Proceedings of the
International Conference on Mechanical Engineering 2011
(ICME2011) 18-20 December 2011, Dhaka, Bangladesh

ICME11-TH-034

EXPERIMENTAL INVESTIGATION OF THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF ETHYLENE GLYCOL-BASED NANOFLUIDS

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ABSTRACT

The effective thermal conductivity and effective thermal diffusivity of several ethylene glycol–based nanofluids were simultaneously measured by using a transient double hot-wire technique. Sample nanofluids were prepared by dispersing 1 to 5% volumetric concentration of titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3) nanoparticles in ethylene glycol. The effective thermal conductivity and effective thermal diffusivity were found to be higher than those of base ethylene glycol and they increase significantly and almost linearly with volumetric loading of nanoparticles. The increments of the effective thermal diffusivity of nanofluids are slightly larger than their thermal conductivity values. Besides particle volume fraction, nanoparticle shape and materials have also considerable influence on these properties of nanofluids. Based on the calibration results with the base fluid, the transient double hot-wire technique demonstrated very good accuracy to simultaneously measure the effective thermal conductivity and effective thermal diffusivity of nanofluids.

Keywords: Nanofluids, Nanoparticles, Thermal Conductivity, Thermal Diffusivity, Hot-Wire Technique.

1. INTRODUCTION

The mixtures of nanometer-sized (typically less than 100 nm) solid particles, rods, or tubes in conventional heat transfer fluids such as water, ethylene glycol and engine oil are termed as nanofluids. The concept of nanofluids was coined by Steve Choi in 1995 [1]. In recent years, nanofluids have evoked immense interest from researchers worldwide because of their superior thermal properties compared to their base fluids as well as due to their potential applications in diverse areas such as microelectronics, microfluidics, transportation, and biomedical and so on [2-3]. Nanofluids are also believed to be the next-generation heat transfer fluids [4]. Nanofluids with metallic and oxide nanoparticles as well as carbon nanotubes have been investigated by many research groups [2-3, 5-10] and most of them found significant enhancement of thermal conductivity compared to base fluids for volume fraction ranging from 0.1% - 6%. While research works on measurement and prediction of the effective thermal conductivity and other heat transfer properties of nanofluids have been conducted extensively [1-3], very little effort has been made to determine the effective thermal diffusivity which is especially important in evaluating their thermal performance under flow conditions and other heat transfer- based applications.

The measurement of thermal conductivity of nanofluids by various methods, particularly by the single hot-wire method is well-reported in the literature [5-7]. However, the accurate and simultaneous measurement of thermal conductivity and thermal diffusivity is much more complex for composite fluids like nanofluids compared to solids or gases. Due to complexities and low measurement accuracy, the existing methods such as the flush method [11], the thermal–wave cavity technique [12] and the temperature oscillation technique [13], are not suitable for the convenient and accurate determination of the thermal diffusivity of nanofluids. Very few studies have been reported on the determination of the thermal diffusivity of liquids by the conventional hot-wire method due to its considerably low measurement accuracy. For example, Nagasaka and Nagashima [14] measured the thermal conductivity and thermal diffusivity of toluene. Their thermal diffusivity measurements were less satisfactory and the accuracy was low compared to the thermal conductivity measurement. Thus the conventional single hot-wire method [7, 14] is not suitable for accurate and simultaneous measurement of the effective thermal diffusivity of nanofluids.

Among a handful of studies, Wang *et al.* [15] was the first to report the effective thermal diffusivity of a nanofluid (CuO/water). They measured the thermal conductivity and specific heat of nanofluid by a quasi-steady state technique and thereby calculated the effective thermal diffusivity. However, their calculated results were found to fluctuate severely with particle volume fraction. Most of the cases the measurement uncertainty for the effective thermal diffusivity was considerably high.

In this study, a transient double hot-wire (DHW) method is used for simultaneous measurement of the effective thermal conductivity and thermal diffusivity of nanofluids. The theoretical bases for determining the effective thermal conductivity and effective thermal diffusivity by using this method are presented. The effects of particle volume fraction and particle shape on these properties of nanofluids are studied. The experimental results are analyzed and compared with literature data for the sample nanofluids.

