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Study on thermal conductivity of water-based nanofluids with hybrid suspensions of CNTs/Al_2O_3 nanoparticles

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Abstract The aim of this work was to investigate the effects of temperature and solid volume fraction on thermal conductivity of CNTs–Al_2O_3/water nanofluids. Both Al_2O_3 nanoparticles and CNTs are dispersed in the base fluid with equal solid volume. Experiments were conducted with various solid volume fractions of 0.02, 0.04, 0.1, 0.2, 0.4, 0.8 and 1.0 % and various fluid temperatures of 303, 314, 323 and 332 K. Measured data reveal that the thermal conductivity of nanofluid highly depends on the solid volume fraction. Also, temperature may play an important role in enhancing thermal conductivity of CNTs–Al_2O_3/water, especially at high solid volume fractions. Based on experimental data, correlations are proposed for different temperatures by nonlinear regression. These correlations are able to predict thermal conductivity of nanofluid with high precision. Besides, a general correlation of thermal conductivity with function of temperature and solid volume fraction was proposed.

Keywords Thermal conductivity · Nanofluid · Hybrid suspensions · Correlation

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List of symbols

A, *B*, *C*, *D*	Constants
k	Thermal conductivity (W m^{-1} K^{-1})
T	Temperature (K)

Greek

φ	Solid volume fraction

Subscripts

bf	Base fluid
nf	Nanofluid
P	Nanoparticle
corr	Correlation
exp	Experimental

Introduction

Suspension of nanoparticles in base fluid is introduced to augment the heat transfer from 20 years ago [1]. Since thermal conductivity of nanofluids is greater than the common fluids (e.g., water, ethylene glycol and oil), nanofluids can be used for heat transfer enhancement applications [2–4]. Other applications include such diverse fields as electronic industry, electronic device, heating–cooling system, HVAC, heat exchangers, solar energy collectors, cooling systems for nuclear reactors, and heat exchangers. Heat transfer enhancement in various energy systems is vital because of the increase in energy prices. In recent years, nanofluids technology is proposed and studied by some researchers experimentally or numerically to control heat transfer in a process. The nanofluid can be applied to engineering problems, such as heat exchangers, cooling of electronic equipment and chemical processes. Thermal conductivity of nanofluids has been investigated analytically by a number of researchers [5–9]. Also, most of the researchers reported that the thermal conductivity of nanofluids is a function of temperature, nanoparticle size, concentration and shape of the nanoparticles suspended in the base fluid. Several reports for the thermal conductivity of oxide nanofluids are presented in Table 1.

Among the common nanoparticles, carbon nanotubes (CNTs) have been extensively studied as wonder nanomaterials because of unique thermal properties. A summary of existing studies for the thermal conductivity of CNT nanofluids, in room temperature, is given in Table 2. Due to the fact that the experimental measurement of thermal conductivity of nanofluids is costly and time-consuming process, many researchers presented empirical equations based on experimental data for different nanofluids. In this regard, Chon et al. [10] reported an experimental correlation for the thermal conductivity ratio of Al_2O_3 nanofluids as a function of temperature ranging from 21 to 71 °C and nanoparticle diameter range of 11 nm to 150 nm. Li and Peterson [11] dispersed Al_2O_3 and CuO nanoparticles with diameters of 36 and 29 nm, respectively, in distilled water. They measured the thermal conductivity of the discussed nanofluids over a volume fractions range of 2.0–10.0 % for temperature ranging from 27.5 to 34.7 °C. Using experimental data, they suggested two empirical correlations for Al_2O_3/water and CuO/water nanofluids. Determination of the thermal conductivity of three nanofluids containing Al_2O_3, CuO and ZnO nanoparticles dispersed in a base fluid of 60:40 (mass%) EG and water mixture was performed experimentally by Vajjha and Das [12]. Experiments were carried out over a temperature ranging from 25 to 90 °C for volume fractions up to 10.0 %. They developed a correlation for the thermal conductivity of three nanofluids as a function of volume fraction and temperature.

