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Reduced graphene oxide dispersed nanofluids with improved photo-thermal conversion performance for direct absorption solar collectors

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ABSTRACT

Reduced-graphene oxide (RGO) dispersed nanofluids were prepared by irradiating a graphene oxide (GO)/water one under UV light for different times. X-ray photoelectron spectroscopy (XPS) analyses verified the reduction from GO to RGO under the UV irradiation and indicated that the reduction degree increased with the time. Zeta potential measurements suggested that the RGO/water nanofluids obtained under the irradiation time of 340 s or less can keep stable at elevated temperatures. The transmittance of the RGO/water nanofluids was quite less than that of the GO/water one, indicating that the change from GO to RGO greatly enhanced optical absorption. The RGO/water nanofluid obtained under the irradiation of 340 s possessed higher thermal conductivity and less specific heat than the GO/water one. The good stability along with the high optical absorption and thermal conductivity make the RGO/water nanofluid exhibited superior photo-thermal conversion efficiency to the GO/water and graphene (GE)/water ones at the same loading, which reached 96.93% at 30 °C and 52% at 75 °C. It is revealed that the RGO/water nanofluid prepared from the GO/water one shows greater promise for use as the working fluid in low-temperature direct absorption solar collectors.

1. Introduction

Solar radiation is the largest renewable energy resource for human beings. Solar thermal utilization is the most practical and effective way for using solar energy. In any solar thermal utilization systems, solar thermal collectors are the core components, where the solar irradiation is absorbed and converts the energy to heat [1]. Undoubtedly, developing novel solar thermal collectors with high efficiency helps to improve the utilization efficiency of solar energy. Direct absorption solar collectors (DASCs), first proposed by Minardi and Chuang in 1970s [2], are a novel kind of solar thermal collectors showing promise in achieving high efficiency. In a DASC, the solar irradiation is absorbed by working fluid, which acts as both an absorber and a heat transfer medium. Since the high temperature occurs in the fluid, the temperature difference between the surface of the DASC and the surroundings is minimized. Consequently, the heat loss to the surroundings is much more decreased in DASCs, compared to those in the conventional solar collectors such as flat plate collectors and vacuum tube collectors [3,4]. Obviously, the efficiency of DASCs are greatly dependent on the thermal characteristics of working fluids. The working fluids with high thermal conductivity, excellent optical absorption property and good photo-thermal conversion performance are highly desirable for developing high-efficiency DASCs.

Recently, an increasing attention has been paid on nanofluids for use as working fluids in DASCs. Nanofluids, firstly proposed by Dr. Choi [5] in 1995, are a kind of suspension liquids prepared by dispersing nano-sized materials (1–100 nm) into base liquids such as water, glycol, thermal oil, etc. [6–8]. A lot of researches have revealed that nanofluids exhibit enhanced thermal conductivity and improved heat transfer coefficients [9–14]. Beyond that, a remarkable improvement in optical absorption property has been found after a certain amount of nanomaterials has been dispersed into base liquids [15–19]. The enhanced thermal conductivity along with the improved optical absorption property makes nanofluids promising working fluids for DASCs. Although the nanofluids containing metal and metal oxide nanoparticles have been explored for use in DASCs [20–25], carbon nanomaterials, including graphite nanoparticles [22,26], single-, multi-wall and functional carbon nanotubes [27–29], carbon-coated metal [30–32] and carbon nanohorns [33,34], seem to be better nano additives for preparing the working fluids, due to their high thermal conductivity along with their dark color suitable for optical absorption.

In our previous work, we have explored graphene (GE)-dispersed nanofluids for use in DASCs, and found that the GE/ionic liquid nanofluids show excellent optical absorption property and high photo-

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Nomenclature

ζ	zeta potentials (mV)	D	diameter of collector (cm)
$T(\lambda)$	transmittance (%)	m	mass of nanofluids (g)
$K_{e\lambda}$	extinction coefficient	T_i	initial temperature (°C)
y	optical length (mm)	T_s	instantaneous temperature (°C)
α	thermal conductivity (W m^{-1} K^{-1})	A	top surface area of the receiver (m^2)
c_p	specific heat (J/g/°C)	G	the heat flux of the incident light (W m^{-2})
H	collector height (cm)	Δt	the time exposed to the light radiation (s)
		η	photo-thermal conversion efficiency

thermal conversion performance [35]. However, GE exhibits good dispersion in ionic liquids rather than in water. More recently, we found that graphene oxide (GO) has excellent dispersion in water, owing to the presence of rich hydrophilic groups on its surface [36], but the GO dispersed nanofluids exhibit limited optical absorption and photo-thermal conversion performance as compared to those GE dispersed nanofluids. In the current work, aiming at developing novel nanofluids with good dispersion stability, excellent optical absorption property and high photo-thermal conversion performance by combining the advantages of the GE and GO-dispersed nanofluids, reduced graphene oxide (RGO) dispersed nanofluids were prepared by irradiating a GO/water nanofluid under UV light, which reduction degrees were controlled by modulating the irradiation time. The dispersion stability, optical absorption property, thermal-physical property and photo-thermal conversion performance of the as-prepared RGO/water nanofluids were investigated in details, together with those of the GO and GE-dispersed nanofluids for comparison purposes. It is found that the RGO/water nanofluids not only possess excellent long-term dispersion stability, even at elevated temperature, but also exhibit good optical absorption property and high photo-thermal performance, making them show great potential for use as the working fluids in low temperature DASCs.

