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Effect of the condenser type and the medium of the saline water on the performance of the solar still in hot climate conditions

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ABSTRACT

This paper presents an experimental work to study the effect of the condenser and the medium of saline water types on the performance of the solar still. Single slope solar still facing the south is used in this work. Also, four types of the condenser are tested: (i) glass, (ii) aluminum plate, (iii) aluminum heat sink with pin fins, and (iv) aluminum plate covered with an umbrella. Moreover, four mediums of the saline water inside the basin are examined: (i) only saline water in the basin, (II) Layers of black steel fibers in the basin, (iii) saturated sand with saline water, and (iv) mixture of sand and black steel fibers saturated with saline water. The solar still of only glass walls and only saline water in the basin is taken as a reference case. The performance of the other cases is referred to the reference case. The results indicate that using heat sink condenser increases the temperature of the saline water. Also, it increases the temperature difference between the condenser and the saline water relative to using glass condenser. Also, using a glass condenser with black steel fibers inside the water basin increases the daily productivity of freshwater by 35%. Using the heat sink condenser increases the daily productivity from 31% in the case of using only saline water to 52% in the case of using black steel fibers in the basin. Using an umbrella of 20 cm wide at the top of the aluminum plate condenser decreases the daily productivity by 26%. Increasing the umbrella wide to 40 cm decreases the daily productivity by 31%.

1. Introduction

The composition of water on the earth is about 97% saltwater, 2% frozen in glaciers and polar snow-caps and the rest is freshwater [1]. The requiring of fresh water production is growing progressively during the coming century due to the growth of the world population, the climate changes, and the industrial processes. By the year of 2025, it is expected that one-quarter of the world inhabitants will be affected by water shortage, and the rest of the population will experience vital water requirements conditions [2]. Therefore, the research in this domain is essential to discover new techniques or to develop the current techniques for the the efficient production of fresh water. Desalination is one of the important techniques that meet this demand. However, the conventional distillation processes such as flash distillation, multi-effect distillation, membrane distillation; thin film distillation, ion exchange, multi-effect fresh evaporation, electrodialysis, and forward and reverse osmosis [2,3,4] are not efficient for large freshwater requirements or are energy intensive techniques. In addition, the availability of energy in remote areas and most arid regions is low [5,6,7]. Therefore, solar distillation looks to be a promising process and an alternative way of providing small communities in remote regions and islands with freshwater. Solar distillation appears to be an economical, effective and eco-friendly technique overall the conventional distillation techniques. Additionally, it is a promising method for providing potable water to small communities in remote regions and islands [6]. Solar radiation is free, everlasting and available on site. Moreover, using the solar energy diminishes fossil-fuels consumption and pollutants. Numerous solar desalination devices have been developed over the years. The most conventional solar desalination units are solar stills. Solar still utilizes the solar energy to purify contaminated or saline water using distillation principle. In general, solar still works on the process of evaporation-condensation. The saline water inside the solar still is evaporated by utilizing solar energy, and the condensate is collected on the solar still walls and exits as freshwater. The solar still are mainly categorized into two categories: active and passive solar stills [8]. For passive solar still, solar radiation is the unique parameter which generates the evaporation but for active solar stills, evaporation is also generated by using an additional device like fan [9], pump [10], system of sun tracking [11] or solar collectors [12–14]. Many researchers have studied theoretically and experimentally the solar still

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performance. They concluded that active solar stills are less economical to produce fresh water in comparison to passive solar stills. But, active solar stills also could use waste heat from other processes or devices to improve the rate of evaporation of water and the productivity (yield) of water of the solar stills depends on climatic conditions and various other parameters [15]. Solar stills are cheap, simple, need low maintenance, do not need fossil fuels and environment-friendly technology, but they suffer from low productivity [1,4,5,16,17,18]. Because of the solar still advantages and to overcome its disadvantages, scientists have performed many studies to enhance the solar stills performance. The solar still efficiency depends on many parameters: solar still design, basin design, and conditions, climate conditions, an evaporation process of the saline water, condensation process of the humid air, etc. So, a large number of researchers has focused on these parameters during theoretical and experimental studies to increase the productivity and the performance of the solar still. Some of these researchers performed their work in the basin medium; Muftah et al. [19] reported a review paper on the factors affecting the productivity of the basin type solar stills. They concluded that the productivity of the solar still depends on its body, its orientation, water depth, vapor tightness, and inclination of condensing cover. Mahdi et al. [20] studied the performance of the wick type solar still, where the absorber/evaporator material is charcoal cloth, and it is used for saline water transport. Janarthan et al. [21], and Alaian et al. [22] presented an experimental investigation on the performance of a solar still with an evaporated surface of wicked pin fins. They concluded that the still productivity is improved when the wicked pin fins are applied in the basin. Sahota and Tiwary [23] found that a solar still with Al_2O_3 water nanofluid in the basin enhances the productivity by 12.2% while Omara et al. [24] achieved 25% higher productivity using the same nanofluid under vacuum conditions. Other researchers conducted their work by concentrated on the condensation process to increase solar still productivity. Kabeel et al. [25] presented a detailed review paper on solar still with an external condenser. Kumar et al. [26] provided an external condenser to collect part of the humid air from the solar still and to condense the vapor. Jianyin et al. [27] designed a new multi-effect solar still with an enhanced condensation surface, where it applies the corrugated shape structure. Belhadj et al. [28] studied a single-basin, double slope solar still joined with a condensation cell composed of liquid plate with feed reservoir. Other research studies aimed at climate conditions like Mohamed et al. [29] presented double slope solar still with sand as a porous medium in hot climate conditions. Kabeel et al. [30] enhanced the productivity of the solar still by using solar dish concentrator in hot climate conditions. The desalinated water cost decreases continuously because of the achieved improvements in the desalination techniques. The cost of the desalinated water by the solar still becomes economically feasible and competitive to the other methods in remote areas as it is a free energy cost. Srivastava1 and Agrawal [33] performed an economic study on the solar stilled water plant. The study revealed that the high-performance unit achieves a percentage decrement of 36% in the cost of the produced water relative to the conventional unit. Kumar1 et al. [34] introduced an economic analysis on a double slope solar still working under different additives to the saline water in the basin. They found that the payback period is 67 days. Malaiyappan and Elumalai [35] presented a thermal and economic study on a single slope solar still at three low-cost basin materials, they are glass, plastic, and aluminum. The plastic basin achieved the lowest cost and the aluminum basin achieved the highest productivity.