2. EXPERIMENTS DETAILS

2.1 Theoretical Basis

The measuring principle of the transient DHW technique is based on the calculation of the transient temperature field at some distance away from the source wire. The transient double hot-wire method makes use of two parallel wires. One wire acts as a heat source while the other functions as a temperature sensor. More details about this method will be discussed in the following section and can also be found in a previous paper [16]. However, development of theoretical formulations used in this method is briefly presented here. In order to facilitate understanding of theoretical basis and components of double hot-wire technique, a schematic concept of this method is shown in Fig. 1. Generally, the heat supplied through the source wire (q_{hs}) is higher than that through the sensor wire (q_{ts}). The lengths of the sensor and source wires are different ($L_{hs}>L_{ts}$) but both wires are of the same diameter (radius is denoted by a). The wires are considered as individual line heat sources in an infinite medium since the distance between the two wires (d) is very large compared to the wire radius.

Like the single hot-wire method [7, 14], the temperature increment of the sensor wire in DHW system due to constant heat supply (q_{ts}) through only the sensor wire can be expressed as [7]

$$\Delta T(a,t)=\frac{q_{ts}}{4\pi k}[\ln t+\ln\frac{4\alpha}{a^2C}] \qquad (1)$$

where q_{ts} is the constant heat supply per unit length of the sensor wire, $C=e^{\gamma}\approx 1.781$ where γ is the Euler's constant, and k and α are the thermal conductivity and thermal diffusivity of the surrounding medium, respectively.

From the analogy of the Wheatstone bridge circuit as shown in Fig. 1 and temperature increments of sensor wire as given by Eq. (1), an integrated correlation for the unbalanced circuit voltage (V_g) is developed to calculate the thermal conductivity a of nanofluids as given [7]

$$V_g=\frac{\beta R_3 R_{ts} V_s q_{ts}}{4\pi k(R_3+R_{ts})^2}[\ln t+\ln\frac{4\alpha}{a^2C}] \qquad (2)$$

where β is the resistance-temperature coefficient (the resistance- temperature coefficient of platinum wire used in this experiment is β =0.0039092/°C [17]), V_s is the supply voltage, R_3 is a circuit resistant and R_{ts} is the sensor wire resistance (Fig. 1). Equation (2) is obtained due to heat supply through the sensor wire only. Heat rate per unit length of sensor wire can be determined from

$$q_{ts}=\frac{1}{L_{ts}}\frac{V_s^2 R_{ts}}{(R_3+R_{ts})^2} \qquad (3)$$

Applying Eq. (3) into Eq.(2) and taking the slope of Eq.(2), we have the thermal conductivity expression

$$k=\frac{\beta R_3 R_{ts}^2 V_s^3}{4\pi L_{ts}(R_3+R_{ts})^4}/\frac{dV_g}{d\ln t} \qquad (4)$$

Since V_g can be obtained directly from the Wheatstone bridge circuit through the Analog to Digital (A/D) converter or digital voltmeter, the thermal conductivity of the sample medium is easily calculated from Eq. (4).

The total temperature increment in the sensor wire due to heat supply through itself (q_{ts}) and due to the source wire (q_{hs}) (located at a distance d) can be determined from [16]

$$\Delta T(a,t)=\frac{(q_{ts}+q_{hs})}{4\pi k}\ln t+\frac{1}{4\pi k}[q_{hs}\ln\frac{4\alpha}{(a+d)^2C}+q_{ts}\ln\frac{4\alpha}{a^2C}] \qquad (5)$$

where the heat rate per unit length of source wire

$$q_{hs}=\frac{1}{L_{hs}}\frac{V_s^2}{R_{hs}} \qquad (6)$$

Based on the total temperature increment of sensor wire as given by Eq. (5), a mathematical formulation for the unbalanced circuit voltage (V_g) was developed to calculate the thermal diffusivity of sample fluid as expressed [16]

$$V_g=\frac{\beta\xi_1 V_s^3}{4\pi k L_{ts}R_{ts}(1+\xi_1)^4}\left\{(1+f)\ln t+\ln\left[\frac{(2.25\alpha)^{1+f}}{(1+\varepsilon)^{2f}a^{2+2f}}\right]\right\} \qquad (7)$$

where $\varepsilon=\frac{d}{a}$, $\xi_1=\frac{R_3}{R_{ts}}$, $f=(\xi_2+\xi_1\xi_2)^2$, and $\xi_2=\frac{R_{ts}}{R_{hs}}=\frac{L_{ts}}{L_{hs}}$ (for the same diameter and same material of the source and sensor wires). Equation (7) can be rewritten in the form of

$$V_g = A \ln t + B \tag{8}$$

where slope $A = \dfrac{\beta \xi_1 V_s^3}{4\pi k L_{ts} R_{ts} (1+\xi_1)^4}(1+f)$ (9)

and intercept

$$B = \frac{A}{1+f} \ln \left\{ \frac{(2.25\alpha)^{1+f}}{(1+\varepsilon)^{2f} a^{2+2f}} \right\} \tag{10}$$

