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Experimental investigation of the effect of nanoparticle size on thermal conductivity of in-situ prepared silica–ethanol nanofluid☆

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ABSTRACT

In this study the effects of particle size, temperature and volume fraction of SiO_2 nanoparticles on thermal conductivity of nanofluid were investigated. Silica nanoparticles were prepared by the Stöber method. The results of experiments showed that with the increase of particle size, temperature and volume fraction the thermal conductivity of silica–ethanol nanofluid increased. Effect of particle size on thermal conductivity of nanofluid was attributed to high surface hydrophilicity of silica nanoparticles resulting decrease in interfacial thermal resistance with the increase of particle size. Also an empirical equation incorporating particle size, volume fraction and temperature was proposed for estimation of thermal conductivity of nanofluid. Comparison between this correlation and measurements showed that the deviation of calculated data from experimental results is within −9.5% to 5.4%. The literature results agree well with the predictions by correlation proposed.

1. Introduction

Nanofluid is a dispersion of nanometer sized particles dispersed in a base fluid [1]. Due to some especial thermal properties of the nanofluids, many researchers have paid attention to the nanofluids and their thermal applications [2,3]. Since the thermal conductivity of the nanofluids is higher than that of base fluids [4], heat transfer rate increases and smaller equipment may be used in applying nanofluid. Thermal conductivity of nanofluids depends on several parameters such as temperature, particle size and volume fraction of nanoparticles [5].

The enhancement of nanofluids thermal conductivity was attributed to the Brownian motion of particles, interfacial thermal resistance at the fluid–nanoparticle interface, high thermal conductivity as well as high surface area of nanoparticles and the sorted liquid molecules near the surface of particles [6].

Although, the effects of nanoparticle volume fraction and temperature on the thermal conductivity of nanofluids have been investigated widely; there are few studies focusing on the effects of particle size on the thermal conductivity of nanofluids.

The thermal conductivity of Al_2O_3/water nanofluid was studied by Chon et al. [7] with different nanoparticle sizes. They showed that the thermal conductivity of nanofluid decreased with the increment of nanoparticle size. Teng et al. [5] investigated the effect of particle size, temperature, and weight fraction of alumina nanoparticles on the relative thermal conductivity of alumina (Al_2O_3)/water nanofluids. Their results exhibited that the increase in particle size decreased the ratio of thermal conductivities at fixed particle mass fraction and temperature. Chopkar et al. [8] investigated the effect of Al_2Cu and Ag_2Al volume fraction and nanoparticle size on the relative thermal conductivity of nanofluid and showed that the relative thermal conductivity of nanofluid decreased with particle size. Xie et al. [9] measured thermal conductivity of nanofluids containing different sizes of alumina nanoparticles. They observed that with the increase of particle size in alumina–water and alumina–pump oil nanofluids the thermal conductivity of nanofluid decreased. In contrast, other studies have reported instances of a decrease in thermal conductivity with decreasing particle size [1,6,10,11].

Beck et al. [6] reported measurements for thermal conductivity enhancement in nanofluids containing Al_2O_3 nanoparticles in water and ethylene glycol as base fluid with different particle sizes. Their results exhibited that the enhanced thermal conductivity of nanofluid decreases as the mean particle diameter decreases below 50 nm. Chen et al. [1] measured thermal conductivity of silica–water nanofluids with different mean particle diameters. It was shown that for silica nanoparticles with different particle sizes the thermal conductivity ratio of nanofluids, (which is the ratio of the thermal conductivity of the nanofluid to the base fluid), increased. They concluded that particle–liquid interface affects thermal conductivity of nanofluid [12]. Warrier et al. [10] presented a model for the prediction of thermal conductivity of nanofluids containing metallic nanoparticles. They reported

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Nomenclature

k	Thermal conductivity
φ	Volume fraction of nanoparticles
T	Temperature
D	Diameter
α	Thermal diffusivity
μ	Viscosity
ρ	Density
κ	Boltzmann's constant
l	Molecules' mean free path
β	Fraction of the liquid volume travels with a particle
C_P	Heat capacity
$f(T,\varphi)$	Interaction function
T_0	Reference temperature, 273 K

Subscripts

nf	Nanofluid
w	Water
p	Nanoparticle
bf	Base fluid
0	Reference condition

the thermal conductivity of nanofluids containing silver nanoparticles with different particle sizes and volume loads. They also showed that the decrease in size of nanoparticles reduced the thermal conductivity of nanofluid which was in agreement with their model predictions.

Some of the previous studies claimed that the thermal conductivity of nanofluid decreased with the nanoparticle size [5,7–9] while other studies reported an increase in nanofluid thermal conductivity vs particle size [1,6,10,11]. It seems that the main reason for the opposite conclusions on the effects of the nanoparticle sizes on the thermal conductivity of nanofluids is possibly due to the instability of nanofluids and possible agglomeration of nanoparticles in some studies. In this research, therefore, in situ synthesis of nanoparticles in the base fluid was followed to prevent agglomeration of nanoparticles. The nanofluids synthesized in one step are stable and thermal conductivity measurements are free of possible instabilities.

