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Volumetric solar steam generation enhanced by reduced graphene oxide nanofluid

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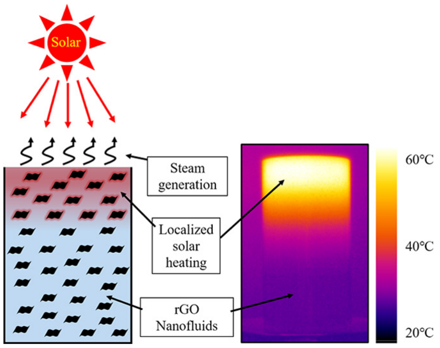
HIGHLIGHTS

- Well dispersed rGO nanofluids were used as volumetric broadband solar-absorber.
- Solar steam generation efficiency of rGO nanofluids could be up to ~47%.
- Rapid local evaporation was realized while the bulk fluid temperature was still low.

GRAPHICAL ABSTRACT



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ABSTRACT

Solar steam generation is a highly efficient photo-thermal conversion method that has a wide range of applications in water purification, distillation, power plants, and seawater desalination. Low steam generation efficiency was obtained for solar steam generation using traditional working media. Therefore, reduced graphene oxide (rGO) nanofluids with good stability and light absorption capability were fabricated to achieve highly efficient volumetric solar steam generation in this work. The effects of rGO mass concentration and light intensity on solar steam generation enhancement were investigated experimentally. It was found that a hot area was formed at water–air interface due to the unique lamellar structure of rGO with good light absorption characteristic, and sunlight was absorbed by the hot area to generate steam locally, which reduced thermal loss and improved evaporation efficiency. The solar steam generation enhancement achieved by the rGO nanofluids reduced evaporation costs and expanded their applicability in seawater desalination, clean water production, sterilization of waste, etc.

1. Introduction

With the depletion of traditional fossil fuels and the increasing emission of greenhouse-gases, solar energy has been identified as a green and renewable alternative [1–4]. There are two strategies to utilize solar energy: photo-electric conversion [5] and photo-thermal conversion [6]. Despite rapid developments in photo-electric conversion applications, photo-thermal conversion is a highly efficient technique that has more applications [7] such as solar water heating [8], space heating and cooling [9], refrigeration [10], industrial process

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heating [11], and thermal power generation [12]. Solar steam generation is a typical method to achieve photo-thermal conversion and has a wide range of applications in water purification [13], distillation [14], power plants [15], and seawater desalination [16,17]. For instance, in the concentrating solar power (CSP) system, the sunlight incident is absorbed by surface absorber and converted to heat, then the heat is carried away from the absorber by heat transfer fluid (HTF), subsequently, the HTF delivers heat to a heat engine, which generates electricity [12]. In traditional solar steam generation systems, solar energy is usually received and absorbed by the tube receiver, and then used to heat the bulk fluid through thermal conduction and thermal convection. As most of absorbed solar thermal energy is used to heat the bulk fluid and heat transfer resistance between the absorber and HTF is high, the steam generation efficiency is relatively low (35–45%) [18,19]. Using volumetric absorbers such as gas–particle suspensions, molten salts, and nanofluids is a simple and effective approach to improve light absorption capacity and reduce thermal loss, which could absorb the solar energy directly [20,21].

Choi [22] first proposed that nanofluids have many special properties due to the effects of nanoparticles (NPs). A nanofluid is a fluid containing nanometer-sized particles [23]. Unlike traditional fluids, nanofluids could enhance thermal conductivities [24,25], specific heat capacities [26], heat transfer coefficients [27–29], and sunlight absorption capacities [30,31] which could help enhance the solar steam generation efficiency. Many nanofluids have been explored to enhance solar steam generation, such as noble metals and composite NPs based nanofluids. Zhang et al. [32] and Chen et al. [33] studied photo-thermal conversion with gold and silver nanofluids, respectively, and the results demonstrated high efficiency for solar heating. Neumann et al. [34,35] investigated the solar steam generation properties of Au nanofluids and demonstrated a device efficiency of 24% with a solar power of 1000 sun (1 sun = 1 kW m^{-2}). Furthermore, Jin et al. [36] experimentally studied the steam generation performance of Au nanofluids under 220 sun irradiance and revealed that localized boiling occurred in the nanofluid. Liu et al. [37] investigated solar steam generation with liquid dispersed nanoparticles and realized highly efficient seawater purification. Guo et al. [38] explored the effect of Au NP diameters on photothermal conversion during the volumetric solar steam generation process. Amjad et al. [39] proposed a new integration method to calculate the sensible heating contribution in the Au NPs based nanofluids volumetric solar steam generation.

