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Desalination and hot water production using solar still enhanced by external solar collector

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ABSTRACT

A unit consisting of a solar still enhanced by an external solar collector to desalinate and produce hot water was designed and tested. The unit consists of three main parts: water basin, external solar collector, and heat exchanger. The water in the basin is heated by direct solar irradiation and by hot water flowing in the heat exchanger heated by the external collector. This enhances water evaporation from the basin. The produced vapor condenses on the lower part of the double glass cover through which cooling water flows. The condensate is withdrawn as desalinated (fresh) water. The effect of cooling water flow rate, ambient temperature, solar intensity, and hot water production rate on the amount of desalinated water produced was investigated. The results showed that the production rate is proportional to the solar irradiation, ambient temperature, and cooling water flow rate. On average the unit was capable of producing 0.4 l/h desalinated water of low salinity (2–6 ppm) and hot water of temperature up to 87°C.

Keywords: Desalination; Solar energy; Water; Solar collector; Solar units

1. Introduction

Desalination has long been applied as a way of making saline water drinkable and purifying water in remote locations. As early as the fourth century BC, Aristotle described a method to produce vapor from impure water and then condense it to get fresh water [1]. Desalination technologies have brought fresh water and hence industrial and commercial development to areas of the world that otherwise might have remained unproductive. Not only has development been enhanced by these technologies, but more importantly, the health and welfare of many people have been improved by the supply of sanitary fresh water supplies. Many techniques have been used for desalination, among them, solar desalination based on solar still. Various methods and approaches have been used based on the conventional solar still or its modifications. Many designs for solar stills have been conducted with varying parameters being considered in each of them such as regenerative solar still, double basin solar still, pyramid shaped solar still, and many others [2].

Velmurugan and Srithar [3] and Abdallah et al. [4] attempted to improve the regular solar still by using different types of absorbing materials like black volcanic rocks and metallic wiry sponges (coated and uncoated) [4] to increase the free surface area of water

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in the solar still. They found that the uncoated sponge has the highest water collection during day time, followed by the black rocks, and then coated metallic wiry sponges. Collected distilled water including overnight water collections were improved by 60, 43, and 28% for black rocks, uncoated, and coated metallic wiry sponges, respectively. Performing analysis on a multiple-effect basin-type solar still of triangular cross-section made from a number of vertical parallel partitions that contain pieces of wick among them, Tanaka et al. [5] found that the productivity of the still increased in winter with an increase in the angle between the glass cover and the basin and decreased in summer. In the spring and autumn seasons, productivity had a gentle peak between 40° and 45° angle. The productivity of the still of 13 partitions with 5-mm gaps and a 40° angle of the glass cover was four times more than the basin-type stills, and the still was more productive than the conventional multiple-effect stills by about 40% or more. Abdel-Rehim and Lasheen [6] made two modifications to improve the performance of solar systems. The first modification involves installing a packed material made from glass balls and laying on the bottom of the basin. These balls worked as a thermal storage system. The second one is by using a rotating shaft near the basin water surface to break the interface hence enhancing evaporation. The results showed that the two modifications enhanced the performance of the solar still. The first modification improved the efficiency by 5% in May, 6% in June, and 7.5% in July. The second improvement, however, improved the efficiency by 2.5% in May, 5% in June, and 5.5% in July. Mahdi and Smith [7] combined a V-trough solar concentrator with an inclined flat-plate wick-type solar still. They found that the productivity was more on clear days in winter than on clear days in summer. Rahim [8] presented a design having the evaporating and condensing zones separated in two different units. The advantages of the force condensing technique and shallow basin still were integrated together to improve the system performance. Tayeb [9] studied the performance of four different designs of basin-type stills. The stills have the same area of evaporation but different shapes so different areas of condensation. The results show that a higher ratio of condensation area to evaporation area leads to a higher productivity. The efficiency of these different stills was found to range from 14.9 to 21.8%. Abu Arabi et al. [10] desalinated water using falling film solar desalination unit. They studied the effect of weather condition, solar irradiation, and film flow rate on the productivity of the unit. Their results showed that on average 0.61/m^2 h fresh water could be produced in hot months of Jordan summer. They also modeled the above unit theoretically and a good agreement between the experiments and the theory was achieved [11].

