Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.874113

53 (2015) 2875–2881
March

An empirical evaluation of an integrated inclined solar water desalination system with spray jets variation

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Received 25 August 2012; Accepted 19 November 2013

ABSTRACT

In this study, the productivity of an integrated inclined solar water desalination system with spray jets was empirically investigated. The effects of the feed water flow rate, solar radiation, ambient temperature, absorber plate temperature, cavity air temperature, glass cover temperature, variation in number of spray jets, and inlet and outlet temperature of the feed water on the daily production of the system were studied. The results show that the system productivity increases with two spray jets rather than with four and six jets tested on the system. The daily production also increases by cooling the system glazing and by solar radiation intensity. The inclusion of a wick (black cloth) on the absorber plate has a significant effect on the system production. The wick improved the daily production of the system by 23%. The daily production of the system with a wick on the absorber plate in the summer season is recorded as 6.41 kg/m^2 while the daily production with a bare plate absorber is recorded as 5.19 kg/m^2. The system (with wick) has a daily production of 3.327 kg/m^2 in the winter season. The experimental results in this study were compared with published data related to solar desalination units.

Keywords: Inclined solar water desalination system; Spray jets; Solar radiation; Wick; Daily production

1. Introduction

A solar desalination system is a simple device that uses the heat from solar energy to vaporize water, which later condenses at the glazing cover of the system. The solar desalination technique has witnessed many modifications over the years to improve its daily production. Some of the common types of solar desalination techniques include solar stills, incline water desalination, and humidification–dehumidification systems. For more than 50 years, solar stills remain the most extensively studied solar desalination technique. Some of the outstanding work on solar stills can be found in literature [1–19].

Most of the attempts to increase the daily production of solar stills are broadly classified into passive and active methods. The passive methods include the effect of dye on production [8–10], the effect of water mass on the daily production [11,12,15], the effects of wind on the thermal performance of the system

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[16,17], the effects of different types of insulation [17], and the effect of an external reflector [10]. The active method modification includes integrating the collector with the basin [18] and the use of the hot water produced for other purposes [1,19].

One type of solar desalination technique that still needs studying is the inclined solar water desalination system (ISWD). A few modifications found in literature for ISWD (a falling film approach to solar desalination in general) are given here [20–26]. Aybar et al. [20] designed and tested ISWD for the first time, and since then no major studies have been done on this system to improve the daily production and provide solution to some of the technical limitations faced in the study. In addition, Aybar [21], Abu-Arabi et al. [22], and Mousa et al. [23] have theoretically investigated this type of solar desalination system. Aybar's [21] theoretical investigation revealed that the system is capable of 3.5–5.4 kg/d m^2 daily production in a typical summer day, while Aybar et al.'s [20] experimental work carried out in 2005 gave the daily production of the system as 2.995 kg/d m^2. Abu-Arabi et al.'s [22] and Mousa et al.'s [23] theoretical work revealed that the maximum hourly production of their system can be 0.6 kg/h, but 0.26 kg/h was produced under normal conditions when the glazing cover temperature was not controlled.

In this paper, an experimental investigation of integrated ISWD with spray jets was performed in both summer and winter seasons. This design of the incline water desalination system aimed to solve some of the challenges (uneven distribution of feed water and low daily production) by Aybar et al. [20] and to improve the system's thermal performance, by re-injecting the hot water produced by the system into the feed tank, to raise the temperature of the inlet water.

2. Experimental set-up and instrumentation

The integrated ISWD system with spray jets was constructed and tested for daily performance and productivity in both winter and summer seasons. The system was tested with a bare plate absorber and also when the absorber plate was covered with black wick. Fig. 1(a) shows the schematic diagram of the improved ISWD system while Fig. 1(b) shows the pictorial view. The improved ISWD systems consisted of an absorber plate and a glass cover that creates a cavity. The cavity dimension was 1 m^2 with height of 0.2 m. A galvanized steel sheet of 0.4 cm was used as the absorber plate, which was painted matte black to increase the surface absorptivity (absorptivity of 0.96 and emissivity of 0.08). The cavity was constructed from a stainless steel sheet due to its better resistance to corrosion and the inner surface of the cavity was painted matte black. The outer surface was insulated at the sides and at the bottom was insulated with specialized foam. The insulation was needed to prevent heat losses from the stainless sheet material [17]. The system is covered with a 3 mm glass, with transmissivity of 0.88. The system was inclined at a 36° angle to optimally utilize the 1 m^2 surfaces (solar radiation incidence) of the plate and to allow water flow through the whole length and width of the surface. The system feed water was sprayed intermittently through the jet (nozzles) on the absorber plate (a variation in number of jet applies), the use of jets to spray water evenly on the absorber plate was to improve Aybar et al.'s [20] design.

