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Experimental study on pyramid solar still utilizing different types of nano-particles

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ABSTRACT

The primary objective of this study is to increase the productivity of distilled water of the pyramid solar still (PSS) throughout using different types of nanoparticles. The effect of the use of different types of nanoparticles at different concentrations on freshwater production was experimentally investigated under the climatic conditions in Jordan. In this study, the PSS with the basin absorber plates have been designed and constructed, which covers an area of 0.36 m^2, and the glass cover of the pyramid was made using local materials. Two different types of nanoparticles (aluminum oxide $Al2O_3$ and silica oxide SiO_2) were used at specific concentrations of 0.2%, 0.4%, and 0.6%; they were selected to add them with water to the PSS. The experimental results show that the addition of aluminum oxide particles by 0.6% and 0.4% resulted in increasing the amount of distilled water by 11.78% and 10.95%, respectively, when compared with the still without adding any nanoparticles.

Keywords: Pyramid solar still; Distillation; Solar still; Nanoparticles

1. Introduction

Water is an essential element for life; it plays a critical and central role in all aspects of life, from public health to safety, and the foundation of our economy. We use water for many different purposes. There is plenty of water on earth. However, it is undrinkable, and we cannot use it for agricultural purposes. That is because most of the water on Earth is saltwater. We, humans, like all living things, need freshwater to survive. Water is considered as an essential element for sustaining human life.

Several advanced desalination methods are used to produce clean, pure water. However, people living in remote, impoverished areas cannot get or use these technologies. Researchers and scientific groups are working hard to use different technological methods such as solar still to turn non-potable water into fresh water in order to overcome the issue, as mentioned above. Solar still is one of the techniques of supplying pure water by using renewable and free energy sources. Solar still system is a technology that has been proven to remove pathogens, heavy metals, and reduce salinity. Although this technology can provide a cheap source of pure water, it supplies us with a few amounts of distilled water daily, and that is considered as a disadvantage of this technology.

Many researches have been conducted to increase the productivity of solar still by using different ways such as: increasing the absorption area [1], minimizing water depth [2], increasing the difference between water–glass temperatures [3], increasing inlet water temperature [4], adding phase change material [5], vacuum technology [6], and several other techniques.

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The evaporation rate of water in the solar still is proportional to the surface area of water absorption. Many researchers used fins for increasing the heat transfer rate in solar thermal conversion devices [7,8]. Velmurugan et al. [9] conducted an experimental study aimed to increase the distilled water productivity for the single basin solar still by increasing exposure area in different ways (still with sponges, wick type solar still, and still with fins at the basin). The results show that 29.6% productivity increased when wick type solar still was used, 15.3% productivity increased when sponges were used, and 45.5% increased when fins were used. Velmurugan et al. [10] studied the productivity of the single basin solar still augmented by integrating fins at the basin plate, It was found that the evaporation rate increases by 53% when fins were integrated at the basin plate. Kabeel [11] experimentally studied a new design of solar still with a wicked concave surface used for increasing solar radiation absorption area as well as the evaporation area. The results showed that the average distilled water production through the day was 4.1 L/m^2, and the efficiency for concave solar still reached to 45%. He also found that the cost per liter is about 0.065$. Appadurai and Velmurugan [12] studied the performance analysis of fin-type solar still integrated with fin-type mini solar pond to improve the system productivity. It was found that fin-type mini solar pond with conventional solar still fin-type single basin solar still and fin-type mini solar pond integrated with fin single basin solar still have increased the water collection gain, which is estimated at 47%, 45.5%, and 50%, respectively.

Abu-Hijleh and Rababa'h [13] studied experimentally the performance of solar still with different sponge cubes sizes that were placed in the basin water in order to increase the surface area. The results showed an increase in distillate water production ranged from 18% to 273% compared to the same still without sponge cubes under the same weather conditions.

The basin water depth has a significant effect on the productivity of the solar still; the maximum distillate productivity is obtained at the lowest water depth. Several researchers have inferred that the depth of water is inversely proportional to the productivity of the solar still [14,15]. Tripathi and Tiwari [16] have conducted experiments for passive and active solar stills for different water depths in the basin (0.05, 0.1, and 0.15 m), under New Delhi climate conditions, they found that the productivity was high after the sunset due to the storage effect. Khalifa and Hamood [17] studied the effect of water depth on the performance of basin-type solar still with five different water depths, namely, 1, 4, 6, 8, and 10 cm. They found that still productivity decreases with increasing brine depth. In the final analysis, they established that the nocturnal output increased due to the heat stored through the sunshine hours in the higher brine depth.

The temperatures of the glass cover, saltwater, and the difference between them (ΔT) are one of the important factors on the daily productivity of solar still. The water–glass cover temperature difference is considered one of the most important parameters of the solar desalination technique. Suneesh et al. [18] have conducted experiment in a "V" type solar still with a "cotton gauze top cover cooling" (CGTCC) without and with airflow over the glass cover. The results showed that the productivity of the still with water owing over the bare glass (without CGTCC) was 3.3 L/m^2/d. The productivity increased to 4.3 L/m^2/d with the use of CGTCC, and it also increased to 4.6 L/m^2/d with CGTCC and airflow. Abu-Hijleh [19] has conducted a theoretical study to study the effect of water film cooling of the glass cover on the efficiency of a single basin still, he found that the efficiency was enhanced by 6% by proper use of cooling.