The objective of this work was to design a unit that utilizes solar energy to produce both hot and desalinated (fresh) water. The effect of operational parameters and weather conditions on the productivity of the unit was tested.

2. Experimental part

The solar desalination unit consists of three main parts namely: solar collector, solar basin, and a heat exchanger (see Fig. 1). The basin has a square bottom ($1 \times 1\,m^2$) and a height of 0.16 m at the front side and 0.92 m at the back side with the front side facing south. The basin is covered by double glass layers 1 cm apart. The bottom part of the basin is painted black to absorb solar energy. The water in the basin is supplied via a basin feed tank (20 L) so that the water in the basin feed tank and the basin are both at the same level. A heat exchanger which is basically a coil made from aluminum (1 cm diameter) is immersed in the water of the basin and it is connected to the solar collector. The solar collector is rectangular in shape (length = 2 m, width = 1.25 m, and height = 0.1 m) with bottom surface made of highly selective material to maximize solar energy absorption. Copper tubes ($D = 8$ mm) are laid on the bottom surface. There are 10 parallel tubes spaced 10 cm apart and are covered by 4 mm prismatic glass. The tubes contain water that circulates through the tubes and the heat exchanger in a close loop due to density difference (thermo syphoning).

Thus the water in the basin is heated by two means: first by the absorbed solar energy in the basin and by the heat it receives from the solar collector. As the water in the basin is heated, evaporation takes place. The vapor rises to the top and condenses on the lower glass surface of the glass cover. The condensation process is enhanced by allowing cold water to pass through the two layers of the glass cover. The condensate slips on the inner glass surface and falls in a trough located at the lower end of the glass cover and then it is withdrawn as fresh water. Therefore this unit serves as a source of fresh water and a source of hot water which comes from both the water in the basin whose temperature may reach as high as 87°C and the cooling water whose temperature may reach as high as 56°C in summer time. The salinity of the fresh water produced was tested by measuring its conductivity which was found to be in the range of 2–6 ppm. A schematic diagram of the unit is shown in Fig. 1.

The effect of the following parameters on the unit productivity (defined as the amount of fresh water the

