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Improving the Basin Type Solar Still Performances Using an Internal Solar Collector

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A B S T R A C T

This paper presents a new experimental approach proposed to improve the conventional basin type solar still performances by integrating an internal solar collector. A serpentine heat exchanger is integrated inside the still acting as a solar collector to form an active solar still. The still productivity enhancement is verified experimentally through a comparative study with and without the internal solar collector during typical summer days. The effect of water depth is evaluated by varying the water amount in the basin still. The experimental tests show that the integrated internal solar collector acts as an effective heat source allowing more solar energy absorption which contributes to improving the still productivity. It was found that the still daily output is increased by about 20% and its thermal efficiency is improved by 16.8%.

Introduction

The drinking water scarcity is a great problem that treats the human life in many regions around the world [1]. The use of solar energy for brackish and seawater distillation seems to be one of the most promising solutions for drinking water supply, especially in remote and arid areas where sunshine is abundant and fresh water is scarce [2-4]. Solar desalination strategy is recommended regarding to its economic benefits, increasing as fossil fuel reserves diminish as well as for reasons related to environment protection.

Conventional Solar Stills (CSS) are selected due to their simplicity and passive nature, no need for hard maintenance or skilled persons. However, they suffer from low production of distilled water, which sometimes limit the use of these systems [5,6]. Improving solar still productivity has been the subject of several research papers and remains a challenge to scientists [7]. However, this improvement can be achieved by a proper modification in the still design and operation [8-10]. In fact, these improvements are resulted from enhancing evaporation, condensation and heat storage [11].

Increasing the basin water temperature is one of the most efficient methods used to improve the still productivity. Since, the evaporation rate depends mainly on the difference in temperature between water and glass cover. For this reason, several techniques are proposed like: reducing the water mass [12], an increase in solar radiation amount by using reflectors [13] or sun-tracking systems [14], by the addition of thermal storage materials (like dyes, rubber, gravel, sand, saw dust,…) in the basin [15,16] and also using an external heat source [17,18]. Consequently, the temperature difference between water and glass cover will increase, allowing better evaporation and condensation rates.

Active solar still (ASS) is one of the forms achieved by transforming the Conventional Solar Still (CSS) to an ASC using an external heat source [19-22]. Thereby, the basin water temperature could be raised in order to accelerate water evaporation by feeding thermal energy from an external solar collector like: parabolic concentrator, evacuated tube collector (ETC), flat plate collectors (FPC) and hybrid photovoltaic (PV-T) solar still. Several research works have been dedicated to active solar stills [23] and a detailed review of active solar distillation systems is reported by Sampathkumar et al. [7]. In fact, integrating an external solar collector requires an extra space and maintenance cost in comparison to the CSS [24,25]. Due to the large system area, the daily yield can decrease due to convective heat loss [12,26]. As reported by Tiwari and Dhiman [27], the system efficiency is reduced with the increase in the effective area. Their experimental study showed that only 12% in still yield is achieved when the solar collector length is varied from 6 to 12m and its efficiency varied from 15% to 19%. Kumar and Tiwari [28] observed that the water temperature and the system thermal efficiency are decreased due to the large storage capacity of the water mass and depth, respectively.

In the scope of this study, a new ASS design is proposed by integrating an Internal Solar Collector (ISC) inside the conventional basin type solar still. The idea is based upon integrating a vertical serpentine heat exchanger attached against the back-wall of the still. The introduction of an ISC at this location allows more solar energy absorption that contributes to increase the basin water temperature and consequently improve the evaporation rate and still productivity. This design allows getting a compact solar still with reduced cost, low maintenance and space requirement.

Outdoor experimental tests were conducted in typical days during June and July 2015 to investigate the effect of adding the ISC in the still thermal performances. The still improvement is tested through a comparative study between two identical solar stills, the modified one (with ISC) and the simple one (without ISC). The experimental tests show that the daily yield of the modified still is 20% higher than the CSS. The effect of water mass on the system productivity is also studied by varying the water mass from 4 to 6 kg. The experiments show that as the water mass decrease, the still daily productivity is increased. Economic analysis of the proposed still is conducted and the still's payback period was estimated to 157 days.

