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EXPERIMENTAL INVESTIGATION OF A SOLAR STILL COUPLED WITH A FLAT-PLATE COLLECTOR

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ABSTRACT

The objective of the present study was to investigate the possibility of developing and improving a basin-type solar still under local conditions. Basin-type solar still was connected with flat-plate collector to rise the temperature of saline water and tested with four modes of operation: (1) underground water feed, 2500 ppm, with the still operating alone, (2) underground water feed of the same salinity, with the still connected to the collector during daylight hours from 7 am to 6 pm, (3) saline water feed, 35000 ppm, with the still operating alone and (4) saline water feed of the same salinity, with the still connected to the collector during daylight hours from 7 am to 6 pm. Intensity of solar radiation, temperatures and distilled water productions were measured for several days at various operating conditions. The obtained results showed that the mass of distilled water production using augmentation was increased by 32 % in the case of underground water feed and by 29 % in the case of salt water feed. It was concluded that the solar still which connected with a flat-plate collector could be an effective approach for solar distillation process with high productivity under Egyptian conditions.
Keywords: Solar still; Saline water; Flat-plate solar collector; Productivity.

INTRODUCTION

Solar distillation is becoming increasingly important for sustaining arid land with fresh water. Shortage of fresh water for domestic uses and cultivation is a huge problem in arid land in Egypt, particularly in northern coast and eastern coast. Therefore, there is a great need to develop and improve solar distillation system to deal with such water problems under Egyptian conditions.

Shortage of water will be the biggest problem facing the whole world during this century due to increasing the consumption rates and population growth. Solar stills seem to be a promising and the most appropriate way to deal with water problems such as being either lack or polluted, especially in deserts, in traditionally dry regions and in modern industrial areas. The solar stills have many advantages that include wide availability of solar energy, simple and low-cost operation, low maintenance requirements and low-cost construction. Moreover they could be clean and friendly to the environment. Therefore, solar still is one of many processes available for water purification, it is a great practical alternative method to distill fresh water from saline and brackish water (Abdul-Fattah, 1986; Ghoneyem and Ileri, 1997; Tiwari and Tiwari, 2006).

The idea behind a solar still is very simple: saline water inside a black-painted basin enclosed in a completely air-tight area formed by a transparent cover is heated up and evaporated due to incident solar irradiance that passes through the transparent cover. Consequently water vapor is directed upward and condenses in pure water as it comes in contact with the cooler inside surface of the cover. Distilled water is collected in a vessel nearby (Voropoulos *et al.,* 2003). A simple solar still consisting of a water basin and a single glass cover is the first proposed design of solar still that is easy to construct and it has virtually no operating cost. It is generally classified as a passive and active distillation systems (Tiwari and Tiwari, 2006).

Despite the simplicity and advantages of solar stills, their most important drawback is low water productivity (or performance) in comparison with other thermal desalination methods and to high land requirement (Eibling *et al.,* 1971). This occurs since productivity rate of solar stills depends on the solar radiation available, meaning that during no sunshine periods production is practically zero. For this, research activities nowadays move in the direction towards increasing performance and output of solar stills by using several techniques (Malik *et al.,* 1982). These are all targeted on the concept of increasing the difference between saline water temperature and glass cover temperature. Since this temperature difference (T_w - T_c) is actually the driving force of the distillation process.

In addition, the amount of distilled water that can be produced varies quite dramatically with the geographical position, the sun's position, prevailing meteorological conditions, solar still design, and operational techniques (Malik *et al.,* 1982). Other parameters such as water depth, salinity, black dye, wind speed and direction have an effect on the output of the solar stills. (Tamimi, 1987 and Akash *et al.,* 1998). Several of still exist, the simplest of which is the single-basin type. But the yield of this still is in the range of 2-4 L/d per m^2 of still area which is very limited. There are, however, several methods to augment this yield, which generally fall into two categories: concentrators and flat-plate collectors. This system, also called the "active" system (Malik *et al.,* 982).