Compared to noble metal NPs, carbon nanomaterials have better potential for solar steam generation due to the high thermal conductivities and low cost. Ni et al. [21] reported a vapor generation efficiency of up to 69% under 10 sun irradiance using a graphitized carbon black nanofluid and revealed that a global temperature rise in the fluid medium was a significant mechanism in steam generation. Wang et al. [40] obtained a high evaporation efficiency with carbon nanotube nanofluids in a direct solar steam generation experiment. Reduced graphene oxide (rGO) is a kind of new carbon material possessing superior features such as high strength, flexibility, good conduction, high thermal conductivity, and excellent optical properties. rGO has good stability even at high temperature, which enables its possible applications in many areas [41,42]. The layered structure of rGO makes it more stable than other carbon materials in evaporating water. A more concentrated hot area will form in the top surface of bulk water to heat a small portion of water for evaporation, which could reduce thermal loss to the bulk fluid and increase the evaporation efficiency. Besides, the lamellar structures intertwine in bulk water, resulting in scattering and refraction of incident light, which will contribute to light absorbance by the upper area, thus increasing the evaporation rate. Therefore, solar steam generation enhancement could be achieved using rGO nanofluid due to multiple effects.

Despite some previous work on nanofluids based volumetric solar steam generation, the evaporation efficiency is still low. In addition, the stability of the nanofluids is still a problem for a long term solar steam generation. The mechanism of thermal and mass transfer in volumetric solar steam generation should be further addressed. In this work, graphene oxide was synthesized by the Hummers method and then high solar absorption rGO was obtained by the reduction of graphene oxide. The morphologies, structures, and properties of rGO were characterized. Furthermore, well dispersed and stable rGO based nanofluids were prepared for the volumetric solar steam generation. Finally, to explore the solar steam generation enhancement by the rGO nanofluids, solar steam generation experiments were conducted.

2. Experimental

2.1. Synthesis

Graphite powder, ammonia water, L-ascorbic acid (L-AA), $NaNO_3$, $KMnO_4$, H_2SO_4, and H_2O_2 were supplied by Aladdin Chemical Co., Ltd. GO was synthesized via a chemical exfoliation of the graphite powder by a modified Hummers method [43] as follows: 46 mL concentrated H_2SO_4 was slowly added into a mixture of 2 g graphite powder and 1 g $NaNO_3$ at 0 °C. Then, 6 g $KMnO_4$ was added with stirring while the temperature of the mixture was maintained below 20 °C using an ice bath. Afterward, the ice bath was removed, and the temperature of the mixture was raised to 35 °C and stirred for 30 min. Then, 92 mL deionized water was added to the mixture with stirring for 15 min, followed by the addition of 60 mL H_2O_2 solution at 60 °C. After the suspension turned brown, it was washed with deionized water and centrifuged for several times.

rGO was obtained by the reducing of GO with L-AA as reductant in aqueous solution [44]. To prepare rGO, the GO solution (100 ppm) was dispersed in deionized water and ultrasonicated for 1 h. Ammonia water was then added to regulate the pH to 10 with sonication for 30 min. L-AA (10 mg/mL) was added and the mixture was maintained at 95 °C for 3 h for the completion of reaction. The rGO solution was filtered to obtain rGO on the filter paper. Finally, rGO nanofluids were prepared by sonicating the filtered powder in a certain amount of deionized water. The entire process is shown in Fig. 1.

2.2. Solar evaporation experiments

Fig. 2 shows the experimental setup for solar steam generation. Solar light was generated by a solar simulator (CEL HXF300, CEAULIGHT, Beijing, China). The light was generated by a 300W Xenon lamp, which could realize the exportation of collimated light with high energy. The Xenon lamp is one of the most common types of lamp for continuous solar simulators. It offers high intensities and an unfiltered spectrum matching reasonably well to sunlight. The spectra of the light generated by Xenon lamp is shown in Fig. S1. An acrylic tube with a thermal insulation layer was used as a solar collector, and the temperature was measured and recorded using thermocouples (TT-T-40-SLE, Omega, US) and a data-acquisition system (34972A, Agilent Technology, Santa Clara, CA, US). Mass change was measured using an electric balance (Practum313–1CN, Sartorius, Göttingen, Germany). The inner height and diameter of the solar collector were 80 mm and 40 mm, respectively. The size and weight of the designed solar collector tube could be matched with the size of the solar light simulator and weighing range of the electric balance in the experiments. Seven T-type thermocouples were inserted into the solar collector at different heights (H = 10, 20, 30, 40, 50, 60, and 70 mm).

2.3. Characterization

Transmission electron microscopy (TEM) images of the rGO were obtained using a field emission microscope (Tecnai G2 F30, FEI, Portland, US). Atomic force microscopy (AFM) images were obtained using a Bruker Dimension Icon with ScanAsyst (Karlsruhe, Germany) for further thickness characterization of the rGO. Ultraviolet–visible