Despite the large number of researches on the solar still, still a work could be introduced to improve its productivity and performance. In this work, the effect of using two new proposed condenser types (aluminum heat sink and aluminum plate) on the performance of the solar still is studied. Also, the effect of using new medium in the basin (layers of black steel fibers) is presented in this work. Moreover, studying the effect of using an umbrella on the top of the condenser on the productivity of the solar still is considered. To the authors' best knowledge, no one studied the heat sink as a condenser and steel fibers in the basin before. Therefore, four types of the condenser are considered: glass, aluminum plate, heat sink with pin fins fabricated from aluminum, and aluminum plate covered with an umbrella. Four mediums of the basin are considered: only saline water in the basin with salinity percent 4% by mass for all case, saturated sand with saline water, steel fibers saturated with saline water, and a mixture of sand and steel fibers saturated with saline water. The reference case is the conventional solar still of glass walls and only saline water in the basin, and the performance of the other cases is compared to it.

Fig. 1. Front view of the solar still.

2. Experimental work

A single acting solar still is constructed and installed on the roof of the laboratory to perform the experimental study as shown in Figs. 1 and 2. Fig. 1 shows a front view of the solar still, Fig. 2a shows a back view of the solar still with glass condenser, Fig. 2b shows the solar still with heat sink as a condenser. Fig. 3 presents a complete layout of the experimental setup. The experimental work is carried out in the faculty of Engineering, Assiut University, Assiut, Egypt, where the latitude angle is 27° and longitude angle is 31°. The used solar still consists of shallow basin (1) which is made of 1 mm thick galvanized steel sheet with dimensions of 80 × 180 × 2 cm. Black paint paints the shallow to increase its absorptivity. The basin is located inside a wooden frame of 5 cm thickness for insulation purpose. The walls of the solar still are made of glass of 3 mm thickness with the dimensions shown in Fig. 3. The inclination angle of the front wall is set at 27° with the horizontal according to the latitude angle of Assiut city. Four cases are examined for the back wall (3) of the solar still which is called a “condenser” in our study. The examined case are: (i) a glass cover of 3 mm thickness, (ii) an aluminum plate of 1 mm thickness and (iii) a heat sink consists of an aluminum plate of 1 mm thickness with aluminum pin fins. The fins are made of aluminum rods of 15 mm diameter and 40 mm length. The fins are distributed uniformly on the aluminum plate with 75 mm apart from each other. The case (iv) is an aluminum plate of 1 mm thickness covered with an umbrella. Two width values of the umbrella are examined 20 and 40 cm. The solar still is supported by stands (4) fabricated from steel as shown in Fig.1. Two water tanks (5) are connected in series with the basin to supply it with makeup saline water. The first tank has a higher level corresponding to the second tank, and the second is used as a supply tank where its level is controlled by floats (Fig.3). The second tank is utilized to control the water level in the basin to achieve its level constant through all the experiments. The condensed freshwater is collected in a flask (6). The whole experimental setup is assembled and oriented to the south during all the experiments to receive the maximum solar radiation.

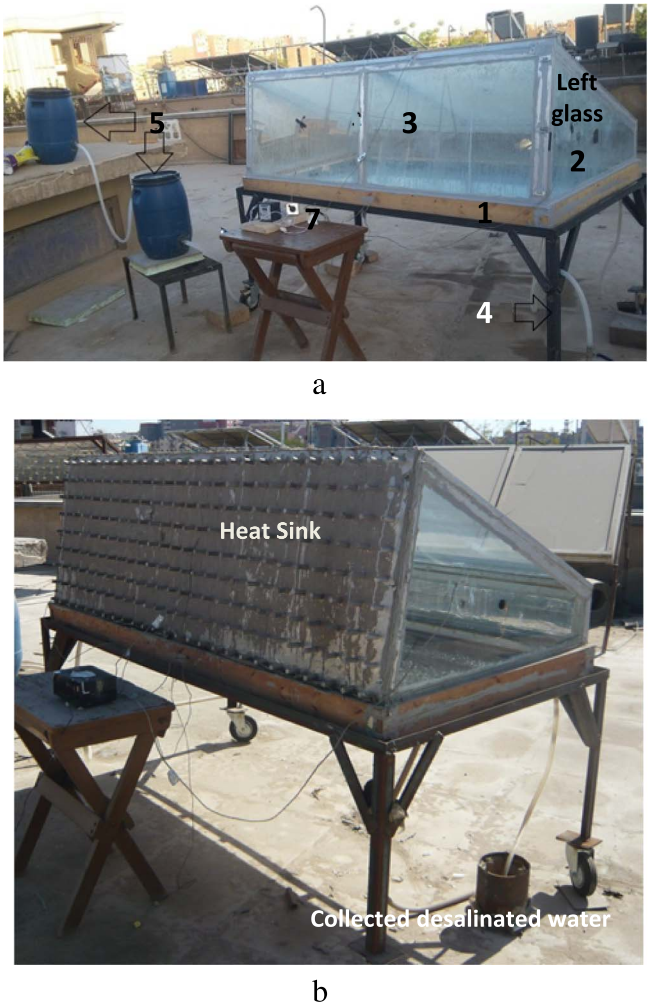

Fig. 2. a. Back view of the solar still with glass condenser. b. Back view of the solar still with heat sink condenser.

2.1. Studied cases

The experimental work is performed at different condenser materials and designs and at different mediums of the saline water in the basin. For the condenser, four cases are studied: (i) Using glass plate of 3 mm thickness, (ii) using an aluminum plate of 1 mm thickness, (iii) using an aluminum plate covered at its top with two different umbrellas (umbrella 1 and umbrella 2) of 20 cm and 40 cm wide respectively as shown in Fig. 3 and (iv) using an aluminum heat sink. Also, four cases are studied of the saline water medium inside the basin: (i) only saline water in the basin, (ii) Sand saturated with saline water, (iii) 1 kg of black steel fibers of 0.1 mm diameter formed in layers (porous media) saturated with saline water, and (iv) Mixture of the sand and 0.5 kg of black steel fiber layer saturated with saline water. In all studied cases, the depth of the saline water or the saline water with the different mediums in the basin is fixed at 10 mm.