2. Solar still description

A schematic description of the proposed solar still is given in Figure. 1. It consists mainly of a basin type, single slope, solar still in which an ISC is integrated in the still. The basin area of the still is 0.36 m², fabricated using galvanized iron of 1.0 mm thickness and painted with black spray paint to increase solar ray’s absorption. The basin is placed inside a rectangular wooden box and the space between them is filled with glass wool to reduce the bottom thermal losses. The left and right vertical walls of the still are formed with glass sheets of 3 mm. Thereby; the total glass cover area is extended to 0.62 m². This arrangement is selected to increase the condensation rate and to get more solar rays reaching the still in the morning and in the evening.

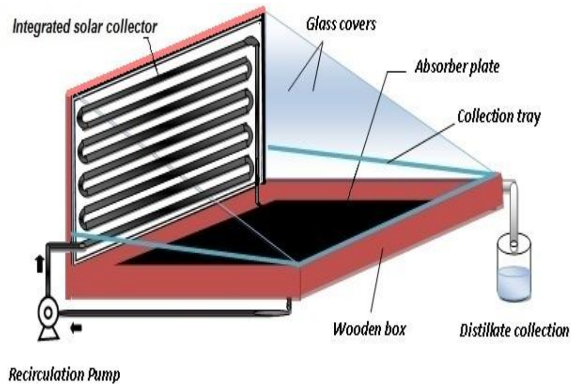

Figure 1. A schematic description of the proposed still

The top glass cover is fixed at an inclination of 36°. The three glass covers are attached to an iron frame to get free access to the still, for cleaning and maintenance operations. A plastic trough along the lower edge of each glass is used to collect and guide the distillate water towards the collection bottle. To avoid vapor leakage, the whole system is sealed using silicone rubber.

The ISC is fixed at the still rear side, which represents a significant area receiving solar rays. This location has not been used in previous works except to reflect solar radiation towards the basin liner [12]. Solar radiations passing through the glass cover will undergo several reflections inside the still. A portion of these rays will be reflected towards glass cover which leads to an increase of its temperature and consequently a reduction in the condensation rate. At the same time, a portion of the reflected solar rays will be absorbed by the still air cavity leading to an increase vapor pressure inside the still and then a decrease in its productivity. The ISC is a serpentine heat exchanger designed from a copper tube of 4.5 m length and an internal diameter of 12 mm. The tube is welded to a rectangular galvanized plate of 0.2 m² forming a flat plate collector. The collector was painted black to increase the capacity of solar ray’s absorption. To reduce heat losses, a polystyrene sheet of 15 mm thickness is placed between the galvanized plate and the still rear side.

A 12V DC pump is used to maintain water circulation between the basin and the ISC to allow better heat removal from the ISC. The water flow direction is upwardly to exhaust air from the heat exchanger. The electrical power consumption of the pump is about 24 Watt. Knowing that a photovoltaic PV solar panel can be provided to ensure pump operation. In this study, a 12 Volt source is used to supply the electrical power needed for pump operation. To prevent the pump overheating or failure, two parallel 12V DC pumps are used and operated alternately by manual switching each hour.

3. Experimental study

Two identical solar stills were designed and built (Figure. 2) to study the effect of integrating the ISC on the still thermal behaviour as well as on its daily output. The study was done during June and July 2015 at the Faculty of Science and Applied Sciences, Oum-El-Bouaghi University, Algeria (Latitude: 35°79'N, Longitude: 7°40'E). The experimental tests presented in this paper concern three typical days characterized by a clear sky and high solar radiation. The experimental setup is suitably instrumented to measure the main temperatures in the stills, total solar radiation and the amount of distillate output for both stills. The temperature of the basin plate, saline water and the top glass cover are measured using calibrated K-type thermocouples. The ambient temperature is sensed using a digital WT-2 type thermometer. A CMP3 pyranometer is used to measure the solar radiation.

