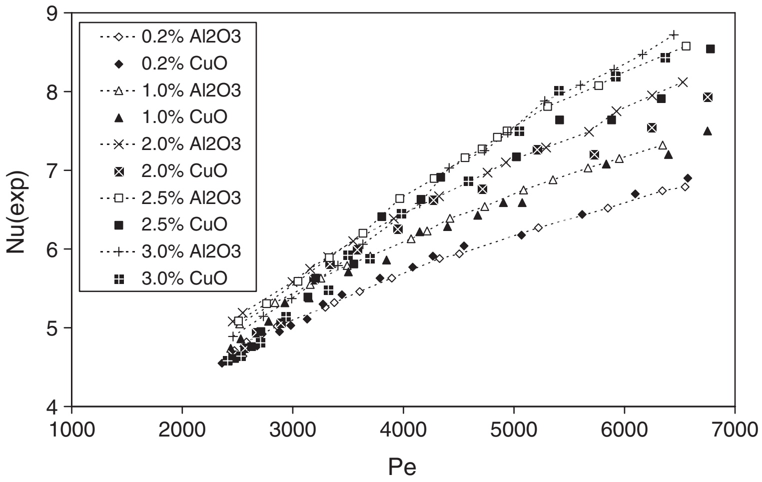

Fig. 4. Experimental Nusselt number versus Peclet number for Al_2O_3/water and CuO/water nanofluids.

increases with particle concentration, it seems there may be an optimum concentration for nanoparticles in nanofluid suspension. As shown from Figs. 4 and 5 the heat transfer enhancement for 2.5% concentration of each nanofluids is higher than that of 3.0% and therefore the optimum concentration of Al_2O_3 and CuO nanoparticles are between 2.5% and 3.0%.

To interpret the experimental results and deviation from the theoretical equations it should be noted the enhancement of heat transfer greatly depends on particle type, particle size, base fluid, flow regime and specially boundary condition. The presence of nanoparticles in fluid changes the flow structure so that besides of thermal conductivity increment, chaotic movements, dispersions and fluctuations of nanoparticles especially near the tube wall leads to increase in the energy exchange rates and augments heat transfer rate between the fluid and the tube wall.

7. Conclusion

This paper presents the experimental results of the convective heat transfer of CuO/water and Al_2O_3/water nanofluids. The experiments carried out for the laminar flow regime under constant wall temperature boundary condition. The experimental results indicate that for both nanofluid systems, heat transfer coefficient enhances with increasing nanoparticles concentrations as well as Peclet number. But the Al_2O_3/water nanofluids show more

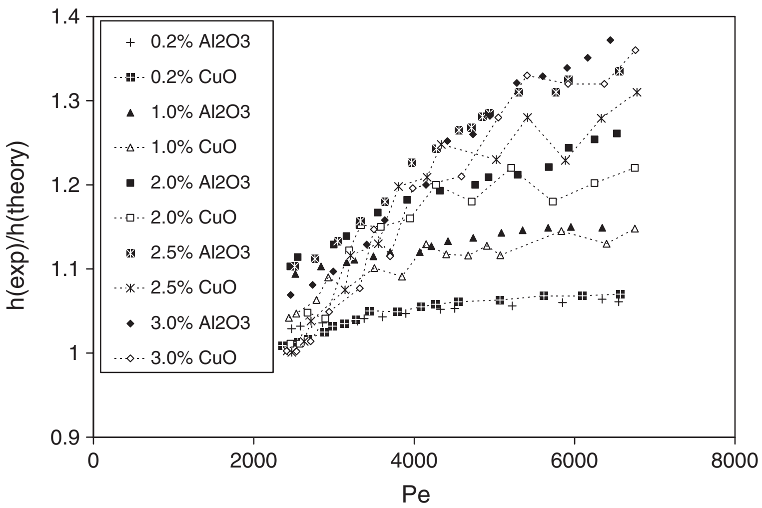

Fig. 5. The ratio of experimental heat transfer coefficient to Seider–Tate equation prediction for Al_2O_3/water and CuO/water nanofluids versus Peclet number for different concentrations.

enhancement compared with CuO / water. Also an optimum concentration can be found for each nanofluid systems in which more enhancements available. It is concluded that heat transfer enhancement by nanofluid depends on several factors including increment of thermal conductivity, nanoparticles chaotic movements, fluctuations and interactions.

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