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Effect of morphology of carbon nanomaterials on thermo-physical characteristics, optical properties and photo-thermal conversion performance of nanofluids

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ABSTRACT

Graphite nanoparticles (GNPs), single-wall carbon nanotubes (SWCNTs) and graphene (GE) were dispersed into an ionic liquid (IL) to prepare nanofluids at different mass fractions, respectively. The thermo-physical characteristics, radiative properties, and photo-thermal conversion performance of the IL-based nanofluids containing the carbon nanomaterials with different morphologies were investigated in details. It is shown that all the nanofluids exhibit an increase in thermal conductivity and a decrease in viscosity as composed with the base liquid, and the enhancement and reduction ratios varied with their morphologies. The GE-dispersed nanofluids exhibit the highest thermal conductivity enhancement ratios as compared to the GNPs- and SWCNTs-dispersed ones at the same mass fractions. Among the nanofluids containing different carbon nanomaterials, the GE-dispersed nanofluids show the lowest transmittance and possess the highest extinction coefficients. It is revealed that the photo-thermal conversion performance of the IL has been enhanced by the addition of the carbon nanomterials, and the GE-dispersed nanofluids exhibit the highest photo-thermal conversion efficiency among the nanofluids containing different carbon nanomaterials. The superiorities in thermal conductivity, optical property and photo-thermal conversion efficiency make the GE-dispersed nanofluids show great potential for use as high-performance HTFs in solar thermal systems such as working fluids for DASCs.

1. Introduction

Dispersing a little amount of nanomaterials including metallic or oxide nanoparticles or carbon nanomaterials into conventional heat transfer fluids (HTFs) such as water, thermal oil, etc., has been proved to be one of the effective routes for heat transfer enhancement [1–4]. This kind of suspensions consisting of base liquids and nanomaterials is named as nanofluid, which term was coined by Choi in 1995 [5]. It has been reported that nanofluids exhibited increased thermo-physical properties especially in thermal conductivity [6–8] and enhanced heat transfer coefficients [2–4,9,10], compared to their corresponding base liquids. Moreover, when nanofluids are used as HTFs, the clogging phenomenon of pumps and pipes can be alleviated owing to the nanoscale of the additives [11]. All these advantages make nanofluids show great potentials for use as novel HTFs in many fields [12–16].

Direct absorption solar collectors (DASCs) is a promising type of novel solar collectors, which concept was proposed by Minardi et al., in 1975 [17]. Different from the commonly used surface-based solar collectors, DASCs, where working fluids directly absorb solar radiation, exhibit reduced heat loss by minimizing temperature differences between the absorber and the fluid, thus promising increased performance [17]. It is obvious that the working fluids that function as both the absorber and the transporter are critical for DASCs. However, the previously used working fluids for DASCs were black inks or solutions containing organic dyes, which suffered from low thermal conductivity and photo-induced instability. Consequently, the DASCs based on those working fluids didn't exhibit high performance as expected. Therefore, it is of great significance to develop novel working fluids with high thermal conductivity, excellent optical property along with good stability for DASCs.

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Recently, nanofluids have attracted an increasingly interest for use as the working fluids for DASCs, which mainly focuses on theoretical prediction and experimental evaluation on efficiencies of the nanofluid-based DASCs [18–21] as well as investigations on radiative properties of the nanofluids [11,22–25]. The researchers from Arizona State University [26,27] reported that a theoretical nanofluid enhancement in efficiency of up to 10% could be achieved by the nanofluid-based DASCs as compared to surface-based collectors. Lenert et al. [28] presented that receiver-side efficiencies are predicted to exceed 35% when the nanofluid-based DASCs are coupled to a power cycle and optimized with respect to the optical thickness and solar exposure time. Taylor et al. [29] obtained extinction coefficients of the nanofluids by both model predictions and spectroscopic measurements and found that over 95% of incoming sunlight can be absorbed by the nanofluids with extremely low nanoparticle volume fractions. All these results show that, nanofluid-based DASCs promise high performance, and nanofluids possess increased extinction coefficients due to the absorption and scattering of the nanoadditives. In addition, nanofluids containing nanoadditives of metal, metallic oxide or carbon are expected to possess superior stability over those inks or solutions of organic dyes. Obviously, nanofluids can be considered as promising working fluids for DASCs. Note that nanofluids containing different kinds of nanomaterials exhibit different thermo-physical and radiative properties. Furthermore, in view of the dual role of the nanofluids used in DASCs, it is rational that the thermo-physical and radiative properties of nanofluids determine their ability to convert light energy to heat, all of which are supposed to play a key role in establishing the collecting efficiency of the nanofluid-based DASCs [11]. Undoubtedly, the nanofluids with high thermo-physical and radiative properties as well as excellent photo-thermal conversion performance are highly desirable for high-efficiency DASCs.

