Renewable Energy 122 (2018) 443–454

Contents lists available at ScienceDirect

Renewable Energy

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

Solar evaporation via nanofluids: A comparative study

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ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form
4 January 2018
Accepted 14 January 2018
Available online 3 February 2018

Keywords:
Direct absorption
Nanofluid
Solar energy
Solar evaporation
Economic analysis

ABSTRACT

Vaporisation (evaporation and boiling) through direct absorption solar collectors (DASCs) has recently drawn significant attention. Many studies suggested that plasmonic nanoparticles, such as gold nanoparticles, can significantly enhance the photo-thermal conversion efficiency of DASCs. However, there is still a lack of comparative studies of the feasibility of using gold nanoparticles for solar applications. This study performed well-controlled experiments for two different categorised particles, i.e., gold and carbon black suspended in water, and assessed their performance in terms of evaporation rate, materials cost and energy consumption. The results show that gold nanofluids are not feasible for solar evaporation applications, where the cost of producing 1 g/s vapour is ~300 folds higher than that produced by carbon black nanofluids. This infeasibility is mainly due to the high cost and the low absorbance of gold comparing to carbon black nanoparticles. Moreover, this work reveals that with the increase of nanoparticle concentration or incident solar radiation, more energy is trapped in a small volume of the nanofluid near the interface, resulting in a local higher temperature and a higher evaporation rate. For efficient steam production, future optimisation of the system should consider concentrating more solar energy at the interface to maximize the energy consumed for evaporation.

1. Introduction

Developing efficient and economically feasible renewable energy conversion technologies is essential to address our imminent problems such as environment pollution, fossil fuel depletion and population increase. Solar energy has been claimed as the energy of our future. However, challenges such as high cost (due to using optical devices such as heliostats or reflectors to concentrate the solar energy, tracking devices to track the energy source, and vast land for installation) and low efficiency (due to the heat losses) of solar energy conversion systems [1–3] limit their wide applications.

Nanoparticle-based direct absorption solar collectors (DASCs), which utilise the high radiation absorption property of nanoparticles suspended in a working fluid, are proposed to increase the efficiency of solar systems. Since the proposition of this method, enormous efforts by research groups around the world have been spent to investigate the effects of nanoparticles' composition, size, and shape on the photo-thermal conversion efficiencies of these DASCs [4–8].

Recently, DASCs have been proposed as novel solar-driven steam generation systems [3], and using gold nanofluids has attracted intense interest [9–15], albeit they are among the most expensive materials. This interest comes from two main reasons: Firstly, most of the solar working fluids are semi-transparent for the visible spectrum, which represents ~40% of the solar energy, and the resonance of the conducting electrons of gold nanoparticles can be tuned so that the peak absorbance occurs in the visible spectrum. As the enhancement in the light absorption has unavoidably a narrow bandwidth of the wavelength [16], this promotes the use of hybrids of different sizes and/or shapes of gold nanoparticles to broaden the bandwidth of the absorption peak [16–19]. However, a reduction in the peak absorption value necessarily occurs due to the dilution of gold nanofluids at a given total particle concentration, according to the Beer's law. This means a higher concentration of gold nanoparticles is needed to prepare a hybrid with a broad bandwidth at the same peak value of absorbance. Secondly, the

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https://doi.org/10.1016/j.renene.2018.01.043
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claim of nanobubbles generation around immersed nanoparticles can enhance the efficiency of solar-driven steam generation, albeit the bulk temperature of a nanofluid is still subcooled [15,20,21], is still subjecting to strong debate. It has been suggested that nanobubbles can only be generated under very high intensity of light, i.e., of thousands of kW/m^2 [13,22–24], which consequently requires expensive optical and tracking devices.

Many studies assumed a uniform temperature distribution within a nanofluid although the effect of the optical path was not negligible, and one temperature was used to analyse the photothermal conversion efficiency [12,15,21,25–28]. However, the non-linearly reduction in the radiative intensity along the depth of the nanofluid should cause large temperature gradient within the nanofluid [13,29]. Neglecting this temperature gradient will lead to an inaccurate analysis of the results such as over-estimation of the solar evaporation efficiency or under-estimation of the energy stored in the bulk nanofluid. 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-driven steam generation 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 [3]. In addition to the efficiency, the cost must be considered very carefully for any practical application. For the purpose of comparison, some estimation of the cost of a unit steam generation rate ($/g/s) from different nanoparticles is preferred.

This study aims to clarify the mechanism of the solar steam generation and to investigate the feasibility of using gold nanoparticles under low concentrations of solar radiation ($\leq$10 Suns). By performing well-controlled experiments, a comparison between aqueous gold (Au) and carbon black (CB) nanofluids was conducted. Evaporation rate, cost of a unit steam rate generation ($/g/s), and energy consumption were calculated from the recorded transient temperature rise and mass change of the nanofluids. Furthermore, more experiments were conducted to investigate the effect of the incident solar radiation intensity on the temperature distribution within the nanofluids.