2.2. Measured parameters

During the experimental work, different measurements are performed. All these measurements are carried from the morning 8 AM to afternoon 5 PM, and the measurements are recorded each 30 min. The experimental measurements are performed during the period from 22/06/2016 to 17/07/2016. Seven temperatures are measured and recorded; the temperature of the saline water, the temperature of the humid air region, the surface temperatures of the front, left and right sides of glass, the surface temperature of the condenser, the temperature of the makeup saline water and the temperature of the condensed freshwater. The previous temperatures are measured by using K-type thermocouples, and the output data of the thermocouples are read and recorded by a digital measuring device (7) of eight registering points. The intensity of the solar radiation is measured by using digital pyranometer (sp lite2 silicon pyranometer), and the humidity ratio of the humid air region is measured by humidity meter. The condensed fresh water on the side walls of the solar still is accumulated by using an inclined channel circulating at the bottom of the solar still walls. So, the total condensed water is flown in the flask. The volume of the total accumulated of desalinated water is measured each 30 min. During the experimental work, the change of the environmental conditions surrounding the experimental setup which affects the diffused solar radiation is avoided as possible. Also, a calibration is carried out for the measured data by the thermocouples, and the results data in this paper are presented by taking into consideration the calibration process.

2.3. Error and uncertainty analysis

The experimental error and uncertainty of the measured values are considered in the experimental work. The errors may come from human use, instrumentation, etc. are considered. During the experimental work, we take into consideration all the necessary precautions to minimize these errors. For example, to ensure that the thermocouple

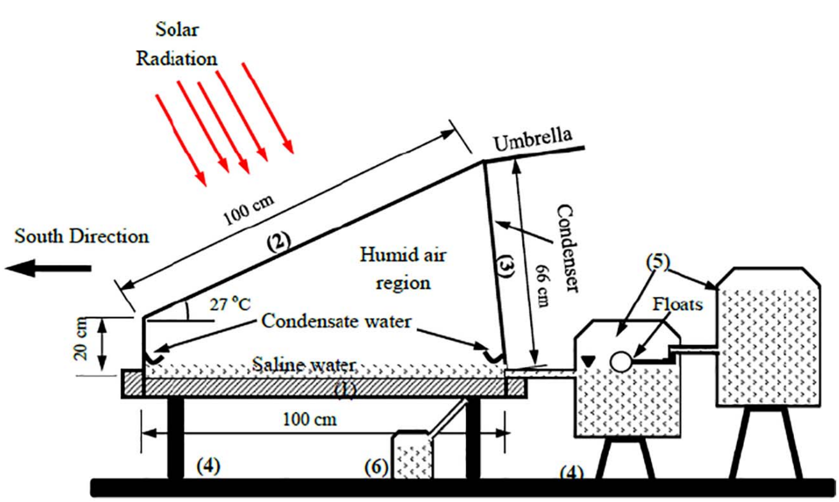

Fig. 3. Layout of the experimental setup.

Table 1
Uncertainty of measuring instruments.

Instrument	Uncertainty
Pyranometer	0.5%
digital measuring device	± 0.1 °C
Graduated balance	± 1 g
Humidity meter	0.1%
Thermocouple	± 0. 4 °C

junction measures the wall (glass, heat sink, and aluminum plate) surface temperature, it is covered with insulating material to avoid the effect of the surrounding temperature of this wall. Also, a calibration for all used thermocouples connected to the measuring instrument is carried out and is considered in the output results. The uncertainty arises from the measuring instruments, and manufacturers' specifications, are shown in Table 1.

3. Results and discussions

This work aims essentially at increasing the productivity of the desalinated water by enhancing the evaporation process of the saline water and improving the condensation process of the evaporated freshwater. The evaporation process can be enhanced by improving the heat transfer process in the basin. The condensation process can be improved by ameliorating the convection heat transfer between the solar still walls and the internal humid air from one side and between the solar still walls and the outside air from the other side. The results of this experimental work are presented for single acting solar still at different condenser types (aluminum heat sink, aluminum plate, and glass) and different saline water mediums (only saline water, and saturated sand with saline water, steel fibers saturated with saline water and saturated sand-steel fibers mixture with saline water). The performance of the all studied cases is referred to the reference case (solar still with glass walls and only saline water in the basin) unless it is stated in the text. By tracking the incident solar radiation on the surfaces of solar still during the time of measurements, it is observed that the solar radiation falls on the front surface during all the reading time of the day with different angles. It falls on the back surface (condenser surface) in the morning until about 10:00 AM and in the afternoon after 2:30 PM until the end of the reading time. It falls on the right glass wall in the morning and on the left glass wall from 2:00 PM until the end of the reading time.

3.1. Solar still temperatures

It is important to study the effect of using condenser types and saline water mediums on the solar still temperatures to well explain and discuss the solar still performance and productivity. Figs. 4 to 10 show the solar intensity and the temperature variations of the saline water, humid air region, front glass, and the condenser surface with the time from 8 AM to 5 PM. Figs. 4, 5, 6, and 7 illustrate theses variations for the heat sink condenser with only saline water, sand, sand-steel fibers mixture, and steel fibers mediums respectively. Fig. 8 illustrates these variations for the glass condenser. Figs. 9 and 10 illustrate theses variations for the aluminum plate condenser without and with an umbrella respectively. The basin medium in Figs. 8 to 10 is only saline water. Figs. 4 to 10 show that the solar intensity and temperature profiles behavior is about the same and the maximum values of these profiles is placed around the noon time. Also, the values of all these temperatures increase from the morning with increasing the solar intensity and reach its maximum value at approximately the same position of the maximum value of the solar intensity. Then, these temperatures decrease with the decrease of the solar intensity. Also, these figures indicate that the temperatures of the humid air region and

