Energy Conversion and Management 86 (2014) 268–274

Contents lists available at ScienceDirect

Energy Conversion and Management

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

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

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ARTICLE INFO

Article history:
Received 4 February 2014
Accepted 14 May 2014
Available online 2 June 2014

Keywords:
Distillation
Solar still
Nanofluids
Vacuum
Aluminum oxide
Cuprous oxide

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

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http://dx.doi.org/10.1016/j.enconman.2014.05.050
0196-8904/

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

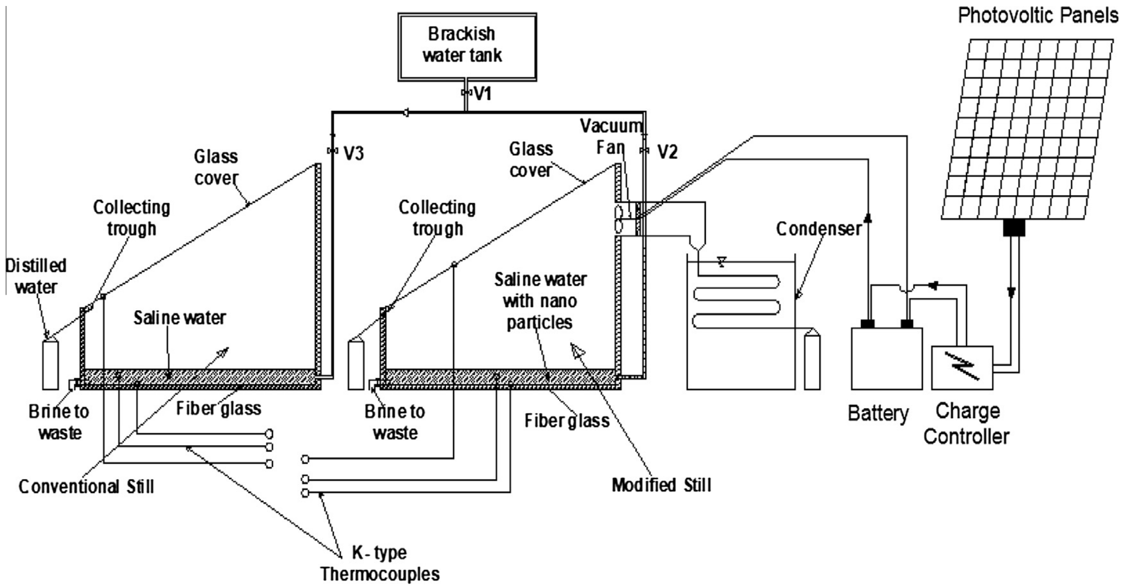

Fig. 1. Lay-out diagram of the experimental setup.

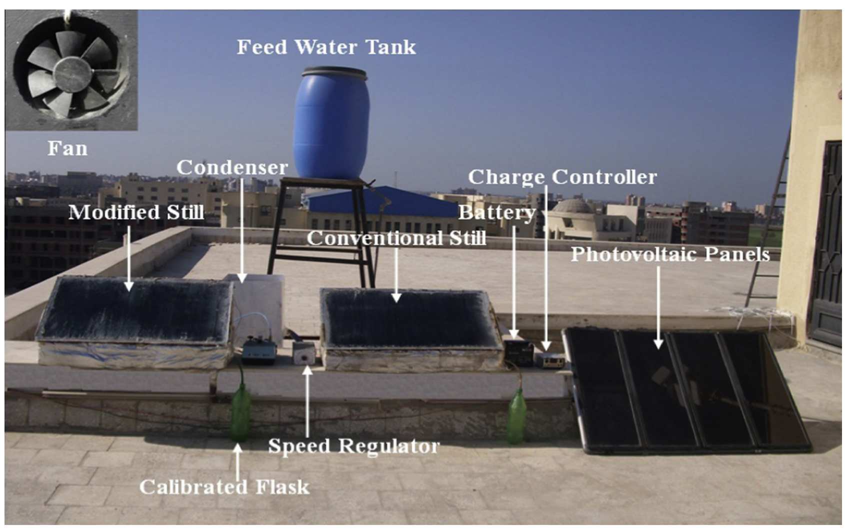

Fig. 2. Photograph of experimental setup.