An active system of single-slope-type stills integrated with a flat-plate collector under the thermosyphon mode of operation was studied by Zaki *et al.* (1983). They found that the maximum increase in the yield was up to 33% when the water in the still was preheated in the solar collector. Voropoulos *et al.* (2003) investigated experimentally the behavior of a conventional greenhouse type solar still which coupled with hot water storage tank through its operation under real conditions by keeping tank water temperature constant at different levels. They found that this design leads to higher distilled water output, due to higher basin water temperatures as a result of hot storage tank water. They also ensures the operation of the system during periods of low or no sunshine due to the continuation of the distillation process in these periods, as a result of the heat transfer from the hotter tank water to the colder basin water. Badran and Al-Tahaineh, (2005) studied the effect of coupling a flat-plate solar collector on the solar still productivity under Jordan conditions. They found that the mass of distilled water production using augmentation was increased by 231% in the case of tap water as a feed and by 52% in the case of salt water as a feed. They also found that coupling of a solar collector with a still has increased the productivity by 36%. The efficiency of the solar still (ranging from 25% to 40% in winter and from 30% to 60% in high-intensity radiation months), depends on the design, the construction, the proper operation and the ambient conditions. Generally in the basin, the temperature of water ranges from 50 to 80°C, and the latent heat of water vaporization is about 2.4 MJ kg^{-1} (Cappelletti, 2002).

Solar still coupled with flat-pale collector could be a good approach to increase the productivity and improve the efficiency of solar still. Therefore, the objective of this study was to enhance the still output through improving the still operation conditions by using a flat-plate solar collector under Egyptian climatic conditions.

MATERIALS AND METHODS

1. Experimental setup

A solar still system was designed, installed and tested at the Agricultural Engineering Department, Faculty of Agriculture, Suez Canal University. A single sloped solar still was coupled with flat-plate solar collector. The still was made of a rectangular iron basin (1.3 m x 0.8 m) and 0.1 m deep. The bottom frame was constructed of wood and insulated by a 0.02 m thick of rock wool (thermal conductivity = 0.0346 $Wm^{-1}k^{-1}$). It has black painted basin (1.04 m^2) fills with brackish water supplied from the solar collector which preheats the water prior to enter the solar still. The outside walls were insulated with 0.07 m thick foam (thermal conductivity = 0.04 $Wm^{-1}k^{-1}$). The solar still was covered with glass sheet (4 mm thick) to transmit the maximum possible of solar radiation flux incident on it. It was orientated to face the south direction with an inclination angle of 31°. This inclination angle may be maximized the solar radiation flux incident. Moreover, with this inclined angle (31°) condensation will run down the underside into the trough rather than dropping from the cover into the basin. A trough running along the bottom side of the glass cover ensures the collection of the distilled water and leads it to the distilled water-collecting vessel and then measures by a graduated cylinder. The system has the capability to collect distillates from three sides of the still (i.e. the north, south and east sides). Rubber is used to prevent leakage from any gab between the glass cover and the still box. An inlet pipe is also fixed at the rear wall of the still for feeding brackish water.

The solar collector was made of twenty parallel tubes (6 mm inside diameter) which located at equidistant of 30 mm and attached to the upper surface of the absorber plate. The absorber plate is rectangular in shape, and formed of a steel sheet which is a good conductor of heat. Its gross dimensions are 1.2 m long, 0.6 m wide and 1.0 mm thick, with a net upper surface area of 0.72 m^2. The tubes and the absorbed plate were painted with matt black paint in order to absorber the maximum amount of the solar radiation incident on it. In the bottom and sides of the solar collector, 100 mm of foam insulation was placed to minimize the heat losses from the collector. It was fixed with a tilt angle of 31° from the horizontal plane. A feeding cylindrical tank was used to compensate the still brackish water on a daily basis. The tank made of plastic, insulated exactly the same way as the basin of still in the sides. A view representing of solar still system is shown in Fig. (1) and a sketch of the system is shown in Fig. (2).