Aybar et al. [20] used a longitudinal slot of 2 mm to feed in water to the system; the distribution of water through the longitudinal slot onto the absorber plate was not effective which affected the performance of the system. This challenge necessitated the replace-

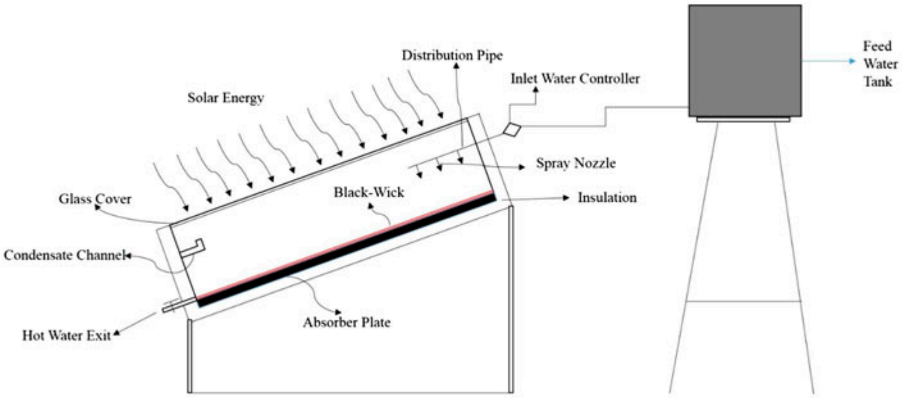

Fig. 1(a). Schematic diagram of the ISWD system.

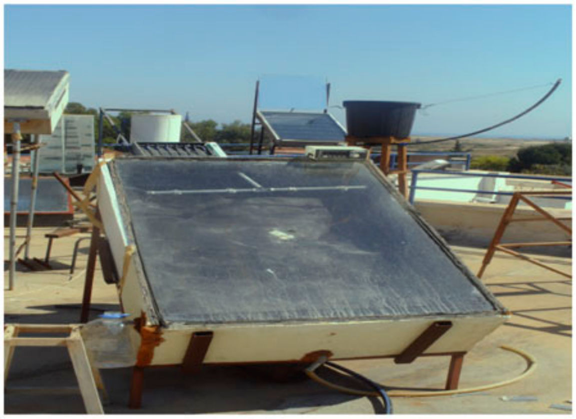

Fig. 1(b). Pictorial view of the ISWD system.

ment of the longitudinal slot with a spray jet where arrangements of two, four, or six jets were tested for optimal performance. The integrated ISWD system with spray jets was exposed to solar energy on a roof top to heat up the absorber plate/wick. The heat from the sun caused some of the water to evaporate and condense due to the temperature difference at the glass top cover. The condensate was collected through a condensate channel extracted from the cavity by a small pipe that extruded from the condensate channel to a plastic water collector outside the system. The remaining water (hot) in the ISWD was collected through an exit and re-fed to the feed water tank to increase the temperature of the feed water, thereby increasing the efficiency of the system.

The selection of materials for construction of the systems was carried out in accordance with AISI standard. The materials were purchased from local markets within the city of Famagusta, where they were relatively cheap. Thermocouples were fixed at various parts of the systems to measure the various necessary temperatures such as the absorber plate temperature, the air temperature, the inner glass temperature, the ambient temperature, and the feed water inlet temperature and the outlet temperature. The temperature readings were retrieved by a 10-Channel Digital Thermometer (MDSSi8 Series digital, Omega) ±0.5˚C accuracy. A calibration test was performed on the thermocouple before use, which returned an accuracy reading of ±0.15˚C. The solar radiation was measured using a Eppley Radiometer Pyranometer (PSP) coupled to a solar radiation meter model HHMiA digital, Omega 0.25% basic dc accuracy, and a resolution of ±0.5 ranging from a value of 0–2,800 W/m^2. The jets spray 0.375 L/min (using a tap setting, similar to conventional liquid flow meter, this setting was calibrated before each experiments) of water into the system cavity four times (total of 4 min) in 1 h (at 15 min interval). The nozzle is the full cone spray nozzle with 1 mm diameter, produced by TARAL Company in Turkey with nozzle type number 840 3014. The hourly measurements of the amount of distillated water and temperatures at different parts of the systems were taken using thermocouples attached with a 10-channel digital thermometer. Uncertainty associated with the experimental measurements is as recorded against the measurement instruments.

The instantaneous efficiency (η_{i}) of ISWD is defined as the ratio of the energy used for water production to the total solar radiation rate given by:

$$\eta_{\mathrm{i}} = \frac{Q_{\mathrm{ev}}}{HA_{\mathrm{b}}} \tag{1}$$

$$Q_{\mathrm{ev}} = M_{\mathrm{ev}}L \tag{2}$$

where Q_{ev} is the evaporative heat transfer (W), M_{ev} is the distilled water production rate (kg/m^2 h), A_{b} is the still base area (m^2), L is the latent heat of vaporization, and H is the total solar radiation falling upon the ISWS surface (W/m^2). ISWD daily efficiency, η_{d}, is obtained by summing up the hourly condensate production multiplied by the latent heat of vaporization, and divided by the daily average solar radiation over the solar cavity area and calculated from the following equation:

$$\eta_{\mathrm{d}} = \frac{\int_0^t m_{\mathrm{ev}} L\,dt}{3{,}600A\int_0^t H\,dt} \tag{3}$$

where t is the time and A is the area (m^2).