Table 1
Specifications of the cuprous and aluminum oxides nanoparticles.

Material	Chemical symbol	True density (kg/m^3)	Thermal conductivity (W/m K)	Average particle size (nm)
Aluminum oxide	Al_2O_3	3900	46	10–14
Cuprous oxide	Cu_2O	6320	76.5	10–14

of the modified still with the new additions was compared with the conventional other one.

4. Error analysis

Several parameters are measured during the experiments in order to evaluate the system performance. The parameters needed to be measured are, the temperatures at different points of the stills (brine and outer glass cover temperatures), ambient temperature, total solar radiation, wind velocity, pressure inside the basin and the amount of distillate. The temperatures have been measured using calibrated copper constantan type thermocouples (±0.5 K) which were connected to a digital temperature indicator. Total insolation was measured on the same level of stills glass covers with the help of a Data logging solar power meter ranged of 0–5000 W/m^2 with an accuracy of ±1 W/m^2. Wind speed was measured with the help of a van type anemometer, ranged of 0.4–30 m/s with an accuracy of ±0.1 m/s. The pressure inside the basin still was measured using a digital pressure indicator, ranged of 0.07–35 bar with an accuracy of ±0.05% FS and ranged of 35–700 bar with an accuracy of ±0.1% FS. A flask of 2 l capacity (an accuracy of 5 ml) was used to measure the hourly yield.

Based on the accuracy of each measuring instrument, an estimate of the uncertainty in measurements has been carried out following the procedure explained by Kline and McClintock [23]. It has been found out that the maximum uncertainty in the measurements is about 2%.

5. Results and discussion

5.1. Effect of using cuprous oxide nanoparticles on the performance of solar still

The variations of solar radiation, atmospheric temperature, basin water temperature, and glass temperature of stills are illustrated in Fig. 3. It is obtained from the figure that the solar radiation intensity and temperature profiles have the same behavior. It has a maximum value around midday and has small values in the morning and afternoon hours. Also, the temperature profile has the same trend of the solar radiation one.

The water and glass temperature differences resulting from using the cuprous oxide nanoparticles are presented in Table 2. It is observed from Fig. 3 and Table 2 that when using the cuprous oxide nanoparticles with a concentration of 0.02% as weight fraction, the saline water temperature of the modified still was more than that of the conventional type by ΔT_w with and without operating the fan at a speed of 1350 rpm from 9:00 a.m. to 17:00 p.m. While the glass temperature of the modified still was increased by ΔT_g more than that of the conventional one and is decreased by another ΔT_g without and with operating the fan during the daytime respectively and so on for the other testing days at different concentrations as reported in Table 2. In addition, if the fan is operated at the same speed through all the effective fan operating period (from 11:00 a.m. to 15:00 p.m.) with using the cuprous oxide nanoparticles at a concentration of 0.10% as weight fraction, the basin water temperature of the modified still would be more than that of the conventional type by ΔT_w with and without operating the fan. While the glass temperature of the modified still would be reduced by ΔT_g less than that of the conventional type at the fan operating period and is increased by another ΔT_g when the fan was off.