Simplifying Eq. (10), we obtain the following final expression for determining the thermal diffusivity of the medium inside the hot-wire cell

$$\alpha = 0.445 a^2 (1+\varepsilon)^{\frac{2f}{1+f}} \exp[\frac{B}{A}] \tag{11}$$

By allowing the current to pass through both wires, the circuit voltage change (V_g) over time is recorded using A/D converter. After plotting this recorded voltage change (V_g) against the natural logarithm of time (ln*t*), the slope (*A*) and intercept (*B*) can easily be obtained from the curve-fitting of Eq. (8). Making use of these slope and intercept, the effective thermal diffusivity of sample fluid can be calculated from Eq. (11).

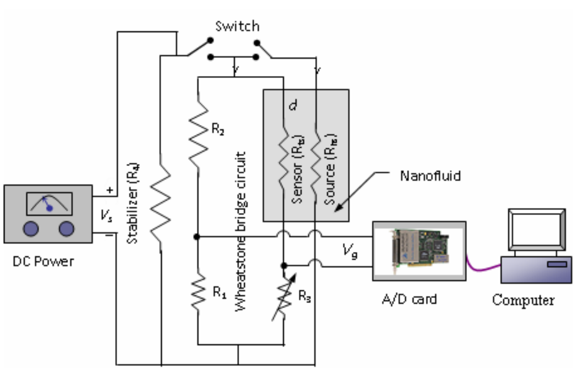

Fig 1. Schematic of the entire double hot-wire experimental setup

2.2 Setup and Measurement Details

A transient double hot-wire (DHW) method was employed for the precise and simultaneous measurement of the effective thermal conductivity and thermal diffusivity of nanofluids. The detailed evaluation of the double hot-wire method can be found elsewhere [16]. The schematic of the double hot-wire experimental system is shown in Fig. 1. The double hot-wire experimental setup has several major units including the power supply, Wheatstone bridge circuit, experimental cell containing both wires and test medium, and data acquisition and control system (A/D converter and computer). Two platinum wires of 50.8 µm diameters were used for both the heat source and the sensor. A separation distance (*d*) of 4 mm was kept between the two wires. The lengths of the sensor and source wires are 200 mm and 215 mm, respectively. The electrical resistances of these wires are known. The volume and diameter of the sample container are 80 mL and 20 mm, respectively.

In the conventional single hot-wire method, a single wire is used as one of the arms of a Wheatstone bridge and serves as both the heat source and temperature sensor. In contrast, the double hot-wire method uses two wires: one serves as the heat source, while the other as the temperature sensor, which is connected to the Wheatstone bridge as one arm. While allowing the current to pass through only the sensor wire, the DHW system works as a single hot-wire system and used to obtain the thermal conductivity, passing current through both the sensor and the source wires the thermal diffusivity of the test medium is determined. The sample fluid is filled into the hot-wire cell of the calibrated experimental setup. After switching on the DC supply through the stabilizer (R_4 in Fig. 1) current is first passed to the sensor wire and then to both wires of the balanced Wheatstone bridge circuit. The temperature sensor detects the temperature increments due to constant heat supply through the source wire and the sensor wire itself. With the increment of temperature, the sensor wire changes its resistance, which produced an unbalanced voltage (V_g) in the Wheatstone bridge circuit. The unbalanced voltages (V_g) for both cases were recorded in the computer by the A/D converter and Labview software. The measured unbalanced voltages versus natural logarithm of time data were then plotted. As mentioned previously, the thermal conductivity and thermal diffusivity of the sample fluids were calculated using Eqs. (4) and (11), respectively. All measurements were performed at atmospheric pressure and room temperature.

3. SAMPLE NANOFLUIDS

Several types of sample nanofluids were prepared by following two-step method which is dispersion of dry nanoparticles in base fluid. Different volume percentages (1 to 5%) of titanium dioxide (TiO_2) nanoparticles of 15 nm and 10×40 nm (nano-rod) and alumina (Al_2O_3) nanoparticles of 80 nm were dispersed in ethylene glycol (EG). Nanoparticles were purchased from Nanostructured and Amorphous Materials, Inc, USA. An ultrasonic dismembrator was used for several hours to ensure proper dispersion of nanoparticles into the base fluid. Very small amount (0.1mM) of Cetyl Trimethyl Ammonium Bromide surfactant was added in the base fluid to ensure better stability and to avoid agglomeration of nanoparticles. All nanoparticles were found to be well dispersed into base liquids and formed stable suspensions. Table 1 presents standard values of thermal conductivity and thermal diffusivity of base fluid and nanoparticles.

