Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2019.24492

165 (2019) 24–34
October

An experimental work on the performance of solar still incorporating with wind turbine and thermal energy storage unit

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Received 20 January 2019; Accepted 2 June 2019

ABSTRACT

The performance of single slope solar still incorporating with a wind turbine by a new coupling technique is investigated experimentally. The coupling technique is based on transferring the output power from the turbine directly to the brackish water in the still basin by utilizing an electrical heater embedded in the still basin. The advantage of this technique is that the turbine power is transmitted directly to the salty water in the basin without any intermediate which affects negatively on the transmitting performance. Moreover, the wind turbine doesn't require extra land than the land occupied by the still where it can be built on the same area of the stills. The system performance (solar still plus turbine) is also studied in case of utilizing thermal energy storage unit of phase change material (PCM) coupled with the still's basin base. Moreover, it is studied in case of using black steel wool fibers (BSWF) in the basin. Four cases are studied to determine the influence of wind power on the performance of the solar still; (i) conventional solar still (CSS) (ii) CSS with wind turbine only, (iii) CSS with wind turbine and BSWF saturated with salty water in the basin, and (iv) CSS with a wind turbine and PCM. The performance of the different cases is experimentally evaluated and compared to each other at the same climate conditions of Borg El-Arab City, Alexandria, Egypt (Longitude/Latitude: E 029°42′/N 30°55′). The findings illustrate that using the turbine increases the still temperatures and yield. BSWF are more effective than PCM in case of CSS but in case of using wind turbine with CSS, PCM is more effective than BSWF. Coupling the wind turbine with CSS rises its yield by around 19.8%, 30.9%, and 20.1% in case of CSS, still with BSWF, and still with PCM, respectively.

Keywords: Solar still; Wind turbine; Phase change material; Black Steel wool fibers; Performance; Yield

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1. Introduction

Freshwater is one of the greatest essential necessities for human kind to survive. Nevertheless, water covers approximately 71% of the earth surface area, about 97% of total water resources are brackish water, and only 3% represents drinking water [1]. Furthermore, around 70% of the available earth freshwater is available as ice covering the mountains regions and the rest is appropriated for agriculture, industrial and drinking necessities [2]. The availability of drinking water diminishes from day to day, while the request for healthy drinking freshwater augments continuously which results in high pressure on the available natural resources. Lately, freshwater shortage has become a profound worldwide crisis essentially in arid and secluded areas with the recent energy crisis, climate change, and global warming. Desalination is known as a worthy method to get transportable freshwater [3]. Water distillation is one of many procedures that can be applied by using any source of heat like solar energy. In

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solar desalination, water is evaporated by utilizing the sun energy afterward the vapor condenses as freshwater where salts and impurities are removed in this technique [4]. Solar still is one of the desalination techniques of yielding freshwater by utilizing solar energy. In this techniques, the evaporation of the brackish water in the still basin is carried out by the incident solar radiation. After that, the vaporized water condenses on the still glass walls. The stills are classified into active and passive still. In passive still, the evaporation of the brackish water is performed by the solar energy without any axillaries connected to the still. Inactive stills, an axillary is connected to the still like fans, pumps, solar collectors, photovoltaics, or any other device or available energy source which can enhance the still performance [5]. Eltawil and Zhengming [6] utilized a small wind turbine to operate a rotating shaft with an impeller to distribute the humid air in the main solar still which supplies water to an inclined solar still. They discovered that the freshwater yield was increased because of the enhancing of the water evaporation. The system achieved well when the wind speed value is more than 2.0 m/s, and it didn't influence sensibly on the still temperatures. Yari et al. [7] studied a CSS coupled with semitransparent photovoltaic (SPV) and evacuated tube collector in natural mode. They found that a maximum water yield of 4.77 $kg/m^2 \cdot d$ was gotten in case of basin depth 0.07 m and number of tubes 30. The still performance with solar fan and preheating solar collector was performed by Bani-Hani et al. [8]. The fan was powered by a small solar cell and was utilized to augment the heat transfer rate on the glass cover surface to rise the condensation rate of the evaporated water. It was remarked that the enhanced still yields 3%, 10%, and 50% more desalinated freshwater than a conventional solar still (CSS) coupled with cooling fan, oil preheating, and both cooling fan and oil preheating systems, respectively. Kabeel et al. [9] compared the performance of two systems: CSS and other CSS incorporated with a latent heat thermal energy storage medium and a parabolic solar concentrator. The findings indicated that the yield of the CSS with PCM and parabolic concentrator was higher in summer with an amount of 55–65% and in winter with an amount of 35–45% compared to the CSS. A comparison of three tubular still systems performance was performed by Elashmawy [10]. The first one is a tubular solar still (TSS) with a rectangular trough filled with black clothes and saturated by raw water. The second is a TSS with a half-cylindrical trough without clothing and the third is a TSS connected to a parabolic concentrator solar tracking system. The findings stated that the obtained productions for 0.059 m^2 were 3.6, 3.53 and 4.71 L/m^2d and the daily efficiencies were 36.5%, 30.5% and 28.5% for the first, second, and third system, respectively. Manokar et al. [11] studied the performance of solar still coupled with PV panel. They found that the solar still yield for inclined PV with the solar still and bottom and sidewalls are insulated, solar still with PV and sidewall insulated and PV with the still without insulation is 7.3, 4.4 and 3.7 kg, respectively. The impact of utilizing wind turbine and fan on the achievement of CSS was performed by Omara et al. [12]. The water fan gained its power from the wind turbine trough a mechanical system (gearboxes, bearings, shafts, brake control) and it was used to provide a movement for the brackish water in the still. The results showed that the water fan speed must be controlled to have a positive impact on the procedure and the water depth must be sufficient to cover the fan. Besides, the still yield was raised by approximately 17% at 30 mm water depth and fan speed 30 rpm. Fathy et al. [1] and Hassan et al. [13] studied the performance of double slope solar still for three various systems (CSS, CSS with fixed parabolic trough collector (PTC) and CSS with tracked PTC). They discovered that the production of the still with tracked PTC was higher than that of the fixed PTC by around 28.1% and for the CSS by nearly 142.3%. However, the daily efficiency of the CSS, solar still with fixed PTC and solar still with tracked PTC was 36.87, 23.26 and 29.81%, respectively. The performance of a stepped solar still connected to photovoltaic thermal (PVT) water collector system was analyzed numerically and experimentally by Naroei et al. [14]. They released that connecting the PVT water collector system to the still increased its energy efficiency by 100% and its freshwater production by 20%.