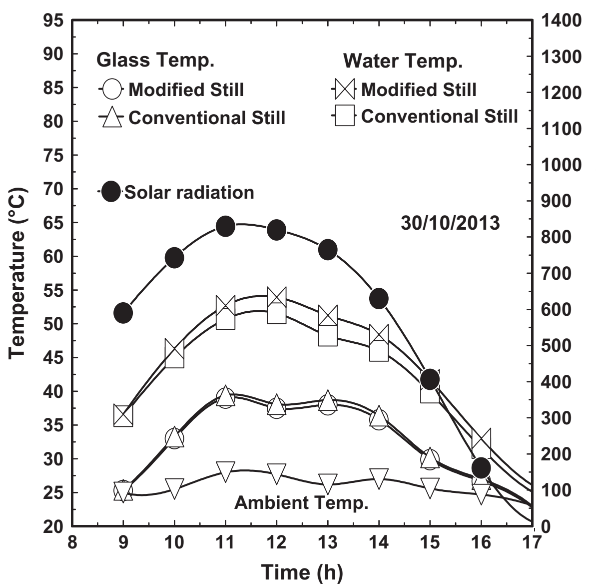

Fig. 3. Hourly temperature variations and solar radiation for the modified and conventional still when using Cu_2O at weight fraction concentration of 0.06% with operating the fan.

Consequently, the difference in temperatures of basin water is higher than that of glass temperatures of the modified still when using the cuprous oxide–water nanofluid in the basin surface with and without operating the vacuum fan as compared to a conventional type. This is mainly because the small power fan is used to exhaust the water vapor from the still to the external condenser. In addition, the fan takes the non-condensable gases away from the basin still to the condenser. Then the effect of non-condensable gases which reduce the rate of condensation is also avoided. Also, the fan causes a circulation of the air inside the solar still. The result is less heating of the glass cover and thus maintaining a high temperature difference between the glass and water in the basin. Because of this difference, the ability of evaporation and condensation, then the production rates in the modified still are faster and more than that of the conventional one.

The production rate of the modified still is also higher than that of conventional type because of the existence of the solid nanoparticles of cuprous oxide mixed with water inside the modified still. This is mainly because nanofluids improve the heat transfer characteristics and evaporative properties of the water. Addition of nanoparticles to the basin water improves the thermal conductivity of the mixture of water and nanomaterial (nanofluid) and also the convective heat transfer coefficient. In addition, these nanoparticles have higher storage material properties than that of water only. For these reasons, the ability of evaporation and condensation, then the production rates in the modified still are more than that of the conventional type.

In addition, the hourly variations of freshwater productivity per unit area for the modified and the conventional solar stills are

Table 2
Variation of temperature for the modified and conventional still when using cuprous and aluminum oxides nanoparticles with and without operating the fan.

Weight fraction concentration [%]	Difference in temperature of modified still as compared to conventional still [°C]	When the fan is off		When the fan is on			
		Increase in temperature		Increase in temperature		Decrease in temperature	
		Cuprous oxide	Aluminum oxide	Cuprous oxide	Aluminum oxide	Cuprous oxide	Aluminum oxide
0.02	ΔT_g	0.0–0.2	0.0–0.2	–	–	0.0–0.5	0.0–0.35
	ΔT_w	0.5–2.0	0.4–1.45	0.0–1.5	0.0–1.05	–	–
0.04	ΔT_g	0.0–0.4	0.0–0.3	–	–	0.0–0.6	0.0–0.45
	ΔT_w	0.7–3.0	0.5–1.8	0.25–2.6	0.2–1.5	–	–
0.06	ΔT_g	0.0–0.4	0.0–0.3	–	–	0.1–0.75	0.1–0.6
	ΔT_w	1.0–3.5	0.8–2.35	0.3–3.0	0.25–1.8	–	–
0.08	ΔT_g	0.1–0.6	0.1–0.5	–	–	0.3–0.8	0.25–0.7
	ΔT_w	1.0–4.5	1.0–3.0	0.3–3.8	0.3–2.2	–	–
0.10	ΔT_g	0.2–0.7	0.2–0.6	–	–	0.3–1.0	0.3–0.85
	ΔT_w	1.0–4.8	1.0–3.2	0.3–4.0	0.3–2.3	–	–
0.12	ΔT_g	0.2–0.8	0.25–0.6	–	–	0.3–1.0	0.3–0.9
	ΔT_w	1.0–4.9	1.0–3.3	0.3–4.05	0.3–2.35	–	–
0.16	ΔT_g	0.2–0.85	0.25–0.65	–	–	0.3–1.05	0.3–0.95
	ΔT_w	1.0–5.0	1.0–3.35	0.3–4.15	0.3–2.4	–	–
0.20	ΔT_g	0.2–0.9	0.3–0.7	–	–	0.3–1.1	0.35–0.95
	ΔT_w	1.0–5.1	1.0–3.4	0.3–4.2	0.3–2.4	–	–

