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Measurement of thermal conductivity of graphene–water nanofluid at below and above ambient temperatures☆

Nizar Ahammed [a], Lazarus Godson Asirvatham [a,*], Joel Titus [a], Jefferson Raja Bose [a], Somchai Wongwises [b]

[a] Department of Mechanical Engineering, Karunya University, Coimbatore 641 114, Tamil Nadu, India
[b] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok, Thailand

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ABSTRACT

The present paper deals with the design, development and the measurement of thermal conductivity of graphene–water nanofluid using a transient hot wire technique at temperatures below and above ambient conditions ranging from 10 °C to 50 °C. The equipment is designed to measure the thermal conductivity using a single platinum wire of diameter 50 μm and 100 mm length. The platinum micro-wire acts both as a temperature sensor and heating element. Low volume concentrations (0.05, 0.1 and 0.15%) of graphene, having the size less than 100 nm, dispersed in 100 ml of water with SDBS (sodium dodecyl benzene sulfonate) as surfactant, for prolonged stability, is used in the present study. The results showed an enhancement in the thermal conductivity of 37.2% for 0.15% volume concentration of graphene at 50 °C when compared with that of the water at the same temperature. An interesting observation from this study is that the average thermal conductivity enhancement percentage with the increase in volume concentration (say from 0.05% to 0.15%) is found to be 3.3% higher when compared with that of the average enhancement with the increase in temperature from 10 °C to 50 °C.

1. Introduction

Thermophysical properties of fluids are the important parameters for any thermal design. Thermal conductivity, a thermophysical property, plays a vital role in thermal management and its consideration. Several methods exist to measure this property such as thermoreflectance technique [1] and 3-omega technique [2–4]. Transient hot wire (THW) method which was developed based on Fourier's transient heat conduction model is the conventional method to measure thermal conductivity accurately. Thermal conductivity of many substances like polymers [5,6], solids [7] and molten substances [8] can be measured using this technique. But thermal conductivity measurement of liquids and gases is complex due to the cause of natural convection. This demands for more modifications in transient hot wire technique for accurate measurement of thermal conductivity of liquids and gases. Water, engine oil, and ethylene glycol are some of the conventional fluids for heat transfer. Nowadays these fluids do not tend to be an effective and promising means for heat transfer due to the increase in demand for high cooling rates. So a fluid with improved thermal properties is to be developed for enhancing the heat transfer capabilities. The conventional heat transfer fluids such as water and ethylene glycol in which solid nanoparticles are suspended are called nanofluids. Dispersion of solid particles improves the thermal properties of the fluid as solid particles have very good thermal conductivity when compared to liquids. Hence, nanofluids have improved thermophysical properties; because of that, they have a wide range of applications.

Many investigations are being carried out in this area due to the exceptional properties of nanofluids. Choi [9] reported that dispersion of carbon nanotubes (CNTs) in engine oil enhanced thermal conductivity by 160%. Peyghambarzadeh [10] conducted an experiment on water/ethylene glycol nanofluid in a radiator for improved cooling of automotive and heavy duty engines. It was inferred from the results that there was a 40% enhancement in the heat transfer coefficient in terms of Nusselt number. Peyghambarzadeh [11] explained that the enhancement of the overall heat transfer coefficient depends on the volume concentration and flow conditions in another experiment. Zhou [12] investigated the thermal conductivity and viscosity with different kinds of surfactant solutions. It was inferred from the experiment that aggregation of nanoparticles can be controlled by the use of a surfactant. It was also found that only up to a specific concentration of a surfactant does the value of thermal conductivity increase, and above that, it decreases. Parekh and Lee [13] reported that for Fe_3O_4 nanofluid with temperatures ranging from 25 °C to 65 °C and at 4.7% volume concentration the thermal conductivity enhancement is 30%. Lee et al. [14] observed 20% enhancement with 4% volume concentration of CuO dispersed in ethylene glycol. Syam Sundar [15] investigated the thermal conductivity of Fe_2O_4 nanoparticles experimentally with ethylene glycol–water

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* Corresponding author. Tel.: +91 99944 55741; fax: +91 422 2615615.
E-mail addresses: godson@karunya.edu (L.G. Asirvatham), Somchai.won@kmutt.ac.th (S. Wongwises).

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Nomenclature

I	current (A)
l	length of the micro wire (m)
k	thermal conductivity (W/mK)
k_r	thermal conductivity ratio, $\frac{k_{nf}}{k_w}$
q	heat flux (W/m)
R	resistance (Ω)
S	switch
T	temperature (K)
T_f	absolute temperature ratio, $\frac{T_{nf}}{T_\infty}$
t	time (s)
V	voltage (V)
U	uncertainty