Teng et al. [13] examined the thermal conductivity ratio of Al_2O_3/water nanofluids under different mass fractions (0.5–2.0 mass%), temperatures (10–50 °C) and diameter of nanoparticles (20–100 nm). They also presented the correlation to estimate the thermal conductivity ratio of Al_2O_3/water nanofluid as a function of mass fraction, temperature and particle size. Ghanbarpour et al. [14] added Al_2O_3 ($d_p = 75$ nm) nanoparticles to distilled water and measured the thermal conductivity of Al_2O_3/water nanofluids over a concentration ranging from 3 to 50 % in mass for temperature ranging from 20 to 37 °C. Based on their experimental results, they proposed a simple correlation using nonlinear fitting of data. Hemmat Esfe et al. [15] measured the thermal conductivity of COOH-functionalized DWCNTs/water nanofluid at volume fractions and temperatures ranges of 0.01–0.4 % and 27–67 °C, respectively. Properties of these nanotubes have been listed in Ref. [15]. Using the experimental data, an experimental correlation for thermal conductivity of COOH-functionalized DWCNT/water nanofluid was derived by the regression analysis. In another study of these authors, the thermal conductivity of COOH-functionalized MWCNTs/water was measured at different temperatures (25–55 °C) and concentrations (0.05–1 %) [16]. Using the curve fitting of the experimental results, the correlation was proposed for prediction of the thermal conductivity of COOH-functionalized MWCNTs/water nanofluids.

To the best knowledge of authors, there is no study on thermal conductivity of CNTs–Al_2O_3/water nanofluid in the literature, so far. Thus, with the aim of contributing to the development of nanofluid thermophysical properties database and expanding models, thermal conductivity of water-based nanofluid containing nanotubes and Al_2O_3 nanoparticles is measured experimentally. Furthermore, several correlations are presented for estimating thermal conductivity of CNTs–Al_2O_3/water at different temperatures and solid volume fractions.

Table 1 Some studies on the thermal conductivity of oxide nanofluids

Author	Base fluid	Dispersed particles	Temperature range/°C	Nanoparticle size/nm	Concentration range/%
Das et al. [17]	Water	Al_2O_3	20–50	38.4	1.0–4.0
Das et al. [17]	Water	CuO	20–50	28.6	1.0–4.0
Li and Peterson [18]	Water	Al_2O_3	27–37	36 and 47	0.5–6.0
Chandrasekar et al. [19]	Water	Al_2O_3	NA	43	0.33–5.0
Reddy et al. [20]	EG–water	TiO_2	30–70	21	0.2–1.0
Sundar et al. [21]	Water	Fe_3O_4	20–60	13	0.0–2.0
Jeong et al. [22]	Water	ZnO	NA	20–40	0.05–5.0
Hemmat Esfe et al. [23]	EG	MgO	25–55	20, 40, 60 and 100	0.2–5.0
Li et al. [24]	EG	ZnO	15–55	30	1.75–10.5
Hemmat Esfe et al. [25]	EG	$Mg(OH)_2$	25–55	20	0.1–2.0

Table 2 A summary of existing studies for the thermal conductivity of CNT nanofluids

Author	Base fluid	Dispersed particles	Conditions	Maximum enhancement (%)
Xie et al. [26]	Water	MWCNT	1.0 vol% of CNT	7.0
Assael et al. [27]	Water	MWCNT	0.6 vol% of CNT	38.0
Hwang et al. [28]	Water	MWCNT	1.0 vol% of CNT	11.3
Amrollahi et al. [29]	EG	SWCNT	2.5 vol% of CNT	20.0
Nanda et al. [30]	PAO (oil)	SWCNT	1.1 vol% of CNT	12.0
Nanda et al. [30]	EG	SWCNT	1.1 vol% of CNT	35.0
Glory et al. [31]	Water	MWCNT	3.0 mass% of CNT	64.0
Jha and Ramaprabhua [32]	Water	Ag-MWCNT	0.03 vol% of CNT	37.3
Liu et al. [33]	EG	MWCNT	1.0 vol% of CNT	12.4
Harish et al. [34]	EG	SWCNT	0.2 vol% of CNT	14.8

Preparation of nanofluid

The required amount of CNTs and Al_2O_3 is weighted to prepare nanofluid at different concentrations of 0.02, 0.04, 0.1, 0.2, 0.4, 0.8 and 1.0 % using water as the base fluid. Then, carbon nanotubes with outer diameter of 5–15 nm and alumina nanoparticles with diameter of 20 nm, in the same volume, are mixed with water. The magnetic mixer is employed to mix the fluid for a 1 h. Next, the mixture is placed in ultrasonic vibrator (1200 W, 20 kHz) for a period of 7 h to attain the uniform dispersion of the nanoparticles.