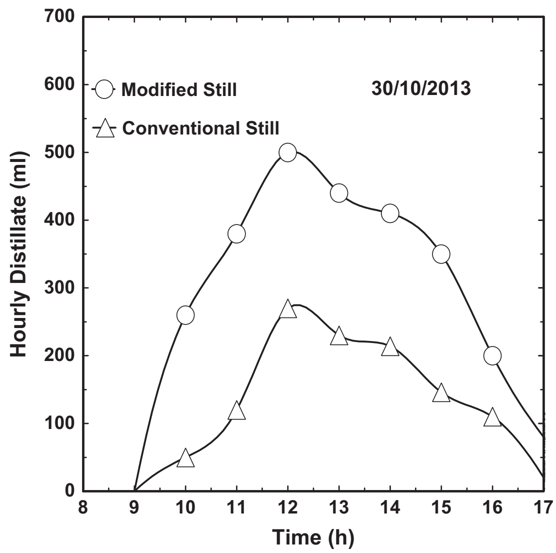

Fig. 4. Variations of fresh water productivity for the modified and the conventional still when using Cu_2O at weight fraction concentration of 0.06% with operating the fan.

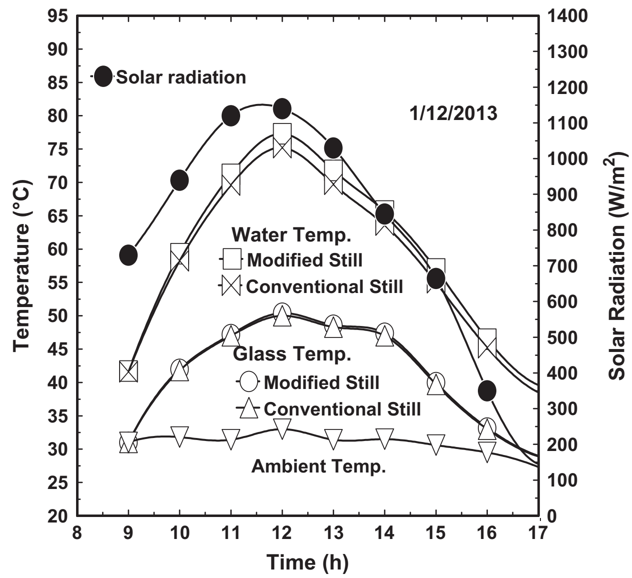

Fig. 5. Hourly temperature variations and solar radiation for the modified and conventional still when using Al_2O_3 at weight fraction concentration of 0.06% without operating the fan.

shown in Fig. 4. It can be observed that the hourly freshwater production increases during the daytime as solar radiation intensity increases till it reaches the maximum value around midday, after that, in the afternoon, the decrease in temperature gradually reduces the production rate. The hourly production rate is increased a huge in modified still than conventional still. This is due to the combination of the reasons of increase in water temperature which is caused because of the particles of studied nanomaterial. In addition, the reason of decrease in glass temperature which is caused because of operating the fan. So the advantages of applying the vacuum and introducing the nanomaterials were achieved. Moreover, It can be obtained that the amount of accumulated distilled water for the modified solar still when using the cuprous oxide–water nanofluid with and without operating the vacuum fan is greater than that of the conventional one. In addition, if the fan is operated through all the effective fan operating period, it could be observed that the distillate reached approximately 1040 ml/m^2/day for the conventional still and 2240 ml/m^2/day for the modified still when mixing the cuprous oxide nanoparticles with a concentration of 0.10% as weight fraction in the feed water to the modified still. The increase in distillate production for the modified still was also 115.38% higher than that for the conventional still and the fan consumed power was 44 W h.