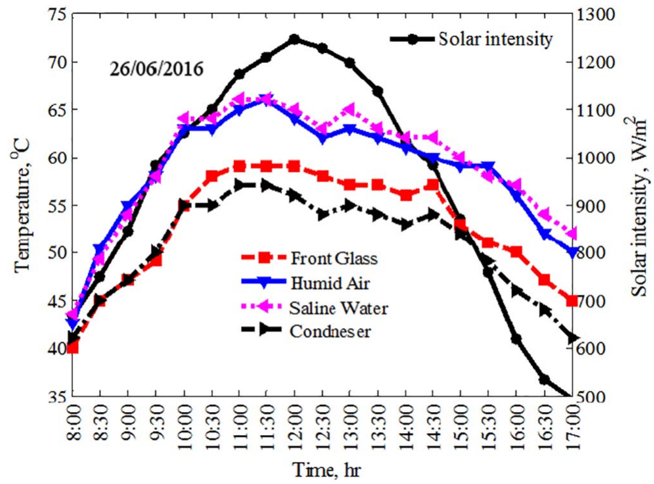

Fig. 4. Solar intensity and the temperatures of the solar still elements for the heat sink condenser with only saline water in the basin.

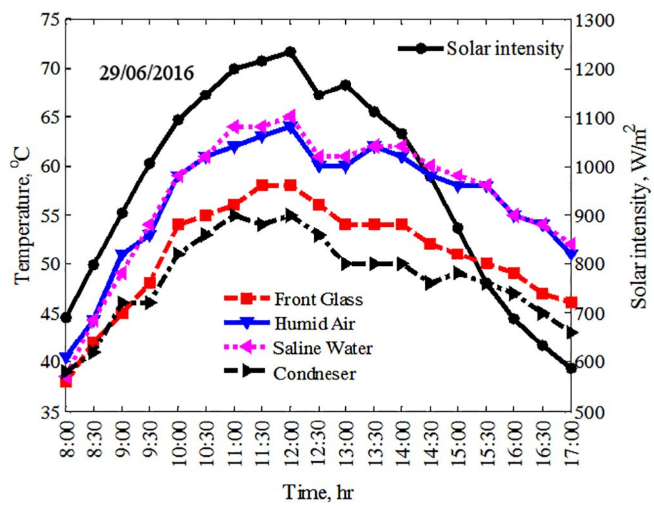

Fig. 5. Solar intensity and the temperatures of the solar still elements for the heat sink condenser with saturated sand in the basin.

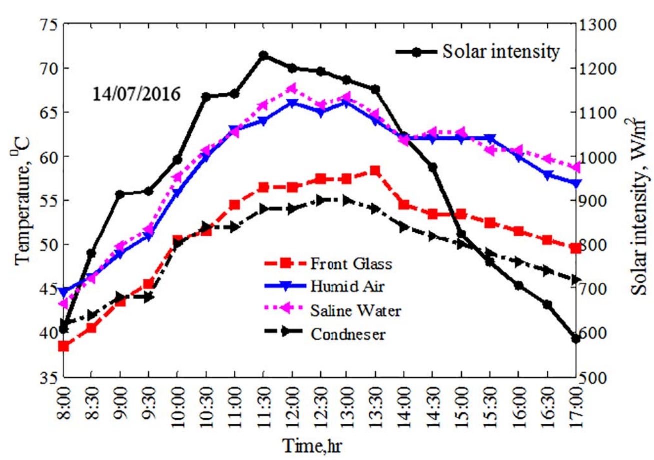

Fig. 6. Solar intensity and the temperatures of the solar still elements for the heat sink condenser and with sand-steel fibers mixture in the basin.

the saline water at all results are greater than the temperatures of the glass and the condenser at most of the measured time. Figs. 4 to 7 show that the temperature of the condenser is smaller than the glass temperature. Also, the difference between the temperatures of the condenser and the front glass from one side and the saline water from

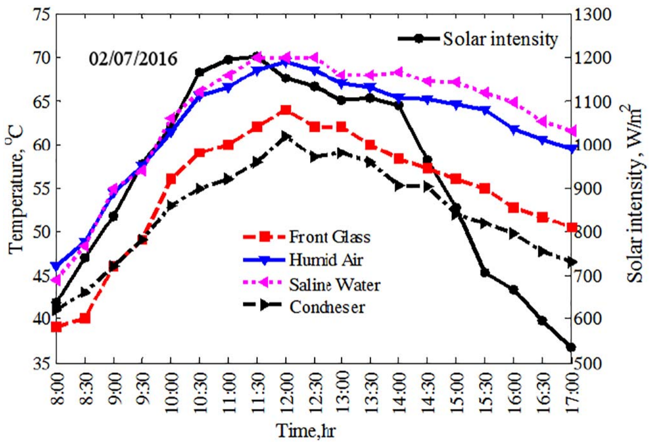

Fig. 7. Solar intensity and the temperatures of the solar still elements for the heat sink condenser with steel fibers in the basin.

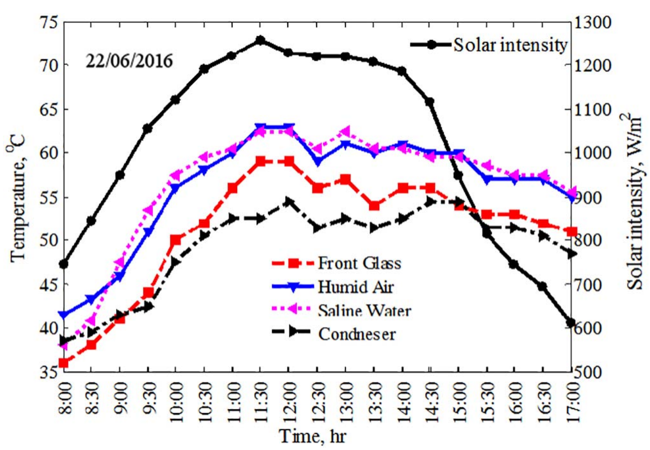

Fig. 8. Solar intensity and the temperatures of the solar still elements for glass condenser with only saline water in the basin.

