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A comparative study of several water-based nanofluids for a solar steam generation

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Abstract
Experimental research on the evaporation performance of several water-based nanofluids for solar steam generation has been carried out in the current study. Considered nanofluids include graphene nanoplate (GNP), single-walled carbon nanotube (SWCNT), graphene oxide (GO), multi-walled carbon nanotube (MWCNT), Titanium dioxide (TiO_2), Zinc oxide (ZnO), mixed Iron oxide with graphene nanoplate (Fe_3O_4@GNP) and mixed graphene nanoplates with multi-walled carbon nanotube (GNP@MWCNT). The nanofluids with a mass concentration of 0.004% were prepared to be exposed to 3.5kW/m^2 (i.e., 3.5 suns) in a solar simulator. Results illustrate that the light absorption will increase by adding nanoparticles to water which leads to generating vapor bubbles around the nanoparticles and finally solar steam is generated. Therefore, nanofluids are an excellent alternative medium for solar energy harvesting and clean water production. Additionally, the economics and commercial potential of the above nanofluids have been compared. For various nanofluids, the price of producing 1 gram of solar steam per second has been determined. Finally, the findings show that while GNP@MWCNT offers the best rate of evaporation, its cost for producing steam is the highest of all nanofluids. Therefore, less expensive nanoparticles are more cost-effective. If space is not an issue, with having a greater radiation exposure area, less expensive nanoparticles can produce the same quantity of steam.

Keywords: steam generation, nanofluids, evaporation, solar

Introduction

Population growth is accompanied by an increase in energy consumption, so the need for energy will become a crucial and strategic issue for businesses and industries [1]. Additionally, solar energy has long been regarded as a clean, renewable alternative to fossil fuels. Absorbing sunlight in water for steam generation is one of the common methods for harvesting solar energy [2] [3]. However, one of the biggest obstacles to their commercialization continues to be the ineffectiveness of these energy systems. In essence, traditional solar energy harvesting systems lose a lot of energy. In conventional solar energy harvesting systems, a surface absorber absorbs solar radiation, transforms it into heat, and then transfers the thermal energy to a fluid. As a result, the large radiative and convective losses may be caused by the absorber temperature being much higher than the ambient temperature. Due to its great potential efficiency in solar energy harvesting, using nanofluids to capture solar energy directly has recently gained more attention among the many methods [4].

Direct steam production utilizing nanoparticles was announced in 2013 [5] as a novel way to use solar power, Despite the fact that it has been known since 2007 that nanoparticles can generate heat [6]. According to where light is converted to heat, two categories of direct solar steam production using nanotechnology can be identified: interfacial (also known as interfacial or floating) [7] [8] [9] and volumetric [10] [11] approaches. Membranes belong to the category of interfacial techniques for solar steam generation, whereas nanofluids are regarded as volumetric methods. Nanofluids have demonstrated a remarkable capacity to absorb light and turn it into heat. Without considerably raising the bulk temperature, nanofluids locally raise the fluid temperature by directly absorbing solar radiation. This lowers heat loss to the surrounding environment and boosts evaporation efficiency [12]. According to Figure 1, because the fluid and metal contact surfaces have different thermal conductivity coefficients after the sunlight has been absorbed by the nanoparticles, the temperature of the particles will increase. This local temperature rise might be sufficient to make the surrounding fluid evaporate. Constant sunlight causes the vapor cover surrounding the nanoparticles to grow and eventually causes bubbles to float. When the bubbles reach the surface level of the fluid and get freed, it leads to unstable and relatively intense production of steam.

However, generated bubbles in the lower depth will distill because of the heat transfer with the surrounding fluid which leads to an increase in the bulk temperature of the fluid [13] [14].

