



Experimental photothermal performance of nanofluids under concentrated solar flux



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ABSTRACT

Nanoparticle based direct solar absorption is a promising technology for future solar thermal systems. Having so many individual studies on different nanomaterials for solar energy harness, a comprehensive comparison of photothermal conversion characteristics of various nanofluids at the same experimental conditions is much needed. The photothermal conversion performance of six commonly used nanomaterials in direct absorption solar collectors (DASC) was investigated under a focused simulated solar flux. The contribution of sensible heating and latent heat of vaporization of the nanofluids was revealed in context of their photothermal performance. The results show that all the nanofluids have higher solar energy absorption than the base fluid and silver nanofluid turned out to be the best amongst all due its strong plasmonic resonance nature. A 99.7% enhancement in the photothermal conversion efficiency of silver was achieved within the experimental domain. A simulation model was proposed to state the temperature difference between the surface of the nanoparticle and the surrounding fluid under lower solar flux.

1. Introduction

With increasing concerns over global warming and environmental issues, developing renewable energy is becoming more and more important to secure our energy needs. Solar energy is the most abundant source of energy and is easily accessible. However making efficient use of solar energy is not an easy task [1]. A conventional plate-type solar collector absorbs solar energy on an absorbing plate, and transfers the heat via a wall to a working fluid running inside [2–4]. It is a surface-based absorption, which limits the effective utilization of solar energy by creating a large temperature difference between the absorbing plate and the working fluid, especially for concentrated solar energy applications [5].

The limitations of surface absorption can be mitigated by a volume based solar absorption in which the working fluid directly absorbs energy from the Sun, named as direct absorption solar collection (DASC). The concept has its origin back in 1970 [6] and is receiving an increasing interest and attention recently by using different nanoparticles. Several nanomaterials like silver [7–9], gold [10,11], carbon nanotubes [12–14], copper [15], aluminum oxide (Al₂O₃) [1,16–19] and graphite [20] have been examined experimentally as well as

numerically [21–26] for their capabilities to enhance solar absorption individually. Light to thermal conversion characteristics of these nanofluids have been investigated at various concentrations. For example Enio et al. [8] examined Ag nanofluid in a volume concentration range of 0.0001625–0.065% while Zhang et al. [10] explored the effect of adding Au nanoparticles in DI water in the range of 0.00028% to 0.0112 wt%. Yousefi et al. [14] used 0.2 wt% multiwall carbon nanotubes (MWCNT) in water with varying pH values in a flat plate solar collector and Qenbo et al. [15] employed Cu nanoparticles with 0.001–0.02% volume concentration. Similarly Yousefi et al. [19] used 0.2% and 0.4 wt%, Hament et al. [1] used 0.001–0.05% by volume and Said et al. [18] used 0.05–0.1% volume concentration of Al₂O₃ nanoparticles. Except that of Zhang et al. [27] who examined various types of nanoparticles at the same concentration under 1 Sun, each of the above mentioned study was based on only one particular type of particle. A comparative assessment of the performance of commonly used nanomaterials for solar energy harness is much needed. The effect of these nanomaterials must be investigated at the same concentration and under similar operating conditions to reveal their photothermal conversion performance.

This study identified six most commonly used nanomaterials in

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direct absorption solar collectors and investigated their photothermal performance under a focused solar simulator (i.e. 12 Suns). The bulk temperature rise of the nanofluids was measured with the help of three K-type thermocouples under the LabVIEW environment. Their photothermal conversion efficiencies and specific rate of absorption were obtained for comparison and possible mechanisms were examined. An analytical model was developed to state the temperature difference between the surface of the nanoparticle and the surrounding liquid.

2. Materials and methods

2.1. Materials

Commercial nanopowders of six materials including Ag, Cu and Zn (Sigma Aldrich Co.) and Fe, Si and $\text{Al}_2\text{O}_3\text{-}\gamma$ (Nanostructured & amorphous material Inc.) were used as received. Tri-sodium citrate (99.8%, Fisher Scientific) was used as the dispersant and stabilizing agent and DI water was used as the base fluid throughout the experimental procedure.

2.2. Nanofluids preparation and their characterization

Different metallic nanopowders of Ag, Zn, Fe, Cu, Si and $\text{Al}_2\text{O}_3\text{-}\gamma$ were used to prepare nanofluids by the two-step method. In this method, selected nanopowders were directly mixed with a 0.5 wt% of tri-sodium citrate solution in DI water. For instance, to prepare a nanofluid of 0.01% weight concentration, 0.01 g nanopowder was mixed with 99.99 g of a 0.5 wt% aqueous solution of trisodium citrate (TSC) under vigorous stirring. The acquired mixture was sonicated by a high energy probe (1200 W) for 5 min where the temperature was controlled at 40 °C. The suspensions were then cooled down naturally to the room temperature and were sonicated for 10 min before the photothermal conversion experiment.