Many works have been performed on using phase change materials (PCM) to raise the yield of the still by storing the heat loss from the still inside the PCM during the daytime and reused it during the nighttime to evaporate the brackish water. Ansari et al. [15] Longitude: 4°20′W stated that the selection of the PCM depends on the brackish water temperature and the climate conditions of the experimental places. Dashtban and Tabrizi [16] tried to enhance the performance of solar still coupled with PCM storage unit below the basin. Their findings demonstrated that the total freshwater productivity for CSS was augmented from 5.1 to 6.7 $kg/m^2 \cdot d$ because of utilizing the PCM unit. The effect of using solar concentrator and hemispherical solar still and PCM unit was presented experimentally by Arunkumar et al. [17]. They discovered that the modified system augmented the freshwater yield by about 26% with respect to CSS. The effect of using PCM with concentric TSS was examined experimentally by Arunkumar and Kabeel [18]. Their outcomes revealed that the daily freshwater productivity was augmented by 9.4% due to utilizing the PCM. Yousef and Hassan [22] presented an experimental work on the impact of solar still coupled with PCM with and without imbedded hollow cylindrical fins inside the PCM. Their findings revealed that the still with PCM and fins had a daily productivity 17% and 7% greater than CSS and CSS with PCM only, respectively.

In addition, some researchers investigated the still performance in case of using porous medium or wicking material inside the basin of the still to enhance the heat transfer through salty water in the basin and hence augment the water evaporation rate. The influence of utilizing thermocol section covered by jute clothes inside the still basin on its yield was performed by Srivastava and Agrawal [19]. Their findings indicated that the still production was improved by around 6.8% compared to the CSS. The influence of using black cloth submerged in the brackish water of a corrugated basin was examined by Matrawy et al. [20]. They stated that the modified still has around 34% increasing in its freshwater production with respect to the CSS. Omara et al. [21] studied experimentally the performance of corrugated still and CSS at various brackish water depths. They used double layer wick material and reflectors. Results of the work indicated that the yields of the corrugated one with wick and reflectors are about 145.5% higher than the CSS at water depth 10 mm, and its daily efficiency is greater than the CSS by 26%. The solar still performance with sand and steel fibers as a porous medium in the still basin was examined by Hassan and Abo-Elfadl [4]. Their work stated that the total daily yields of CSS, CSS with sand, CSS with a mixture of sand and steel fibers, and CSS with only steel fibers are 2.715, 2.975, 3.236, and 3.678 L/m^2·d, respectively.

Egypt has appropriate wind regimes in most of all regions thanks to its promising topography [23]. Furthermore, Egypt suffers from freshwater leakage, despite it locates on a long coastline rich of brackish water and high solar energy all over the year. These conditions make Egypt a promising country for utilizing solar desalination techniques and at the same time profiting from its available wind speeds. In previous work, researchers tried to augment the input energy to the solar still to increase the evaporated water by using an axillary system such as solar collector, photovoltaic system, preheating solar collector, rotating shafts inside basin, etc. Even though all these methods enhance the evaporation rate from the still, it requires an external area to collect the additional required solar energy. Additionally, these methods decrease the system efficiency due to the multiple efficiencies of the different components and transitions of the intervention system. So, in this paper, a new technique is utilized to enhance the performance of the solar still and profit of the available variable wind speed. The technique is based on incorporating the wind turbine with the solar still where the turbine power is transmitted directly to the brackish water through an electrical heater implanted in the salty water in the still basin. The advantage of this technique is that the wind power is transmitted directly to the salty water without intervention like using shaft or pump rotating by wind turbine [6,12]. Then it has higher efficiency compared to previous methods because it doesn't suffer from multiple efficiencies as previous methods. Additionally, the direct turbine power transferred to the brackish water raises the water temperature which is reflected positively on the evaporation process of the water especially during the low solar energy in winter times. Moreover, this system is working at low and variant wind velocity which can't be used in another application. Furthermore, this system represents a reusing of the space used by the solar still where the wind turbines farm can be built directly on a high level at the same land area occupied by the solar stills planet. Due to the increase of the inlet energy to the salty water because of using the turbine power, the modified system is studied for two cases. Firstly, using phase PCM to store the heat loss from the basin base during the daytime to reuse it during the nighttime. So, the system performance (solar still plus wind turbine) is studied in case of using thermal energy storage unit of PCM coupled with the still basin. Secondly, porous material (black steel wool fibers, BSWF) is utilized in the basin to augment the evaporation of the hot brackish water. Hence, the impact of coupling the wind turbine on the performance of the still is studied for various case; (i) CSS, (ii) CSS with wind turbine, (iii) CSS with wind turbine and BSWF saturated with water in the basin, and (v) CSS with wind turbine and PCM unit. This study is carried out experimentally under the same climate conditions of Borg El-Arab City, Alexandria, Egypt (Longitude/Latitude: E 29°42′/N 30°55′).

2. Experimental work

To perform the experimental study of the performance of the solar still combined with the wind turbine, two identical single slope solar stills are constructed and installed on the roof of energy resources engineering department laboratory as shown in Fig. 1. One solar still is considered the reference still (CSS). The other still is supplied with a copper heater insulated electrically with a material of high thermal conductivity and it is inserted inside the still basin and joined to the wind turbine shown in Fig. 2. The electrical heater has an electrical resistance of 0.6 Ω. The out-

Fig. 1. Front view of the two solar stills.

Fig. 2. Photo of the wind turbine utilized with the solar still.