2. Preparation of nanofluids

2.1. Synthesis of gold nanofluid

In this study, gold nanofluid (Au) was synthesised by the citrate reduction method as reported by Chen and Wen [30] and Zhang et al. [31]. Typically, 100 ml of 5 mM $HAuCl_4$ solution was mixed with 100 ml of 10 mM tri-sodium 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 placed in a beaker filled with deionized (DI) water of 2000 ml and stirred by a magnetic stirrer. The DI water was changed twice a day for ten days.

2.2. Preparation of carbon black nanofluid

Carbon black (CB) nanofluid was prepared by the two-step method, i.e. by dispersing a certain amount of pre-synthesised nanopowder to a hosting liquid, i.e., deionized (DI) water in this work. The carbon black nanopowder was purchased from Alfa Aesar (CAS# 1333-86-4, purity 99.9$^+$%, average particle size 42 nm, S.A. 75 m^2/g, bulk density 80–120 g/l and density 1.8–2.1 g/cm^3 @ 20 °C). Since Tween compounds are widely used as surfactants, emulsifiers and wetting agents [32,33], it is common to use them in stabilising nanofluids. Tween®80 was purchased from Sigma Aldrich. Tween was added to DI water at 0.02 vol %, and the hosting liquid was magnetically stirred when controlled amount of nanopowder was added. After 15 min, the sample was put into an ultrasonication bath (Fisher Scientific, 750 W power) for 30 min, followed by a powerful probe sonication (Fisher Scientific, 700 W power, and 20 kHz frequency) for extra 30 min, i.e. 80 W for 5 min, followed by 5 min for cooling down the sample, and followed by another 80 W, 5 min sonication, and so on.

3. Characterisation

A flame atomic absorption spectrometer (AAS) was used to measure the concentration of prepared gold nanofluid, which turned out to be 250 mg/l. Different dilutions (25, 50, and 100 mg/l) were prepared from the stock nanofluid, as shown in Fig. 1 and Table 1. A UV-Vis Spectrophotometer (UV-1800, Shimadzu Corporation, Japan) was used to measure the capability of radiation absorption of gold and carbon black dilutions. The absorption spectra are shown in Figs. 2(A) and 3(A) respectively. The results reveal an excellent agreement between the absorbance results and the Beer's law, which indicates a linear relationship between absorbance and solution concentration, as shown in the insets of the two figures. The slope of the absorbance line of the gold nanofluids is 0.01$\frac{1/\text{cm}}{\text{mg/l}}$, while it is 0.029 $\frac{1/\text{cm}}{\text{mg/l}}$ for the carbon black nanofluids. It is clear that gold nanofluids have good absorbance in the range of 300–600 nm wavelength and the peak value is around 528 nm, which is due to the local surface plasmon resonance. However, the absorption capability of the carbon black nanofluids is better than the gold nanofluids over the measuring spectrum. As the absorbance of a nanofluid depends on the size and shape of the nanoparticles, the spectrophotometer was used to examine the nanofluid stability [34]. Negligible changes were detected on the absorbance of the prepared nanofluids after a week of storing on shelf. Moreover, the Zeta-potential and hydrodynamic nanoparticle size distribution were measured by a Malvern Zetasizer (NanoZS90 5001). The Zeta-potentials were (−37.6 ± 0.7 mV) and (−32.3 ± 1 mV) for gold and carbon black nanofluids respectively, which revealed good stability

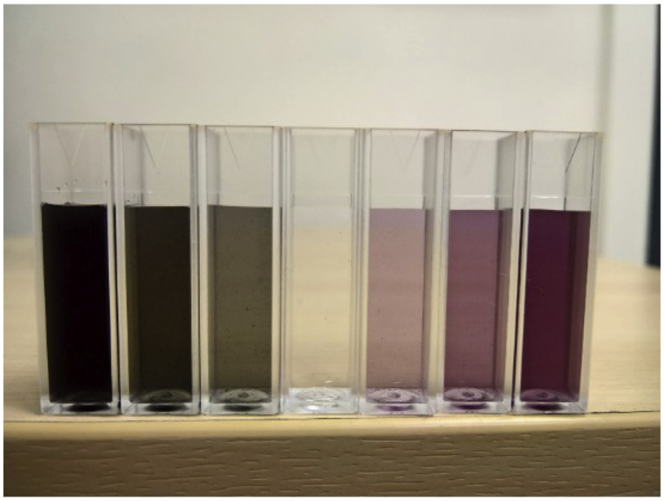

Fig. 1. Picture of gold and carbon black nanofluid dilutions. The mid sample is DI water, to the right are gold nanofluids and to the left are carbon black nanofluids. The concentrations are 25, 50, and 100 mg/l respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)