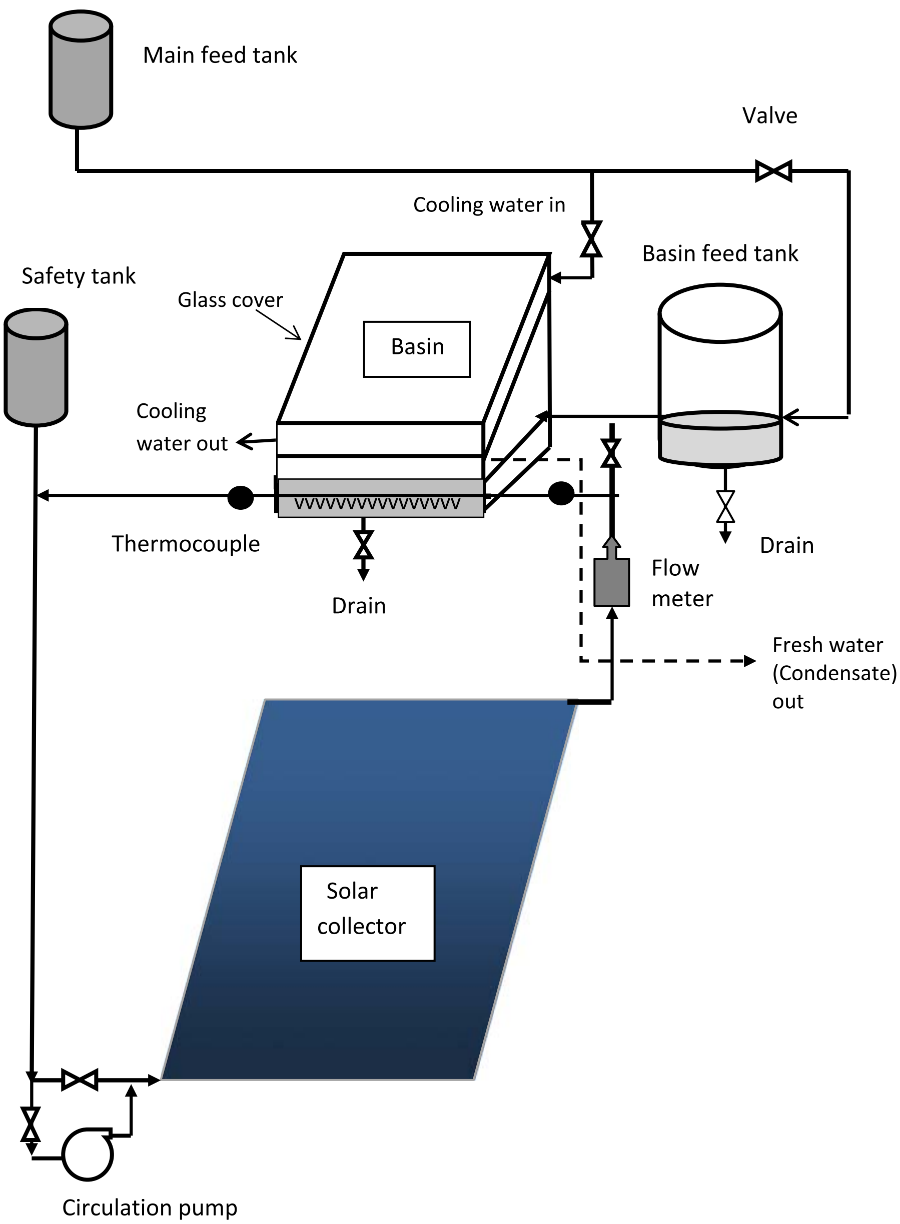

Fig. 1. Schematic diagram of the experimental setup.

unit produces) was investigated: Solar collector enhancement, cooling water flow rate, solar irradiation intensity, hot water production rate, recycling of the cooling water to the basin feed tank. The amount of fresh water that can be produced after working hours and sunset was also measured.

3. Results and discussion

The unit was first operated without being connected to the solar collector to measure the amount of fresh water that can be produced. Several experiments were then performed under similar weather conditions with the solar collector allowing heating water to circulate through the system to assess the enhancement of fresh water production. The results showed that the amount of water that was produced increased from 800 to 2,280 ml within 5 h (160–456 ml/s) due to the enhancement by the solar collector (see Fig. 2). It should be noted that the experiments were performed during the month of July (8 and 14) where the ambient temperature was 34 ± 3°C with cooling water flow rate of 10 ml/s. The solar irradiation in the 14th of July is presented in Fig. 3.

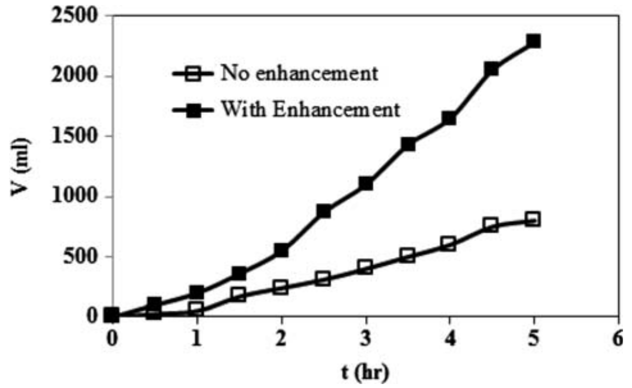

Fig. 2. The amount of fresh water produced with and without enhancement. The average ambient temperature is 34℃, $Q = 525 \pm 18\ W/m^2$, the cooling rate is 10 ml/s.