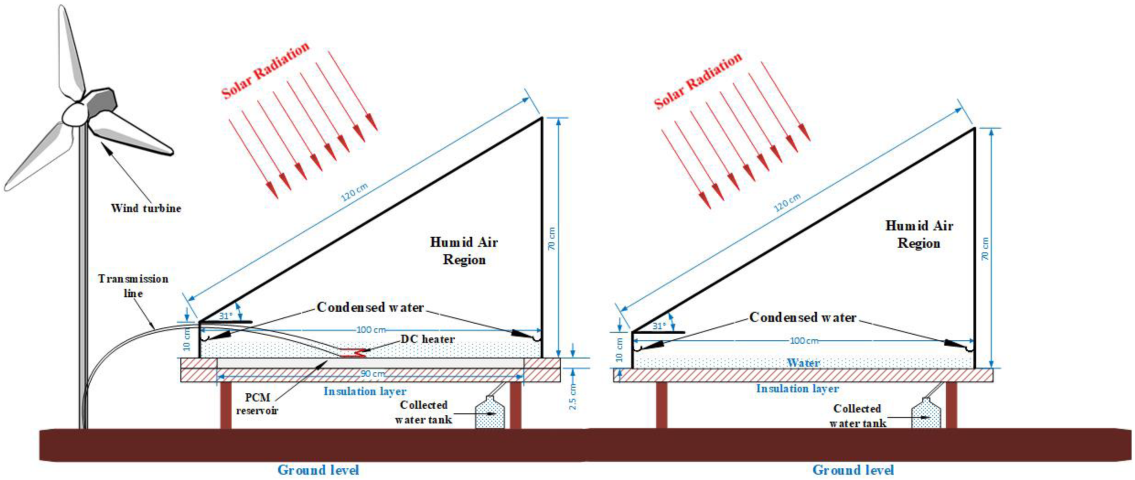

Fig. 3. Layout of the experimental setup.

put power from the turbine is transmitted directly to the copper heater inside the basin by a copper cable connecting between the turbine and the heater in the basin. A layout of the experimental setup is indicated in Fig. 3 where the experimental work is carried out in Borg El-Arab City, Alexandria, Egypt (Longitude/Latitude: E029º42´/N30º55´). This experimental work was carried out during the period between 16th of April 2018 to 30th of April 2018 on the roof of the Energy Resources Engineering building, E-JUST University, Borg El-Arab, Egypt.

Each solar still is fabricated from 4 mm glass walls on each side. The front glass has dimensions of 120×100 cm and facing south with an angle of 31° with the horizontal which is the same latitude angle of Borg El-Arab city. While, the back glass (condenser) is a vertical glass with dimensions of 70×100 cm. The still basin is fabricated from 2 mm thick galvanized steel sheet with dimensions of 100×100×5 cm which is painted with black paint to augment its absorptivity and it is well insulated to diminish the heat losses from the still. The utilized solar stills are supported by stands fabricated from steel as illustrated in Fig. 1. In case of considering the PCM, the solar still is equipped with an extra basin for the PCM attached behind the essential basin of the still. Paraffin wax with melting temperature of 56°C is used as a thermal storage material. The properties of the used Paraffin wax material are tabulated in Table 1. The capacity of the used PCM reservoir is 15 kg of paraffin wax when it is filled totally with the PCM. The bottom wall of the PCM reservoir is made from a galvanized iron sheet of 90×90 cm. The upper wall of the PCM reservoir is the still absorber plate and the side walls of the PCM reservoir is well insulated from the ambient. In all cases, the bottom of the stills is well insulated from the surrounding except in case of using PCM reservoir. Two small channels are soldered through the inner sides of the still with 5° inclination angle downward to gather the condensed freshwater. The collected water from the channel is gathered in a bottle as shown in Fig. 1 and then it is estimated by utilizing a calibrated flask. The used wind turbine illustrated in Fig. 2 is of mark Zephyr Z-501 small-scale Wind Turbine (WT). The specifications of the used Zephyr Z-501 wind turbine are listed in Table 2.

Table 1
Paraffin wax properties [24]

Properties	Values
Melting point temperature	56°C
Thermal conductivity	0.24 W/m °C
Liquid/solid heat capacity	2.51/2.95 kJ/kg°C
Liquid/solid density	760/818 kg/m^3
Latent heat	226 kJ/kg

Table 2
Principal data of Zephyr Z-501 Wind Turbine [25]

Parameter	Value
Wind turbine rotor diameter	1170 mm
No. of blades	3
Start of power generation (cut-in) wind speed	2.5 m/s
Cut-in rotational speed	500 rpm
Rated output speed	1700 rpm
Rated output power (rated wind speed 12.5 m/s at the time)	400 W
Maximum output power	450 W
Cut-off speed	14 m/s
Rated output voltage	12 V

2.1. Studied cases and methodology

Different solar still systems are examined and compared at the same conditions to determine the impact of wind turbine power on the performance of solar still. To decrease the impact of the ambient conditions and to study the effect of coupling the wind turbine on the different solar still system performance (aim of this work), we compare each case of CSS with the wind turbine with a reference case. So, two solar stills are constructed as stated before, one solar still system with the wind turbine and the other system without the wind turbine and they work and measure at the same day to consider the impact of wind turbine on the system. These systems are CSS, CSS with a wind turbine, CSS with BSWF, CSS with BSWF and wind turbine, CSS with PCM, and CSS with PCM and wind turbine. For all cases, the whole experimental setup is assembled and oriented to the south during all the experiments to receive the maximum solar radiation. At the beginning of the measurement and for all measurement's cases, the brackish water is put in each still basin with an initial water depth of 1.3 cm. Before caring out the experimental measurements for the modified cases, one day measurements are performed on the two stills without any modification to guarantee that they have the same performance. The first measurements are carried out at the same time between the CSS and the solar still with the wind turbine. The second measurement is carried out for one solar still with BSWF in the basin and the second still with the same amount of BSWF in the basin and coupled with the wind turbine. For the third measurement case, a CSS with PCM is compared with the second solar still with PCM and wind turbine to verify the effect of wind turbine on the system performance with the PCM. In this case, 15 kg of paraffin wax with the properties mentioned in Table1 is put in a reservoir below and contacted the basin liner for both solar stills. The studied cases for the two solar stills at the corresponding time of reading are stated in Table 3.