5.2. Effect of using the aluminum oxide nanoparticles on the performance of solar still

The variations of solar radiation, atmospheric temperature, basin water temperature, and glass temperature of stills are shown in Fig. 5 and Table 2. It is observed that when using the aluminum oxide nanoparticles with a concentration of 0.02%, the basin water temperature of the modified still was more than that of the conventional type by ΔT_w with and without operating the fan at a speed of 1350 rpm from 9:00 a.m. to 17:00 p.m. While the glass temperature of the modified still was increased by ΔT_g more than that of the conventional one and is decreased by another ΔT_g without and with operating the fan during the daytime respectively and the same behavior for the other testing days at different concentrations occurred as illustrated in Table 2. In addition, if the fan is operated at the same speed through all the effective fan operating period with using the aluminum oxide nanoparticles at a concentration of 0.10%, the basin water temperature of the modified still would be more than that of the conventional type by ΔT_w with and without operating the fan. While the glass temperature of the modified still would be reduced by ΔT_g less than that of the conventional type at the fan operating period and is increased by another ΔT_g when the fan was off as obtained from the table.

As a result, the difference in temperatures of basin water is higher than that of glass temperatures of the modified still when using the aluminum oxide–water nanofluid in the basin surface with and without operating the vacuum fan as compared to a conventional type. As was detailed in the previous part of using cuprous oxide nanoparticles, because of this difference in temperatures, the ability of evaporation, condensation and the production rates in the modified still are faster and more than that of the conventional one, and for the nighttime, the production rate of the modified still is also higher than that of conventional type.

In addition, the hourly variations of freshwater productivity per unit area for the examined solar stills are shown in Fig. 6. It can be illustrated from the figure that the hourly freshwater production behavior was not changed. It increases during the daytime till it reaches the maximum value around midday, after that, in the afternoon, the decrease in temperature gradually reduces the production rate.

It is obtained that the amount of accumulated distilled water for the modified solar still is greater than that of conventional still. However, if the fan is operated at the speed of 1350 rpm through all the effective fan operating period, the distillate reached approximately 1020 ml/m^2/day for the conventional still and 2095 ml/m^2/day for the modified still when mixing the aluminum oxide nanoparticles with a concentration of 0.10%. The increase in distillate production for the modified still was also 105.39% higher than that for the conventional still and the fan consumed power was 44 W h.

5.3. Comparison between using cuprous oxide nanoparticles and aluminum oxide nanoparticles

Fig. 7 shows a comparison between using cuprous oxide nanoparticles and aluminum oxide nanoparticles at different weight fraction concentrations with and without operating the fan. It can be observed from the figure that the increase in productivity

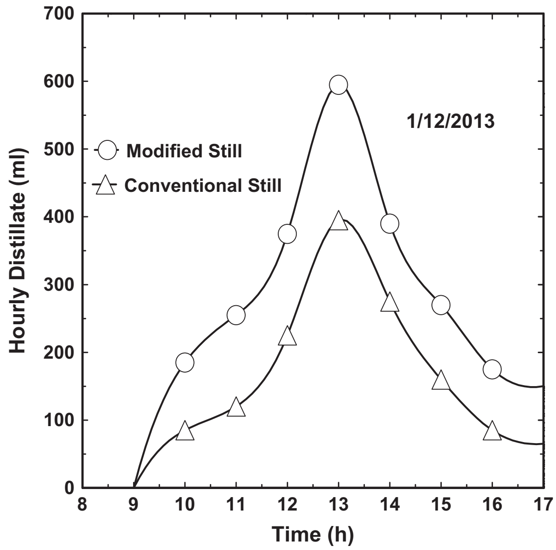

Fig. 6. Variations of fresh water productivity for the modified and the conventional still when using Al_2O_3 at weight fraction concentration of 0.06% without operating the fan.