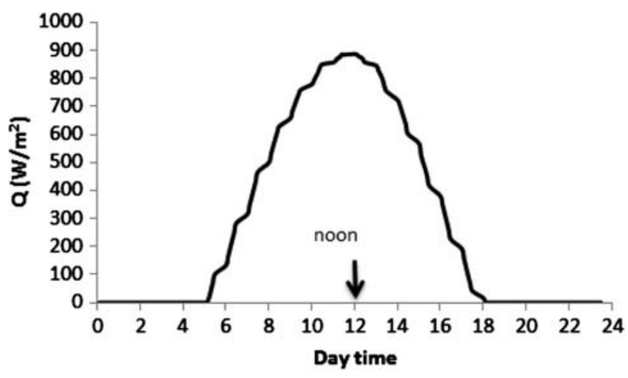

Fig. 3. The solar irradiation vs. day time (14 July 2011).

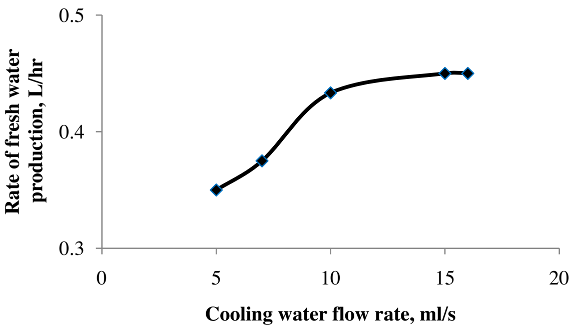

Fig. 4. The effect of cooling rate on fresh water production rate. The experiments were performed during the month of July where the average ambient temperature is 35 ± 2℃, $Q = 519 \pm 12\ W/m^2$.

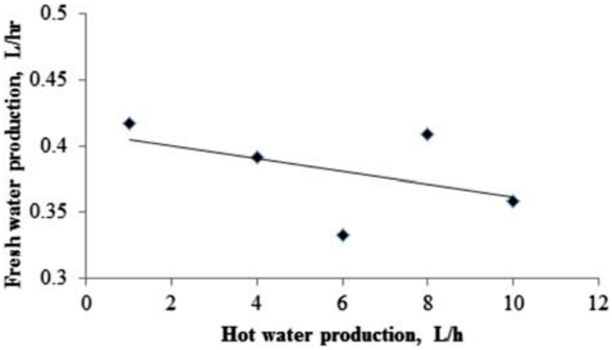

Fig. 5. Hot water production rate vs. fresh water production rate. The period of the experiments is 6 h and were performed during the month of July where the average temperature is 36.5 ± 3℃, $Q = 500 \pm 10\ W/m^2$. The cooling rate is 10 ml/s. The average hot water temperature in the basin during the experiments is 84 ± 3℃.

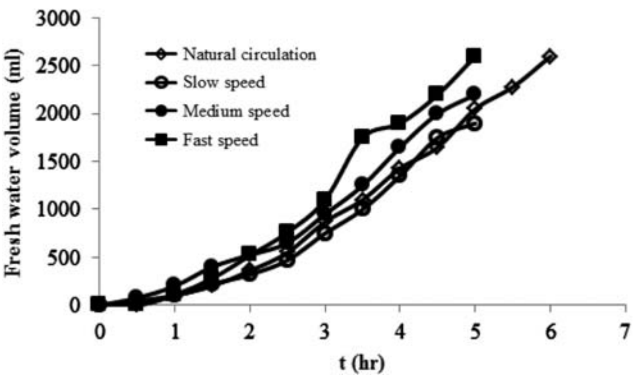

Fig. 6. The effect of circulation speed on the unit productivity. The experiments were performed during the month of August where the ambient temperature was 35℃, $Q = 509 \pm 19\ W/m^2$ and the cooling water rate was 10 ml/s.

The effect of cooling water flow rate is shown in Fig. 4. As can be seen, the productivity of the unit initially increases as the cooling water flow rate increases till it reaches 10 ml/s then no effect is noticed. The reason for this is that the cooling water lowers the temperature of the inner glass surface which enhances condensation hence fresh water production. However, when the cooling water flow rate becomes larger than 10 ml/s, the basin temperature drops. Consequently the evaporation rate decreases. The competition between the enhancement of the condensation and the decrease in evaporation causes the production of fresh water to become unaffected by increasing the cooling water flow rate.

