Solar Energy 161 (2018) 74–82

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A comparative study of direct absorption nanofluids for solar thermal applications

Aimen Zeiny[a,c], Haichuan Jin[b], Lizhan Bai[b], Guiping Lin[b], Dongsheng Wen[b,a,*]

[a] School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK
[b] Laboratory of Fundamental Science on Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China
[c] Department of Mechanical Engineering, University of Kufa, Najaf, Iraq

ARTICLE INFO

Keywords:
Direct absorption
Nanofluids
Nanoparticle
Solar energy
Solar thermal system

ABSTRACT

Direct absorption nanofluid has been introduced as an effective alternative to increase solar thermal conversion efficiency. Hybrid nanofluids were also recently proposed to broaden the absorption spectrum. However, a comparative assessment of the performance of commonly used nanomaterials for solar energy harness is still lacking. In this study, a well-controlled experiment was performed using three different categorised nanofluids, i.e., gold, copper, carbon black nanofluids and their hybrids, to assess their performance in terms of photothermal conversion efficiency (PTE), specific absorption rate (SAR) and materials cost. A mathematical model was built based on the Beer's law to predict the PTE enhancement. The results revealed, contrary to previously reported, the PTE was not increased by blending different nanofluids with different absorbance peaks, which is mainly due to the dilution of nanoparticles' concentration. Furthermore, it is found that although gold nanofluids have high SAR, their expensive cost limits their practical use, whereas carbon black nanofluids are more feasible. In addition it was found that the theoretical PTE can be well predicted mathematically based on the optical properties of the used nanofluids.

1. Introduction

Solar energy has been claimed as the energy of our future but comes with many challenges to overcome such as the high cost and the low efficiency (Otanicar et al., 2010; Gupta et al., 2015). Solar thermal system, which typically has an absorbing plate with fluid running inside pipes, is a common way of utilising solar energy. Its efficiency is limited by not only how efficiently the solar energy is captured by the absorbing plate, but also how effectively the absorbed energy is transferred to the running fluid (Otanicar et al., 2010). This surface-limited thermal energy transfer process limits the solar energy utilisation efficiency especially for high-temperature applications such as solar thermal power plants (Lenert and Wang, 2012).

Direct absorption solar collector (DASC) was proposed in the 1970s. In this approach, the solar energy is directly absorbed by the working fluid by seeding certain particles in it (Minardi and Chuang, 1975; Arai et al., 1984; Bertocchi et al., 2004). Early studies were focused on micrometre-sized particles, and using nanoparticles is a recent development (Zhang et al., 2015, 2014; Otanicar et al., 2010; He et al., 2013). Many studies have been conducted and most of these studies were based on the optical properties and characterised by the extinction coefficient (Mercatelli et al., 2011; Otanicar et al., 2009, 2010; Sani et al., 2010, 2011; Taylor et al., 2011; Chen et al., 2016). Although the extinction coefficient is a key factor, which determines the absorbed and scattered light by a nanofluid, it may not represent the actual photothermal conversion process (Zhang et al., 2014).

The photothermal conversion efficiency of different nanoparticles, ranging from metal (such as Au, Ag, Cu, and Al), metal oxides (such as CuO, TiO_2, Al_2O_3, and Fe_2O_3) and carbon (such as Graphite, carbon nanotubes (CNTs), and carbon nanohorns (CNHs)), have been investigated under the laboratory and outdoor conditions. Plasmonic nanoparticles (such as Au and Ag) have attracted intense interest due to the effect of surface plasmon resonance (SPR), which usually occurs in the visible light spectrum, which represents almost 40% of the total solar energy (Gueymard, 2004) but weakly absorbed by most of the heat transfer fluids. Among these studies, Zhang et al. (2014) showed that using 6 ppm (~116 mg/l) aqueous gold nanofluid could enhance the photothermal conversion efficiency by ~80% and reached a specific absorption rate (SAR) of ~1 kW/g under a solar simulator. Amjad et al.(2017) and Wang et al. (2017) investigated the heating enabled by