Fig. (1): The solar still system, connected with solar water heater

Thermocouples were fixed in different positions to measure inside and outside glass cover, solar basin water, ambient air and vapor temperatures. All experiments were conducted during the month of August and September. Data were used to compare the relative performances of the still with four modes of operation.

Testing was performed with a four modes of operation: (1) underground water feed 2500 ppm with the still operating alone, (2) underground water feed of the same salinity with the still connected to the collector during daylight hours from 7 am to 6 pm, (3) saline water feed 35000 ppm with the still operating alone and (4) saline water feed of the same salinity with the still connected to the collector during the same time.

Fig. (2): A schematic diagram showing the arrangement of the still-collector system.

The efficiency of the solar still unit with free condensation facilities was calculated using the following relationship according to Kudish (1991)

$$\text{Efficiency} = \frac{Q_v \Phi_p}{I} x100\%$$

Where: Qv = 2.434x10^3 kJkg^{-1}, the energy required to evaporate 1kg of brackish water at 40°C; Φ_p is still productivity in kgm^{-2}d^{-1}; I, total radiation in kJm^{-2} d^{-1}.

RESULTS AND DISCUSSION

The temperature of the basin water, inside surface of the glass cover, vapor, ambient temperature and intensity of solar radiation against time for still alone underground water feed mode are shown in Fig. (3). It reveals that, the temperature rises during the day time up to the maximum value at 13:00 h, and then decreased slowly. It can be also noticed that the water temperature in the base of the still was always the highest among all the temperatures since the solar energy is absorbed there (Akash, *et al.,* 2000).

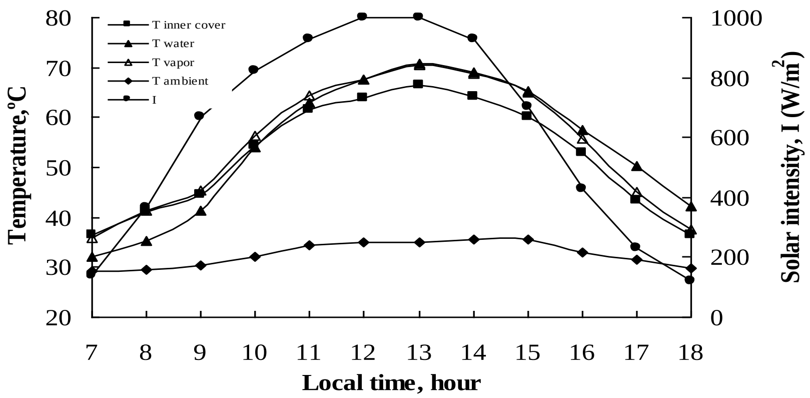

Fig. (3): Hourly variation of temperature for the still alone underground water feed mode, and the solar radiation.

Based on the obtained results, the maximum values of temperature for water of basin, inside surface of the glass cover, vapor and ambient air were 62.2 ºC, 58.4 ºC, 62.8 ºC and 34.4 ºC respectively. As it was expected and illustrated in the figure, the solar radiation increases until it reaches its maximum value at noon, then it decreases again. The highest recorded value of solar radiation was 965 Wm^{-2} at 12:00 h. There are shifts of the peak positions of about 1 h for the different temperatures. This may be due to the thermal inertia of the still.

