International Communications in Heat and Mass Transfer 57 (2014) 128–131

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Enhanced thermal conductivities of graphene oxide nanofluids☆

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ARTICLE INFO

Available online 17 July 2014

Keywords:
Graphene oxide
Thermal conductivity
Nanofluid
UV–vis

ABSTRACT

In this study, graphene oxide (GO) nanosheets were synthesized by the modified Hummers method. GO structure was estimated by XRD, UV–vis-spectrophotometer and SEM imaging. Then homogeneous and stable GO/water nanofluid was prepared. The effects of GO concentration and temperature on the thermal conductivity were investigated.

The measurements of thermal conductivity indicate that the nanofluids have substantially higher thermal conductivities than the base fluid.

The thermal conductivity enhancement depends strongly on the concentration of GO and increases with the increasing loading. When the nanosheet loading is 0.25 wt.%, the enhancement ratio is 33.9% at 20 °C and when the temperature increased to 40 °C the enhancement is up to 47.5%. Therefore the level of enhancement is dependent of temperature in the measured temperature range.

1. Introduction

Most industries (power generation, automobiles, air conditioning, microelectronics and cooling systems) use conventional fluids like water, ethylene glycol (EG) and transformer oil as heat transfer fluids [1]. Poor thermal conductivity of these fluids greatly limits the cooling role in heat exchangers [2]. Thus, improvement of the heat transfer capabilities of fluids is an urgent need. The advances in nanotechnology have resulted in the development of a class of fluids termed nanofluids (NFs). NFs, which are suspensions prepared by dispersing nanoparticles, rods or tubes in the base fluids with high stability have attracted much attention due to the anomalous thermal conductivity enhancement [3] which translates into lower operating costs, higher energy efficiency and better performance [4–6].

Carbon nanostructures have higher thermal conductivity than other nanoparticles because of their large intrinsic thermal conductivity and low density compared with metals or metal oxides and also due to strong C – C covalent bonds and phonon scattering [7]. The experimental results demonstrate that carbon materials, such as carbon nanotubes [8–13], graphite nanoparticles [14,15], exfoliated graphite nanofibers [16] and diamond nanoparticles [17,18], are good candidates for use in NFs. For example, axial thermal conductivity of carbon nanotubes (CNTs) is 3000 W/mK [19] and in-plane thermal conductivity of single-layer graphene is 5000 W/mK [20]. Superb thermal conduction property of graphene is beneficial for their application in NFs [21].

Graphene has 2D structure, and the heat transfer properties and mechanism are different from nanoparticles (NPs) and CNTs [22]. Therefore it is very interesting to investigate the thermal properties of NFs.

Many methods have been applied to prepare graphene, such as sonication in various solvents [23], solvothermal synthesis [24], micromechanical methods [25] and chemical vapor deposition (CVD) [26]. Among them, the chemical approach is suitable to produce graphene nanosheets [27]. Graphite is a usual raw material for production of graphene nanosheets (GNS) by the chemical methods. Therefore, in this paper, graphite powder was applied to produce graphene oxide nanosheets (GONs) which are the nanoparticles for water-based NFs. Heat transfer by convection process depends in part upon thermal conductivity of the fluid. Therefore in all of the physical properties of NFs, thermal conductivity is the most complex and for many applications the most important one.

2. Materials

Graphite powder (99.99%, 45 μm) was purchased from Bay Carbon, Inc., USA. Nitric & sulfuric acids, potassium permanganate, sodium nitrate and hydrogen peroxide were analytical grade. Deionized water (DI) was used throughout the experiment.

Graphite oxide (GO) was prepared from graphite powder by the modified Hummers method as described elsewhere [28]. Briefly, 2 g of natural graphite powder was treated with 46 ml of mixed concentrated nitric and sulfuric acids in an ice bath. 1 g of sodium nitrate was slowly added to the above solution, followed by the addition of 6 g of potassium permanganate.

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.07.018
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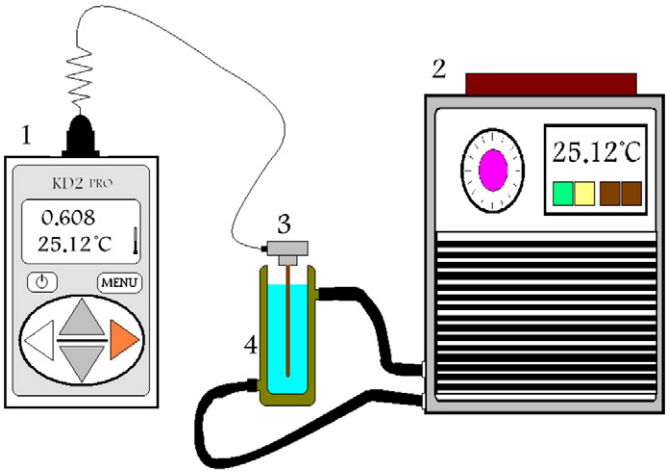

Fig. 1. Schematic of experimental set-up for measuring thermal conductivity of the NFs.

During the reaction of natural graphite flakes with concentrated nitric and sulfuric acids, water molecules, NO_3^- and SO_4^{-2} cations were inserted into the graphene layers and expanded the interlayer spacing in the graphite crystal structure. At room temperature, specific quantity of water was added to the above mixture. After 15 min the suspension was further treated with hydrogen peroxide and was filtered. The graphite oxide can be effectively exfoliated via ultrasonic vibration to generate GO. Finally the filter cake was washed with copious quantity of DI water. At last, the suspension was filtered and dried in a vacuum oven at 40 °C for 8 h. The product was a loose brown powder, and it could be dispersed well in water.

