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Optimization on the photo-thermal conversion performance of graphite nanoplatelets decorated phase change material emulsions

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ABSTRACT

Carbon nanomaterials decorated phase change material emulsions (PCMEs) are promising working fluids for direct absorption solar collectors (DASCs). Aiming at realizing an optimization, eleven PCMEs with different mass fractions of graphite nanoplatelets (GNPs) (0.04%, 0.055%, 0.07%, 0.085% and 0.10%) and paraffin (15%, 20% and 25%) were prepared, and their thermophysical characteristics, optical absorption properties, and photo-thermal conversion performance were investigated systematically. It is shown that the thermal conductivity and optical absorption of the GNPs decorated PCMEs increase with the mass fraction of the GNPs, but show a reverse trend as the mass fraction of the paraffin is increased. The viscosity increases with the increase of the paraffin mass fraction at the same temperature, and gradually decreases along with the temperature increases. The photo-thermal conversion performance of the 0.04% GNPs decorated PCMEs is inferior to that of the ones at higher loadings of the GNPs; while, at high loadings of the GNPs, an interaction between the effect of the GNPs and that of the paraffin should be considered. It is revealed that thermal conductivity is an important factor influencing the temperature distributions within the PCMEs. And to avoid the evaporation of the water included in a PCME to weaken the incident light consequently, its optical absorption property should match with its thermal conductivity. The 0.07% GNPs decorated 20% PCME possesses the best photo-thermal conversion performance, and the relative heat storage capacity is 1.64 times as higher as that of distilled water. The 100 heating-cooling cycles test indicates that the 0.07% GNPs decorated 20% PCME exhibits good thermal reliability, making it show great potentials for use in DASCs.

1. Introduction

Solar thermal utilization is one of the most practical and effective ways to alleviate energy crisis and reduce environmental pollution, since solar energy is abundant, renewable and clean. In any solar thermal utilization systems, solar collectors are the vital components because their performances have the direct impact on the efficiency of the solar thermal utilization systems. Direct absorption solar collectors (DASCs), proposed in the 1970s, have been proved to be a new concept of high-efficiency collectors [1]. Different from traditional solar collectors, a DASC directly and volumetrically absorbs and converts solar energy to thermal energy through a heat transfer fluid (HTF) inside it, thereby leading to a lower temperature on its surface and thus a less heat loss [2]. Undoubtedly, the efficiency of DASCs is greatly depended on the optical absorption and thermophysical properties of the HTFs, namely the working fluids [3–5]. Therefore, High-performance working fluids are highly desirable for DASCs.

Nanofluids, a kind of suspensions prepared by dispersing a little amount of nanomaterials into conventional HTFs such as water, ethylene glycol and thermal oil, etc., have been verified to exhibit enhanced thermal conductivity [6–8] and improved optical absorption property [9,10], making them promising candidates as working fluids for DASCs. Consequently, a variety of nanofluids have been investigated with the purpose of being employed as the working fluids for DASCs in recent years, in which metal [3,11–13] and metal oxide [14–17] nanoparticles, as well as carbon nanomaterials [18–21], were applied as the nanoadditives. Among all those nanoadditives, carbon nanomaterials seem to be the most suitable ones due to their high thermal conductivity and dark color for optical absorption [22–24]. Furthermore, theoretical analyses and experimental investigations have proven that the nanofluids based DASCs did exhibit higher receiver efficiency as compared to that of the base fluid [13,25–27]. However, since the energy storage density of nanofluid is limited, a large volume of the container is needed for achieving the required energy storage capacity.

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Apparently, novel working fluids with good photo-thermal conversion performance and high energy storage density are highly desirable for DASCs.

In our previous work [28], graphite nanoparticles decorated phase change material emulsions (PCMEs) were first explored for use as the working fluids in DASCs, which were prepared by directly incorporating PCMs and graphite nanoparticles into water with the help of surfactants; It has been found that, compared with the 0.1 wt% graphite nanoparticles/water nanofluid that showed a decrement in receiver efficiency from 99.8% to 63% at the temperature range from 30 to 75 °C, the 0.1% graphite nanoparticles decorated PCME could maintain a receiver efficiency of as high as 86.8% at 80 °C [28]; The good receiver efficiency at a wide temperature range makes the graphite nanoparticles decorated PCME more suitable for use as the working fluids in DASCs. In the current work, aiming at optimizing the performance of the carbon nanomaterial decorated PCMEs, eleven PCME samples containing different mass fractions of graphite nanoplatelets (GNPs) and a paraffin were prepared. The thermal characteristics, thermophysical properties, optical absorption properties, and temperature rise curves of the obtained GNPs decorated PCMEs were measured, with the purpose of elucidating the effects of the mass fractions of the paraffin and the GNPs. Finally, an optimal GNPs decorated PCME with the highest photo-thermal conversion performance and energy storage capacity was obtained, and its thermal reliability was evaluated.

2. Experimental section

2.1. Materials

Paraffin (melting peak temperature was 62–64 °C) was purchased from Huayong Paraffin Co, Ltd. Polyvinyl alcohol (PVA) AH-26, whose degree of alcoholysis was 97.0–98.8% and molecular weight was about 110,000, was supplied by Sinopharm Chemical Reagent Co., Ltd. Polyethylene glycol-600 (PEG-600) was purchased from Shanghai Chemical Reagent Co., Ltd. GNPs were purchased from Nanjing XFNano Material Tech Co., Ltd.