Measurement of thermal conductivity

In this work, KD2 Pro (Decagon Devices, USA) thermal properties analyzer has been used to measure thermal conductivity of nanofluid. This instrument is commercial device, which is commonly used to define thermal conductivity of fluid (nanofluid) in the range of 0.02–2 W m- $°C^{-1}$ with KS1 sensor employing transient hot-wire method. The KS1 sensor made of stainless steel and has accuracy of 5 % and 60 mm long and 1.27 mm diameter, which is placed in nanofluid. The THW method measures the temperature/time response of the wire to an abrupt electrical pulse. To verify the accuracy of the measurements, all the experiments performed at least three times.

Results and discussion

In the first of this section, the thermal conductivity of CNTs–Al_2O_3/water hybrid nanofluids has been experimentally investigated. Then, accurate empirical correlations to prediction of the thermal conductivity are derived by nonlinear regression. Nanofluids have an equal volume of carbon nanotubes and alumina in the base fluid. Various suspensions are tested at solid volume fraction of 0.02, 0.04, 0.1, 0.2, 0.4, 0.8 and 1.0 % for temperature ranges from 303 to 332 K.

The variation of relative thermal conductivity versus temperature for different solid volume fractions is depicted in Fig. 1. It is evident from Fig. 1 that the thermal conductivity enhances with an increase in temperature. The enhancement of thermal conductivity at low solid volume fraction of nanofluid is relatively small. But with increasing the solid volume fraction of nanoparticles, the enhancement of thermal conductivity due to an increase in temperature is significant. Also, for a given temperature, it can be seen that the thermal conductivity is an increasing function of solid volume fraction. This phenomenon may be owing to the increase in number of particles suspended in the base fluid (with a very high surface to volume ratio),

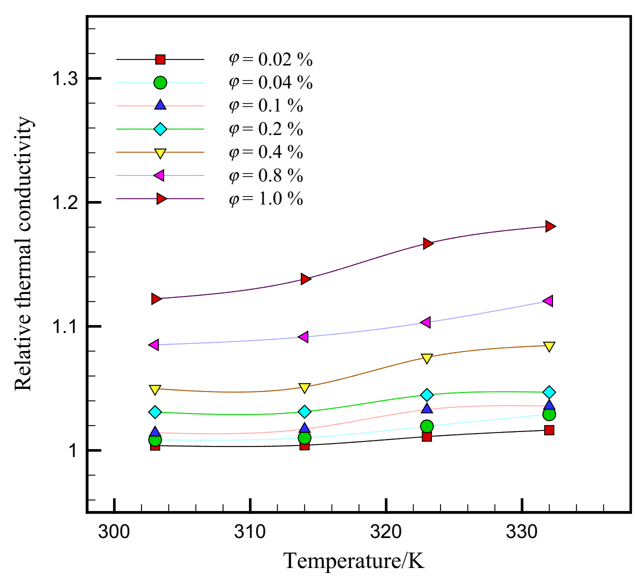

Fig. 1 Relative thermal conductivity of CNTs–Al_2O_3/water versus temperature for different concentrations

increase in collisions between particles and increase in Brownian motion. Undoubtedly, the solid volume fraction of nanoparticles is the most important parameter affecting the thermal conductivity and other thermophysical properties of nanofluids. Solid volume fraction is almost the only parameter that was used in all common existing classical and experimental correlations for the thermal conductivity of nanofluids. At all temperatures, the increase in the volume fraction enhances the thermal conductivity of nanofluid by a similar trend.

Figure 2 shows the variation of relative thermal conductivity versus solid volume fractions at different temperatures. It is apparent from Fig. 2 that the effects of temperature on thermal conductivity of nanofluids at higher solid volume fractions are more considerable, which is caused by increasing the particles numbers at higher concentrations and consequently increasing the particles collisions at higher temperatures. Increase in collisions due to rising temperature can increase the Brownian motion. Also, it can increase the possibility of aggregation of the nanoparticles, which enhance the thermal conductivity.