2.1. Characterization techniques

The size and morphological characterization of the GONs were examined by using scanning electron microscopy (SEM, Hitachi S-4200 scanning electron microscope). The SEM samples were prepared by dispersing the powder products in alcohol by ultrasonic treatment, dropping the suspension onto a holey carbon film supported on a copper grid and dried in air [22].

The UV–vis spectrum (PerkinElmer Lambda 900 spectrometer operating between 200 and 1100 nm) was used. The samples were diluted up to the extent that they were suitable for UV–vis measurements. One hour before the measurement, the UV spectrometer was turned on to be warmed up. The GO/water NFs were filled in a 1 cm quartz cuvette. When filling the cuvettes, care was taken to avoid bubbles, while visually inspected for bubbles [29]. Each measurement was repeated for three times to achieve a better accuracy.

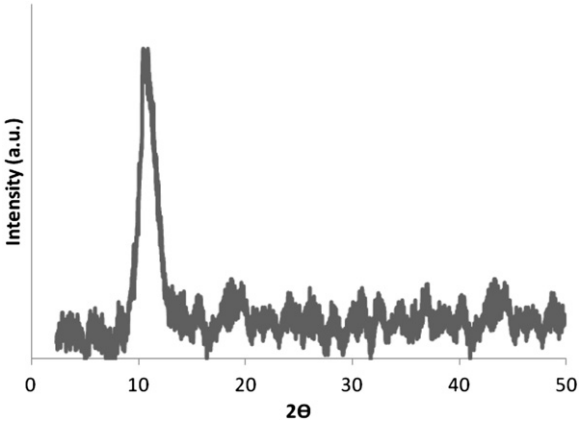

Fig. 2. XRD patterns of GO.

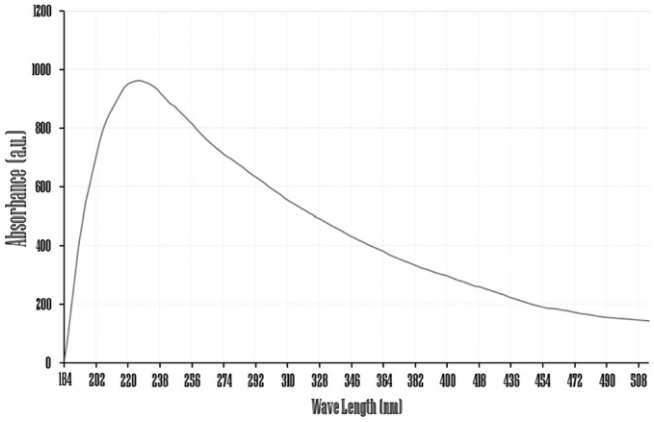

Fig. 3. UV–vis spectra of GO dispersed in water.

A transient short hot-wire technique was applied to measure thermal conductivities of NFs from 10 to 40 °C [30] by a KD2 Prothermal properties analyzer (Decagon devices, Inc., USA). Fig. 1 illustrates the experimental set-up for measuring thermal conductivity.

The instrument had a probe of 60 mm length and 1.3 mm diameter, a thermoresistor and a microprocessor to control and measure the conduction in the probe. The instrument had a specified accuracy of 5%. In order to obtain precise results, the sample and the probe were maintained at constant temperature for about 15 min.

A temperature-controlled bath (Ningbo Scientz Co., Ltd.) was used to maintain different temperatures of NFs during the measurement process. After the sample temperature reached the bath temperature, sample was kept at temperature for a further 30 min to ensure temperature equilibrium before a measurement was taken. Numbers of thermal conductivity measurements were taken for each sample and only a mean value of those with correlation coefficient greater than 0.99 was considered.

2.2. Graphene oxide structure

The crystal structure of GONs was investigated by an XRD diffractometer (X-pert Philips, pw 3040/60, Cu, $\lambda = 1/54{,}056$, $\beta = 0/1$ or 10%, on a 2100 series). The XRD pattern of GO was shown in Fig. 2.

As shown in Fig. 2, one high-intensity broad peak appeared about $2\theta = 12.5$ corresponding to (002) diffraction line (d-space 3.4 Å) plane of graphite. The GO structure was proved [32].

UV–vis spectroscopy analysis is a convenient way to characterize the structure of carbon allotropes [31]. It is known that GO is active in the UV–vis region and exhibit characteristic bands corresponding to

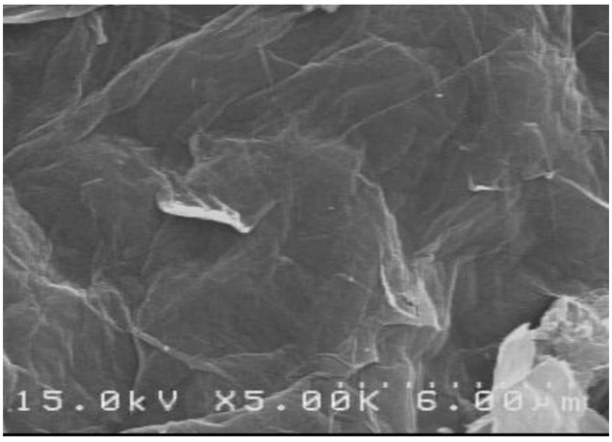

Fig. 4. SEM image of GO.