Preheating saline water before entering the solar still is considered one of the techniques used to enhance its hourly or daily yield of pure water. Abad et al. [20] have carried out experimental tests in a still coupled with a pulsating heat pipe (PHP). The use of a flat plate collector with PHP in a still increases productivity. The set-up consists of two parts, the first part is the solar still and the second part is the flat plate collector with PHP. The material used for PHP is copper that is used to improve productivity. The productivity was found to be 875 mL/m^2 h for this set-up. The optimum water depth and a filling ratio of the PHP were found to be 1 cm and 40%, respectively. The filling ratio is defined as "the volume of working liquid divided by total volume." Also, reaching maximum productivity was when the inclination angle of the flat plate collector and PHP were equal to 351° (latitude of Tehran, Iran).

In recent years, advancing in material processing and manufacturing is remarkable. One of the most industrial materials is the phase change materials (PCM). The phase change materials have the advantages of energy storage. These advantages are found due to both sensible and latent heat storage capability. PCM in the last years have been employed in the heat transfer and energy storage applications in many fields such as heat exchangers, heat and ventilation air conditioning systems, and solar energy storage systems. The PCM thermal properties have been augmented via numerous methods. One of the most enhancement techniques is using nanoparticles.

Phase change material PCM was widely used in different thermal applications. PCM is "a substance with a high heat of fusion, where melting and solidifying at a certain temperature is capable of storing and releasing large amounts of energy." Heat is absorbed when the material changes from solid to liquid, and heat are released when the material changes from liquid to solid. Hence, PCM's are also called latent heat storage systems.

Ghalambaz et al. [21] have studied the impact of the magnetic induction and cavity inclination angle on the melting phenomenon of an MHD phase change process. The left and right vertical walls are maintained at a constant temperature Th and the bottom and top walls are kept thermally insulated. The effects of crucial parameters such as the Hartmann number and inclination angle of cavity are studied. The results of the present study are compared with the experimental and numerical results available in the literature and found to be in reasonable agreement. The outcomes of the present study can be summarized as follows:

- The utilized enthalpy–porosity formulation can model the phase change phenomenon for a pure substance.
- The increase of the Hartmann number tends to suppress the convective mechanism and decrease the rate of the phase change process.

- The liquid fraction is a decreasing function of the Stefan number. Furthermore, the augmentation of the inclination angle makes an asymmetric melting, and consequently, a decrease in the liquid fraction is predicted.

El-Sebaii et al. [22] have conducted experiment in single basin solar still by integrating a thin layer of stearic acid as a PCM beneath the basin liner to enhance the productivity of the still. The results were compared to the still without PCM. After the study was conducted, the results show that productivity decreases with the increase of the PCM mass, but the night productivity increased with the increase of the PCM mass. Also, the productivity of the still was 9.005 and 4.998 kg/m^2/d for the still with PCM and without PCM, respectively. Sathyamurthy et al. [23] investigated experimentally the solar still by separating the evaporation and distillation chambers and putting the phase change material between them. The use of phase change material resulted in storing a portion of the solar energy in it. By restoring this energy, it produced about a 52% yield increase and a 14% efficiency increase.

The effect of vacuum inside the still is to avoid any heat transfer due to convection in the still. Therefore, the heat loss from the water in an insulated still is due to the evaporation and the radiation only. Al-Hussaini and Smith [24] investigated the impact of providing vacuum to a solar still on distilled water production. It was suggested that providing vacuum to the solar still improved distilled water production by more than 100%. In addition, it was found that the main reason for the improvement of distilled water production was the absence of convection heat loss from water and the non-condensable gasses. Nassar et al. [25] conducted experiments inside a solar desalination system working on the basis of evacuation. Concave mirror was used to concentrate the solar energy on the still. The still works under vacuum conditions (25 kPa absolute) to reduce the boiling point of the saline water. A condenser condenses the outlet vapor and the distillate was collected. The productivity of the still was found to be 20 L/m^2/d of the reflector compared to 5 kg/m^2/d for the conventional still. The results showed that the productivity of the still was about 303% compared with the other stills. The performance ratio was found as 900%. The vacuum pump in the still may be operated by means of the photovoltaic system to provide potable water to the nearby villages.

Ali [26] investigated the effect of air movement inside three-square meter solar still on the still performance. A fan was added to the still to allow air movement inside it. It was noted that the incorporation of a fan and an insulated air channel makes the still about 29.7% more efficient than the conventional one. Taamneh and Taamneh [27] constructed pyramid solar still (PSS) with a total basin area of 0.95 m^2 and a pyramid glass cover. The experimental results showed that the solar still daily productivity using fan work with photovoltaic of freshwater was 2.99 L, and it was increased by 25% compared to free convection solar still.

Many endeavors have been made to enhance solar stills performance utilizing various experimental techniques. One of these techniques is the use of nanotechnology in fluids to enhance heat transfer properties. Heat transfer plays a primary role in several applications, such as air-conditioning, power generation, and transportation. Since an excellent thermal conductivity performance is widely required for different applications, serious attempts were aimed to improve working fluids' thermal conductivity. Nanotechnology attracts full attention in this field as it directly affects the thermal conductivity of fluids.