* Corresponding author at: School of Aeronautic Science and Engineering, Beihang University, Beijing, 100191 & Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK.
E-mail addresses: d.wen@buaa.edu.cn, d.wen@leeds.ac.uk (D. Wen).

https://doi.org/10.1016/j.solener.2017.12.037
Received 6 February 2017; Received in revised form 7 December 2017; Accepted 18 December 2017

gold nanofluids for direct solar steam generation. The highest evaporation efficiency (~40%) was achieved under 10 Suns irradiation by 178 ppm (~3436 mg/l) gold nanofluid (Wang et al. 2017), which might be not economically feasible due to the high cost of gold. An enhancement of 144% in the photothermal conversion efficiency and ~0.6 kW/g were achieved by using 6.5 ppm (~68 mg/l) silver aqueous nanofluid in the outdoor conditions (Bandarra Filho et al., 2014). However, the enhancement of absorption of plasmonic nanofluids has unavoidably a narrow bandwidth owing to their resonance characteristic (Jeon et al., 2016).

To achieve a broadband absorption, blending of different absorption peak nanofluids was suggested by some researchers. A blend of spherical gold nanoparticles with two different sized gold nanoshells was proposed by Cole and Halas (2006). They determined, theoretically, the ideal fractions of the blended nanofluids that match the AM 1.5 solar spectrum, and revealed that mixing 35.9% gold nanospheres of 32 nm radius, 22.8% gold nanoshells of 28 and 42 nm core and shell radii, and 41.3% gold nanoshells of 47 and 58 nm core and shell radii respectively, can achieve a photothermal conversion efficiency of ~84%. Lee et al. (2012) investigated theoretically the efficiency of a direct solar collector using a hybrid core-shell gold nanofluid generated by mixing four different core and shell sizes. An efficiency of 70% was achieved by 0.05 vol% (~3220 mg of gold/l) hybrid nanofluid. However, although the tunability of the optical properties of such core-shell nanoparticles is achievable, the difficulty in manufacturing this type of nanoparticles makes it not suitable for further solar applications (Jeon et al., 2016). Very recently, a blend of three different aspect ratios of gold nanorods was suggested by Jeon et al. (2016) to optimise the solar absorption efficiency. The photothermal performance of the blended nanofluids was checked by measuring the temperature rise with time. However, a common problem among these studies is the hybrid nanofluids had much higher concentration than their individual counterparts due to the mixing. A fair comparison of the photothermal performance under a given concentration between the hybrid and its original nanofluids is still lacking. Such a comparison is crucial to check the feasibility of hybrid nanofluids.

In most of the previous studies, a uniform temperature distribution within a nanofluid was assumed although the effect of the optical path was not negligible, and one temperature was used to calculate the photothermal conversion efficiency (He et al., 2013; Bandarra Filho et al., 2014; Chen et al., 2015; Yousefi et al., 2012; Qu et al., 2017). However, the non-linearly reduction in the radiative intensity along the depth of the nanofluid should cause a temperature difference within the nanofluid (Jin et al., 2016c, 2016a). Neglecting this temperature difference would lead to an inaccurate calculation of the efficiency (Jin et al., 2016a). Moreover, most of the published work was based on only one particular type of particles, and a comparative assessment of the performance of commonly used nanomaterials for solar energy harness is still lacking. The effect of these nanomaterials needs to be investigated at the same concentration and under similar operating conditions to reach a fair comparison. In addition to the efficiency, the cost has to be considered very carefully for any practical application. For the purpose of comparison, some estimation of the cost of a unit thermal power generation ($/kW) from different nanoparticles is preferred.