2.2. Preparation of GNPs decorated PCMEs

Different amount of the paraffin was dispersed into water to prepare a series of PCMEs, in which the mass fractions of the paraffin were set at 15%, 20% and 25%, respectively. Specifically, 60 g of the 20% PCME was prepared by emulsifying 12 g of the paraffin into 45.6 g of water on a rotor-stator homogenizer (model FJ200-SH, Shanghai Specimen Model Factory) at a rotation speed of 10000 rpm for 5 min at 80 °C using 2.4 g of a mixture of PVA and PEG-600 as the emulsifier. Here, the mass ratio of PVA to PEG-600 was 50:50, and the mass ratio of the mixed emulsifier to the paraffin was 1:5.

For preparing the GNPs decorated PCMEs, different amounts of the GNPs were added into the three PCMEs, in which the mass fractions of the GNPs were set at 0.04%, 0.07% and 0.10%, respectively. In addition, 20% PCMEs containing 0.055% and 0.085% GNPs were also prepared by the same method, with the purpose of further optimizing the photo-thermal conversion performance of the GNPs decorated 20% PCMEs. Consequently, eleven GNPs decorated PCME samples were obtained, which were named as 15–0.04%, 15–0.07%, 15–0.10%, 20–0.04%, 20–0.055%, 20–0.07%, 20–0.085%, 20–0.10%, 25–0.04%, 25–0.07%, and 25–0.10%, respectively.

2.3. Characterization and measurement

The morphologies and microstructures of the GNPs and the GNPs decorated PCMEs were observed through a Zeiss Merlin Compact field emission scanning electron microscope (SEM).

The phase change temperature, enthalpy values and apparent specific heat of the samples were measured by a differential scanning calorimeter (DSC, Q20, TA Instruments, USA) under N_2 atmosphere at a flow rate of 50 ml min^{-1} with accuracy within ± 1%. The temperature was ramped from 20 to 95 °C at a scanning rate of 5 °C min^{-1}.

To evaluate the thermal reliability, the GNPs decorated PCME was heated to 80 °C and kept for 30 min, and then cooled to 20 °C and kept for 30 min, with the help of a thermo scientific HAAKE bath (HAAKE phoenix II, Thermo Electron Corporation, USA). This process was repeated for 100 times. The sample after experiencing 100 heating-cooling cycles was then examined by SEM and DSC.

The densities of the GNPs decorated PCMEs were measured by a densimeter (OC-300JH, Ocean Instruments & Materials Ltd., Hong Kong) at the temperature ranging from 20 to 80 °C. The density of each sample was measured three times, and an average value was then obtained.

The apparent thermal conductivities of the samples were measured at 30 °C using a thermal constants analyzer (Hot Disk TPS 2500s, Hot Disk AB, Sweden), with the purpose of investigating the effects of the mass fractions of paraffin and the GNPs on the apparent thermal conductivities of the GNPs decorated PCMEs. To control the temperature precisely, all samples were equilibrated for at least 20 min before testing. The thermal conductivity of every sample was measured three times, and an average value was obtained.

In order to acquire the optical absorption spectra of the GNPs decorated PCMEs, the GNPs decorated PCMEs were dried with a freeze dryer (Scientz-10ND, Ningbo Scientz Biotechnology Co., Ltd., China) firstly, and the obtained bulk samples were directly measured in the wavelength range from 400 to 800 nm by a UV–vis spectrophotometer (U 3010, Hitachi, Japan) at room temperature, using barium sulfate as a reference sample. Besides, the room temperature optical absorption spectrum of water was recorded in the wavelength range from 400 to 800 nm with a UV–vis spectrophotometer (UV-2050, Shimadzu, Japan) using a cuvette with an optical path length of 10 mm.

2.4. Evaluation of photo-thermal conversion performance

An experimental apparatus for evaluating the photo-thermal conversion performances of the GNPs decorated PCMEs was shown in Fig. 1. The experimental apparatus consists of two components: a data collection system and a photo-thermal conversion system. The data collecting system consisted of a computer, three type-K thermocouple probes, and a data acquisition system (34970A, Agilent, USA). The photo-thermal conversion system was composed of a light source, a quartz beaker, and a foam insulation system. A solar simulator (SOL-AREDGE 700, Perfectlight, China) was used as the irradiation source. An irradiatometer (ST-80C, Photoelectric Instrument Factory of Beijing Normal University, China) was used to measure the average radiative heat flux, and the measurement accuracy of radiative heat flux was within ± 4%. During the evaluations, each sample was placed into the beaker, while the temperatures at different positions were monitored with three type-K thermocouple probes, along with an infrared (IR) imager (Fluke Ti9, USA).

Furthermore, the thermal storage capacity of the GNPs decorated PCMEs was calculated as following [29]. The thermal storage capacity of a GNPs decorated PCME sample includes the sensible heat stored within the GNPs decorated PCME and the latent heat stored by the part of the paraffin that has made a phase change from solid to liquid.

Specifically, the stored sensible heat was determined through integrating the temperature profile along the height of the sample, as shown in Formula (1).

$$Q_{sensible} = \int C_p(y)[T(y) - T_0]\,\rho(y)\,A_c\,dy \tag{1}$$

where y is the sample height along the lighting direction, T(y) is the temperature distribution function along the y direction, T_0 is the initial temperature, and A_c is the cross-sectional area of the container.