Table 1: Standard values of thermal conductivity and thermal diffusivity of base fluid and nanoparticles

Materials	**Thermal conductivity** (W/m·K)	**Thermal diffusivity** (m^2/s)
Ethylene glycol	0.255 [18]	9.38×10^{-8} [18]
TiO_2	8.04 [18]	2.9×10^{-6} [18]
Al_2O_3	18.83 [19]	11.9×10^{-6} [19]

4. CALIBRATION AND ACCURACY ESTIMATION

Before commencement of the experiments with the sample nanofluids, the experimental apparatus was calibrated by measuring the thermal conductivity and thermal diffusivity of the base fluid i.e., ethylene glycol. A high-resolution programmable analog to digital (A/D) converter was used to record the voltage changes (V_g) in the circuit over time. Under the same operating conditions, the effective thermal conductivity and thermal diffusivity were measured several times for each sample and average where taken. Comparisons of the measured and the standard values of these properties of base fluids are shown in Table 2. Based on the deviations between the standard values of thermal conductivity and thermal diffusivity (Table 1) and their measured values in calibration operation, all measurement system and procedure errors were found to be within ±2.3%.

Table 2: Calibration results with base fluid

Properties	**Accuracy estimation**	**Ethylene glycol**
Thermal conductivity (W/m·K)	Measured values	0.249
	Deviation from the standard value (%)	2.3
Thermal diffusivity (m^2/s)	Measured values	9.48×10^{-8}
	Deviation from the standard value (%)	1.0

5. RESULTS AND DISCUSSION

Figures 2-3 demonstrate the effect of particle volume fraction on the effective thermal conductivity and thermal diffusivity of TiO_2/EG-based nanofluids. Nanofluids showed enhanced effective thermal conductivity (k_{nf}) and thermal diffusivity (α_{nf}) compared to base fluid and they increase substantially with increasing nanoparticle volume fraction. For example, for maximum 5 % volumetric loading of TiO_2 nanoparticles of 15 nm and 10× 40 nm in ethylene glycol, the maximum increase in effective thermal conductivity was found to be 17 % and 20 %, respectively (Fig. 2). Wang et al. [10] also observed similar results for TiO_2 (40 nm)/EG-based nanofluids particularly for 3 and 4% volumetric loadings of nanoparticles. Whereas at the same particle volume fraction, the maximum increase in effective thermal diffusivity of these nanofluids with spherical and cylindrical nanoparticles are 24% and 29%, respectively (Fig. 3). For CuO/water-based nanofluids, Wang *et al.* [15] also showed significant enhancement of thermal diffusivity over base fluid. Nanofluids with rod-shape nanoparticle found to have a little larger enhancement in thermal conductivity as well as thermal diffusivity compared to those of spherical nanoparticles. Similar higher thermal conductivity enhancement of cylindrical shape nanoparticles over spherical shape was observed previously for water-based nanofluids [7]. These results indicate that along with the particle volume fraction, particle shape and materials also affect the enhancement of thermal conductivity and thermal diffusivity of nanofluids.

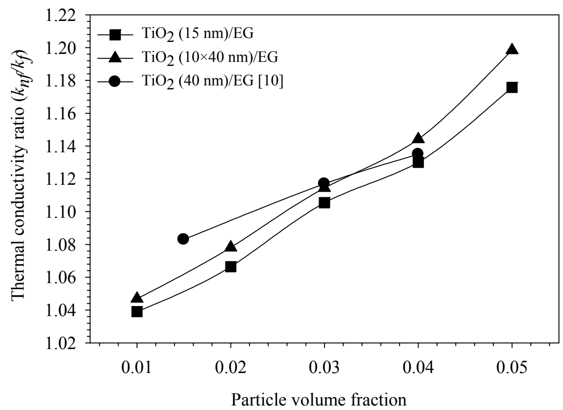

Fig.2. Effective thermal conductivity of TiO_2/EG nanofluids with particle volume fraction

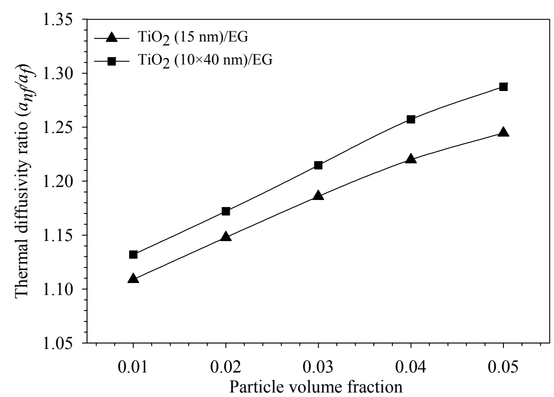

Fig.3. Effective thermal diffusivity of TiO_2/EG nanofluids with particle volume fraction