Adding nanoparticles to still solar technology can enhance the thermal characteristics of the basin water because it has many unique properties compared to its base liquid, such as high thermal conductivity and high solar intensity absorptivity [28,29]. Therefore, it will improve the performance of the thermal system. In general, there are two mechanisms to improve heat transfer by introducing nanoparticles into the base fluid:

- To increase nanoparticle concentration in the base fluid, which will increase the heat transfer rate accordingly.
- The collisions occur between nanoparticles and the base fluid molecules on the first hand, and the impacts of the particles on the solar still wall, on the other hand, results in an energy increase.

Manufactured nanoparticles display physicochemical characteristics, coatings that impart upon them unique electrical, thermal, mechanical, and imaging properties that are highly desirable for applications within the commercial, medical, and environmental sectors. Potential occupational and public exposure to manufactured nanoparticles will increase dramatically soon due to the ability of nanomaterial to improve the quality and performance of many consumer products, as well as the development of medical therapies and tests which will use manufactured nanoparticles. Currently, information describing the relative health and environmental risk assessment of manufactured nanoparticles or nanomaterials is severely lacking. Only recently, critical questions regarding the potential human health and environmental impact of manufactured nanoparticles or nanomaterials have been raised [30].

Eastman et al. [31] have conducted an experimental study to determine the thermal conductivity of water containing a concentration of 5% of copper oxide nanoparticles. The authors established that thermal conductivity was 60% greater than that of pure water. Likewise, the thermal conductivity was 40% greater than that of pure water for water containing a concentration of 5% of alumina nanoparticles.

Xie et al. [32] conduct experimental work to determine the nanofluid's thermal conductivity for different sizes of alumina nanoparticles within the scale of 12.2 to 304 nm, found that there is an inverse relationship between the thermal conductivity and the particle size, with the exception of the largest particles. Das et al. [33] studied the impact of temperature on nanofluids' thermal conductivity. In Al_2O_3 and CuO nanofluids, the thermal conductivity increases as the temperature increases. This behavior is very typical for nanofluids at greater temperature ranges as well.

Nijmeh et al. [34] investigated the impact of utilizing different absorbing materials on the productivity of a single-basin solar still. They made a comparison between the theoretical and experimental productivities of the solar still. The results showed that the addition of 70 mg/L of potassium dichromate $K_2Cr_2O_7$ and 50 mg/L of potassium permanganate $KMnO_4$ improved the daily efficiency of the still by about 17% and 26%, respectively. The best improvement for the productivity of the still was obtained utilizing violet dye by about 29%. They also studied the impact of utilizing charcoal at different concentrations on the still performance. The outcomes demonstrated that the optimum daily efficiency and productivity of the still were 17.3% and 5,290 mL/d achieved when 50% of the basin area is covered by charcoal. Furthermore, theoretical values were in good agreement with the experimental results. Gnanadason et al. [6] investigated experimentally the effect of using carbon nanotubes (CNTs)-based nanofluids on the performance of single slope solar still equipped with a vacuum pump. They concluded that adding nanofluids to the basin of solar still can enhance efficiency by up to 50%.

Kabeel et al. [35] studied the effects of using different weight fraction concentrations of solid nanoparticles (Cu_2O and Al_2O_3) on the performance of single basin solar still with and without providing vacuum. The results showed that using Cu_2O and Al_2O_3 nanoparticles increased the distilled water productivity by about 133.64% and 93.87% for cuprous oxide, and 125.0% and 88.97% for aluminum oxide with and without operating the vacuum fan. Elango et al. [36] have studied the effect of using alumina, zinc oxide, iron oxide, and nanoparticles of tin oxide on the production of pure water for the slope of the solar slope. The results showed that alumina nanofluid has the highest production of pure water compared to water only with 29.95%.

Nasrin et al. [37] study the influences of physical parameters, wave amplitude, and the number of waves on the natural convection boundary layer flow inside a solar collector with water-Al_2O_3 nanofluid. Various wave amplitudes and the number of the waves have been considered for the flow and temperature fields as well as the convective and radiative heat transfer rates, mean bulk temperature of the fluids, and average velocity field in the collector while ϕ, Ra, Pr, and ε are fixed at 5%, 104%, 6%, and 0.9%, respectively.

Chamkha and Selimefendigil [38] performed a numerical simulation of a PV-thermal module with SiO_2-water nanofluid was performed. It was observed that cylindrical shape particles give the best performance in terms of efficiency enhancement. Total PV/T module efficiency enhances by about 7.39% at the highest volume fraction with cylindrical shape particles. As compared to spherical ones, up to 4% more in the efficiency enhancement was observed with cylindrical shape particles.

Sahota and Tiwari [39] modeled double slope solar still using three different inorganic based nanofluids, including alumina oxide, titanium oxide, and copper oxide at a mass concentration of 0.25%. They found that the thermal and exergy efficiencies of the solar still were maximized by using alumina oxide. The thermal and exergy efficiencies alumina-water based solar still was approximately 13% and 9% higher than those of conventional ones, respectively. Sharshir et al. [40] studied the influence of graphite and copper oxide micro-flakes with different concentrations with glass cover cooling on the solar still performance; the results showed that the solar still productivity increased by about 44.91% and 53.95% using the copper oxide and graphite micro-flakes, respectively. Mahian et al. [41] investigated the effects of nanoparticle suspensions on the performance of solar still equipped with a heat exchanger experimentally and theoretically. The results reveal that using the heat exchanger at temperatures lower than 60°C is not advantageous and the corresponding yield is smaller than that of solar still without the heat exchanger; although in such a case, using nanofluids as the working fluid in the heat exchanger can enhance the performance indices about 10%.