Up to now, the nanomaterials used for preparing the nanofluids for DASCs mainly include the nanoparticles of Al, Au, Ag, Al_2O_3, TiO_2, etc. [18,27,29,30], together with the carbon nanomaterials such as graphite nanoparticles [31], single- and multi-wall carbon nanotubes [23,32,33] and carbon nanohorns [34]. Among them, carbon nanomaterials are the most attractive nanoadditives due to their ultra-high thermal conductivity along with the black color suitable for optical absorption. The thermal conductivity of carbon nanomaterials (2000 W m^{-1} K^{-1} for graphite, 2000–6000 W m^{-1} K^{-1} for carbon nanotubes and 5000 W m^{-1} K^{-1} for graphene, etc.), is order of magnitude higher than that of the metallic or oxide nanomaterials such as aluminum (237 W m^{-1} K^{-1}) and aluminum oxide (40 W m^{-1} K^{-1}) [35]. Furthermore, our previous work [36] demonstrated that, when the pure and carbon-coated Ni nanoparticles with the same average sizes of 40 nm were dispersed into the same base liquid at the same loading, respectively, the obtained nanofluid containing the carbon-coated Ni nanoparticles exhibited better radiative property than the un-coated Ni nanoparticles dispersed one, revealing that carbon coated on the surfaces of Ni nanoparticles enhanced the radiative property of the nanofluid containing them. Apparently, the thermal and optical superiority of carbon nanomaterials over metallic and oxide nanoparticles makes them show greater potential for use to prepare the nanofluids with high thermal conductivity and excellent radiative property for DASCs. Note that carbon nanomaterials are a family of carbon materials with numerous members showing different morphologies. Therefore, in order to exploit high-performance nanofluids for DASCs, it is necessary to conduct a systematical investigation on the effect of morphology of carbon nanomaterials on the thermo-physical and optical properties as well as the photo-thermal conversion performance of the nanofluids containing them.

In the current work, three kinds of carbon nanomaterials with different morphologies were chosen as the nanoadditives to prepare ionic liquid (IL)-based nanofluids suitable for medium-temperature DASCs, which are zero-dimensional graphite nanoparticles (GNPs), one-dimensional single-wall carbon nanotubes (SWCNTs) and two-dimensional graphene (GE), respectively. The effect of morphology of the carbon nanomaterials on the thermo-physical characteristics and optical properties of the obtained nanofluids has been investigated for the first time. Furthermore, the photo-thermal conversion performance of the nanofluids containing different carbon nanomaterials has been evaluated. It is found that the GE-dispersed nanofluid exhibits superior thermal conductivity, radiative properties and photo-thermal conversion performance over those SWCNTs- and GNPs-dispersed ones, suggesting its great potential for use as the high-performance working fluid for DASCs.

2. Experimental section

2.1. Materials

$[BMIM]BF_4$ (CAS Number: 174501-65-6) was provided by Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, China. GNPs, SWCNTs and GE were purchased from Nanjing XFNano Material Tech Co., Ltd., China. According the specifications provided by the manufacturer, the morphological characteristics of the three kinds of carbon nanomaterials are as follows. GNPs have an average size of less than 30 nm and a specific surface area of more than 600 m^2/g. For the SWCNTs, their average diameter is less than 2 nm, and lengths range from 5 to 30 μm; the specific surface area of the SWCNTs is between 500 and 700 m^2/g. GE is a single layer nanoplatelet with the thickness about 0.8 nm and single layer ratio is about 80%, it has a dimension between 0.5 and 2 μm and a specific surface area between 500 and 1000 m^2/g. Furthermore, the carbon nanomaterials were observed using a transmission electron microscope (TEM, Hitachi H-7650, Japan), and the obtained TEM images are shown in Fig. 1. The GNPs are almost spherical and have a narrow size distribution, except for several large particles, which are likely the aggregates of the primary particles. The SWCNTs tend to entangle with one another due to their large aspect ratios. The GE nanosheets are transparent, suggesting that they are composed of few layers. It is obvious that the GNPs, SWCNTs and GE have different morphologies, which correspond to zero-, one-, and two-dimensional nanomaterials, respectively.

2.2. Preparation of IL-based nanofluids

Nanofluids were prepared via the two-step method by dispersing the carbon nanomaterials into the IL, respectively. Specifically, a certain amount of each carbon nanomaterial (GNPs, SWCNTs, and GE) was added into $[BMIM]BF_4$, followed by magnetic stirring for 15 min. The obtained suspensions were thoroughly dispersed for 1 h using an ultrasonic apparatus at 400 W (KQ-400KDE, Kunshan of Jiangsu Equipment Company, China). The mass fractions of each material were set at 0.005% and 0.01%, respectively.

2.3. Measurements

2.3.1. Thermal conductivity

Thermal conductivity of the samples was measured at the temperatures ranging from 20 °C to 145 °C using a thermal constant analyzer (TPS2500, Hot Disk Inc., Sweden). In order to precisely control the temperature, a cyclic phenylmethyl silicone oil bath was applied. After every increase in temperature, the samples were