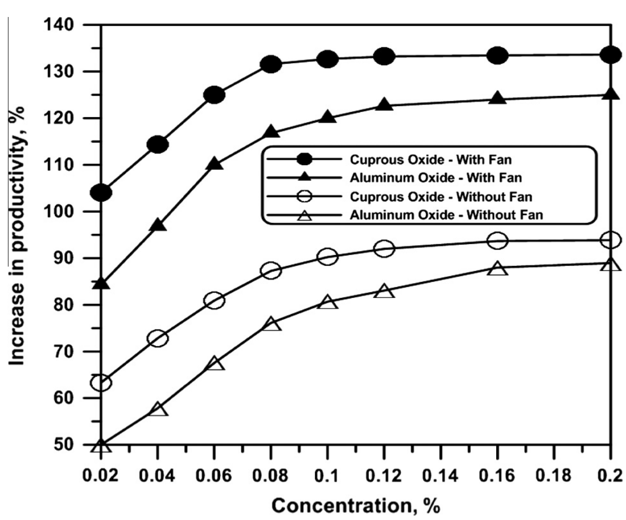

Fig. 7. Variations of increase in productivity for the solar still when using nanofluids with and without fan.

as a percentage increases with increasing the weight fraction concentration of nanoparticles for both of cuprous oxide and aluminum oxide. But when using the cuprous oxide nanoparticles the increase in productivity is greater than that when using the aluminum oxide nanoparticles for the same concentration.

In addition, it can be observed that Fig. 7 can be divided into three parts. The first one is from $\varphi = 0.02\%$ to $\varphi = 0.08\%$ and from $\varphi = 0.02\%$ to $\varphi = 0.1\%$ with and without operating the vacuum fan as cleared from Fig. 7 respectively. In this part, there is a rapid increase in productivity when using the cuprous oxide nanoparticles, as well as the aluminum oxide nanoparticles, with the different investigated concentrations as shown in Fig. 7. The second part is from $\varphi = 0.08\%$ to $\varphi = 0.12\%$ and from $\varphi = 0.1\%$ to $\varphi = 0.16\%$ with and without operating the vacuum fan as obtained from Fig. 7 respectively. In this second part, there is a slow increase in productivity when using the cuprous oxide nanoparticles, as well as the aluminum oxide nanoparticles, with the different examined concentrations as shown in Fig. 7. Finally, the last part is from $\varphi = 0.12\%$ to $\varphi = 0.2\%$ and from $\varphi = 0.16\%$ to $\varphi = 0.2\%$ with and without operating the vacuum fan as shown in Fig. 7 respectively. In this third part, there is no marked increase in productivity when using the cuprous oxide nanoparticles, as well as the aluminum oxide nanoparticles, with the different studied concentrations as shown in Fig. 7.

Moreover, the optimum concentration of nanomaterials for producing the maximum productivity when using the fan is lower than that is without using the fan as shown in Fig. 7. After reaching the optimum concentration, there is no marked increase in productivity when using both of cuprous oxide nanoparticles and aluminum oxide nanoparticles. But the optimum concentration when using the cuprous oxide nanoparticles is lower than that when using the aluminum oxide nanoparticles. It can be observed from Fig. 7 that the increase in productivity when using cuprous oxide nanoparticles at low concentrations is much higher than that when using aluminum oxide nanoparticles. On the contrary, at higher concentrations the difference between the increase in productivity, for using cuprous oxide and aluminum oxide, decreases because using cuprous oxide nanoparticles utilizes the available incident solar energy more rapidly than that when using aluminum oxide nanoparticles.