To understand the changes in thermal conductivity of CNTs–Al_2O_3/water nanofluids with the temperature and the solid volume fraction of nanoparticles, percentage of thermal conductivity enhancement with temperature and volume fraction changes is presented in Fig. 3.

Since there is not sufficient correlation to predict the thermal conductivity of nanofluids and also due to the necessity of accurate correlation for estimating it, several exact experimental correlations for prediction of CNTs–Al_2O_3/water nanofluids are proposed in this work. First, a general correlation depends on temperature and solid volume fraction is presented; then, different correlations to estimate the thermal conductivity of CNTs–Al_2O_3/water nanofluids at different temperatures are proposed.

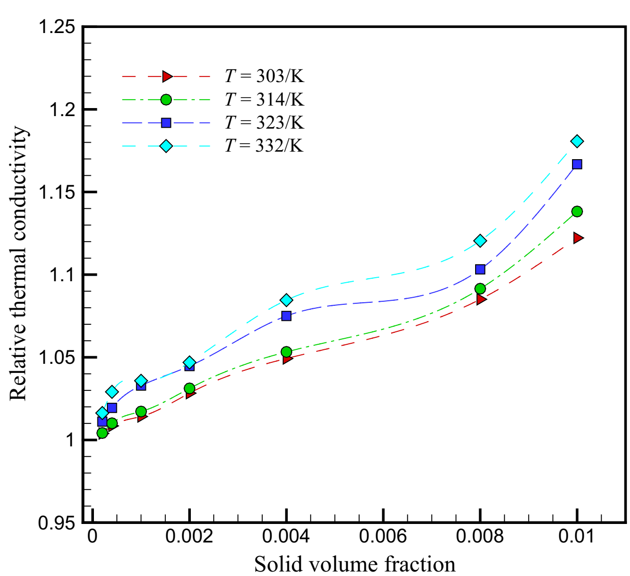

Fig. 2 Relative thermal conductivity of CNTs–Al_2O_3/water versus solid volume fraction for different temperatures

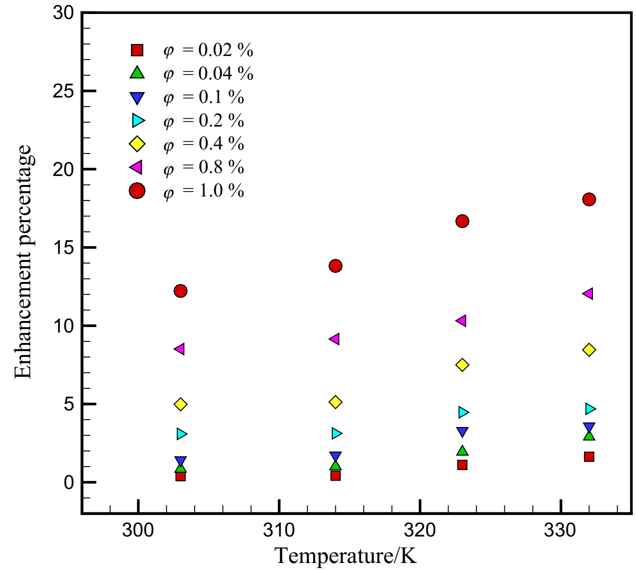

Fig. 3 Enhancement percentage of thermal conductivity of nanofluid compares to base fluid at different temperatures and concentrations

General correlation

As mentioned before, the thermal conductivity of CNTs–Al_2O_3/water nanofluid changes with variations in temperature and concentration of nanoparticles. Hence, the empirical correlation to estimate the thermal conductivity of this nanofluid is proposed in Eq (1), which is a function of temperature and solid volume fraction of nanoparticles. Despite its simplicity, this correlation is very accurate and useful, which is able to predict the thermal conductivity of CNTs–Al_2O_3/water nanofluid with very low error.

$$\frac{k_{nf}}{k_{bf}} = \frac{A+T}{B+C\varphi} + \frac{D}{T} \qquad (1)$$

In the above correlation, the k_{nf} and k_{bf} stand for the thermal conductivity of nanofluid and base fluid, respectively. This correlation is usable in the temperature ranging from 303 to 332 K and solid volume fractions up to 1.0 %. The values of constants *A*, *B*, *C* and *D* are listed in Table 3.

To ensure the accuracy of the suggested correlation, the margin of deviation can be defined as Eq (2).