2.2. Measured parameters

During the experimental work, different measurements are performed. All these measurements are achieved during the whole day from the morning 1 AM to midnight of the second day 12 AM (24 h), and the measurements are recorded each 1 h. The experimental measurements are carried out during the period from 16/04/2018 to 30/04/2018. The temperatures of the absorber plate, humid air region, salty water, inside and outside surfaces of the front glass, back glass (condenser), and surrounding temperature are measured and registered for each still. For the PCM case, five temperatures are measured and registered in the middle and four corners of the PCM unit. The previous temperatures are measured by using K-type thermocouples, and the output data of the thermocouples are read and recorded by a data logger device (Omega 320 datalogger) connected to a laptop for saving the measured data. The intensity of the solar radiation is measured by using digital pyranometer (li-core 300 pyranometer), and the wind velocity is measured by a fan meter. The wind power reaches the electric heater is calculated from the measured value of the voltage by using a voltmeter and the resistance of the electric heater by using ohm-meter. The condensed freshwater 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 flows into the flask. The volume of the total accumulated of desalinated water is measured each one hour. 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, and the results data in this paper are presented by taking into consideration the calibration processes.

Table 3
Studied cases with reading date

Measurements day	First still	Second still
16/04/2018	CSS	CSS and wind turbine
18/04/2015	CSS with BSWF	CSS with BSWF and wind turbine
30/04/2018	CSS with PCM	CSS with wind turbine and PCM

2.3. Error and uncertainty

In this experimental study, the uncertainty and the experimental errors of the measured values and the measured devices were considered. Furthermore, during the experimental work, all the essential precautions were considered to minimalize the results errors. As an example, to assure that the thermocouples measure well the still walls (glass, absorber plate, etc.) surface temperatures, the thermocouples side facing the surrounding was covered with an insulating material to elude the impact of the surrounding conditions. Moreover, a calibration for all measuring thermocouples and wind velocity sensor with the measuring devices is executed and considered in the results. Table 4 illustrates the uncertainties coming from the manufacturers' specifications and the used devices.

3. Results and discussions

This work aims mainly at augmenting the yield of the desalinated water by enhancing the evaporation of the salty water. The evaporation enhancement is performed by augumenting the input energy to the salty water by using the wind turbine and improving also the heat transfer process. The performance of the still with the wind turbine is performed in case of coupling thermal storage material (PCM) below the basin liner. Moreover, its performance with the wind turbine is carried out in case of utilizing BSWF in the basin. The role of the BSWF in the basin is to augment the heat transfer in the basin and hence increases the evaporation process especially due to the additional energy from the wind turbine. The performance of the all studied cases is compared to each other's. All measurements are recorded within 24 h from 1 AM to the midnight 12 AM to consider the wind turbine which works for 24 h.

Table 4
Uncertainty of the measuring devices

Device	Uncertainty
li-core 300 pyranometer	0.5%
Omega 320 data-logger	± 0.1%
Thermocouple	± 0.4°C
Fan meter	± 0.1 m/s
Flask to measure water volume	5 ml
Measuring volt	0.1 V
Measuring resistance	0.1 Ω

3.1. Solar still temperatures

It is important to study the impact of the wind turbine, salty water mediums and PCM on the solar still temperatures to explain well the solar still yield and performance. Figs. 4–9 show the variation of the solar intensity, wind power and temperatures of the saline water, humid air region, front glass, back glass, PCM and the ambient with time. Figs. 4 and 5 illustrate these variations for CSS and the second still coupled with the wind turbine respectively. Figs. 6 and 7 illustrate these variations for CSS with BSWF in the basin and the other solar still connected to the wind turbine and has also the same BSWF in the basin respectively. Figs. 8 and 9 illustrate these variations for the CSS with PCM and the other still combined with wind turbine and has PCM respectively. Figs. 4–9 demonstrate that the solar intensity increases with time until it reaches the maximum intensity at beneath 12 PM, and then it decreases with time. They also show that the end of solar intensity is at about 19:00 PM and its maximum value is beneath noon time. The results findings demonstrate that the temperature profiles have approximately the same trend of the solar intensity where they augment gradually until about 1 PM and then they decrease with time until the end of readings. Furthermore, these figures indicate that the temperatures of the humid air region and the saline water at all results are greater than the temperatures of front glass and back glass (condenser) at most of the measured time. Moreover, these results illustrate that the humid air temperature has

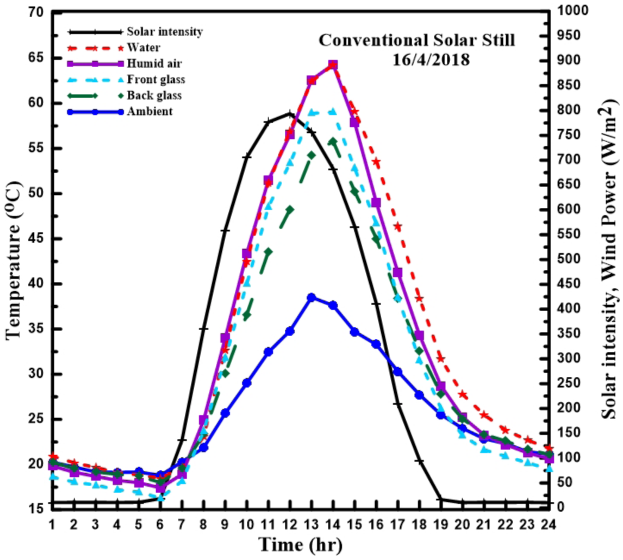

Fig. 4. Variation of the temperatures and solar intensity with time for CSS.