Some researcher by using experimental and theoretical methods, like Mercatlli et al. [15], Otanicar et al. [16], and Kumar et al. [17], concentrated on the optical and thermal properties of nanofluids and their temperature changes under direct sunlight. Their research revealed that adding specific nanoparticles, such as silver, copper, and single-walled carbon nanotubes, to the base water exhibited good potential for direct solar steam

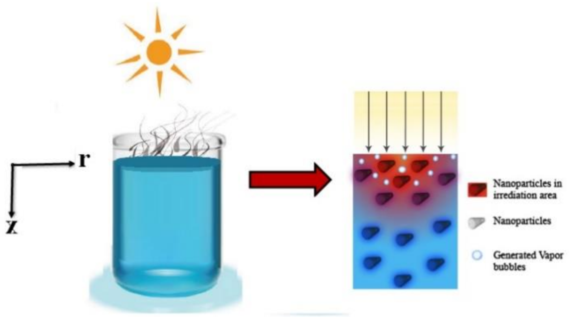


Figure 1, schematic of heat localization and sunlight absorption by nanofluid.

nanoparticles [5] [11]. The outcomes showed that direct steam can be generated with a 24% evaporation efficiency from the gold nanofluid using an energy input that is 1.4 times that of sunlight. Much other research was conducted after Neumann's pioneering studies [5] [11]. In these investigations, different kinds of nanoparticles were mixed with water to produce steam by light intensity as you can see in the table below.

Until 2016, major nanoparticle studies were about plasmonic and expensive nanoparticles (like single-wall carbon nanotubes [25]) which proved they play an important role in increasing evaporation efficiency. Since these nanoparticles were expensive, their commercialization was not easy. For instance, Marciano and his colleagues [26] designed a solar steam system (using gold nanofluids) and compared its cost with other solar steam generation. They pointed out that in terms of economics, they do not find it reasonable for producing solar steam due to its high costs (For example 20ml of water-based gold nanoparticles with a concentration of $1.8*10^{14}$ particles per ml costs 185 US dollars). Zeiny and his colleagues [27] compared the performance of gold nanoparticles with other nanoparticles like black carbon. It was estimated in their study that the cost of generated steam via gold nanoparticles is 300 times the generated steam with carbon black.

A review of the literature reveals that the novel topic of solar steam generation utilizing nanofluids still has a lot of unresolved issues that need to be resolved. For instance, more research is required on the evaluating performance of the nanofluids under the same conditions with low intensity and the search for efficient and yet economical nanoparticles. Therefore, in the present study, a comparison between various nanoparticles with different shapes has been examined. Nanofluids containing GNP, TiO2, ZnO, Fe3O4@GNP, SWCNT, GO, MWCNT, and GNP@MWCNT have been prepared with a constant mass concentration of 0.004% and exposed at a 3.5 kW/m2 irradiation using a solar simulator. Finally, their cost of solar vapor production and evaporation efficiency has been calculated and compared.

Materials and Equipment

1. Nanofluids Preparation

A two-step process was employed to prepare the nanofluids after purchasing the nanoparticles from Vira Carbon Nano Material Co. expect for Tio2 [13] and ZnO [28] one-step method was used. nanofluids containing GO, SWCNT, TiO2, ZnO, Fe3O4@GNP, GNP, and MWCNT nanoparticles have been investigated in this study.

In the first stage, according to a mass concentration of 0.004%, nanofluid's weights were determined, and then, they were added to a water-based solution. Then Surfactants were added for more stability. Gum Arabic was added to GNP@MWCNT, Ammonia was used for Fe3O4@GNP, and for the rest of the nanoparticles, SDB[1] was added. after adding surfactant, the solution was subjected to ultra-sound waves for 30 minutes. After the color of the nanofluid completely changed, it was cooled down to room temperature [28] [13] [14].

2. Experimental setup

Figure 1 depicts the experimental setup for determining the temporal changes in fluid temperature and the rate of vapor production. The primary parts include a sun simulator with a 1600-watt xenon bulb (with a radiation temperature of 6000K), a glass vessel containing the nanofluid (a beaker with a 38mm diameter and 70mm height), temperature sensors, and a digital weighing scale (Kernel with the accuracy of 0.0001 gram, Germany), A data accusation system, a CMP3 secondary standard pyranometer, with a 1Wm-2 precision and a 200–2800 nm wavelength range, were purchased from Kipp & Zonen Co. Three sensors are set at distances of 50, 30 and 10 mm from the vessel's bottom in order to

Table 1 summary of related studies to the solar steam generation using nanofluids

