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Direct vapor generation through localized solar heating via carbon-nanotube nanofluid

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ABSTRACT

Traditional solar-energy collection systems experience high thermal losses because of the high surface temperature of the absorber. Nanofluid developments have led to extensive studies on their suitability for direct absorption as solar-energy collectors. A potential approach for solar steam generation via nanoparticle absorption of solar light and its conversion to thermal energy for water evaporation has been introduced recently. Direct solar vapor generation enabled by carbon-nanotube nanofluids was investigated experimentally in the present work. The effects of solar-power density and carbon-nanotube concentration on solar steam-generation performance are discussed. The evaporation rate increases with an increase in solar power and carbon-nanotube concentration. A high evaporation efficiency (46.8%) was obtained with a 19.04×10^{-4} vol.% carbon-nanotube nanofluid under a solar illumination power of 10 Sun (1 Sun = 1 kW m^{-2}). A high evaporation rate was achieved by localized heating of the nanofluid rather than by a bulk temperature increase, which provides a mechanism for low-temperature solar vapor generation and exhibits broad solar-energy applications such as seawater desalination, waste sterilization and power generation.

1. Introduction

Inexhaustible solar energy is regarded as one of the most promising renewable energy sources with long-term benefits to human beings. Development of this technology as a low-cost, clean technology for highly effective solar-energy utilization is the key in its many applications. In the large-scale applications, Weinstein et al. [1] reviewed the development of concentrating solar power (CSP) technology and concluded that CSP will maintain its role as a main part of the green energy landscape in the future; Elimelech and Phillip [2] pointed out that solar sources could feed energy into the large-scale seawater desalination plants; Oelgemöller [3] reviewed and summarized the solar photochemical synthesis from the photochemistry to the solar manufacturing of commodity chemical products. In the small-scale applications, Neumann et al. [4] used broadband light-absorbing nanoparticles as solar heater to generate high temperature vapors for the medicinal sterilization; Owrak et al. [5] used a porous bed as solar heat-storage to keep the building warm; Bae et al. [6] employed adiabatic plasmonic nanofocusing to attain ultrabroadband light absorption and efficient water vapor generation; Ghasemi et al. [7] utilized a double-layered carbon porous structure to achieve a high solar thermal efficiency up to 85%.

Nanofluids are a type of fluid suspensions that contain nano-sized (1–100 nm) materials [8]. Their thermophysical properties, such as heat capacity, thermal conductivity, viscosity, surface tension, latent heat and critical heat flux have been studied widely. For instance, Murshed et al. [9] measured the thermal conductivity of TiO_2-water based nanofluids and acquired a notable enhancement on the thermal conductivity. Amiri et al. [10] synthesized graphene nanoplatelets-based nanofluids and they exhibited higher thermo-physical properties compared to the distillated water. Motivated by their excellent thermophysical properties, many researchers have investigated their heat-transfer performance in natural convection, forced convection, pool boiling and condensation systems. For example, Mirzaei et al. [11] numerically investigated the laminar flow and heat transfer of water-Al_2O_3 nanofluids. Jamal-Abad et al. [12] experimentally studied the heat transfer coefficient Al–water and Cu–water nanofluids in the laminar flow regime under a constant thermal boundary condition. Song et al. [13] studied the critical heat flux enhancement of SiC nanofluids in the pool boiling experiments.

Recently, nanofluid-based direct-absorbing solar-energy collectors (DASCs) have attracted much attention for high-efficiency solar thermal harvesting, which uses nanoparticles to absorb solar

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light to convert it to working fluid thermal energy even at low particle concentrations [14]. The dual-use application of nanofluids, heat-transfer fluids and volumetric solar receivers exhibits significant potential for high-efficiency, low-cost existing systems. Many researchers have focused on photothermal properties and temperature changes of nanofluids experimentally and theoretically. He et al. [15] investigated the photothermal properties of Cu–H_2O nanofluids and showed that Cu–H_2O nanofluids could increase the temperature in a direct absorption solar thermal energy system. Tyagi et al. [16] used a two-dimensional model to analyze heat transfer numerically in a direct-absorption solar collector and obtained a 10% enhancement in absolute efficiency. Karami et al. [17] prepared aqueous suspension based carbon nanotubes as the absorbing medium and found that their promising thermal and optical properties make carbon nanotube dispersion interesting for enhancing low-temperature direct absorption solar collector efficiency. Otanicar et al. [18] studied the performance of a direct-absorbing solar-energy collector experimentally with different kinds of nanofluids and demonstrated an improvement in efficiency of up to 5%. Sani et al. [19] investigated the thermal and optical properties of carbon nanohorns-based nanofluids. Mercatelli et al. [20] investigated the scattering and solar light absorption properties of single-wall carbon nanohorns-based nanofluids and found that this new kind of nanofluids could be used as potential alternatives to solar-energy collectors. Because of the localized surface plasmon resonance effect of precious metal nanoparticles, Chen et al. [21] added plasmonic silver nanoparticles to the working fluid to improve the solar thermal conversion efficiency. Zhang et al. [22] investigated the photothermal conversion capability of gold dispersions and yielded a high photothermal conversion efficiency.