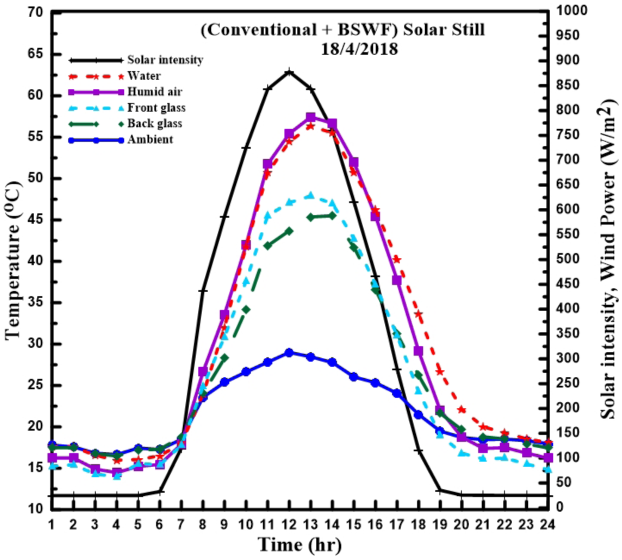

Fig. 6. Evolution of the temperatures and solar intensity with time for CSS with BSWF.

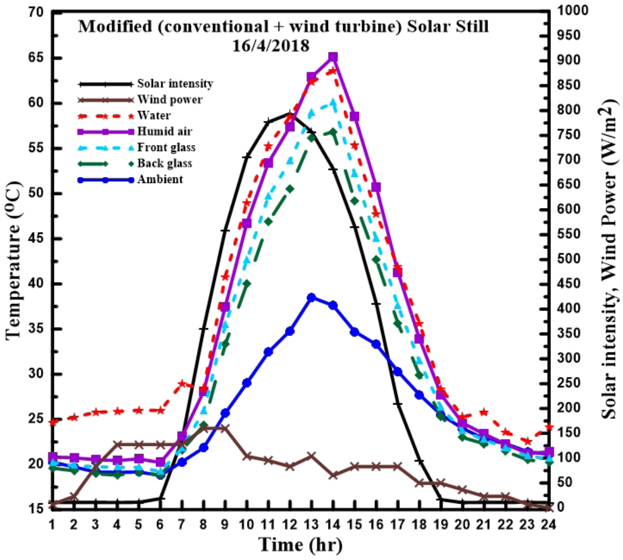

Fig. 5. Variation of the temperatures, turbine power and solar intensity with time for CSS with wind turbine.

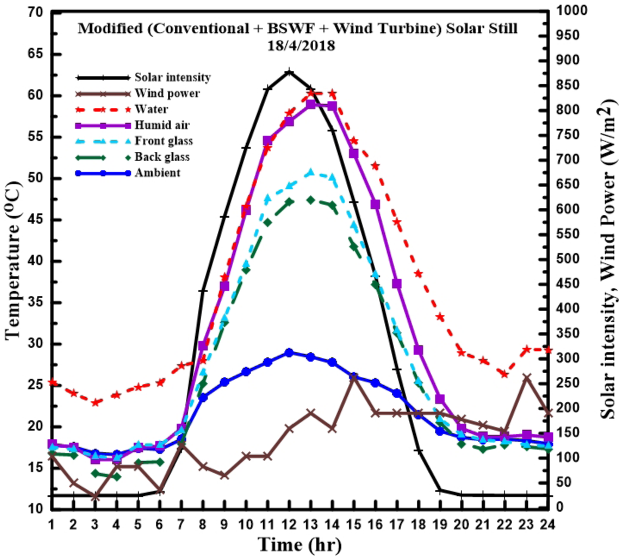

Fig. 7. Evolution of the temperatures, turbine power and solar intensity with time for CSS with wind turbine and BSWF.

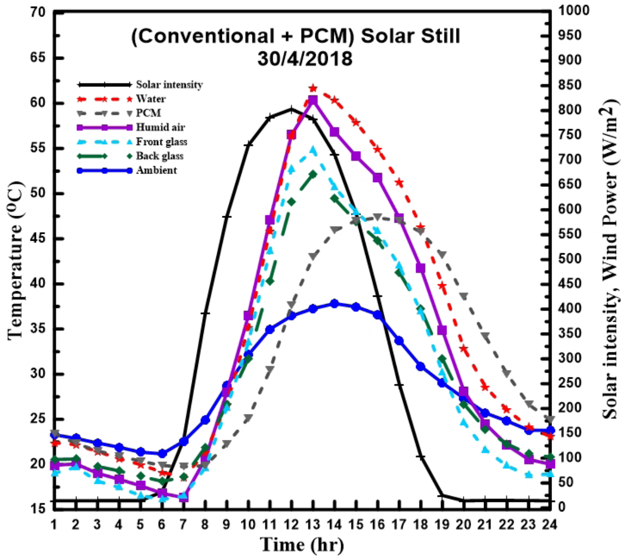

Fig. 8. Evolution of the temperatures and solar intensity with time for CSS with PCM.

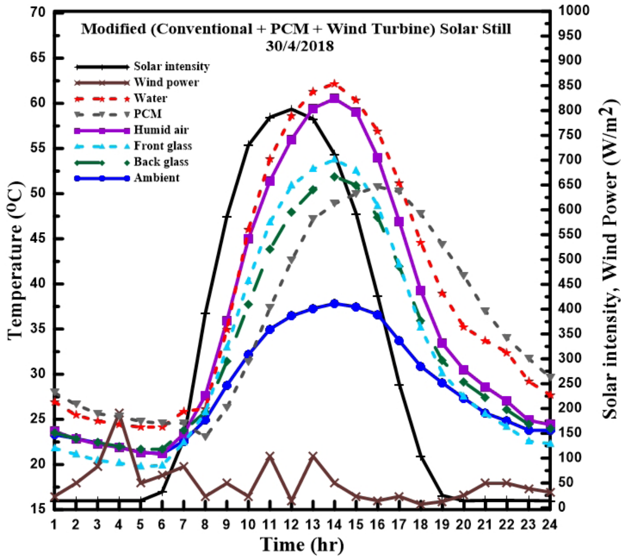

Fig. 9. Variation of the temperatures, turbine power and solar intensity with time for CSS with wind turbine and PCM.

approximately the same value of the saline water temperature for the period from the sunshine to the noon time. This is due to during this period, a part of the solar energy is consumed in heating of the saline water and the system. However, afternoon time, the saline water temperature is higher than the humid air temperature. It is also noticed that the back glass (condenser) temperature is lower than front glass temperature because the front glass gains more solar radiation because of its direction and it faces the solar for a longer time than a back-glass surface. It is found that from these figures during the measuring periods that the maximum amount of solar radiation is about 878.2 W and the maximum turbine power is about 262.4 W corresponding to a wind velocity of 10.3 m/s as will be indicated later.