Greek symbols

φ	volume concentration
σ_{TCR}	temperature coefficient of resistance

Subscript

1, 2, 3	arms
f	fluid
IN	input
nf	nanofluid
OUT	output
r	ratio
w	water
W	wire
WO	wire at $t = 0$
WT	wire at $t > 0$
∞	ambient

under different mixtures by weight like 20:80%, 40:60% and 60:40% respectively, for the range of temperatures varying from 20 °C to 60 °C and concentrations ranging from 0.2% to 2.0%. The experimental results showed an enhancement of 46% when 2% nanoparticles are dispersed in 20:80% ethylene glycol–water mixture. It was also observed that thermal conductivity increased with the increase in the particle concentration and temperature. Pang [16] conducted an experiment with Al_2O_3 and SiO_2 nanoparticles with methanol as the base fluid and found that thermal conductivity was enhanced by 10.74% and 14.29% for 0.5% volume concentration respectively. Lee [17] reported that SiC/water nanofluid at 3.0% volume concentration gave enhanced thermal conductivity by 7.2%. Yu [18] used aluminum nitride nanoparticles for improving the thermal conductivity of ethylene glycol and propylene glycol. It was observed from the results that as the volume concentration of nanoparticles in the base fluid increased, the thermal conductivity of both the fluids increased. Philip [19] investigated the Fe_2O_3 nanofluid having a size of 6.7 nm with kerosene and found 300% enhancement in thermal conductivity for 6.3% volume fraction.

Based on the survey of literature mentioned above it is clearly observed that the thermal conductivity of a nanofluid increases with increasing temperature and volume concentration of nanoparticles. So far, most of the researchers have measured the thermal conductivity of nanofluids using metal oxide nanoparticles with relatively higher volume concentrations say > 1%. Further it is also observed that most of the research works on thermal conductivity of nanofluids using different types of nanoparticles such as CNTs, metallic oxide particles (Al_2O_3, CuO, Fe_3O_4, TiO_2 and SiC) and pure metallic particles (Cu, Al, Fe) have been measured only at ambient temperatures. Further, only a small number of works have been done on the measurement of thermal conductivity using graphene–water nanofluid. Although some information is currently available, the experimental investigations focused only on room temperature, the measurement of thermal conductivity of graphene–water nanofluid at temperatures below and above ambient conditions remains unstudied. Hence in the present study an attempt is made to determine the thermal conductivity of graphene–water nanofluid by suspending very low volume concentrations (0.05, 0.1 and 0.15%) of graphene with water at temperatures below and above ambient conditions ranging from 10 °C to 50 °C using transient hot wire method. The results will be useful in the design of heat exchangers or energy devices which work under a wide range of temperatures.

2. Experimentation

2.1. Preparation and characterization of nanofluid

The graphene–water nanofluid is prepared using the two step method. The graphene nanopowder is purchased from SkySpring Nanomaterials, Inc., Houston, USA (product number — 0540DX, lot number 0540-061814). The thickness of the graphene used in the present study is 1–5 nm. Only a small amount (5% of each volume concentration) of SDBS (sodium dodecyl benzene sulfonate) has been used for stabilizing the graphene in the base fluid. The surfactant is first added to the base fluid and then after stirring, the graphene is added. The mixture is sonicated for 30 min using an ultrasonic vibrator to break down agglomeration of the nanoparticles. The graphene–water nanofluid is prepared for different volume concentrations of 0.05%, 0.1% and 0.15% by suspending the required amount of graphene and SDBS. The graphene is characterized by a scanning electron microscope (SEM, JSM 6390, JEOL, USA) and a Zeta potential analyzer (Nano ZS90 ZETASIZER Nano Series, Malvern, USA) to study the shape, size and phase distribution.

Fig. 1 shows the SEM image of graphene taken at 7500× magnification. It is clearly observed from Fig. 1 that the graphene is randomly distributed as a flake-like structure less than 100 nm in thickness. The measured zeta potential for the graphene–water nanofluid at temperatures 25 °C and 55 °C is shown in Fig. 2. The zeta potential is the potential difference between the stationary layer of fluid attached to the dispersed particle and dispersion medium. The degree of repulsion between adjacent, similar charged particles in dispersion is designated by zeta potential value. The solution with high (negative or positive) zeta potential value indicates high repulsive force between the particles. So the particles do not agglomerate, hence the colloidal solution is electrically stabilized. Generally, the nanoparticles with zeta potential values greater than + 25 mV or less than − 25 mV typically have high degrees of stability. The zeta potential and total count values of − 63.7 mV, 175,000 and − 31.2 mV, 185,000 are respectively observed at temperatures 25 °C and 55 °C for the graphene nanofluid. The zeta

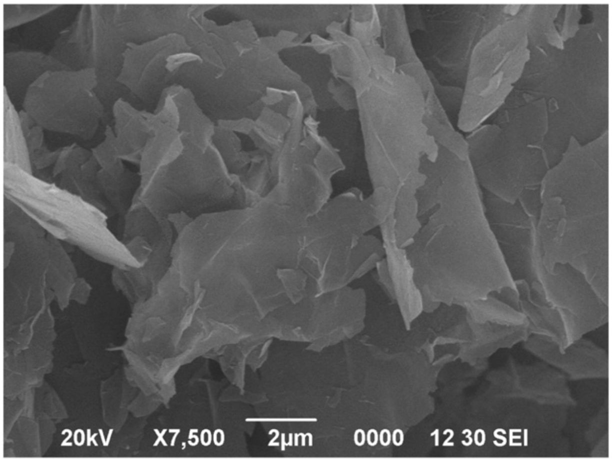

Fig. 1. SEM image of 0.15% volume concentration of graphene.