Similar trends were observed for all experiments (Figs. 4, 5 and 6). The maximum water temperature always occurred at the hour of 13:00; it ranged between 62.2 and 72.8 ºC. Ambient air temperature for all experiments were in the range 28.6 - 37.7 ºC

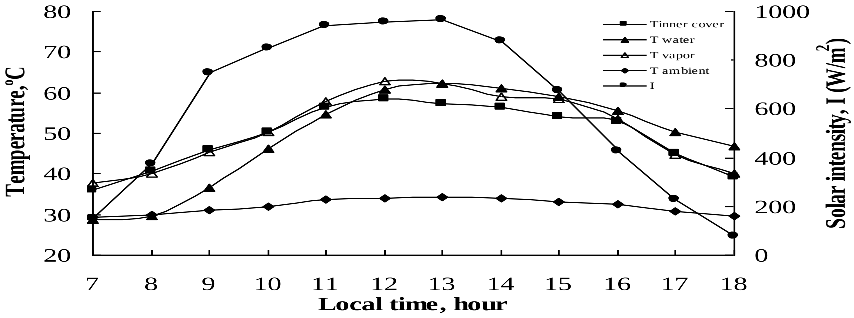

Fig. (4): Hourly variation of temperature for the still connected with the collector (7-18) underground water feed mode, and the solar radiation

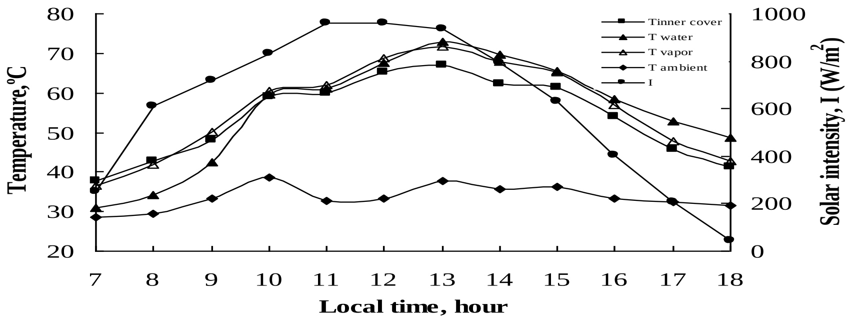

Fig. (5): Hourly variation of temperature for the still alone under saline water feed mode, and the solar radiation.

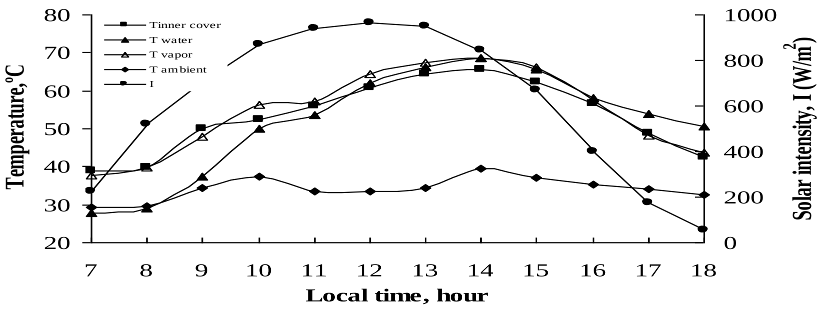

Fig. (6): Hourly variation of temperature for the still connected with the collector (7-18) under saline water feed mode, and solar radiation

Fig. (7) shows a comparison between the water production rate of the solar still only and solar still with the collector in case of underground and saline water feed for the four successive days characterized by similar weather conditions. Based on the obtained results, the fresh water production was found to be directly proportional to basin water temperature. The production rate starts with a very little amount due to the thermal capacity of the still. At the beginning of the experiment, the still stores a significant part of the incident radiation within its structure particularly in the early morning. A peak production rate was achieved at about 14:00 h in both cases. Furthermore, after that, it begins to decrease. The higher the temperature the higher the output will be from the distillation system. This high productivity is expected as a result of coupling the solar collector with solar still. This can be explained by the fact that solar collector will preheat the water prior to enter the solar still. Increased temperature of the water in the basin led to increase the rate of fresh water production.

Fig. (7): Comparative variation of still productivity with underground water (A) and saline water (B)

The production and daily efficiency at different operation modes and weather conditions are listed in table 1. From the obtained results listed in the table, it can be observed that the daily efficiency of the first mode (still operating alone, underground water feed) and the second mode (still connected to the collector, underground water feed) was 34 %, and 42 % respectively. Comparing the daily efficiency of the two modes, it is clear that there is considerable increase (8 %) in daily efficiency of the still augmented with the solar collector over that of the still alone. In case of saline water feed, it is clear that there is a significant increase (11 %) in daily efficiency of the still connected to the solar collector over that of the still alone.