6. Cost evaluation

Cost estimation for various components used in the present basin solar stills is given in Table 3. The fixed cost of the conventional still is about $F = 103\$$. Assume variable costs V equal 0.3 F per year [24], and C is the total costs, where $C = F + V$ and for the expected still life 10 years, then $C = 103 + 0.3 \times 103 \times 10 = 412\$$ where the minimum average daily productivity can be estimated from the analyses of different experimental data, and it is assumed that 2.5 l/m^2 a day, Assume still operates 340 days in the year, where the sun rise along the year in Egypt. The total productivity

Table 3
Costs of fabricated solar stills.

Units	Cost of active still with vacuum fan (US$)	Cost of active still with AL_2O_3 nanomaterial (US$)	Cost of active still with Cu_2O nanomaterial (US$)	Cost of conventional solar still (US$)
Iron sheet (1.5 mm thick)	45	45	45	33
Glass cover	6	6	6	6
Paints and silicon	13	13	13	12
Insulation	5	5	5	5
Support legs	11.5	11.5	11.5	11.5
Vacuum fan	10	10	10	–
Ducts and hoses	14	14	14	10.5
Production	35.5	35.5	35.5	25
Nanomaterials	–	120	128	–
Total fixed costs (F)	140	260	268	103

during the still life = 2.5 × 10 × 340 = 8500 l. Cost of distilled litter from the conventional still = 412/8500 = 0.048$.

In addition, for total fixed and variable costs = 1072$ when using the cuprous oxide nanoparticles in the modified basin still where the minimum average daily productivity can be estimated by 9 and 7 l/day with and without providing vacuum respectively. The total productivity during the still life = 30,600 and 23,800 l with and without providing vacuum respectively. Cost of distilled litter from the modified still = 1072/30,600 = 0.035$ and = 1072/23,800 = 0.045$ with and without providing vacuum respectively.

And whereas the cuprous oxide nanoparticles are changed by the aluminum oxide nanoparticles in the modified basin still; the total fixed and variable costs = 1040$ where the minimum average daily productivity can be estimated 8 and 6 l/day with and without providing vacuum respectively. The total productivity during the still life = 27,200 and 20,400 l with and without providing vacuum respectively. Cost of distilled litter from the modified still = 1040/27,200 = 0.038$ and = 1040/20,400 = 0.051$ with and without providing vacuum respectively.

Water analyses were done before and after distillation process in terms of TDS and PH. The tested samples indicated that the TDS values were 932 and 82 mg/l before and after desalination, respectively. While, the PH values were 8.9 and 7.1 before and after desalination process, respectively. From the observed result it was found that the water quality lies in the acceptable range according to WHO [25].

7. Conclusions

The following conclusions can be made based on the results presented in this context.

(1) The productivity of the basin solar still can be increased by addition of nanofluids in the basin surface as the nanoparticles raise the water temperature, thermal conductivity and convective heat transfer coefficient by increasing heat transfer rate and hence increasing the evaporation rate.
(2) The maximum increase in productivity of the modified still is achieved when using the cuprous oxide–water nanofluid (133.64% and 93.87% higher than the productivity of the conventional still with and without operating the fan through all the daytime).
(3) Using the aluminum oxide–water nanofluid increased the distillate productivity of the modified still by 125.0% and 88.97% higher than that of the conventional one with and without the fan through all the daytime respectively.
(4) The optimum concentrations when using the cuprous oxide nanoparticles are $\varphi = 0.08\%$ and $\varphi = 0.12\%$ and when using the aluminum oxide nanoparticles are $\varphi = 0.10\%$ and $\varphi = 0.16\%$ with and without operating the fan respectively.
(5) The estimated cost of distilled litter for the modified solar still when using cuprous oxide nanoparticles, as well as the aluminum oxide, with and without the fan are approximately 0.035$, 0.045$, 0.038$ and 0.051$ respectively. And for the conventional solar still is 0.048$.

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