2. Experimental procedure

2.1. Materials

This research was conducted using different types of nanoparticles with different concentrations; the main types were used are aluminum oxide Al_2O_3 and silica oxide SiO_2. The preparation of nanofluids requires the precise composition of stable nanoparticles dispersed in a base fluid. Accordingly, the prepared dispersion should be kept stable. Commonly, there are three methods to avoid settling the particles as follows:

- controlling the pH of the dispersion,
- introducing surfactants,
- using the ultrasonic method.

The mentioned methods affect the surface properties of suspended nanoparticles, and cluster formation does not occur. Therefore, dispersions become stable. The aluminum oxide nanoparticles were used in experiments with 10–14 nm average particle size, 3,900 kg/m^3 density, 773 J/kg K specific heat, and thermal conductivity around 46 W/m K. On the other hand, the specification for silica oxide nanoparticles was 10–14 nm average particle size, 2,530 kg/m^3 density, 800 J/kg K specific heat, and thermal conductivity around 1.4 W/m K.

2.2. System description

In this work, a PSS is presented. It has a saline water basin with a black bottom, a transparent cover, and collecting pipes, which give the condensed water as the final product. Sunlight heats the water in the basin. This heated water evaporates and re-condenses on the underside of the sloping transparent cover and runs down into collecting along the inside lower edges of the transparent cover. Usually, the transparent cover is made of glass or plastic, such as polyvinyl chloride. PSS top cover is in the shape of a pyramid. There were mainly two shapes in this category: triangular PSS and square PSS. The main difference between these two types is the shape of the basin. In triangular PSS, the basin is of triangle shape, whereas the square-shaped basin used in square PSS.

Advantages of PSS over conventional single slope solar still:

- In conventional single slope solar, solar still must be located so that its inclined surface faces directly sun, that is, facing toward the south for the northern hemisphere and facing toward the north for the southern hemisphere and also continue to be moved as sun travel for gaining maximum solar radiation throughout the day. In contrast, in PSS, this is not required.

- In PSS, shading of the sidewall on the water surface is less than that in the case of conventional solar still.
- For the same basin area, the cover area is higher for pyramid shape, so this will increase the condensation as a condensing area in a pyramid shape is higher than that of a single slope shape.
- In PSS, any side of cover directly gains direct and higher solar radiation than the other side. So the other side remains at a lower temperature than this side, which enhances the part of condensation that occurs on these sides due to the higher temperature difference between the water surface and the cover.

Fig. 1 shows the schematic diagram of the system, and Fig. 2 shows the 3D model for PSS.

2.3. Solar still design and fabrication

PSS has been designed, fabricated, and constructed to investigate its performance in producing distilled water. The temperature of basin water, glass temperature, and vapor temperature have been measured using the thermocouple, the hourly solar radiation. Ambient temperature data has been imported from the PV project at the university. The PSS consists of a glass cover, internal galvanized iron sheet, insulation, and external galvanized iron sheet. The glass cover is 6 mm thick; each glass plate of the glass cover is 60 cm wide, a height of 25 cm, and a slope angle of 30°. The 1.25 mm-thick internal galvanized iron sheets combined forming a closed box with a base area (absorber area) of 0.36 m^2 (0.6 m × 0.6 m), and a height of 30 cm. Furthermore, the 0.9 mm-thick external galvanized iron sheets combined forming the external surface with a base area of 0.49 m^2 (0.7 m × 0.7 m), and a height of 30 cm. Moreover, there is a 5 cm polystyrene insulation between them. Fig. 3 shows the PSS that was used in the experiment.

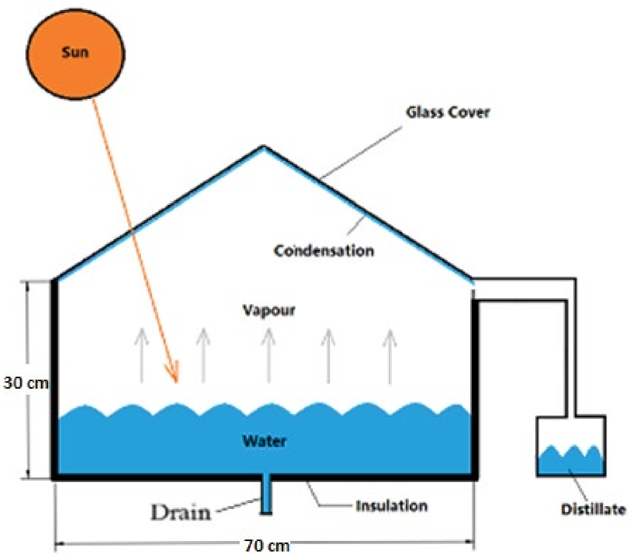

Fig. 1. Schematic of the system.

Several parameters need to be measured in this experiment, such as the temperatures at different points of the still (basin and outer glass cover temperatures), ambient temperature, total solar radiation, and the amount of distillate. The temperatures have been measured using a digital thermometer (±0.5°C). The solar radiation has been measured using the radiation sensor, and the temperature sensor measured the ambient temperature. It should be noted that the sensor was not installed to direct sun or close to heat-producing equipment.

In this research, two groups of experiments were carried out. The first part was carried out on the still using silica oxide nanoparticles (SiO_2) combined with water (nanofluid) at different concentrations. The second part was completed by repeating the same steps of the first group but by replacing the silica oxide nanoparticles (SiO_2) with aluminum oxide nanoparticles (AL_2O_3). Water depth inside the PSS remained at a constant value, which is 2.7 cm.