2. Experimental section

2.1. Materials and preparation

GO dispersion liquid (10 mg/ml) was purchased from Chengdu Organic Chemicals Co. Ltd., Chinese Academy of Sciences. According to the information provided by the manufacturer, the thickness of the GO nanosheets is 0.55–1.2 nm and the size is 0.5–3 µm. Polyvinylpyrrolidone (PVP) was purchased from Shanghai BoAo biological technology Co. Ltd. GE was purchased from Nanjing XFNano Material Tech Co., Ltd., China.

A GO/water nanofluid with a mass fraction of 0.02% was prepared by dispersing the GO dispersion liquid into the water containing 0.02% of PVP, followed by the ultrasound dispersion for 5 min to make the PVP absolutely dissolved.

RGO/water nanofluids were obtained by irradiating the as-prepared GO/water nanofluid under a UV light (365 nm, 1000 W, the distance from the light to the surface of the nanofluid is about 8 cm) for 260, 300, 340, 380 s, respectively.

For the purpose comparison, a GE/water nanofluid with a mass fraction of 0.02% was prepared by dispersing GE into the water containing 0.02% of PVP, followed by the ultrasound dispersion for 5 min.

2.2. Characterization and measurements

RGO samples were separated from the RGO/water nanofluids obtained under different irradiation times by centrifugation, respectively, followed by the characterization using X-ray photoelectron spectroscopy (XPS) with a Kratos Amicus instrument.

The Zeta potential (ζ) of samples were measured by Nano-ZS90 (Malvern Instruments, England). The samples were measured from 30 °C to 70 °C at an interval of 10 °C. The measurement accuracy of Zeta potential (ζ) was within 2%.

Transmission spectra of each sample was measured in the wavelength range from 220 to 2000 nm on a double-beam UV–Vis–NIR spectrophotometer (PerkinElmer Lambda 950) using a quartz cuvette with an optical path length of 10 mm at room temperature.

Thermal conductivity of the samples was measured at temperatures ranging from 30 °C to 80 °C at an interval of 10 °C by a thermal constant analyzer (TPS2500, Hot Disk Inc., Sweden), and a cyclic phenylmethyl silicone oil bath was applied to control the temperature more precisely. After being heated to the setting temperature, the samples were equilibrated for 10 min before being measured. The measurement at each temperature was repeated three times, and an average value was obtained. The measurement accuracy of thermal conductivity was within ± 3%.

A differential scanning calorimeter (DSC, Q20, TA Instruments, USA) was used to measure specific heat of the samples by the sapphire method. The temperature was kept at 0 °C for 5 min, and then programmed to 90 °C at a rising rate of 10 °C/min followed by keeping isothermal for another 5 min. The measurements were repeated for three times to obtain average values. The measurement error ranges from 0.2%~1%.

2.3. Evaluation of photo-thermal conversion performance

In order to evaluate the photo-thermal conversion performance of the nanofluids, an experimental setup was installed, elaborated in Fig. 1. A 700 W solar simulator (Solaredge 700, Perfect Light Co., China) was used as the solar light source, equipped with an AM1.5 optical filter. The average heat flux incident was measured by an irradiatometer (ST-80C Peifbnu Inc.), and the measurement accuracy of radiative heat flux was within ± 4%. A common quartzglass static cylinder insulated with the sponge of low thermal conductivity was used to load these nanofluids, and the diameter of quartzglass static

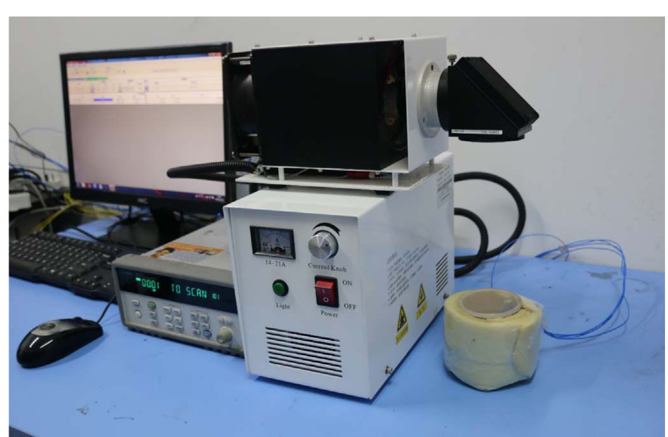

Fig. 1. Schematic of the experimental setup for evaluating photo-thermal conversion performance of nanofluids.