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Improving the performance of solar still by using nanofluids and providing vacuum

A.E. Kabeel [a,*], Z.M. Omara [b], F.A. Essa [b]

[a] *Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt*
[b] *Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt*

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ABSTRACT

The experimental modifications were carried out into the conventional solar still, considerably increasing the distillate water productivity. The effects of using different types of nanomaterials on the performance of solar still were studied. The investigated solid nanoparticles are the cuprous and aluminum oxides. The performance was investigated at different weight fraction concentrations of nanoparticles in the basin water with and without providing vacuum. These additions and modifications greatly improve the evaporation and condensation rates and hence the distillate yield was augmented. The research was conducted for range of concentrations starting from 0.02% to 0.2% with a step of 0.02%. The maxima productivity was obtained for using the cuprous oxide nanoparticles with a concentration of 0.2% with operating the vacuum fan. The results obtained that using cuprous oxide nanoparticles increased the distilled productivity by 133.64% and 93.87% with and without the fan respectively. On the other hand, using aluminum oxide nanoparticles enhanced the distillate by 125.0% and 88.97% with and without the fan respectively as compared to the conventional still. The estimated cost of 1.0 l of distillate are approximately 0.035$, 0.045$ when using the cuprous oxide nanomaterial with and without the fan and, as well as the aluminum oxide nanoparticles, 0.038$ and 0.051$ respectively, and for the conventional still is 0.048$.

1. Introduction

The availability of drinking water is reducing day by day; whereas the requirement of drinking water is increasing rapidly. Although more than two thirds of the earth has been covered with water, but only about 0.014% of global water can be used directly for human and industrial purposes [1]. So, the accessibility to drinking water is one of the main problems for human being in arid remote areas all over the world. Solar stills can solve part of this problem in the areas where solar energy is available plenty. Basin type solar stills are simple in design, cheap, have low technologies and it has an important advantage, pollution free. Hence, no high maintenance expenses are required. Although solar stills have low productivities, they are being a sustainable water production method. Solar stills continue to attract wide research attention that is targeted to improve their yield. Many experimental and theoretical studies are being carried out to improve the performance of solar stills [2].

Xiao et al. [3] stated in their study that the climate and operating conditions affecting the solar still productivity include solar radiation intensity, wind velocity, and ambient temperature for climate conditions and the cover angle, the material coated on the basin, the water depth, the temperature difference between the water and cover, and the insulation for the operating conditions.

Several researchers have reviewed, thoroughly, the work on solar distillation system [4–6]. They have described the design, affecting parameters and the performance of a wide range of solar stills.

A good condensation condition can make the evaporation rate of brine water in the still faster. Solar still with sponge cubes in basin is studied by Bassam and Hamzeh [7]. Vinothkumar and Kasturibai [8] investigated the performance of a solar still with improved condensation. An external condenser [9] is attached with a solar still to enhance the productivity of the solar still. The condensation occurs due to the temperature difference not only on the glass surface but also on the four sidewalls, which can be cooled by water circulation through tubes attached on the wall surface for efficiency enhancement. Such an arrangement [10] is made to enhance the productivity of the solar still. The maximum daily production of the solar still was about 1.4 l/m^2/day, and its

* Corresponding author.
E-mail address: kabeel6@hotmail.com (A.E. Kabeel).

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efficiency was about 30% with corresponding average solar insolation of 28 MJ/day. The effect of integrating the passive solar still with a separate condenser was investigated by Madhlopa and Johnstone [11]. They concluded that the theoretical productivity of the modified still was 62% higher than that of the conventional one. The influence of coupling the single basin type solar still with an outside condenser on the performance of the solar still was studied by E1-Bahi and Inan [12]. The productivity reached 7 kg/m^2/day, and the daily efficiency was 75% from June to August. So, a separate condenser could improve the water yield, while the vapor channel should be designed carefully to avoid much increase in vapor diffusing resistance. If a lot of vapor stays in the evaporator, it will reduce solar radiation to the basin plate and increase the partial pressure of vapor, which impedes the evaporation of brine in the basin. A novel multi-effect solar still with enhanced condensation surface is carried out by Xiong et al. [13]. They concluded that when the starting temperature is relatively high, the overall desalination efficiency and performance ratio of the equipment can reach 0.91 and 1.86, respectively. El-Sebaii et al. [14] enhanced the daily productivity of the single effect solar stills. A conventional single basin still integrated with a shallow solar pond to perform solar distillation at a relatively high temperature. Al-hussaini and Smith [15,16] investigated theoretically the effect of applying vacuum on the productivity of solar still. Their results indicated that the water yield could be increased by 100% when considering complete vacuum.