3. Results and discussion

The experiment was conducted during the period of the end of June to the first of September 2018 on the roof of the mechanical engineering department, Jordan University of

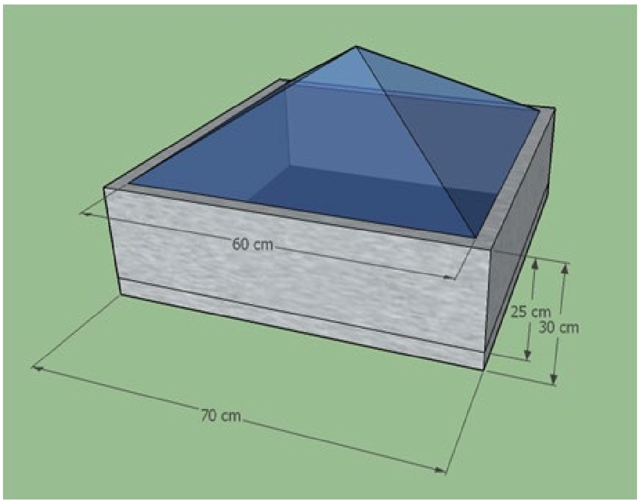

Fig. 2. 3D Model for pyramid solar still.

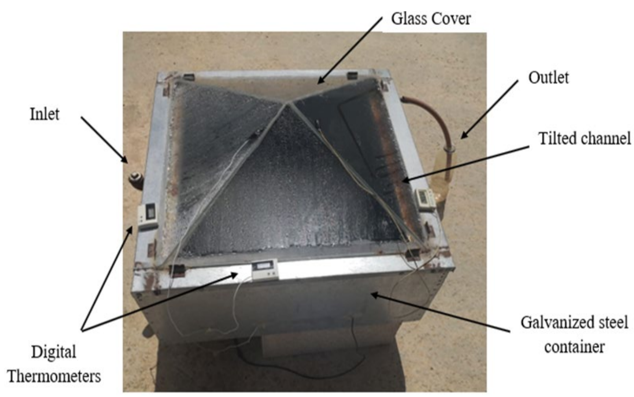

Fig. 3. pyramid solar still that used in the experiment.

Science and Technology (JUST). Irbid (latitude 32.48, longitude 35.98), PSS was assembled and tested. Two parts of the experiments were carried out; the first part was performed by adding different types of nanoparticles with different concentrations at a constant depth.

3.1. Freshwater hourly productivity

Fig. 4 shows that the variation of solar radiation during the sunshine days through the experimental period; it can be seen that the change in solar radiation is insignificant through the experimental days. Besides, it is noticed that the solar radiation increases with time to reach a maximum value between 1:00 and 2:00 pm.

Also, the same trend for ambient temperature is observed in this experiment.

Fig. 5 shows the ambient temperature of the sunshine days of the experimental period; it is noticed that the ambient temperature increases with time to reach a maximum value between 3:00 and 4:00 pm, which is the same trend for the solar radiation.

Fig. 6 shows the variation of distilled water productivity for PSS by adding different concentrations of SiO_2 nanoparticles compared to not adding any concentration of nanoparticles. The experimental results indicate that an increase in the nanoparticle concentration leads to an increase in the PSS productivity during the period from 8 am until 2 pm and a sharp reduction in the PSS productivity after 2 pm. Because the nanoparticles improve the heat transfer characteristics and evaporative properties of the basin water. The addition of nanoparticles to the basin water improves the thermal conductivity of the mixture of water and nanoparticles and the convective heat transfer coefficient, so the ability of evaporation and condensation is more than the case of water only, especially during intensive solar radiation hours.

Fig. 7 shows the variation of distilled water productivity for PSS by adding different concentrations of Al_2O_3 nanoparticles compared to not adding any concentration

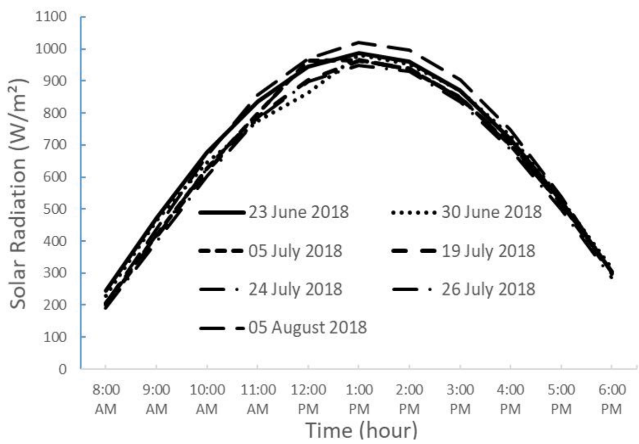

Fig. 4. Variation of solar radiation during different experimental days.