Figs. 5, 7 and 9 demonstrate that the wind power inlet to the heater in the salty water varies with time and its value is proportional to the values of wind speed as will be seen later. So, the performance of coupling the solar still with the wind turbine is influenced by the wind velocity of the measuring region. Also, it is observed that the temperature difference between the salty water and glass temperature in all cases of wind power is higher than other cases without wind power. Figs. 4 and 5 illustrate that in case of higher wind power (1 AM to 11 AM and from 19 PM to 12 AM), the water temperature is higher in case of utilizing the wind turbine than the still without using the wind turbine. However, in case of low wind power, the influence of wind power on the salty water temperature is not highly sensible compared to the case of still without wind turbine. By comparing the results of Figs. 6 and 7, it is found that in case of using the wind turbine, the salty water temperature is greater than the humid air temperature (maximum value near 10°C) almost all the day compared to the case without using wind turbine due to the power extracted from the turbine. This is due to the wind turbine power goes directly to the salty water and heats it. This represents an advantage of this wind turbine-solar still coupling, however, the solar energy is divided between the salty water, humid air, glass covers, etc. Hence, the high temperature difference between the salty water and humid air raises the evaporation of the water and hence it affects positively on the freshwater yield. In case of utilizing PCM with the solar still as shown in Figs. 8 and 9, it found that the still temperature (salty water and humid air) is greater than the surrounding air temperature all the day because of the influence of the PCM. The PCM during the daytime stores the heat loss from the water and during the nighttime; it dissipates this stored heat to the water. So, the temperature of the PCM is lower than the water temperature during the daytime and contrarily during the nighttime as illustrated in Figs. 8 and 9. The same previous remarks in case of utilizing the wind turbine where the difference between the salty water and the humid air is greater than the case of still without the turbine. It is observed that PCM temperature (maximum temperature 47°C) doesn't reach the temperature of complete melting (56°C) in these atmospheric conditions where the maximum solar radiation is not high. However, using an additional source of heat (wind power) makes the PCM is partially melted where its maximum temperature is of 50°C. Figs. 4 and 5 reveal that the maximum temperature difference between the water and the condenser is about 6.76°C and 8.45°C for CSS and CSS with wind turbine, respectively due to the effect of the power from the wind turbine. By comparison the various cases of joining the wind turbine with the still, Figs. 5, 7 and 9 indicate that the maximum temperature difference between the salty water and the condenser is about 8.45°C, 13.5°C and 10.87°C for solar still with wind turbine, solar still with wind turbine and BSWF and finally CSS with wind turbine and PCM, respectively.

3.2. Freshwater yield

Figs. 10–12 expose the variation of the wind velocity and the hourly yield of freshwater for the various studied cases with time. Fig. 10 illustrates this result for CSS and CSS with the wind turbine. Fig. 11 illustrates the same result

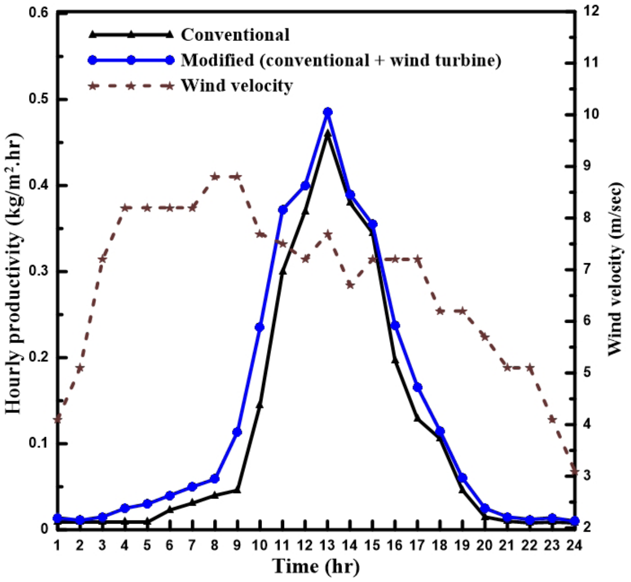

Fig. 10. Evolution of the wind velocity and the hourly yield with time of CSS and CSS with the turbine.

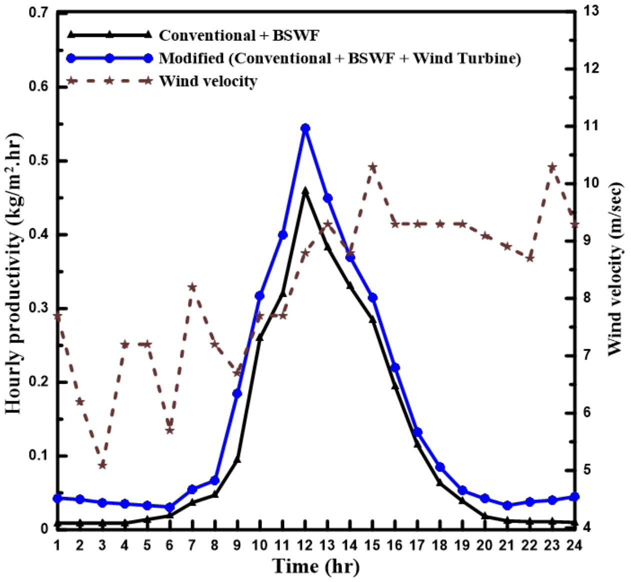

Fig. 11. Evolution of the wind velocity and the hourly yield with time of CSS with BSWF and CSS with BSWF and wind turbine.