Table 3 Values of constants for general correlation, Eq.(1)

A	B	C	D
−0.21483E+3	0.34658E+3	−0.10698E+3	0.22769E+3

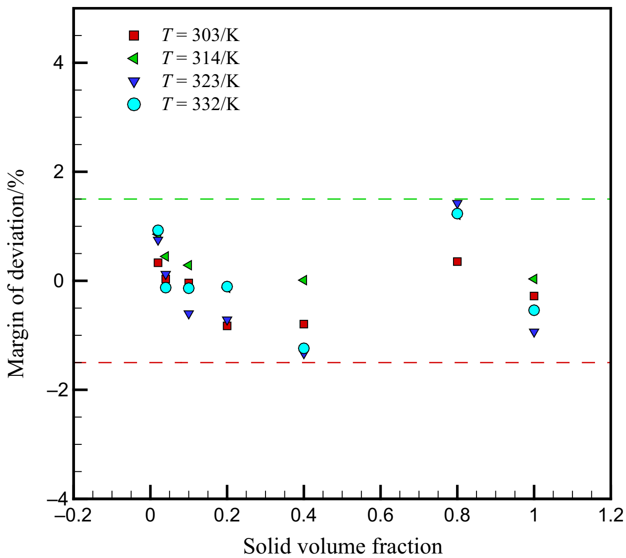

Fig. 4 Margin of deviation of the proposed correlation versus solid volume fraction

$$\text{Margin of deviation } (\%) = \frac{k_{corr} - k_{exp}}{k_{exp}} \times 100 \quad (2)$$

where k_{corr} and k_{exp} are the thermal conductivity obtained through the correlation and experimental tests, respectively. Figure 4 exhibits the margin of deviation with respect to solid volume fraction at different temperatures. As can be observed, the margin of deviation does not exceed 2 %, which indicates the acceptable accuracy of the proposed correlation for estimating the thermal conductivity.

Correlations for different temperatures

As we know, the different industries, researchers and engineers need thermophysical properties of the fluid at different temperatures and working conditions. Due to these requirements, the correlations to accurately predict the thermal conductivity of CNTs–Al_2O_3/water nanofluids at different temperatures of 303, 314, 323 and 332 K are presented. The suggested correlation is given in Eq. (3).

$$\frac{k_{nf}}{k_{bf}} = 1 + A\varphi + B\varphi^2 + C\varphi^3 + D\varphi^4 \quad (3)$$

In the correlation, there are four constant coefficients (*A*, *B*, *C* and *D*) that the values of these coefficients for different temperatures are given separately in Table 4. By determining and substituting the constants coefficients in Eq. (3), the unique correlation for each temperature can be achieved.

Table 4 Values of constants in Eq. (3)

T/K	A	B	C	D
303	0.1767	−0.1365	−0.024	0.1058
314	0.2037	−0.255	0.1386	0.0507
323	0.3606	−0.5755	0.2676	0.1138
332	0.4252	−0.8242	0.6995	−0.1201

Conclusions

In the present study, the thermal conductivity of CNTs–Al_2O_3/water hybrid nanofluids is experimentally investigated. Experiments were performed at solid volume fraction of 0.02, 0.04, 0.1, 0.2, 0.4, 0.8 and 1.0 % for temperature ranging from 303 to 332 K. Both alumina nanoparticles and carbon nanotubes were suspended in the base fluid with equal volume. Measured results revealed that the thermal conductivity of nanofluids highly depends on the solid volume fraction, and at high solid volume fractions the temperature effect is notable. A general correlation as a function of temperature and solid volume fraction of nanofluids was formulated by nonlinear regression on experimental data to estimate the thermal conductivity. Comparing the regression results with the experimental values showed that the maximum margin of error was about ±2.0 %, which indicates the excellent accuracy of the proposed correlation. Finally, because of the numerous industrial applications of nanofluids and also due to the necessity of accurate correlation for estimating the thermal conductivity of nanofluids, different correlations to estimate and predict the thermal conductivity of CNTs–Al_2O_3/water nanofluids at different temperatures were proposed. Each of these correlations has a very high accuracy; thus, these correlations have high capability to estimate the thermal conductivity of CNTs–Al_2O_3/water nanofluids at a specific temperature in different solid volume fractions.

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