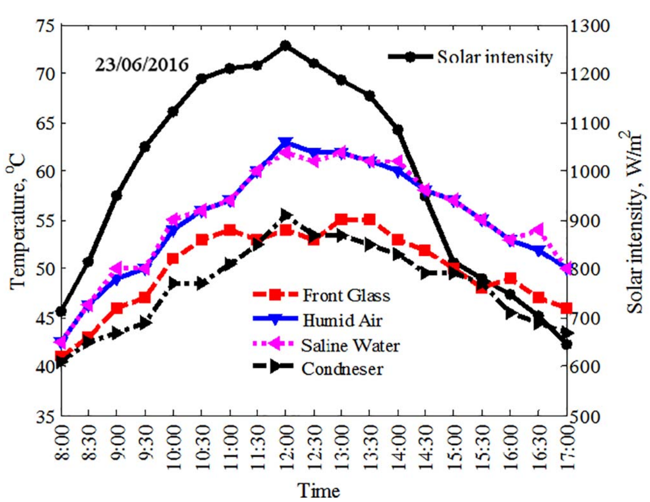

Fig. 9. Solar intensity and the temperatures of the solar still elements for aluminum plate condenser with only saline water in the basin.

the other side increase by using sand or steel fibers in the basin. Figs. 4, 5, 6, 7 show that the maximum temperature difference between the saline water and the condenser is about 9 °C, 11 °C, 13 °C and 17 °C for only saline water, sand, sand plus steel fiber and steel fibers medium respectively. Using steel fibers or sand in the basin enhances the heat transfer process inside the saline water because of the high thermal conductivity of these materials particularly for steel fibers. Also, these

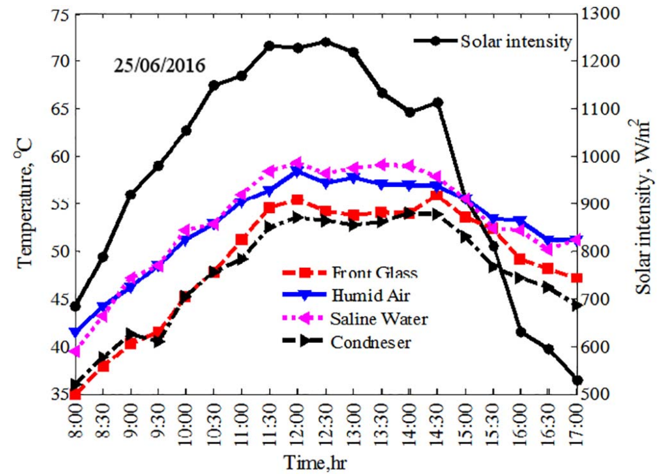

Fig. 10. Solar intensity and the temperatures of the solar still elements for aluminum plate condenser with umbrella 2.

materials increase the absorbed solar intensity because of its high absorptivity particularly the black steel fibers. Moreover, the reflected solar radiation from these materials is small because of the internal reflections of the solar radiation in these materials particularly in case of sand particles. The same previous effects are noticed with using glass and aluminum plate condensers (Figs. 8, 9 and 10). Fig. 8 shows that value of the saline water temperature in case of using glass condenser is lower than this value in case of using heat sink as indicated in Figs. 4 to 7. Figs. 4 to 7 show that the condenser temperature is lower than the glass temperature except in the morning (until about10:00 AM). This is due to that the heat sink temperature takes the time to increase because of the high thermal diffusity of the heat sink material. Also, comparing the results of Figs. 4 to 10, it is noted that the temperature difference between the humid air and the condenser is greater in the case of using heat sink condenser compared with the other cases (glass and aluminum plate condensers). This occurs due to the large value of the heat transfer coefficient between the heat sink and the ambient relative to the other cases, which reduces the heat sink temperature. The advantage of installing an umbrella at the top of the condenser is decreasing the surface temperature of the aluminum plate which increases the heat transfer from the humid air to the aluminum plate and so to the outside. But, using the umbrella decreases the natural convection adjacent the aluminum plate because the umbrella impedes the upward heated air from leaving the condenser surface. This decreases the air velocity and so the outside natural convection. Also, in our climate conditions, there are some of the solar energy falls on the back wall of the solar still in the morning and at afternoon (after 2:00 PM). So, the umbrella prevents a part of the solar energy to fall on the surface of the aluminum plate which decreases the total transmitting solar radiation to the saline as indicated in Fig. 10. Therefore, the reduction of the saline water temperature by using the umbrella signifies that the negative effect of using the umbrella is dominant than its positive effect.

3.2. Hourly productivity

Figs. 11 to 14 show the variation of the hourly productivity of the desalinated water with time at different condenser types and different saline water mediums. Fig. 11 shows the hourly productivity for different condenser types with only saline water in the basin. Figs. 12, 13 and 14 illustrate the hourly productivity for heat sink, glass, and aluminum plate condensers respectively. Figs. 11 to 14 illustrate that the hourly productivity of freshwater increases in the morning with time until approximately the same time of the maximum solar intensity. Fig. 11 illustrates that the solar still with the heat sink

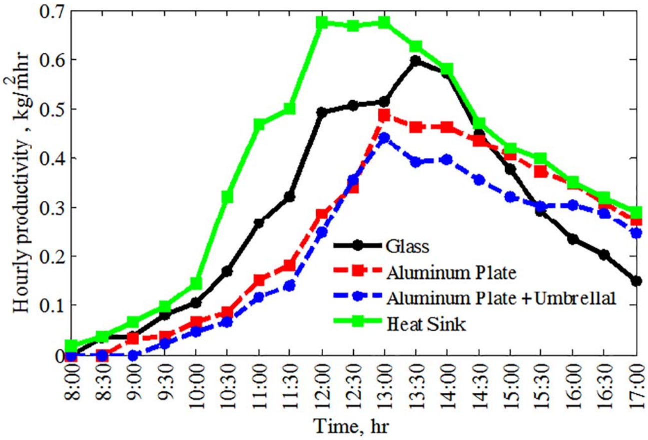

Fig. 11. Hourly productivity of the desalinated water for different condenser types.

