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The effects of flake graphite nanoparticles, phase change material, and film cooling on the solar still performance

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HIGHLIGHTS

- Four modifications on the solar still have been performed in this paper.
- Flake graphite nanoparticles, phase change material, and film cooling were combined.
- The effect of the water depth on the enhancement of productivity was studied.
- The mechanism of the enhancement by flake graphite nanoparticles was discussed.

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ABSTRACT

Solar still is a cheap and convenient device for producing freshwater, but it's not popular due to its low productivity. In this paper, we modified the conventional solar still. The outdoor performance of modified solar stills was studied to assess its potential for real application. The modifications include using flake graphite nanoparticles (FGN), phase change material (PCM), and film cooling. In the presence of the three previous modifications, the productivity was enhanced as high as 73.8% compared with that of the conventional still. The effect of water depth on the enhancement was also investigated. It shows that the enhancement of productivity increases by around 13% when the water depth decreases from 2 cm to 0.5 cm. Besides, an indoor experiment was carried out to analyze the enhancement mechanism by FGN. It shows that the increase in both temperature and saturated vapor pressure contributed to the enhancement.

1. Introduction

In the last few decades, fresh water scarcity has become more and more serious due to the increasing world population, excessive waste and growing pollution of natural water sources [1]. By 2025, there will be a big problem in water vulnerability for more than half of the world population [2]. Hence, people have to use efficient methods to produce freshwater. Solar still desalination is one of these methods. Solar still is a device having the advantages of easily fabricating, cheap, no specific skills to operate, approximately no maintenance and no need of conventional energy. However, on the other hand, it's not popular due to the low efficiency and low productivity.

Many works have been done to improve the performance of solar stills, mainly from three aspects: improving the structure, using special materials or using auxiliary equipment. such as plastic water purifier [3], regenerative desalination unit [4], greenhouse type solar still with mirrors [5]; modifying the solar still by reflector [6] or flat plate collectors [7,8]; changing the thickness of insulation [9]; wick type still [10], triple-basin still [11], capillary film still [12], multi effect still [13]; integrating the still with solar water collector [14], increasing the area of condensation surface [15]; using black gravel or black rubber [16], dye [17], and sponge cubes in the still [18]; double slope solar still[19]; modifying still by electrical blower [20], baffle suspended absorber [21], energy storing and wick materials [22,23]; and hybrid (PV/T) active still [24].

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Besides the modifications we mentioned above, researchers also found that the productivity can be increased by increasing the temperature difference between the water surface and inner surface of the glass cover. The difference can be kept up at a high value by using high cooling film flow rate and low cooling film temperature [25–28]. Meanwhile, many researchers have used phase change material (PCM) as an improving parameter of desalination system [29]. The effect of using latent heat thermal energy storage system (LHTESS) through two cascade stills was investigated by Tabrizi et al. [30]. Results obtained that the output of the basin still with LHTESS is slightly lower in a sunny day but higher in a cloudy day than that of the still without LHTESS. The mathematical study of a still with and without PCM was carried out by Dashtban and Tabrizi [31]. The daily output reached 6.7 and 5.1 kg/m^2 with and without PCM, respectively. Ansari et al. [32] examined a still incorporated with a PCM under the basin plate. The results show that the heat energy storage enhances significantly both the productivity of the fresh water and the efficiency of the distillation system.

Recently, with the development of nanotechnology, nanoparticle has attracted the attention of many researchers in solar desalination area. Normally, researchers using nanoparticles in solar still by making nanofluid. Nanofluid has a lot of special properties compared to its base liquid such as high thermal conductivity [33–40], high solar radiation absorptivity [41], which are helpful parameters to improve the productivity of stills. Nijmeh et al. [42] studied the efficiency of the solar still when using a violet dye, the results showed that the efficiency was enhanced by 29%. Elango et al. [43] examined an experimental study to increase the productivity of the still by using various nanofluid. The productivity of the still is improved by 29.95% when using the aluminum oxide (Al_2O_3) nanofluid, while the productivities of the solar stills with tin oxide (SnO_2) and zinc oxide (ZnO) nanofluid are 18.63% and 12.67% higher than that without nanofluid, respectively.

Kabeel et al. [44] studied the effects of aluminum oxide nanoparticles, vacuum and external condenser on the solar still performance. Results showed that the daily productivity can be increased by 53.2% when the still was provided vacuum inside and the daily productivity can be increased by 116% when the still was provided vacuum inside and added aluminum oxide nanoparticles at the same time. Sahota and Tiwari [45] conducted an experimental and theoretical study to improve the productivity of a double slope solar still (DSSS) by using Al_2O_3 nanoparticles. The productivity of DSSS with aluminum oxide (Al_2O_3) nanofluid was improved by 12.2% and 8.4% at 35 kg and 80 kg base fluid respectively, with 0.12% concentration of Al_2O_3 nanoparticles.