Most of this work has focused on heat generation inside nanofluids. Few researchers have discussed steam generation during the solar-energy collection process. Some researchers have investigated nanofluid solar steam generation with highly concentrated solar illumination or laser power. Neumann and co-workers [23] demonstrated Au-based dispersions for solar vapor generation and achieved a device solar steam efficiency of 24% under concentrated solar energy of 1000 Sun (1 Sun = 1 kW m^{-2}). Baffou et al. [24] experimentally described the generation of microbubbles occurring around gold nanoparticles under continuous laser illumination. Lombard et al. [25] numerically described the dynamics of vapor nanobubbles in water using a hydrodynamics phase-field model. Taylor et al. [26] conducted a laser-induced volumetric steam generation experiment and demonstrated that volumetric nanofluids absorber achieved a more effective coupling between incident light and phase change than surface absorber. Ni et al. [27] reported a vapor generation efficiency of up to 69% at a solar concentration of 10 Sun using graphitized carbon-black nanofluid and demonstrated numerically that nanofluid steam generation results from the global heating of bulk fluid. Jin et al. [28] performed an steam generation experiment with gold nanoparticle dispersion under focused sunlight of 220 Sun and found that the steam was generated by localized boiling and vaporization in superheated region.

However, nanofluid-enabled solar steam generation at low concentrated solar power, and especially the effects of nanoparticle concentration, solar-power density and the steam-generation mechanism have not been investigated fully enough. Sufficient nanofluid absorption is an important factor for efficient steam generation without any electric power or artificial optical devices. Carbon nanotube-(CNT) based nanofluids were selected for further research because of their high and broadband absorption in the solar spectrum. In this work, four different concentrations of single-wall CNTs were dispersed in water and CNT nanofluids were obtained through sonication of the dispersions. Solar steam-generation experiments were conducted to investigate the photothermal properties and evaporation performance of the CNT nanofluids. The effect of CNT concentration (from 2.38×10^{-4} vol.% to 19.04×10^{-4} vol.%) and solar power intensity (from 1 Sun to 10 Sun) is discussed. Finally, a mechanism for CNT-enhanced solar steam generation is proposed.

2. Experimental section

In this section, CNT nanofluids were prepared by dispersing CNTs into water and keep the mixture being sonicated for a long time. Then the structure properties of CNT were characterized through transmission electron microscopy (TEM) and atomic force microscopy (AFM). The optical properties of CNT nanofluids were tested by an ultraviolet–visible (UV–Vis) spectrometer. Finally, the solar steam generation test was conducted under a solar light simulator combined with a temperature and weight change recording system.

2.1. Preparation of CNT nanofluid

Single-wall CNTs were purchased from Carbon Solutions Inc, Riverside, CA, USA and were used as received. CNT nanofluids were prepared by dispersing different masses of CNTs into deionized water and sonicating for 2 h without adding any surfactant. CNT nanofluids were obtained with the volume concentration from 2.38×10^{-4} vol.% to 19.04×10^{-4} vol.% (Fig. 1).

The optical properties of the CNT nanofluids were determined by using a double-beam ultraviolet–visible (UV–Vis) spectrophotometer (TU–1901, Persee, Beijing, China) using a plastic cuvette with 4-mm optical path length (Fisherbrand™ Polymethylmetacrylate Semi–Micro Cuvette). The reference sample was water for all measurements. Multiple reflections between the different media and scattering effects of the CNTs were assumed to be negligible. A CNT nanofluid stability test was carried out by observing the UV–Vis absorption intensity daily for two weeks.

2.2. Characterization

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

2.3. Experimental setup

The experimental setup for solar-enabled steam generation is shown in Fig. 2. The main components of the setup include a solar simulator (CEL HXF300, CEAULIGHT, Beijing, China), volumetric

Fig. 1. Photographs of CNT nanofluids with different concentrations.