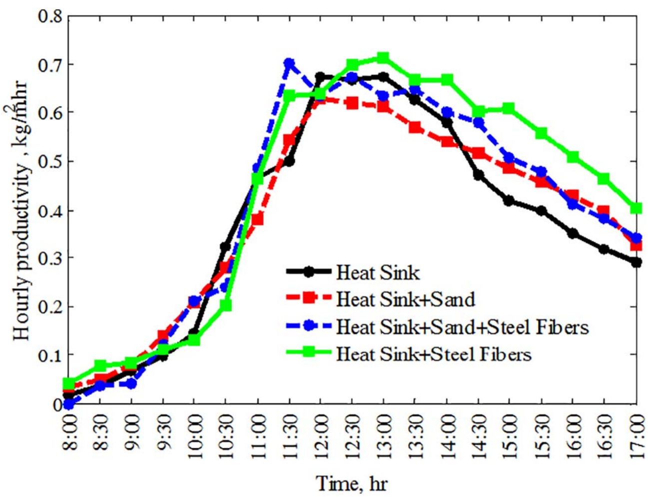

Fig. 12. Hourly productivity of the desalinated water for the heat sink condenser.

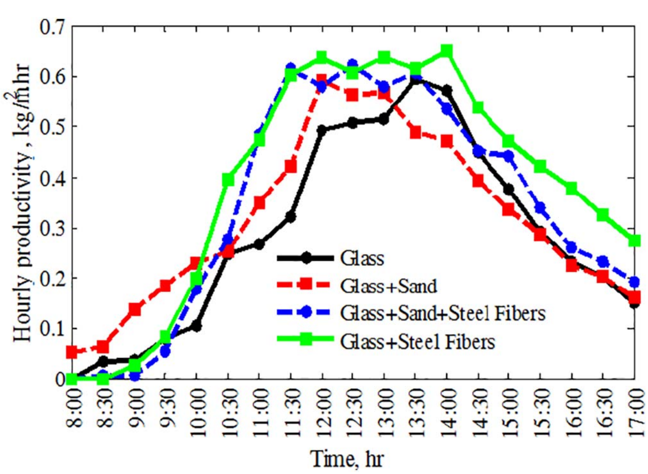

Fig. 13. Hourly productivity for the glass condenser with different basin mediums.

produces the maximum hourly productivity during all the running time. This is a result of the high condensation process due to the high heat transfer coefficient as stated previously. Moreover, Fig. 11 indicates that the solar still of aluminum plate condenser and an umbrella has the minimum hourly productivity of freshwater compared to other cases due to the negative effect of the umbrella as stated previously. Fig. 11 also shows that the hourly productivity of the solar still with the glass condenser decreases largely at afternoon despite the values of the solar intensity are approximately the same for all studied cases (Fig. 4 to 10).

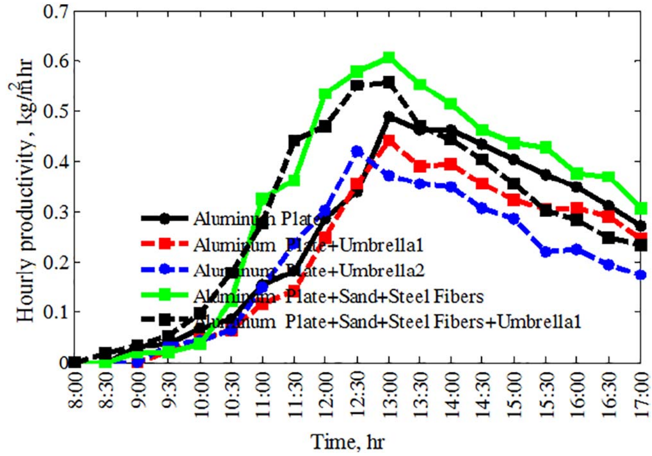

Fig. 14. Hourly productivity for the aluminum plate condenser with different basin mediums.

This is due to the lower temperature difference between the humid air and the condenser relative to the other condensers. This produces a reduction of the condensation of freshwater. Figs. 12 to 14 indicate that at the first two working hours approximately, the productivity of fresh air decreases with increasing the thermal diffusity of the material in the basin (steel fibers, sand, only saline water) due to the absorbed heat in heating these materials. Fig. 12 shows that, in the morning, there is a considerable difference in the productivity between the different studied cases. In the afternoon, the productivity is arranged in ascending order as follows: heat sink, heat sink plus sand, heat sink plus sand-steel fibers mixture and heat sink plus steel fibers. This effect in the afternoon is remarkable in the case of glass condenser (Fig. 13) and aluminum plate condenser (Fig. 14).

3.3. Accumulated productivity and efficiency

Fig. 15 shows the evolution of the accumulated productivity of the desalinated water with time at different condenser types and only saline water in the basin. It is noted that the variation of the accumulated productivity is arranged in descending order as follow; heat sink, glass, aluminum plate and aluminum plate with umbrella though all the reading time. It is also noted that the case of heat sink condenser achieves the greater of the hourly accumulated productivity and the aluminum plate condenser with umbrella achieves the minimum value

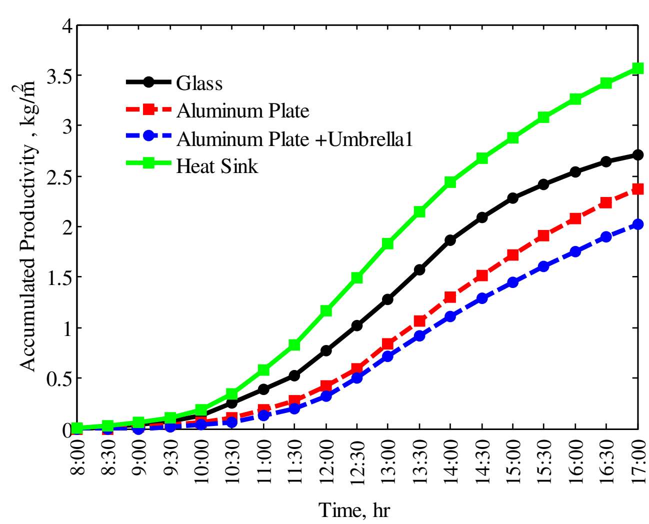

Fig. 15. Accumulated productivity for different condenser types with only saline water in the basin.