This study aims to overcome the issues reviewed above and perform a well-controlled experiment for three different categorised nanofluids, i.e., gold, copper, carbon black nanofluids and their hybrids. A Class AAA solar simulator was used to ensure stable and uniform radiation intensity, and samples of ~3 mm thick were used to eliminate the effect of the absorbing path length. Photothermal conversation efficiencies (PTE), specific absorption rates (SAR) and cost of a unit thermal power generation ($/kW) were calculated from the recorded temperature rise of different nanofluids. In addition, estimated solar photothermal conversion efficiencies (i.e., without the need to measure the temperature rise of the nanofluids) were calculated from the spectral extinction coefficients measured by a spectrophotometer.

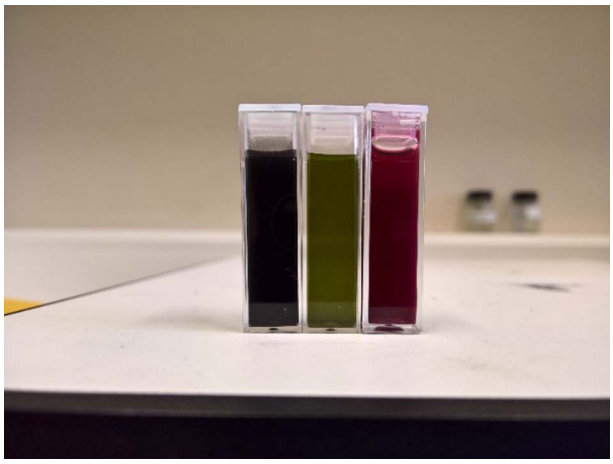

Fig. 1. A photo of the nanofluids: gold nanofluid on right, copper nanofluid in middle, and carbon black nanofluid on left.

2. Experimental approach

2.1. Gold nanofluids preparation

In this study, gold nanofluid was synthesised by the citrate reduction method as reported by Chen and Wen (2011) and Zhang et al. (2014). Typically, 100 ml of 5 mM $HAuCl_4$ solution was mixed with 100 ml of 10 mM trisodium citrate solution. Then, the resultant mixture was heated to the boiling temperature until its colour became wine red. After that, the resultant was put into a sonication bath at 80 °C for 3 h. The synthesised gold nanoparticles were left for 24 h at the room temperature and then purified by the membrane dialysis method. In this process, the gold nanofluid was put in a membrane tube with a pore size of 2–3 nm in diameter to allow a smooth diffusion of ions and keep the gold nanoparticles inside the tube. The membrane tube was located in a beaker filled with DI water of 2000 ml and stirred by a magnetic stirrer. The DI water was changed twice a day for ten days. The gold nanofluid is shown in Fig. 1.

2.2. Copper and carbon black nanofluids preparation

Copper and carbon black nanofluid were prepared by the two-step method, i.e. by dispersing a certain amount of pre-synthesised nanopowder to a hosting liquid, i.e., DI water in this work. The copper nanopowder was purchased from Sigma-Aldrich Corporation, and carbon black nanopowder was purchased from Alfa Aesar, which were vacuum sealed. Extreme caution was applied when dispersing these powders into the base fluid by minimizing the contact time with fresh air to reduce the possible oxidation. The existence of pure Cu was confirmed by the absorbance spectrum before and after the experiments. Dispersing agents of trisodium citrate (TSC) aqueous solution 0.5 M and Gum- Arabic (GA) powder were added to DI water at 2 vol% and 0.5 wt % respectively to prepare the hosting liquid for copper nanofluids, and dispersing agent of Tween was added to DI water at 0.04 vol% for carbon black nanofluid. The hosting liquid magnetically stirred when a controlled amount of nanopowder was added. After 15 min, the sample was put into an ultrasonication bath. For copper nanofluids, the ultrasonication time was one hour, and for carbon black nanofluids, an ultrasonication bath for 30 min was used, followed by a powerful probe sonicator for extra 30 min. The copper and carbon black nanofluids are shown in Fig. 1.

2.3. Nanofluids characterisation

A flame atomic absorption spectrometer (AAS) was used to measure the concentration of the prepared nanofluids. For gold nanofluid, the