Figure 2 . A photograph of the experimental setup

A Davis-type anemometer is used to measure the wind speed variation. The produced condensate water is measured by using a graduated glass bottle of 1.5 kg. The pyranometer and the thermocouples are connected to an automatic data acquisition system. These measurements are recorded for each hour from 7:00 am to 6:00 pm. The accuracy and error percentages of the measuring instruments used in the tests are given in Table 1. The maximum uncertainty in the measuring tools is about 3.1%.

Table 1. Experimental uncertainty errors [2]

Instrument	Accuracy	Range	Error %
Thermocouples	±1°C	0-100 °C	1.4
Thermometer	±1°C	-50-300 °C	1.5
Pyranometer	±1 W/m²	0-2500 W/m²	0.1
Anemometer	±0.1 m/s	0-50 m/s	2.0
Measure jar	±10 ml	0-1500 ml	0.6

4. Results & discussion

Three experimental tests are performed in the scope of this work to investigate the ISC effect on the still behaviour. The test performed in the 28/06/2015 displays a comparative study between the modified still (with ISC) and the CSS (without ISC) for 5.0 kg water mass for each still. While, the tests of the 27/06/2015 and 10/07/2015 are devoted to study the effect of water mass on the modified solar still features for 4, 5 and 6 kg, respectively. The atmospheric conditions during the test days are given in Figures. 3-5. For the three tests, the ambient temperature was in the range of 21-35°C, the total solar radiation varies in 270-980 W/m² and the wind speed was in the range of 2-6 m/s. The still thermal efficiency (η) may be calculated on the base of the distilled water mass ($\dot{m}_{ew}$), the latent heat of evaporation (L_v) and the total solar radiation (I_o) fall upon the still area (A), according to the formula:

$$\eta = \frac{\dot{m}_{ew}.L_v}{I_o.A} \quad (1)$$

1.1. Still features with and without ISC

The experimental data presented in this section concern the still performances with and without ISC for the 28/06/2015 for the same water mass of 5.0 kg in each still. For this test, the water mass flow rate circulating in the heat exchanger is evaluated to 0.034 kg/s. Figures. 6-9 show the main parameters describing the thermal behaviour of the CSS and the modified one. Figure. 6 show the temperature variations for basin liner, basin water and glass cover, for the modified still and the CSS, respectively. The comparison shows that all temperatures in the modified solar still are higher than those in the CSS. The maximum basin wall temperature of the CSS achieves 66.7°C, whereas for the modified one, it increases to 69.3°C. For the modified solar still, the maximum water temperature is 68.1°C and for the

CSS it increased to 64.2°C. This increase in basin and water temperatures for the modified still is the result of an additional thermal energy provided by the ISC. Moreover, it can be seen that the water temperature variation is close to the basin wall temperature for the modified still. Concerning the top glass cover, the maximum temperature in the CSS is 57.8°C, whereas in the modified still it increased to 62.9°C. This increase is explained by the increase in evaporation rate. In other words, the glass cover of the modified still receives more latent heat leading to an increase in its temperature.

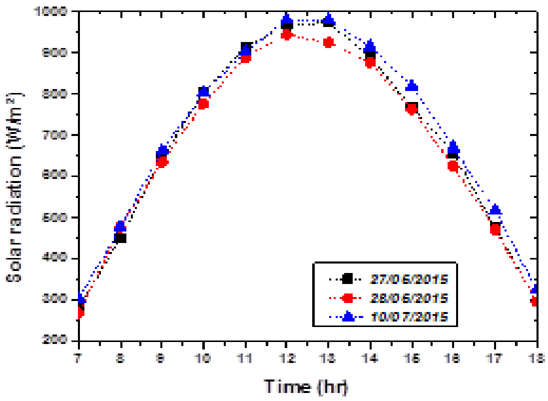

Figure 3. Variation of solar radiation for the test days

The variations of the accumulated and hourly yields of the CSS and the modified still for 5 kg water mass are shown in Figure. 7. Consequently, it is experienced that the still yield is enhanced by the integrated ISC. The daily productivity of the simple solar still is about 3.94 kg/m², whereas for the modified still, it reaches 4.72 kg/m².