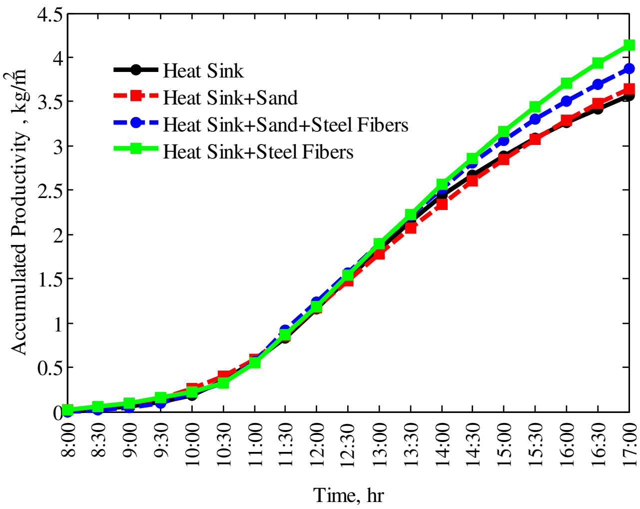

Fig. 16. Accumulated productivity for the heat sink condenser with different mediums in the basin.

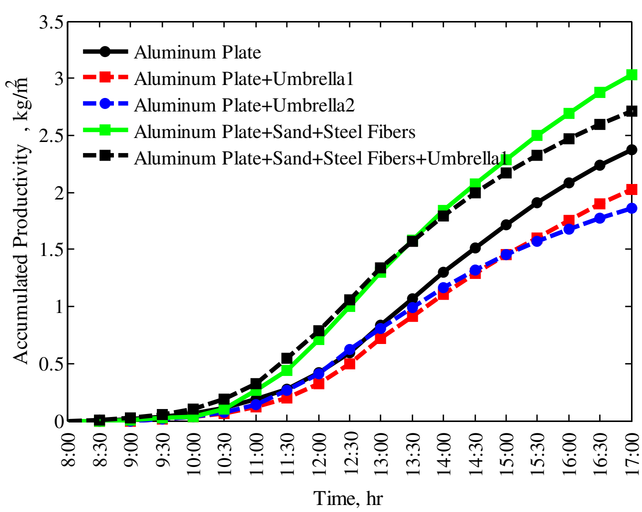

Fig. 17. Accumulated productivity for aluminum plate condenser with different mediums in the basin.

of hourly accumulative production. Fig. 15 also shows that the maximum increase of the maximum accumulative production (at 5 PM) in the case of the heat sink is about 90% compared with aluminum with umbrella 1. Figs. 16 and 17 illustrate the evolution of the accumulated productivity with time at different basin mediums for heat sink and aluminum plate condensers, respectively. Fig. 16 is shown at different mediums in the basin (only saline water, sand, steel fibers and a mixture of sand plus steel fibers). Fig. 17 shows the cases (only saline water medium, a mixture of sand and steel fibers medium, only saline water medium and umbrella 1, only saline water medium and umbrella 2, a mixture of sand plus steel fibers medium and umbrella 1). Figs. 16 and 17 indicate that a considerable influence of the basin medium on the accumulated production is remarked in the case of using aluminum plate condenser. Fig. 16 shows that in the case of heat sink condenser, the medium type in the basin hasn't a great effect on the hourly accumulated productivity until 12:30 PM. After 12:30 PM, the steel fibers medium has the maximum accumulated productivity and only saline water has the minimum accumulated productivity, and the maximum difference between them (at 5.PM) is about 0.58 kg/m^2. Fig. 17 shows that the aluminum plate condenser with the mixture of steel fibers plus sand in the basin has the maximum hourly accumulated productivity compared other cases. Moreover, the negative effect of

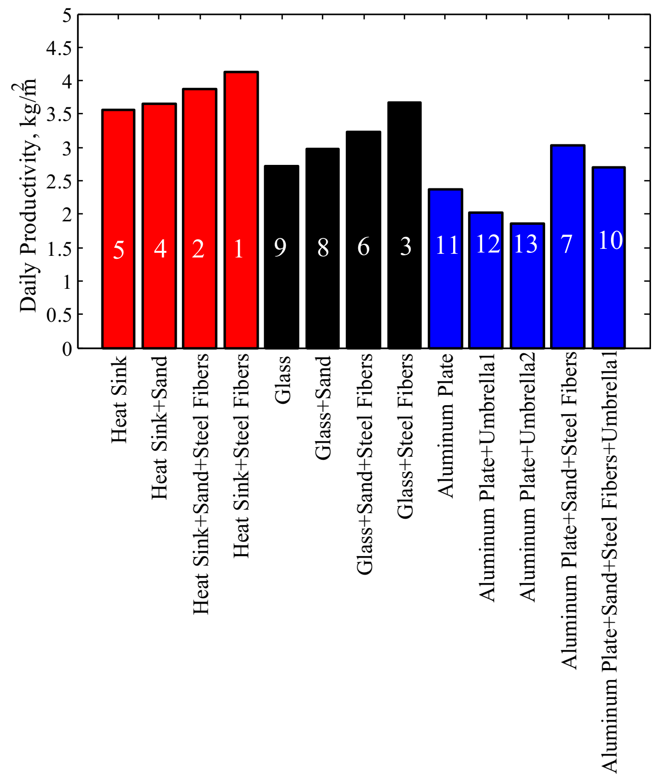

Fig. 18. Daily productivity for different condenser and mediums in the basin.

Table 2
Daily solar still efficiency.

Case	Efficiency %	Case	Efficiency percent
Heat sink + steel fibers	19	Glass + wires	16.4
Heat sink + sand	16.3	Aluminum plate	10.28
Heat sink	16.1	Aluminum plate + umbrella 1	8.90
Heat sink + sand + steel fibers	17.5	Aluminum plate + umbrella 2	8.5
Glass	11.4	Aluminum plate + sand + steel fibers	14.0
Glass + sand	13.82	Aluminum plate + sand + steel fibers + umbrella 1	11.03
Glass + sand + steel fibers	14.59		

using an umbrella for the previous medium inside the basin appears after 2 PM. Fig. 17 also indicates that the maximum increase of the accumulated productivity (at 5.PM) for the different studied cases of aluminum plate condenser is about 62%.