Morphological characterization of the nanopowders is given in Fig. 1 where Fig. 1 (I) (a through f) shows scanning electron microscopic (SEM) images of the nanopowders and transmission electron microscopy (TEM) micrograph of silver nanopowder dispersed in 0.5 wt % aqueous solution of TSC is given in Fig. 1 (II). The nanopowders were mostly clustered (Fig. 1 (I)) before the dispersion but became completely dispersed in DI water in the presence of stabilizing agent after sonication. The dispersion stability can also be seen from the stable absorption spectra in Fig. 3. The optical absorption of these nanofluids was checked by a UV–Visible spectrometer (UV-1800, Shimadzu) using a high precision cell (made of HOQ 310 H) with light path of 10 mm. The primary particle size range of the nanopowders as supplied by the suppliers is given in Table 1.

2.3. Experimental setup

The photothermal conversion characteristics of the prepared nanofluids were investigated using a solar simulator (Newport Co.). It has a class AAA certification to JIS C 8912, and ASTM E 927–05 standards, which has a 450 W xenon lamp as the light source and spectral correction filters (known as Air Mass filters) to correct the light output to closely match the solar spectrum. An air mass filter AM1.5 G was used to simulate the direct solar spectrum when the Sun was at a zenith angle of 48.20 (ASTM E891). The sun simulator has a spectral match 0.75–1.25% fraction of ideal percentage, 2% non-uniformity of irradiance and $\pm 2\%$ spectral instability according to ASTM Class AAA standard. A schematic view of the experimental setup is presented in Fig. 2.

A petri dish of 5.8 cm diameter was used to contain the sample. The bulk temperature change was measured by three K-type (Omega 5TC-TT-K-36–36) thermocouples (TC), which were positioned at an angular

position of 120° at three representatively depths: just under the top surface of the fluid, at the middle and close to the bottom of the petri dish but not in contact. A fourth thermocouple was used to measure the variation of room temperature. The data were registered by a data acquisition device (NI SCXI-1303) under the LabVIEW environment at a sampling rate of 1 Hz. The uncertainty in temperature measurement was calibrated as ± 0.25 °C. The sample container was rinsed with DI water before each experiment to avoid inter-sample contamination.

A Fresnel lens of 5.5×5.5 in.² with a focal length of 10 in. was used to focus the output light onto a nanofluid sample. The focused intensity of light was measured as 12 suns, approximately equal to 11637.5 W/m² (being one sun ~970 W/m²) with the help of a solar intensity meter.

3. Results and analysis

3.1. Optical absorbance

Water is a poor absorber of the solar energy in the visible light spectrum where most of the solar energy is contained as can be seen from Fig. 3. Solar absorption of water can be significantly enhanced by adding nanoparticles that have good absorptivity in the visible region. In this study, the optical absorptivity of the prepared nanofluids was checked by a UV–Vis spectrometer using a high precision quartz cell with light path of 10 mm. The optical absorbance spectra and spectral solar irradiance are shown in Fig. 3.

Different metallic nanofluids have different optical absorption peaks over the UV to visible spectrum. The absorption peak of silver nanofluid is the strongest amongst all the nanofluids compared at the same particle concentration of 0.01 wt% (Fig. 3). This is due to the strong localized surface plasmonic effect in silver nanoparticle that makes it different from the others. The plasmonic resonance frequency of silver nanofluid can be seen around 430 nm from Fig. 3, which is almost the beginning of the visible band of the solar spectrum.

Compared with silver, the optical absorbance of other nanofluids in this study has mostly their absorption peaks in the UV to visible region. Though the absorption peaks of Fe, Si, Cu nanofluids are not very strong in the UV region, the flat absorption curve in the visible region shows that their absorption is far much better than water at such a low weight concentration. The optical absorbance curve of $\text{Al}_2\text{O}_3\text{-}\gamma$ nanofluid is almost similar to that of DI water in the visible region, which is also reflected in the temperature curves, as described below.

3.2. Bulk fluid temperature

The temperature of the nanoparticles in the nanofluid can be assumed as the temperature of the bulk fluid due to very small nanoparticle concentration i.e. only 0.01% by weight. Deionized water and sample of each fluid was heated for a minimum period of 30 min under the solar flux of 12 suns. Fig. 4 (a) represents the temperature variation of three thermocouples for a silver nanofluid sample, and Fig. 4 (b) shows the average temperature profiles of various nanofluid samples under consideration.

As it can be clearly seen from Fig. 4 (a) that all three thermocouples show almost linear increase in bulk fluid temperature at the start of the experiment, and this linearity is lost as the experiment is continued. Such a linearity at the start of the experiment is because almost all of the energy is absorbed by the nanofluid and there is negligible heat leak to the surroundings as also shown in Fig. 6 (a). But as the temperature of the nanofluid increases, the temperature difference between the sample and the surrounding increases, which results in increased heat loss that deviates from the linearity. As the temperature difference goes to the maximum value within the experimental settings, further increase in temperature is small, as can be seen at the later stage of the experiment in Fig. 4 (a). The rate of temperature rise for TC1 is higher

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