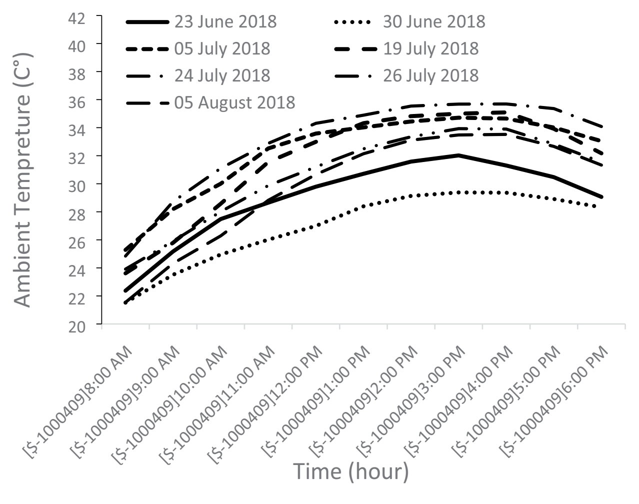

Fig. 5. Variation of ambient temperature during experimental days.

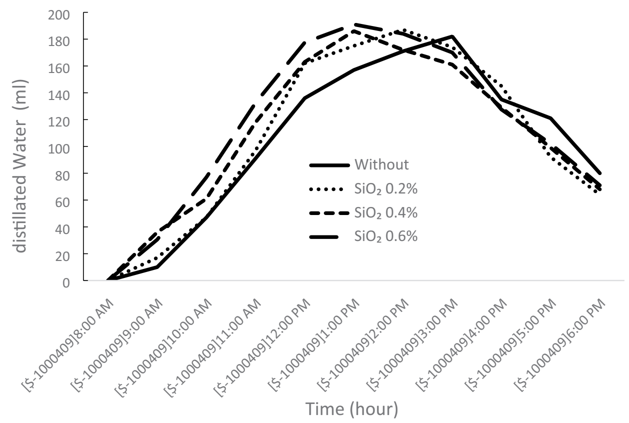

Fig. 6. Variation of distilled water production for pyramid solar still with and without different concentrations of SiO_2 nanoparticles.

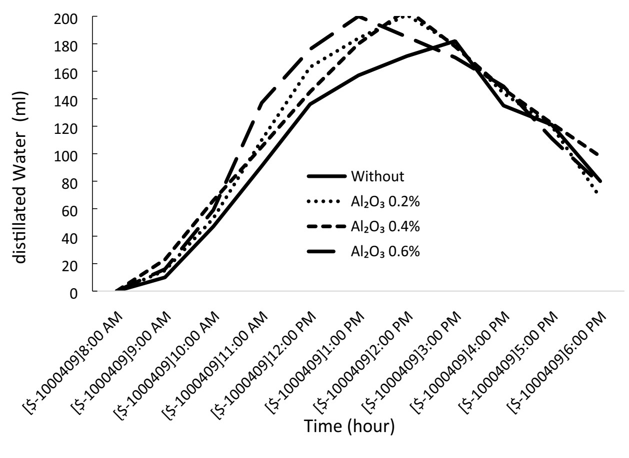

Fig. 7. Variation of distilled water production for pyramid solar still with and without different concentrations of Al_2O_3 nanoparticles.

of nanoparticles. It can be seen that the hourly freshwater production increases gradually until it reaches a maximum value between 1:00 and 2:00 pm for PSS with different concentrations of Al_2O_3 nanoparticles, then around 3:00 pm for PSS without using any concentration of nanoparticles it starts to decrease. This manner is observed in all experiments that were carried out for different concentrations of the aluminum oxide.

It is noticed that the amount of pure water is produced during the daylight hours until 2 pm, and the experiments that contain nanoparticles of all concentrations produce more water than the experiments held without nanoparticles. On the other hand, the experiments held after 3 pm, it is noticed that the amount of pure water produced from the solar still without adding nanoparticles is more than the amount of pure water produced by the solar still with adding nanoparticles. Also, it is observed that the PSS with 0.6% concentration of Al_2O_3 produces the highest amount of freshwater among all nanoparticle concentrations, whereas the PSS without any concentration of nanoparticles produces less amount of freshwater.

3.2. Freshwater accumulative productivity

3.2.1. Results for silica oxide SiO_2

Fig. 8 shows that the maximum production of freshwater is 1,263 mL at a concentration of (0.6%) of SiO_2 nanoparticles, then 1,193 and 1,160 mL for 0.4% and 0.2% concentrations of SiO_2 nanoparticles, respectively. In addition, the PSS produces 1,130 mL without using nanoparticles inside the system.

The comparison between the accumulative amounts of freshwater produced by the PSS with various concentrations of silica oxide nanoparticles SiO_2 and without nanoparticles is shown in Fig. 9.

Fig. 10 shows the percentage enhancement of adding silica oxide inside the PSS compared to not adding any concentration of silica oxide. It can be seen from the figure that the added silica oxide particles with a concentration of 0.6% improve the production of distilled water by 10.5%, then 5.2%, and 2.5% for concentrations 0.4% and 0.2%, respectively.

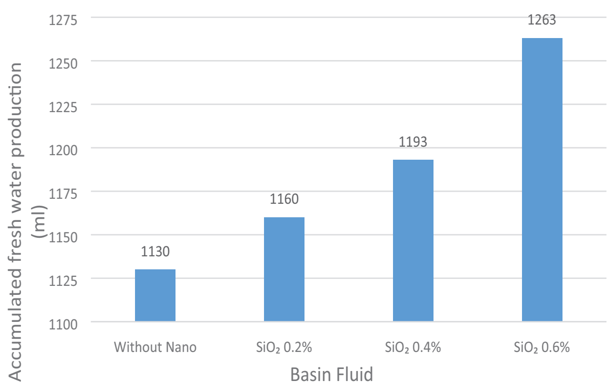

Fig. 8. Total amount of freshwater for solar still with and without utilizing different concentrations of silica oxide SiO_2.