	Nano-particle	Evaporation Efficiency	Intensity (Sun[1])	Ref.
1	Carbon black and graphene	0.6	>10	Ni et al [18]
2	Graphene and graphene-Au nanocomposite	0.592	16.77	Fu et al. [19]
3	Ag@TiO2	0.669	>10	Li et al. [20]
4	Gold	0.803	220	Jin et al. [21]
		0.95	280	Amjad et al. [22]
5	Single and multi-wall carbon nanotube functionalized with carboxyl group	0.468	>10	Wang et al. [23]
		0.603		Shi et al. [24]
		0.48		Wang et al. [23]

[1] One sun = 1kW/m2

[1] Sodium Dodecyl Benzene Sulphonate

monitor the fluid's temperature fluctuations at various heights. To ensure that temperature sensors were not directly exposed to incident light during the experiment, the exposed side of each sensor is covered with a silicone adhesive. The sensors are calibrated using a DS18B20 at temperatures of 100, 80, 50, 40, 30, 20, 10, and 5 degrees Celsius. The computed uncertainty for temperature readings due to equipment repeatability and precision is 0.0.1°C and 0.40°C, respectively, for a total uncertainty of 0.400°C.

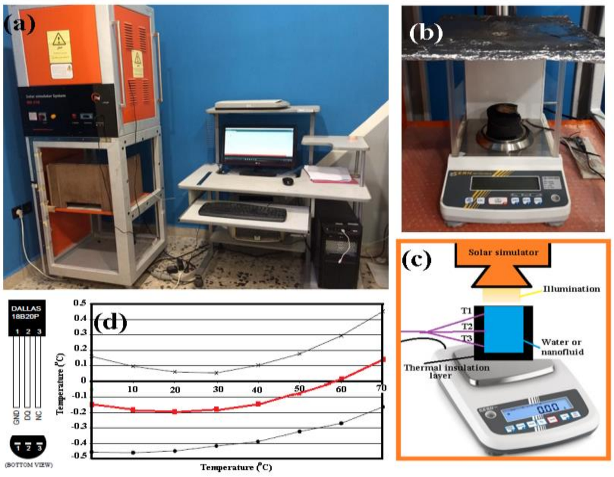


Figure 2 (a) solar simulator and steam generation setup and (b) digital weighting scale, data logger, beaker and sensors, (c) schematic of evaporation system, (d) schematic of the DS18B20 sensor and average accuracy of the sensor in the temperature range

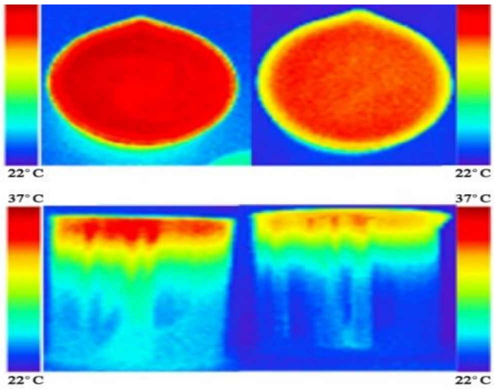
Results

To investigate the affection of solar evaporation, the samples were exposed to the solar simulator for 30 min. Three temperature sensors located at different heights (from the bottom of the beaker) were used to measure the temperature change during the tests. The highest sensor(T1) was located at a height of 50 mm and the lowest sensor(T3) was located at a height of 10mm from the bottom of the beaker. Also, another thermometer was used for measuring the ambient temperature of the laboratory. The temperature changes of nanofluid and water have been shown in Fig. 3 where there is a little temperature variation between the middle and the bottom of the beak. It indicates that the thermal energy applied to the water spent more throw raising the fluid's bulk temperature than by sun evaporation. On the other hand, adding nanoparticles to water increases the temperature differential between the fluid layers, particularly at the surface of the nanofluids which illustrates the heat localization at the surface and around the nanoparticles. Figure 4 demonstrates that the light absorption at the top layers of the nanofluid is greater than that at the bottom layers. According to beer-Lambert's Law, as light interacts with more molecules, more light would be absorbed. As a result, a small amount of light is absorbed in the deeper layers.