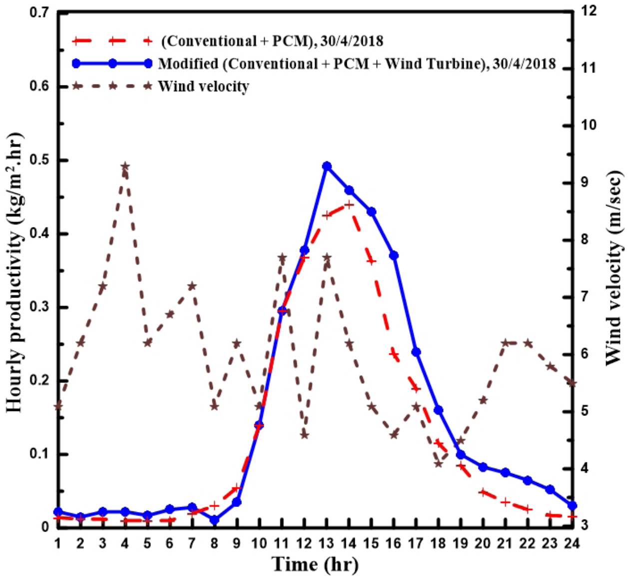

Fig. 12. Evolution of the wind velocity and the hourly yield with time of CSS with PCM and CSS with PCM and wind turbine.

but for CSS with BSWF and CSS with BSWF and wind turbine. However, Fig. 12 illustrates the same this result but for CSS with PCM and conventional solar still with PCM and wind turbine. Figs. 10–12 indicate that the hourly yield of freshwater increases in the morning with time until approximately the same time of the maximum solar intensity (see Figs. 4–9), and after that it reduces with time. These figures also indicate that the variation of the wind velocity has the same trend of the wind power as stated previously in Figs. 5, 7 and 9. Moreover, the maximum wind velocities are around 9, 10.5 and 9.5 m/s for solar still with the wind turbine, still with BSWF and turbine and still with PCM and turbine respectively. Figs. 10–12 reveal that the still with wind power produces highly hourly yield during all the running time compared with still without using wind turbine because of the power produced by the turbine. Furthermore, they illustrate that during the nighttime, the yield of the still is noticeable for high wind speed in case of using the turbine. Additionally, they illustrate that the still with the turbine produces the maximum hourly yield during all day (24 h production) compared with CSS. This is a result of the high evaporation process due to additional heat energy to the saline water supplied from the electrical heater as indicated previously. By comparing the findings of Figs. 10 and 12, it is noticed that the impact of using the turbine on the hourly yield of the still in case of using BSWF in the basin is greater than the CSS (maximum increasing is about 0.1 L). This result is noticed despite the wind velocity from 7 AM is lower in case of utilizing BSWF. This is due to using BSWF where they increase the heat transfer inside the brackish water and hence increase the evaporation of water yielding high freshwater. It is noted that the maximum yield of freshwater in case of still with BSWF is more than the corresponding still with PCM as shown in Figs. 11 and 12. This is attributed to the effect of the PCM which reduces the maximum value but augments the period of yielding freshwater. It also noted that the freshwater yield for the still without the turbine is about zero during the nighttime except in case of using PCM due to the impact of the PCM. Moreover, the influence of the PCM on the nighttime is obviously in case of using wind turbine where more heat loss is stored during the daytime because of the extra power from the turbine from 19 PM to 24 AM as stated in Fig. 12. Fig. 12 indicates that the still with PCM and wind turbine almost has the same yield of other with PCM only during the melting hours. This signifies that an enough part of the wind power is transported to the PCM during this period and this is reflected on the night yield as stated. Fig. 12 illustrates that from 1 to 8 AM, the supplied power is only from wind where part of this power goes to water desalination and the other part transfers and stores in the PCM and hence the desalination productivity is not high. With the same principle, from 8 to 12 AM, in case of solar still with PCM and wind turbine, part of the inlet energy to the system transfers and stores in the PCM. So, it is noticed that from Fig. 12 that there isn't great difference of the productivity between the system of the solar still with PCM and the system of the solar still with PCM and wind turbine. This is due to the stored energy inside the PCM in case of still with PCM and wind turbine system is greater than those of still with PCM system. This will be clear if we compare the PCM temperatures shown in Figs. 8 and 9, it if found that the PCM temperature in case of using wind turbine (maximum 51°C) is greater than system without wind turbine (maximum 44°C). Figs. 10, 11 and 12 indicate that the maximum hourly yield of freshwater is about 0.49, 0.55 and 0.49 L/h for CSS with the turbine, CSS with BSWF and the turbine, and CSS with PCM and the turbine, respectively.

Fig. 13 shows the evolution with time of the accumulated yield of the freshwater for all studied cases. The total daily solar radiation power, total daily wind turbine power, and total daily accumulative freshwater production for the studied cases are indicated in Table 5. Fig. 13 reveals that the accumulated yield of the freshwater in case of using PCM initially rises slower than the still with BSWF and conventional one due to the heat transferring to the PCM. After that, it increases faster than those of other cases due to the heat released from the PCM to the saline water. Contrarily, the trend in case of using BSWF where they rise the evaporation rapidly with the first part of the daytime. Then, their effect reduces due to the reduction of the salty water in the basin especially at the upper surface of the BSWF layers. Fig. 13 and Table 5 reveal that for the still without the turbine, using BSWF rises the total yield compared to the CSS despite the decrease of total incident solar energy to the still. Also, in case of using PCM, the total yield and the total solar intensity augment by round 10% and 3%, respectively compared to the conventional still. In case of using the turbine, the increase of total yield for BSWF in the basin (11.2%) isn't the same for the rising of the total inlet power (16%). This is due to the inserted heater at the base of the saline water losses large amount of its power to the back of the basin due to covering the heat by and BSWF.This augments the heat transfer rate at the bottom of the basin to the PCM or ambient. Moreover, with progressing the time during the day, the water saturating the top layer of BSWF reduces, resulting in a reduction of the evaporation process. This explains the reduction of the yield rate during this period as stated earlier. So, it is recommended in this case using makeup water to compensate the evaporated water in case of using BSWF in the basin. This also explains why in case of using PCM with the still and the turbine, the yield augments (about 10%) compared the CSS despite the reduction of the total power inlet by about (6%) because of the restored heat loss in the PCM. Table 5 tells that utilizing the turbine improves the total freshwater yield by an approximately 19.8%, 30.9%, and 20.1% in case of CSS with the turbine, still with BSWF and the turbine, and still with PCM and the turbine, respectively.