The target of the unit is to produce both fresh water and hot water at the same time. Fig. 5 portrays the effect of hot water production on fresh water production. As can be seen the effect is moderate. Such result is important since it shows that the unit is capable of producing both hot and fresh water at the same

Table 1
Amount of fresh water produced during the working hours and overnight. The experiments were performed on 19 and 24 October where the ambient temperature was 27.5 ± 2.5℃

Cooling rate, ml/s	Production during working hours (9:00 am–4:00 pm), ml	Production after the working hours and overnight (4:00 pm–9:00 am), ml	Total production, ml
0	650	1,020	1,670
10	1,950	2,050	4,000

Table 2
The amount of fresh water produced, the average ambient temperature, the average irradiation rate, and the temperature of the hot water in the basin

Month	Fresh water produced (ml)	Average ambient temperature (℃)	Average irradiation W/m^2	Average hot water in the basin (℃)
14 July 2011	2,600	38	543	81
2 August 2011	2,050	35	502	82
27 September 2011	1,750	35	425	79
4 October 2011	1,300	31	410	81
15 November 2011	1,150	16	328	70
19 December 2011	930	19	309	43
26 January 2012	500	15	–	31

time. It should be noted that the duration of the experiments is 6 h and were performed during the month of July (21–28 July) from 9:00 am to 3:00 pm. The average ambient temperature was 36.5 ± 3℃. The cooling rate was 10 ml/s. The average hot water temperature in the basin during the experiments was 84 ± 3℃.

In the above experiments water circulation in the close loop was natural (thermo syphoning). The circulation rate is determined by the density difference between the hot and the cold sides of the collector which is mainly determined by the solar irradiation intensity. To investigate the effect of circulation rate on the productivity of the unit, a water pump of three different speeds—slow, medium, and fast—was installed on the water line that feeds the solar collector (see Fig. 1). The amount of water collected during 6 h is depicted in Fig. 6. The results showed that increasing the rate of circulation improves the unit productivity by 7 and 27% using the medium and the fast speed conditions respectively. The slow speed has no effect on the unit productivity. This is probably because operating the pump at the slow speed condition does not improve the water circulation compared to the natural one. It should be noted that the experiments were performed during the month of August (2 and 4) where the ambient temperature was 35℃ with a cooling rate of 10 ml/s.

After working hours the unit keeps on receiving solar irradiation for another 3 h and hence production of fresh water continues. Moreover the unit keeps the water in the basin hot for longer time since it is well insulated (note that the double layer glass cover insulates the unit from its top side). This leads to more fresh water production after sunset. Therefore the amount of fresh water produced after the working hours and sunset was measured. Table 1 shows the amount produced for the cases where the cooling water flow rate is 0 and 10 ml/s. It can be seen that the amount of fresh water produced after working hours and during night time is roughly 1.5 times more than that produced during the working hours when the cooling rate is 0 ml/s and roughly equals to that produced when the cooling rate is 10 ml/s.

To test the effect of solar irradiation on the productivity of the unit, experiments were performed in the months of July 2011–January 2012. The amount of fresh water produced during these months with a cooling water flow rate of 10 ml/s is depicted in Table 2. As expected fresh water production increases as the irradiation intensity increases. Measuring the temperature of the water in the basin showed that the unit is capable of producing hot water throughout the year which can be used for the various domestic purposes.

4. Conclusions

The unit designed in this work was capable of producing hot water with temperature as high as 87˚C during summer period. The unit was also capable of producing desalinated water with low salinity (2–6 ppm). The productivity of the unit was found to depend on the cooling water flow rate, the solar irradiation intensity, and weather conditions. The following conclusions can be drawn from the results of the experiments:

(1) Enhancement of the basin by a solar collector increased the productivity of the unit.
(2) Increasing the cooling water flow rate increased the productivity of the unit till a certain flow rate is reached after which no effect was observed.
(3) Production of hot water slightly decreases the productivity of the unit.
(4) Forced circulation of the water in the close loop at high speed and at medium speed improves the unit productivity by 27 and 7% respectively. Low speed circulation had no effect on the productivity of the unit.

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