From the above literature review, it is observed that the effect of using either some new nanoparticle or coupling the nanoparticle with PCM and film cooling are not investigated. In this paper, the flake graphite nanoparticles (FGN) were chosen as the nanomaterial in consideration of its relative high thermal conductivity [46,47], low cost and high solar absorptivity as compared with most of the nanomaterials. Hence, the major target of this work is to enhance the solar still performance by: (A) mixing the FGN with water, (B) mixing the FGN with water and placing encapsulated PCM (paraffin wax in this paper) on basin liner, (C) mixing the FGN with water and using film cooling on glass cover, and (D) mixing the FGN with water, placing encapsulated PCM on basin liner and using film cooling on glass cover.

It should be noted that, for all the modifications, the FGN were simply mixed with water manually without any additives. Most of the particles were deposited on the basin liner during the experiment procedure instead of stable suspended in the water. The large specific surface area of FGN increases the contact area with water, which contributes to a good heat transfer between FGN and water. When the water-FGN mixture (WFGN) is heated, some of the deposited particles flow up and down with water convection due to the relatively low density and small size. Meanwhile, a part of FGN aggregate at the triple phase contact line of the still due to the surface tension and water convection. Compared with making stable nanofluid in other works, the way to use FGN in this paper needs lower technique level and cost, which is highly acceptable in practical application. Besides, the particles can be easily recycled by filtering with cloth due to its relative large lateral size.

2. Experimental setup

The solar stills and all components of the system were manufactured in the school of energy and power engineering, Huazhong university of science and technology, Wuhan, China (Latitude 30°51′N and longitude 114°41′E).

Four modifications named modification (A), (B), (C) and (D) were designed in this paper. For modification (A), at first, 0.5% mass concentration of FGN was mixed with the water by shaking and stirring manually to make WFGN. Then the black WFGN was poured into the solar still through the drain hole of the still. Most of the particles deposited in dozens of minutes. The average lateral size of the FGN is around 1.3 μm, the thickness of the FGN is around 100 nm. The SEM image of the particles is shown in Fig. 3a.

For modification (B), apart from the 0.5% mass concentration FGN, 20 stainless steel pipes with PCM encapsulated inside were put on the basin liner to store the energy. Each pipe is 49 cm in length and 1.6 cm in diameter. The outer surfaces of the pipes were painted black to absorb more solar energy. The specifications of FGN and PCM are shown in Table 1.

Modification (C) added the film cooling on the basis of modification (A). The film cooling means some cold water was flow on the upper surface of the glass cover to cool down the glass cover. The mass flow rate of the cooling film in modification (C) was fixed at about 0.03 kg/s which was measured by collecting the cooling water. A cold water tank with the dimensions of 88 × 42 × 42 cm was used to supply the cooling water. The cooling water flowed out from the holes of a plastic pipe which was connected to the tank.

Modification (D) combined the 0.5% mass concentration FGN, 20 pipes with PCM encapsulated inside and the 0.03 kg/s film cooling all together. It's the union of the modification (A), (B), and (C). If not stated, the water depth in solar stills for all modifications is 0.5 cm.

The experiment system consists of three solar stills. A photograph and a schematic graph of the solar desalination setup are shown in Figs. 1 and 2, respectively. During the experiment procedure, one of the three solar still was used to work as a conventional solar still, and the other two were used to work as the modified solar stills. The area of the still basin is 0.25 m^2 (0.5 m length × 0.5 m width). The height of the low and high side wall is 160 mm and 450 mm, respectively. The stills are made of iron sheets (1.5 mm thick). The inner surface of the basin and the side walls of the solar stills were painted black to absorb the solar irradiation. To decrease the heat loss, all external surfaces were insulated by fiberglass (5 cm thickness). The thickness of the glass cover is 3.5 mm. The tilt angle of the glass cover is 30°. The system was kept in the south direction during the experiment process. A

Table 1
Specifications of FGN and PCM.

Property	Value
Thermal Conductivity of FGN, (W/(m K)	129
Density of FGN, (g/cm^3)	~2
Lateral size of FGN, (μm)	~1.3
Thickness of FGN, (nm)	~100
Mass concentration of FGN in WFGN, (%)	0.5
Melting temperature of PCM, (°C)	48