The percentage of enhancement in productivity during the day time due to coupling of the solar collector (4735 ml) was calculated, and found to be 32% more than that when the still was operated alone (3220 ml) in case of underground water, and 29 % in case of saline water.

Table (1): Production and daily efficiency at different operation modes and weather conditions.

Operation mode and date	Weather conditions	Day time production, ml	Daily efficiency, %
Underground water mode			
Still alone(1/9/2008)	Clear sky	3220	34
With collector (7-18) (31/8/2008)	Clear sky	4735	42
Saline water mode			
Still alone(10/9/2008)	Clear sky	3145	28
With collector (7-18) (9/9/2008)	Clear sky	4400	39

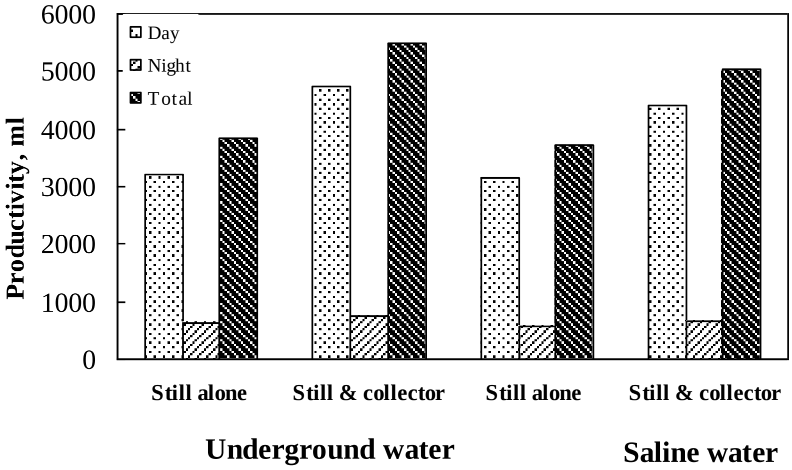

Fig. (8): Comparison of distilled water production at different modes of operation during day and night.

It can clearly seen that in two cases of underground and saline water feed, there was a significant increase in water productivity when the solar still coupled with the solar collector as shown in Fig. (8). Increase in water productivity was observed during the daylight and also at night operations. In case of underground water feed when the still operated alone 3220 ml of the production was achieved during the daylight period while the rest 625 ml was at night. In the same case, when the still connected to the solar collector, 4735 ml of the production was achieved during the daylight period, while the rest 750 ml was at night.

It can be concluded that a considerable increase in production was achieved at night when the still connected to the solar collector over that when the still was operated alone. This increase in the production at night period was expected since the water in basin remained hot enough so that distillation was higher during the night when the still connected to the collector. Therefore, a solar still coupled with the solar collector could be a good approach to achieve a high productivity.

CONCLUSION

From the present study the following conclusions can be drawn as:-

1. In case of underground water feed, the daily production of the still alone was 3.096 $Lm^{-2}d^{-1}$, which gave daily efficiency of 34 %. Also, when the solar collector connected to still, the daily production was 4.553 $Lm^{-2}d^{-1}$ and daily efficiency of 42 %.
2. In the case of saline water feed, the daily production of the still alone was 3.024 $Lm^{-2}d^{-1}$ and consequently the daily efficiency was 28 %. Also, when the solar collector connected with the still, the daily production was 4.230 $Lm^{-2}d^{-1}$ which gave daily efficiency of 39 %.
3. The percentage of enhancement in productivity due to coupling of the solar collector was 32 % in case of underground water feed and 29 % in case of saline water feed.
4. The experimental investigation of the solar still-collector system has been shown that the productivity of the system was substantially increased in comparison with that of the still alone.
5. The most practical operating that achieved high productivity, regardless of the salinity of the feed, was coupled the still with the solar collector.