It can be concluded that the daily production of the modified solar still is increased by about 20% than the CSS. So, the use of the ISC allows more solar energy absorption that contributes to increase the basin water temperature and improves the productivity and thermal efficiency of the still. This improvement in the fresh water productivity can be explained by the increase in the evaporation heat transfer rate between the water and the glass cover. The average thermal efficiency of the CSS is about 34.25%, whereas for the modified still it increases to about 40%.

1.2. Effect of water mass

The effect of water mass on the proposed still (with the ISC) performances is investigated in this section. The experimental tests were performed for water mass of 4, 5 and 6 kg for three typical days,

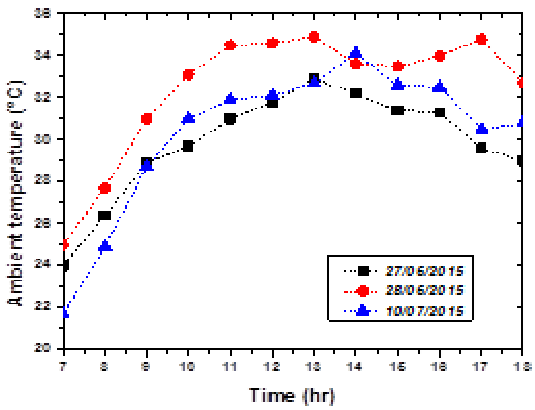

Figure. 4. Variation of ambient temperature

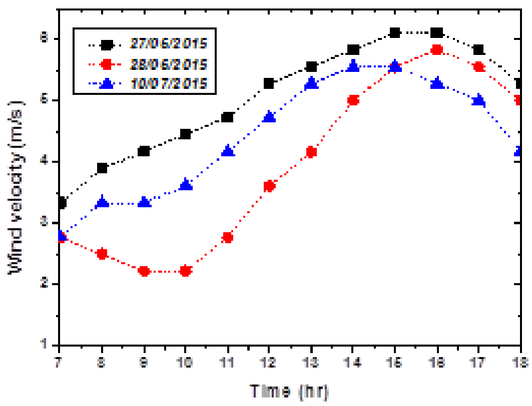

Figure 5. Wind speed variation during the test days

namely: 27/06/2016, 28/06/2015 and 10/07/2015, respectively. It is verified experimentally that a value of 4 kg is considered as the minimum possible water mass to prevent pump cavitation. The daily output of the proposed solar still under the effect of water mass is illustrated in Figure. 8. As the water mass increases in the basin from 4, 5 to 6 kg, the still productivity will decrease from 5, 4.72 to 4.16 kg/m², respectively. The solar still thermal efficiency variation under the water mass effect is presented in Figure. 9. As can be concluded, when the water mass decreases from 6, 5 to 4 kg, the corresponding mean thermal efficiency of the still is increased from 35.84, 40 to 41.5%, respectively.