3.2.2. Results for aluminum oxide Al_2O_3

Fig. 11 shows that the maximum production of freshwater is 1,281 mL at a concentration of 0.6% of Al_2O_3 nanoparticles, followed by 1,269 and 1,237 mL for 0.4% and 0.2% concentrations of Al_2O_3 nanoparticles, respectively.

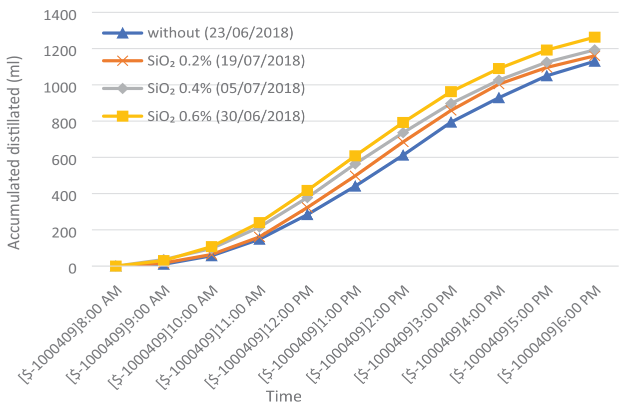

Fig. 9. Accumulative amounts of freshwater produced from solar still with and without utilizing different concentration of silica oxide SiO_2.

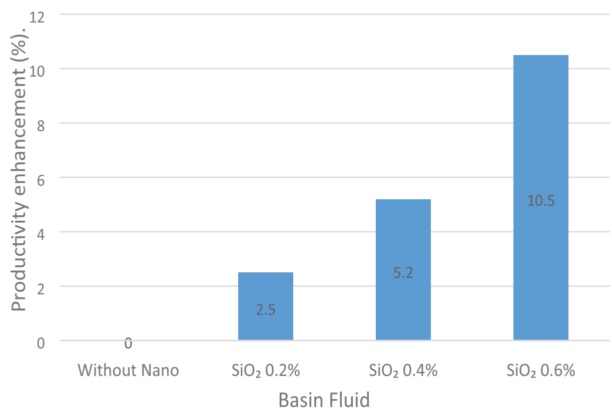

Fig. 10. Percent increase in the distilled water production for the pyramid solar still at SiO_2 nanoparticles concentrations.

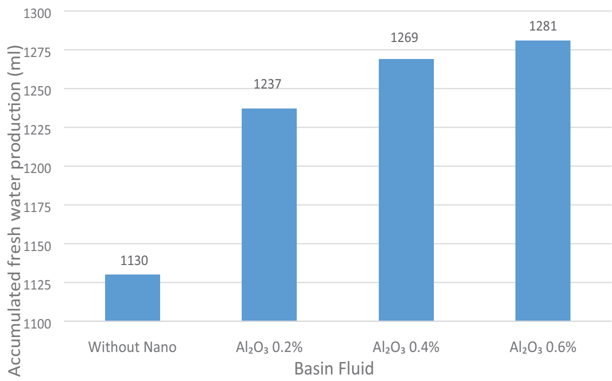

Fig. 11. Total amount of freshwater for solar still with and without utilizing different concentration of aluminum oxide Al_2O_3.

In addition, the PSS produces 1,130 mL without using any concentration of nanoparticles inside its system.

The comparison between the accumulative amounts of freshwater produced by the PSS with various concentrations of aluminum oxide Al_2O_3 and without using any concentration of nanoparticles is shown in Fig. 12.

Fig. 13 shows the percentage enhancement of addition aluminum oxide inside the PSS compared to the PSS without using any concentration of aluminum oxide. As can be seen from the figure that adds aluminum oxide particles with concentration, 0.6% improves the production of distilled water by 11.78%, followed by 10.95%, and 8.65% for concentration 0.4% and 0.2%, respectively.

3.3. Thermal efficiency

We can calculate the hourly efficiency from the following equation [10]:

$$\eta = \frac{\dot{m} \times h_{fg}}{A_g \times I_{(t)}} \tag{1}$$

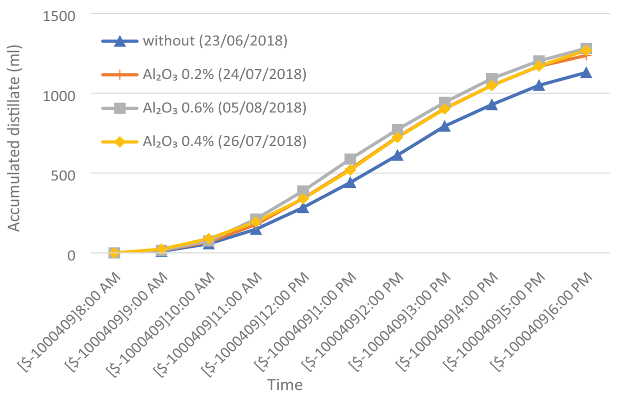

Fig. 12. Accumulative amounts of freshwater produced from solar still with and without utilizing different concentrations of aluminum oxide Al_2O_3.