1.1. Empirical correlation

The most effective parameters that influence the thermal conductivity of nanofluids are temperature, volume fraction and nanoparticle size. The Brownian motion of nanoparticles is affected by temperature and nanoparticle size [13].Based on nanoparticles' motion several studies have been performed to find a correlation that relate thermal conductivity of nanofluid to these parameters (Table 1). Azmi et al. [14] presented a correlation, (Eq. 1), in order to relate nanoparticle diameter, temperature and volume fraction to thermal conductivity ratio of oxide–water nanofluids. Chon et al. [15] correlated an equation, (Eq. 2), in term of Re, Pr and nanoparticle diameter for Al_2O_3/water nanofluid with validity for nanoparticle sizes ranging between 11 and 150 nm, temperature range of 294 to 344 K and two points of volume fractions 1% and 4%. Vajjha et al. [16] proposed a relation, (Eq. 5), to predict the thermal conductivity of oxide nanoparticles dispersed in ethylene glycol/water mixture as base fluids . This was a modification of the correlation proposed by Koo and Kleinstreuer [17].

In this paper an empirical relation incorporating particle size, volume fraction and temperature was proposed based on regression analysis to predict thermal conductivity of nanofluid.

2. Experiments

2.1. Materials

Tetra-ethyl ortho silicate (TEOS) and ethanol with purity of 99.99% was used as a reactant to produce silica nanoparticles. Ammonia solution (25 wt.%) was used as a catalyzing agent to speed up the synthesis and produce size controlled silica nanoparticles, All materials were purchased from Merck Co., Germany. Deionized water was used for washing the laboratory glassware.

2.2. Instruments

A thermal properties analyzer (KD2, Decagon, USA) was used for the measurement of the thermal conductivity of in-situ prepared silica–ethanol nanofluid. Fourier Transform Infrared Spectroscopy (FT-IR) (Tensor 27 Bruker, Germany), was applied for determination of chemical structure of synthesized nanoparticles. Dynamic Light Scattering (DLS) (Malvern, ZetaSizer Nano ZS, United Kingdom), was applied for determination of silica nanoparticles size distribution. Atomic Force Microscopy (AFM) (Bruker, Germany),was applied for determination of shape and morphology of silica nanoparticles. The stability of nanoparticles in base fluid was measured by using Zeta Potential test. Temperature was kept constant using an isothermal circulator bath (F12-ED Jubolo, Germany) for each measurement. In order to separate nanoparticles from the obtained nanofluid, the samples of nanofluid were heated at 60 °C to evaporate base fluid. The weight of the remaining nanoparticles was measured by a precise electric balance (TR 120, SNOWREX, Taiwan) and volume fraction was calculated. Ultrasonic processor (Hielscher, UP400S, Germany) was applied in order to prevent agglomeration of silica nanoparticles during synthesis.

2.3. In-situ preparation of silica/ethanol nanofluid

Silica nanoparticles were prepared following the Stöber method in which TEOS, ethanol and ammonia solution (25 wt.%) were mixed at 25 °C and local pressure of 650 mm Hg. In this method the particle size is controlled by the ratio of reactants [18]. Table 2 shows different amounts of reactants used for producing different sizes of silica nanoparticles. Two solutions of ethanol/TEOS and ethanol/ammonia were prepared in which half of required ethanol was added to TEOS, and the rest of the ethanol was added to the ammonia solution. Two

Table 1
Selected empirical correlation for thermal conductivity of nanofluid.

$\frac{k_{nf}}{k_w} = 0.8938(1+\varphi)^{1.37}\left(1+\frac{T-273.15}{70}\right)^{0.2777}\left(1+\frac{D_P}{150}\right)^{-0.0336}\left(\frac{\alpha_P}{\alpha_W}\right)^{0.01737}$	(1)	Azmi et al. [14]
$\frac{k_{nf}}{k_{bf}} = 1 + 64.7\varphi^{0.746}\left(\frac{D_{bf}}{D_P}\right)^{0.369}\left(1+\frac{k_P}{k_{bf}}\right)^{0.746} Pr^{0.9955} Re^{1.2321}$	(2)	Chon et al. [15]
$Pr = \frac{\mu_{bf}}{\rho_{bf}\alpha_{bf}}$	(3)	
$Re = \frac{\rho_{bf}\kappa T}{3\pi{\mu_{bf}}^2 l_{bf}}$	(4)	
$\frac{k_{nf}}{k_{bf}} = \left(\frac{k_p+2k_{bf}-2\varphi(k_{bf}-k_p)}{k_p+2k_{bf}+\varphi(k_{bf}-k_p)}\right) + \left[5\times10^4 \frac{\beta\varphi\rho_{bf}Cp_{bf}\sqrt{\frac{\kappa T}{\rho_p D_p}}f(T,\varphi)}{k_{bf}}\right]$	(5)	Vajjha et al. [16]
$f(T,\varphi) = (2.8217\times10^{-2}\varphi + 3.917\times10^{-3})\frac{T}{T_0} + (-3.0669\times10^{-2}\varphi - 3.91123\times10^{-3})$	(6)	