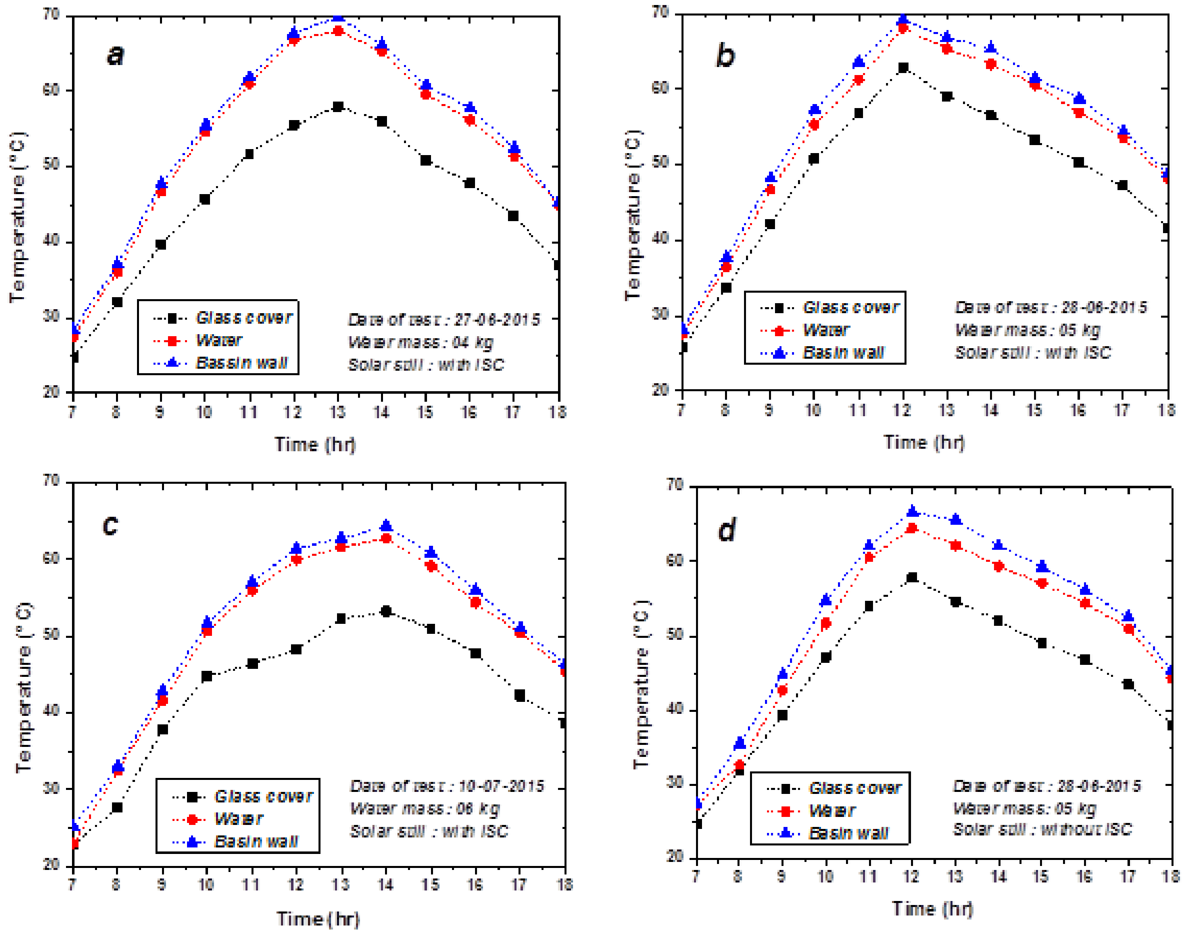

Figure 6. Temperature variations at different locations in the still for the three test days