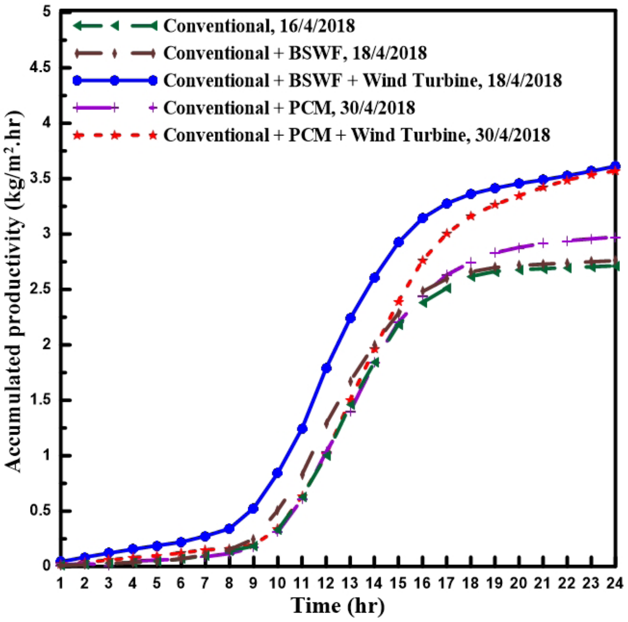

Fig. 13. Evolution of the accumulated yield with time for the studied cases.

3.3. Solar still efficiency

The efficiency, η_d, of the solar still for the studied cases is estimated by the following formula [26,27]:

$$\eta_d = \frac{\sum \dot{m}_w * h_{fg}}{I(t) * A + W_t} \tag{1}$$

where $\dot{m}_w$, is the hourly yield, h_{fg} is the average latent heat at T_w average basin water temperature, W_t is the daily wind

Table 5
Daily input power and yield of the different cases

Case	Daily solar power, W/m²·d	Daily wind power, W/m²·d	Total daily power, W/m²·d	Total daily yield, kg/m²·d
CSS	6200	0	6200	2.713
CSS + wind turbine	6200	1831	8031	3.25
CSS + BSWF	6075	0	6075	2.76
CSS + BSWF + wind turbine	6075	3247	9322	3.612
CSS + PCM	6403	0	6403	2.973
CSS + PCM + wind turbine	6403	1184	7587	3.569

turbine power in W, $I(t)$ is the daily average solar radiation over the projected area A of the device.

The average latent heat h_{fg} is estimated from [16,28]:

$$h_{fg} = 10^3\left[2501.9 - 2.40706T_w + 1.192217 * 10^{-3}{T_w}^2 - 1.5863{T_w}^3\right] \quad (2)$$

Table 6 presents the daily efficiency of the solar still estimated by Eq. (1) for the different studied cases. In this case, the efficiency is estimated depending on the area of the still and the solar total input power because it is proposed that the turbine is installed on the same land area of the still. Table 5 clarifies that the CSS with BSWF and coupled with the turbine has the maximum efficiency and the CSS has the minimum. For the available wind speed of the local region, using the turbine with the still raises its efficiency by around 5.4%. Also, using PCM with the still augments the efficiency by an approximately 3.1% and augments the still coupled with the turbine efficiency by around 1.5%. Furthermore, using BSWF with the CSS coupled with the turbine raises its efficiency by almost 4.29%.

4. Conclusions:

The influence of coupling a wind turbine with single slope solar still on its performance was presented experimentally. The coupling was performed through an electrical heater inserted and distributed in the still basin and connected directly to the wind turbine. Three different cases were studied and compared: CSS compared with CSS with wind turbine, CSS with BSWF saturated with water and wind turbine compared with other solar still with BSWF only, CSS with PCM compared with still with PCM and the turbine. The experiments were carried out through 24 h from 1 AM to 12 AM. The findings revealed that in case of using the wind turbine with the CSS, the turbine power augments noticeably the salty water temperature compared to CSS. Using PCM with the still and the turbine was more effectively than utilizing BSWF in the basin and contrarily in case of solar still without the turbine. Coupling the turbine with the still raised its daily freshwater yield by around 0.537, 0.857 and 0.596 L and still efficiency by approximately 5.35%, 8.57% and 3.75% corresponding to an inlet daily turbine power of 1831, 3247, and 1184 W, respectively and in the case of CSS, CSS with BSWF, and CSS with PCM, respectively compared with CSS. A parametric study on the impact of ambient conditions (wind velocity, solar intensity, ambient temperature, etc.) on the performance of the studied solar still systems coupled with the wind turbine could be studied in the future.

Table 6
Daily solar still efficiency

Case	Efficiency %	Case	Efficiency %
CSS	26.69	CSS + PCM + Wind turbine	33.53
CSS + Wind turbine	32.04	CSS + PCM	29.78
CSS + BSWF	27.76	CSS+ BSWF + Wind turbine	36.33

Acknowledgment

It is a pleasure to acknowledge Ministry of Higher Education (MoHE) of Egypt for providing a scholarship to conduct this study as well as the Egypt Japan University of Science and Technology (E-JUST) and JICA for offering the facility, tools, and equipment needed to conduct this research work.

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