Fig. 18 summarizes the daily productivity of freshwater per square meter for all the studied cases. Fig. 18 illustrates that for different condenser types, using heat sink condenser provides the greatest value of the daily productivity and using an aluminum plate a condenser with umbrella 2 provides the lowest. Moreover, using steel fibers or sand in the basin increases the total productivity of freshwater relative to the only saline water case. For only saline water in the basin, the case of heat sink condenser achieves the daily productivity of freshwater with a value of 3.56 kg/m^2 of a percentage increase of 31%. Also, the aluminum plate condenser with umbrella achieves the minimum value of daily productivity with a value of 1.87 kg/m^2 of a percentage decrease of 31%. For heat sink condenser, the daily productivity increases from 3.56 kg/m^2 with only saline water only to 4.14 kg/m^2 with black steel fibers and the corresponding percentages of increase of total productivity are 31% and 52% respectively. Using of aluminum

Table 3
Cost analysis of the solar still.

	Conventional solar still (glass)	Aluminum plate condenser	Aluminum plate + umbrella	Heat sink condenser	High performance
Cost $/L	0.0147[a]	0.0171[a]	0.0196[a]	0.0125[a]	
	0.015 [35]				
	0.09 [26]				0.06 [26]
	0.035 [31]				0.13 [31]
Daily efficiency	11.4[a]	10.28[a]	8.9[a]	16.1[a]	
	8.6 [36]				14.1 [31]

[a] Present work.

plate condenser with only saline water in the basin decreases the percentage of the total daily productivity by about 13% as shown in Fig. 18. Using umbrella 1 in the previous case decreases the total productivity to 2.02 kg/m^2 with a percentage decrease of 26%. Also, increasing the umbrella width has a negative effect on the daily productivity where it decreases to 1.87 kg/m^2 with a percentage decrease of 31%. For all condenser cases, using steel fibers in the basin achieves the greatest daily productivity, followed by sand-steel fibers mixture. Using an aluminum plate condenser with a wide umbrella (umbrella 2) achieves the lowest daily productivity. Table 2 gives the daily efficiency of the solar still for different cases, which is calculated according to the equation [22,32]:

$$\text{Solar still efficiency } (\eta) = \frac{m \times h_{fg}}{G_t \times A}$$

m is the total mass of desalinated water collected during the working time in kg, h_{fg} is the latent heat of evaporation in J/kg and is taken as an average value of 2200×10^3 J/kg, G_t is the total radiated energy incident on the solar still in J/m^2 during the working time of the solar still, A is the projection area of the solar still in m^2. Table 2 shows that solar still with heat sink and steel fibers has the maximum efficiency of 19% and aluminum plate with umbrella 2 has the minimum efficiency of 8.5%. Table 2 also indicates that the solar still efficiency has the same order of the total mass production shown in Fig. 18. By comparing the results of [31] where the maximum efficiency is about 9% and the present results, it is found that our solar still efficiency is higher than the literature.

3.4. Cost analysis

The cost analysis of the solar still performance is performed in this work. The total fixed cost of the solar still including the glass frame, the insulation, the basin, the holder, the tanks and the auxiliaries are calculated for each case. The calculation procedure can be summarized as follows [26,34–35]:

The Capital Recovery Factor (CRF) is given by [34]

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (1)$$

where r is annual rate of interest which is 10% [33] and n is the number of the useful years for which the solar still can perform which is assumed 10 years. The first annual cost (FAC) is given by [26,33–34]:

$$FAC = CRF \times P \quad (2)$$

where, P is the initial const. The sinking fund factor (SFF) for a system is given by [33,34]

$$SSF = \frac{r}{(1+r)^n - 1} \quad (3)$$

The salvage value (s) is assumed as 50% of first annual cost [33]. The annual salvage value (*ASV*) is given by [34]:

$$ASV = SSF \times S \quad (4)$$

The annual maintenance cost (AMC) is assumed 15% of the first annual cost [33].

$$\text{Annual cost (AC)} = \text{First annual cost} + \text{Annual maintenance cost} - \text{Annual salvage value}$$

Average productivity peryear/m^2 =average daily production/m^2*365.

Table 3 presents the results of the cost analysis model for the different present solar still. It also gives a comparison between the present solar still cost and efficiency and the literature. Table 3 shows that the solar still with heat sink is mostly economical than others where its cost is the minimum compared with glass and aluminum plate solar still. This is due to the cost of heat sink is not expensive compared to glass and it doesn't need maintenance as the glass and it has higher fresh water productivity. Table 3 also indicates that the cost and efficiency of the present solar still is less than the indicated references solar stills.

4. Conclusion

The influence of the condenser type and saline water medium in the basin of the solar still on its performance is performed experimentally. Four types of the condensers are considered: glass plate, aluminum plate, aluminum heat sink with pin fins and aluminum plate covered with an umbrella. Also, four types of saline water mediums in the basin are considered: only saline water, saturated sand with saline water, Layers of black steel fibers in the basin and a mixture of sand and black steel fibers saturated with saline water. The experiments are carried out from 8 AM to 5 PM. Results show that using sand or steel fibers in the basin and heat sink condenser increases the saline water temperature relative to the reference case. Contrarily, using an aluminum plate condenser decreases the saline water and humid air temperatures relative to the reference case. Also, using the saturated sand increases the daily production relative to the using of only saline water in all condenser cases. Mixing the sand with steel fibers increases the daily productivity relative to the using of sand only for all condenser cases. Also, using a glass condenser with black steel fibers increases the percentage of the daily productivity to about 35%. Using the heat sink condenser increases the production of the daily productivity by about 31%. Using an alumnium plate condenser decreases the percentage of the daily productivity of pure water by about 13%. In the case of aluminum plate condenser and only saline water in the basin, using an umbrella of 40 cm wide decreases the daily productivity by about 21%. For the studied cases, arranging the daily production in descending order is as follows: heat sink plus steel fibers, heat sink, glass plus steel fibers, heat sink plus sand, heat sink, glass plus sand, glass, aluminum plate, aluminum plate plus umbrella.

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