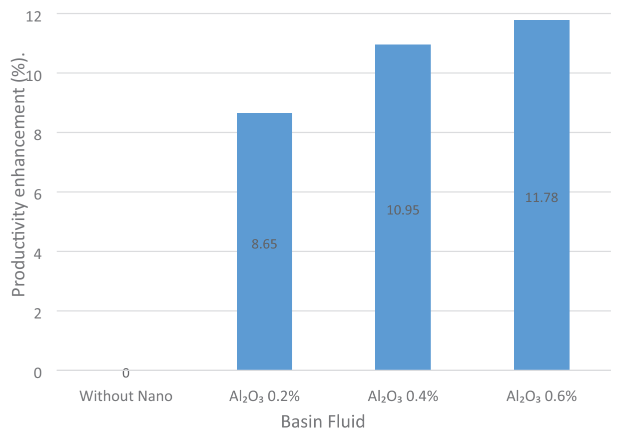

Fig. 13. Percent increase in the distilled water production for the pyramid solar still at Al_2O_3 nanoparticles concentrations.

where η is the hourly thermal efficiency; $\dot{m}$: hourly distilled water production; hfg: latent heat.

$$h_{fg} = \left(2503.3 - 2.398 \times T_w\right) \tag{2}$$

where $I(t)$: hourly average solar radiation; A is the whole area of the PSS.

Fig. 14 shows the hourly variation of the PSS efficiency during the experimental days calculated using Eqs. (1) and (2). The figure shows that the PSS efficiency increases with time until reaching the maximum value around 6:00 pm for different concentrations of nanoparticles.

Notice that there are differences in the still efficiency within hours of the day, but when calculating the overall efficiency of the solar still during those hours of the operation. It is noticed an increase in the still productivity containing nanoparticles.

3.4. Cost analysis

Clean water production through solar still is considered one of the cheapest procedures compared to advanced technologies. Therefore, the cost analysis of the PSS in this project is necessary to determine whether the system is economically productive or not. Table 1 provides a cost estimate for the various components used in the PSS manufacturing.

The total cost of the fabricated PSS is about $200. The cost of per-liter of solar-distilled water could be calculated as follows:

Table 1
Cost estimation for the various components of pyramid solar still

Component	Cost (US $)
Total cost of galvanized steel	60
Cost of tempered glass	35
Cost on insulation and sealing	20
Pipe, fittings and collecting bottle	15
Cost of temperature sensor	20
Cost of labor and machining	50
Total cost	200

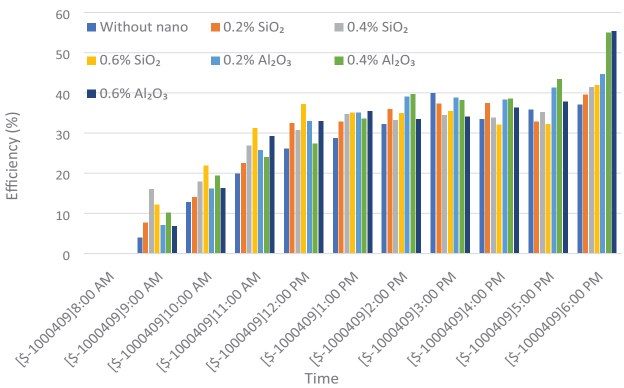

Fig. 14. Hourly variation of the pyramid solar still efficiency during experimental days.

Table 2
Uncertainty of instrument measurement

Instrument	Accuracy	Range	Error
Solar radiation sensor	±1 W/m²	0–2,000 W/m²	0.05%
Temperature sensor	±0.5°C	0°C–100°C	0.5%
Thermocouples	±1°C	0°C–100°C	1%
Flask	±2 mL	0°C–100 mL	2%

- Estimating the still usable lifetime
- Adding all the construction, repair, and maintenance costs throughout its lifetime
- This figure is divided by the total expected lifetime output of the still in liters.

In this research, it was found that the water production average of the modified solar still is about 1.13 L/d/0.36 m^2. For 10 years of useful assumption of the still's lifetime minimal maintenance and 300 sunny days per year, the per-liter cost of the adjusted solar still is estimated at $0.059/L.

3.5. Uncertainty analysis

During the system performance evaluation experiments, different parameters were measured. The parameters indicate different points of the temperature from each of the shots (the basin water and glass cover), ambient temperature, solar radiation, and, finally, the distilled water amount. Measurements must be performed very carefully to minimize the probability of errors as much as possible. Therefore, errors associated with measuring instruments are presented in Table 2.

4. Conclusions

The PSS was designed and constructed to produce distilled water by using a different type of nanoparticles under the weather conditions of Jordan. The results of this study show that:

- Freshwater productivity of the PSS can be increased by adding different types of nanoparticles in the basin fluid, as the nanoparticles raise the water temperature, thermal conductivity, and convective heat transfer coefficient.
- The maximum increase in the PSS productivity is achieved by using the aluminum oxide nanoparticles with 0.6% and 0.4% concentrations (11.78% and 10.95% higher than the productivity of the still without using any concentration of nanoparticles.
- Using Silica oxide nanoparticles increases the distilled water productivity of the PSS by 10.5%, 5.2%, and 2.5%, which is higher than the productivity of the still without using any concentration of nanoparticles.
- The results show that the PSS had a maximum hourly efficiency of 55.29% and 54.96% at 6:00 pm when using the aluminum oxide Al_2O_3 nanoparticles 0.6% and 0.4%, respectively.
- When using silica oxide SiO_2 with concentrations of 0.4% and 0.6%, the maximum hourly efficiency was 41.96% and 41.38%, respectively.

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