The effective thermal conductivity and effective thermal diffusivity of nanofluids with Al_2O_3 (80 nm) nanoparticles in ethylene glycol are demonstrated in Figs. 4 and 5. Results showed that the effective thermal conductivity and thermal diffusivity of these nanofluids increase significantly and almost linearly with nanoparticle volume fraction. Wang *et al.* [10] also observed similar results for the thermal conductivity of Al_2O_3 (28 nm)/EG-based nanofluids (Fig. 4).

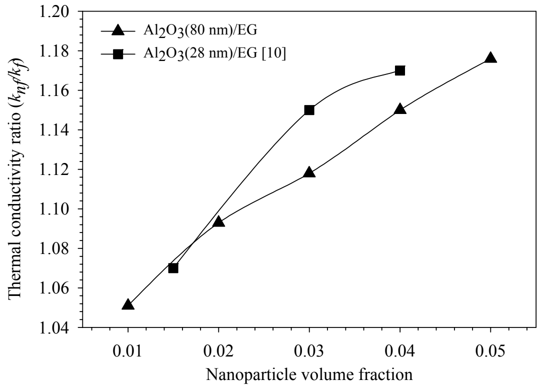

Fig.4. Effective thermal conductivity of Al_2O_3/EG nanofluids with particle volume fraction

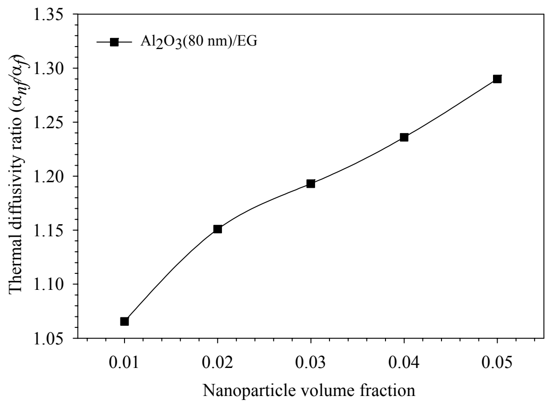

Fig.5. Effective thermal diffusivity of Al_2O_3/EG nanofluids with particle volume fraction

The degree of enhancement of the effective thermal diffusivity of nanofluids is found to be higher than the effective thermal conductivity. One reason is that with an increased volumetric loading of nanoparticle, the heat capacity of nanofluids can decrease which may result in an increase in the effective thermal diffusivity of nanofluids. While the mechanisms for the enhanced thermal conductivity of nanofluids are not yet fully understood to researchers, key factors behind their superior thermal diffusivity remained undiscovered.

6. CONCLUSIONS

The following conclusions can be drawn from the present study:

i. Besides its simplicity, the transient double hot-wire technique demonstrated to be very suitable for simultaneously and accurately measuring the effective thermal conductivity and thermal diffusivity of nanofluids.

ii. Nanofluids containing a small amount of nanoparticles have much higher effective thermal conductivity and effective thermal diffusivity values than those of their base fluids and they increase significantly and almost linearly with the volume fraction of nanoparticles.

iii. The increments of the effective thermal diffusivity of these nanofluids are found to be higher than the enhancements of their effective thermal conductivity.

iv. Results demonstrated that along with the nanoparticle volume fraction, particle shape and materials also play an important role in alteration of these thermal properties of nanofluids. Nanofluids with rod shaped nanoparticles showed higher thermal conductivity and thermal diffusivity compared to spherical shaped nanoparticles of same materials.

v. The mechanisms for the enhanced thermal diffusivity of nanofluids are not yet understood. It is imperative to perform more extensive theoretical and experimental investigations in order to better understand the heat transfer mechanisms and to predict the effective thermal diffusivity of nanofluids.

7. NOMENCLATURE

Symbol	Meaning	Unit
α	Thermal diffusivity	(m^2/s)
β	Resistance- temperature coefficient	(1/K)
a	Wire diameter	(m)
d	Distance between wires	(m)
k	Thermal conductivity	(W/m-K)
L	Wire length	(m)
q	Heat rate	(W/m)
R	Electric resistance	(Ohm)
V	Voltage	(V)

ACKNOWLEDGEMENT

The authors would like to thank FCT- Fundação para a Ciência e Tecnologia, Portugal for financial support through project PTDC/EQU-FTT/104614/2008.

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