1. Estimation of Volumetric Solar Steam Generation Price

Improving evaporation efficiency by various nanofluids may be considered a great success compared to normal water evaporation efficiency, however, economic investigation of generated steam is essential. Since it provides the comparison between different nanoparticles in terms of energy and economics simultaneously. For this purpose, the generation cost for 1 gram of steam per second for various nanofluids has been calculated by

Figure 4 Thermal images of water and nanofluid after 15 minutes



using equation below [27].

$$price\left(\frac{\$}{\frac{g}{s}}\right) = \frac{price_{np}(\frac{\$}{g})}{\frac{\dot{m}_e(\frac{g}{s})}{Vol(ml) \times w(\frac{mg}{l})}}$$

Where Price$_{np}$ is the cost of 1g of nanoparticles. $\dot{m}_e(\frac{g}{s})$ is the evaporation rate; Vol(ml) is the sample volume and $w(\frac{mg}{l})$ is the sample concentration.

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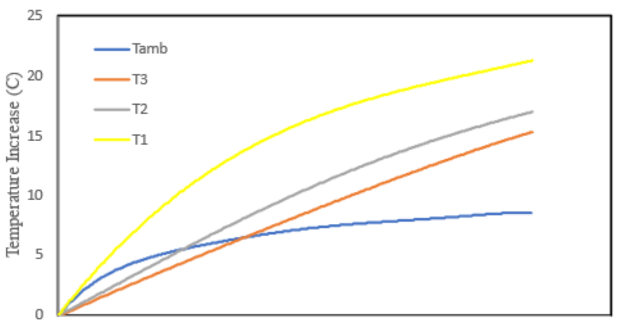

Figure 3 (a) Temperature rise for water, (b)temperature rise for Nanofluid

In this study, in addition to mentioned nanofluids, other nanofluids like Au, Fe2O3@MWCNT, Fe2O3, and Ag@TiO2 have been analyzed, and their best evaporation rate has been considered here for economic comparison. Calculations have been done assuming the same experiment conditions such as concentration, intensity, volume, and price of nanofluids. Figure 5 illustrates that the highest evaporation rate belongs to GNP@MWCNT which has a high solar steam production cost. According to figure 5, solar steam generation with low-cost nanoparticles is more economically reasonable even if they do not have a high evaporation rate. For example, we can use ZnO nanoparticles which is the cheapest and has the lowest evaporation rate to produce steam if the time and space is not an issue because with having a larger radiation exposure area, we can generate the same amount of nanoparticles, including CB [25], Fe3O4@MWCNT [1], TiO2@Fe3O4 [24], SWCNT [25], Au [29], rGo [30], Ag@TiO2, Fe2O3@GNP, Fe2O3, ZnO, TiO2, GNP@MWCNT, GO, MWCNT, and GNP, in international markets with the evaporation rate used for the calculation of 1 gram of generated steam.

Conclusion

In this study, an experimental comparison of the effectiveness of several nanofluids in solar steam generation was conducted. The findings showed that nanofluids perform better than normal water at absorbing solar energy and producing direct solar steam. Also, the temperature rise of the highest sensor (T1) for nanofluid was 294.09 K, compared to 282.95 K for water. Result depicted that how the temperature of the nanoparticles is increase once they have absorbed sunlight. This local