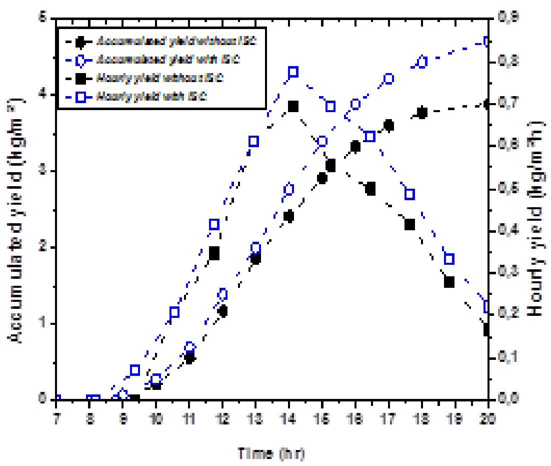

Figure 7. Still productivity with and without ISC
for the 28/06/2015

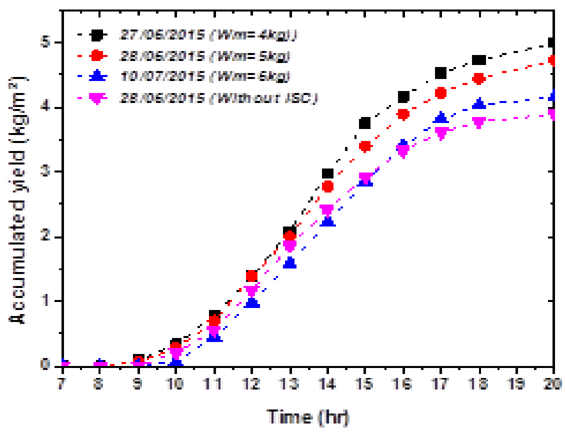

Figure 8. Effect of water mass on the still productivity

2. Economic study

In order to check the still capability, an economic analysis is conducted for both modified and CSS. The analysis is performed according to Kabeel et al. [29]. The still total Annual Cost (AC) is estimated based on the evaluation of Annual Fixed Cost (AFC), the Annual Maintenance Cost (AMC) and the Annual Salvage Cost (ASC). The AFC is obtained by multiplying the total fixed cost (P) by the amortization factor as given by:

$$AFC = \frac{i(1+i)^n}{(1+i)^n - 1} P \qquad (2)$$

The expected lifetime (n) for each still is estimated to 10 years and the rate of interest (i) is taken as 12% of the total fixed cost. The Annual Maintenance Cost (AMC) covers the regular filling of water, collecting the distilled water, cleaning the glass cover and removal of salt deposited. It was estimated at 10% of the total fixed cost. The annual salvage cost (ASC) is given by (Eq. 3), where, the salvage value (S) is taken as 20% of the total fixed cost.

$$\mathrm{ASC} = \frac{\mathrm{i}}{(1+\mathrm{i})^{\mathrm{n}} - 1}\mathrm{S} \tag{3}$$

The annual cost (AC) of the still can be estimated by the following equation

$$\mathrm{AC} = \mathrm{AFC} + \mathrm{AMC} - \mathrm{ASC} \tag{4}$$

The average daily productivity of the CSS is about 2.5 kg/m² assuming that the still is operated for 340 days in the year. As demonstrated by the experimental study, the daily production of the modified solar still can be increased to about 20% than the CSS. Therefore, the average daily productivity of the modified still is 3.0 kg/m². The cost of 1.0 liter of distilled water is estimated by dividing the system annual cost by the still annual yield. The main part of the still cost is devoted to the labour costs, which represent 30% of the fabrication cost. The cost of each part constituting the simple and the modified solar still is given in Table 2 and a summary of the economic analysis is presented in Table 3. It is found that the cost of distilled water for the CSS is 0.015 \$/kgm² and its payback period is 110 days. Although, for the modified solar still, the distilled water cost is 0.022 \$/kgm² and its payback period is estimated to 157 days.

3. Conclusions

This paper presents a new design of an active solar still with an internal solar collector. The effect of integrating an ISC on the still thermal performances was experimentally evaluated under several operating conditions. The experiments show that the integrated ISC acts as an additional and effective heat source allowing more solar energy absorption which contributes to increase the basin water temperature as well as the productivity and thermal efficiency of the still. The analysis of the experimental data enables to underline the following conclusions:

- Integrating the ISC provides a higher yield than the CSS with an increase of 20% in the still productivity.
- The average thermal efficiency and estimated cost of proposed still are about 40% and 0.021 \$/kgm² respectively. Whereas, those of the simple one (without ISC) are 34.25% and 0.015 \$/kgm².
- The daily output of the proposed still increases with the decrease in the water mass and the still productivity is higher for a low water mass in the basin.
- Compared to the active solar still with external solar collector, the proposed design reduces the overall cost and maintenance of the system as well as the space requirement.

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