Nanofluid means mixing the base fluid with a solid-sized nanoparticles. The suspended nanoparticles change the heat transfer characteristics and evaporative rate of the base fluid. Nijmeh et al. [17] indicated that mixing violet dye with the water increases the efficiency by 29%, which is considerable. Faizal et al. [18] investigated numerically the effect of using CuO, SiO_2, TiO_2 and Al_2O_3 nanofluids on the performance of a solar collector. It was estimated that 10,239 kg, 8625 kg, 8857 kg and 8618 kg total weight for 1000 units of solar collectors can be saved for CuO, SiO_2, TiO_2 and Al_2O_3 nanofluid respectively. The influence of using carbon nanotubes-water nanofluid on the distilled water productivity of a modified vacuum solar still was studied by Gnanadason et al. [19].The evacuated tubular solar air collector that integrated with simplified compound parabolic concentrator and special open thermosyphon using water based CuO nanofluid was investigated by Liu et al. [20]. Their experimental results showed that the solar collector integrated with open thermosyphon has a much better collecting performance. Recently, Kabeel et al. [21] conducted an experimental study to enhance the solar still productivity by providing vacuum with integrating an external condenser and also by mixing the aluminum oxide nanoparticles with the feed water to the still (nanofluid).The results showed that providing vacuum inside the modified solar still increases the distillate water yield by about 53.2%. And using nanofluids improves the solar still water productivity by about 116%, when operating the vacuum fan.

The objective of this work is to enhance the distilled water productivity of the solar still by using different types of nanomaterials with different weight fraction concentrations, the ratio of nanoparticles mass to the mass of nanofluid, (φ). This present study was done with and without providing vacuum inside the modified still. The nanomaterials are the cuprous oxide and aluminum oxide nanoparticles at the concentrations from 0.02% to 0.2% to get the optimum concentration in which the highest productivity occurs.

2. Experimental setup

Fig. 1 presents a schematic diagram of the experimental setup. It consists mainly of a saline water tank, a conventional still and another modified basin still integrated with the condensation unit through the vacuum fan. The two basin stills are made from galvanized iron sheets (1.5 mm thick).The conventional still has a basin area of 0.5 m^2. The low-side wall height is 160 mm and the high-side wall depth is 450 mm. The whole basin surfaces are coated with black paint from inside to increase their absorptivity. Furthermore, the still is well insulated with wool to reduce the heat loss from the still to the ambient. The basin is covered with glass sheet of 3 mm thick inclined with nearly 30° on horizontal, which is the latitude of Kafrelsheikh city, Egypt. The gaps between the glass cover and the still body were filled by silicon to prevent any leakage from anywhere inside the basins to outside of them.

The modified still has the same specification and dimensions of conventional still. In addition, inside the still, there is a vacuum port to be able to measure the pressure inside the basin still by the pressure measurement instrument. Also, there is a vacuum fan and its output duct to the condenser as shown in Fig. 1. The condensation unit consists of 3.0 m long copper tubes with 3.81 cm diameter encased in polyethylene tank ($40 \times 40 \times 50$ cm) filled with cold water. A graded container is at the end of the copper tube to collect the condensate water, as shown in Fig. 1. The vacuum fan is of the axial-flow type. It has a blade diameter of 8 cm and is attached by a variable speed indicator on a screen to control the fan speed as shown in Fig. 2. The brushed DC electric motor is used to run the fan. It has a maximum rotational speed of 1440 rpm, power factor of 45°. Also, it consumes 2 A and 12 V and it is operated by the photovoltaic solar panels as illustrated in Fig. 1. The feed water tank is connected to the main line which is divided into two feed water lines. A flow control valve is integrated at each line inlet in order to regulate the flow rate of water as shown in Fig. 1. The K-type thermocouples, Solarimeter and digital air flow/volume meter are the instruments which measure the temperatures at different points of the examined stills, total solar radiation and wind velocity respectively.

It is well known that the properties of the nanofluids depend on the shape and size of nanoparticles. The aluminum and cuprous oxides nanoparticles, purchased from Nanotechnology research Lab. – Faculty of Sciences – Kafrelsheikh University – Egypt, was used for the preparation of the nanofluids. The specifications of the nanoparticles are obtained in Table 1. The aluminum and cuprous oxides nanoparticles were characterized by X-ray diffraction technique (XRD-6000, Shimadzu).To make the nanoparticles more stable and remain more dispersed in the basin water and to minimize the nanoparticles aggregation to improve dispersion behavior, Triton X-100 is used as a dispersant. The optimum of homogeneously dispersed nanoparticle powders was found at about 0.021% wt Triton X-100. Therefore, we choose Triton X-100 concentration equal to 0.021% [22].

3. Experimental procedures

The experiments were done at the period starting from September to December 2013 at the Faculty of Engineering, Kafrelsheikh University, Egypt (Latitude 31.07°N and longitude 30.57°E).From the previous tests in Ref. [21], it has been obtained that the maximum increase in productivity occurred at the fan speed of 1350 rpm. So, two other groups of experiments were done. The first one was done on the stills using cuprous oxide nanoparticles mixed with the saline water (nanofluid) in the modified still, at different weight fraction concentrations, with and without operating the vacuum fan at 1350 rpm. The second group of tests was completed by repeating the steps of the first one of tests with replacing the cuprous oxide nanoparticles by aluminum oxide nanoparticles. The water depth inside the two investigated basin stills remains at a constant value which is 0.5 cm. The performance