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دراسة تأثير اتصال وحدة تقطير شمسي مع سخان مسطح

إسلام حسن الشيخ
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أجري هذا البحث بقسم الهندسة الزراعية – كلية الزراعة - جامعة قناة السويس ويهدف إلي امكانية تطوير وتحسين آداء وحدة تقطير شمسي ذات الميل من جانب واحد تحت الظروف المحلية عن طريق توصيلها بسخان شمسي مسطح. وتتكون الوحدة من حوض معدني سمكه ١,٠ مم وأبعاده هي ١,٣ × ٠,٨ × ٠,١ م طول وعرض وارتفاع علي الترتيب ، موضوع داخل صندوق خشبي أبعاده ١,٤٤ × ٠,٩٤ × ٠,١٢ م طول وعرض وارتفاع علي الترتيب ، تم عزل الحوض المعدني من الجوانب بطبقة من الفوم سمكها ٠,٠٧ م ومن الأسفل بطبقة من الصوف الزجاجي سمكها ٠,٠٢ م. أما سطح التكثيف الرئيسي فهو عبار عن غطاء من الزجاج الشفاف بسمك ٤ مم موجه ناحية الجنوب ويميل بزاوية مقدارها ٣١ درجة علي الأفقي للسماح للقطرات المتكاثفة بالسريان إلي قناة التجميع الموجودة أسفل الغطاء من الناحية الأمامية. والوحدة متصلة بخزان بلاستيك سعة ٥٠ لتر لإمداد الوحدة بمياه البحر. ويتكون السخان الشمسي من سطح ماص أبعاده ١,٢ × ٠,٦ م طول وعرض بالترتيب ويحتوي علي ٢٠ أنبوبة نحاسية بقطر داخلي ٦ مم والمسافات البينية ٠,٠٣ م. وقد تم اختبار الوحدة مع أربعة أنماط للتشغيل هي:

١- تشغيل الوحدة بمفردها مع استخدام المياه الجوفية بتركيز ٢٥٠٠ جزء في المليون.
٢- توصيل وحدة التقطير بالسخان الشمسي مع استخدام المياه الجوفية بنفس التركيز المذكور في النمط الأول.
٣- تشغيل الوحدة بمفردها مع استخدام مياه البحر بتركيز ٣٥٠٠٠ جزء في المليون.
٤- توصيل وحدة التقطير بالسخان الشمسي مع استخدام مياه البحر بنفس التركيز المذكور في النمط الثالث.

وقد أوضحت النتائج ما يلي:

١- عند تشغيل الوحدة بمفردها مع استخدام المياه الجوفية كان الإنتاج اليومي ٣,١ لتر/ م^{٢} وكانت كفاءة الوحدة ٣٤ % ، بينما عند توصيلها بالسخان كان الإنتاج اليومي ٤,٥٥٣ لتر / م^{٢} وكانت كفاءة الوحدة في هذه الحالة ٤٢ %.
٢- عند تشغيل الوحدة بمفردها مع استخدام مياه البحر كان الإنتاج اليومي ٣,٠٢٤ لتر/ م^{٢} وكانت كفاءة الوحدة ٢٨ % ، بينما عند توصيلها بالسخان كان الإنتاج اليومي ٤,٢٣٠ لتر / م^{٢} وكانت كفاءة الوحدة في هذه الحالة ٣٩ %.
٣- كانت نسبة الزيادة في إنتاج الوحدة عند اتصالها بالسخان الشمسي ٣٢ % في حالة استخدام المياه الجوفية بينما كانت ٢٩ % في حالة استخدام مياه البحر.
٤- توصيل وحدة التقطير بالسخان الشمسي يؤدي إلي زيادة إنتاجيتها بغض النظر عن تركيز الأملاح في المياه المستخدمة