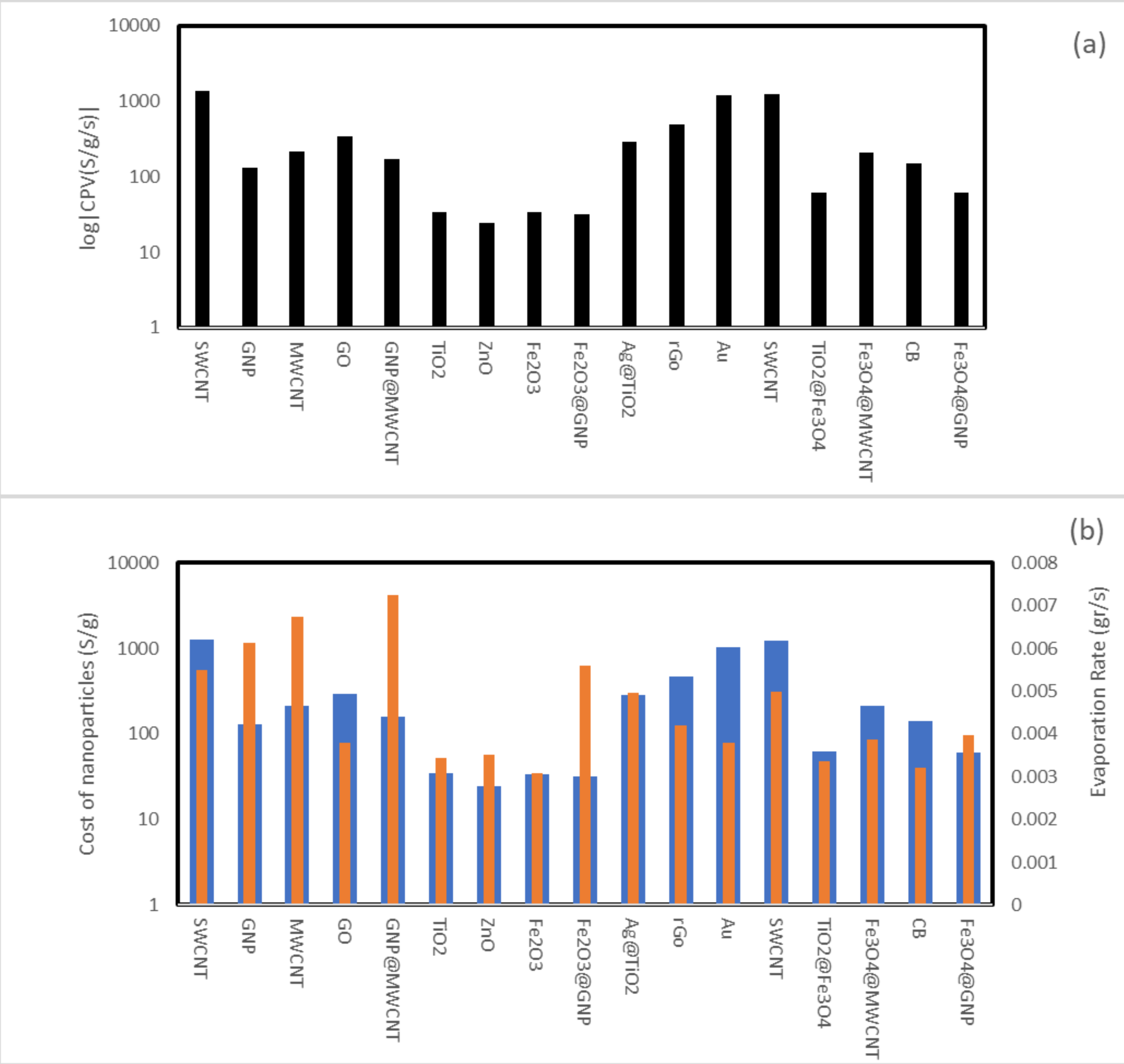

Figure 5 The cost of steam generation by mentioned nanofluids compared to other studies(a), nanoparticles price with evaporation rate under 3 kW/m2 intensity (b)

steam that we can get from expensive nanoparticles. Fig. 5(b) illustrates the cost of steam generation for mentioned nanofluids compared to other studies under 3.5 kW/m. Additionally, figure 5(a) shows the price of temperature increase may be sufficient to cause the surrounding liquid of the nanoparticles to evaporate. Constant sunlight causes the vapor cover surrounding the nanoparticles to grow and eventually causes bubbles to float. As a result, adding nanoparticles to water can boost light absorption and produce solar steam through the localization of heat.

Although GNP@MWCNT has the highest evaporation efficiency among the other listed nanofluids, it does not have a good rank in terms of economics, according to the assessment of the cost of solar steam generation. Therefore, a material's potential for commercial solar steam generation cannot be determined just by its high evaporation efficiency. As a result, cheaper nanoparticles are more economical. if space is not a constraint, with having a larger radiation exposure area, less expensive nanoparticles can create the same amount of steam.

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