3. Experimental results and discussion

The performance of any solar desalination system depends on several parameters, such as the temperature of the absorber plate, the inlet water temperature, the cavity air temperature, the glass temperature, and the distribution of the feed water on the absorber plate [2,3,5,20]. Temperatures of measured parts increase with the time of day, when the solar radiation (as seen in Fig. 2) increases until their maximum values at 13:00 pm. Afterwards, the various temperatures decrease (the absorber, cavity air, glass, etc.) with the decrease in solar radiation and ambient temperature. The maximum temperatures achieved by the absorber plate, cavity air temperature, glass cover temperature, and ambient temperature were 82, 78, 62, and 38˚C for summer and 56, 50, 45, and 21˚C for winter.

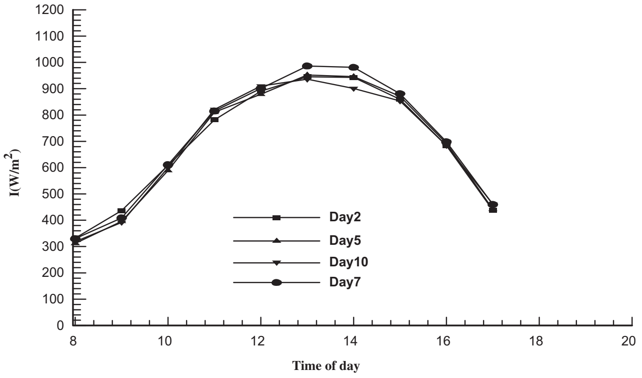

Fig. 2. Hourly variation of radiation intensity for some selected days in summer season. *Day 2 corresponding to 29 July 2010. *Day 5 corresponding to 1 August 2010. *Day 7 corresponding to 3 August 2010. *Day 10 corresponding to 6 August 2010.

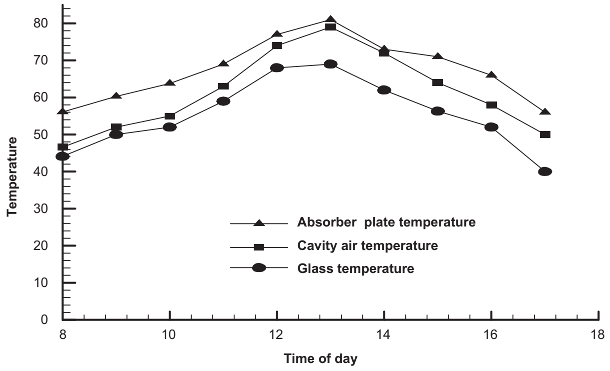

Fig. 3(a). Temperature distribution of the system (with wick) on a typical day (1 August 2010) in summer.

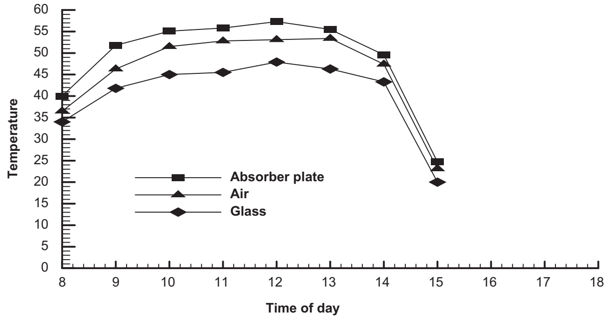

Fig. 3(b). Temperature distribution of the system (with wick) on a typical day (14 February 2011) in winter.

Fig. 2 shows the hourly solar radiation of the four selected days in summer; it will be observed that the hourly solar radiations are consistent over the period of the experiment. The absorber plate temperature, cavity air temperature, and glass surface temperature for a typical day in summer and winter are shown in Figs. 3(a) and 3(b). Figs. 3(a) and 3(b) presents the daily maximum and minimum obtainable temperatures for the plate absorber, the cavity air temperature and the glass temperature, where a wide temperature difference between the cavity air temperature and glass temperature will increase the condensation. In order to increase the temperature between the cavity air and the glass, the glass cover is cooled with water at 15 min intervals.

The ambient air temperature during a typical day in summer and winter is shown in Fig. 4. The ambient temperature, as seen in Fig. 4, is the temperature of the surroundings in which the experiment takes place. Fig. 4 shows the wide difference of ambient temperatures between the two seasons in which the experiments were performed; the consistency in weather conditions is also revealed over the said period of time. Figs. 5(a) and 5(b) shows the hourly inlet and outlet temperature for typical day in summer and winter. The hourly exit water was re-fed into the feed tank.

One major setback was that the exit water had to be collected over a period of 1 h before it was re-injected into the inlet feed system, thereby losing some heat energy (3–5˚C) to the surroundings. Also, observed was that there was no definite pattern in the inlet and out water temperatures due to daily variation in the solar radiation intensity. The feed water used in the experiment was 2,000–4,000 ppm brackish water. The fresh water produced as a result of condensation of the evaporated water in the system was collected and measured while the exit hot water was returned to the in-feed tank to increase the

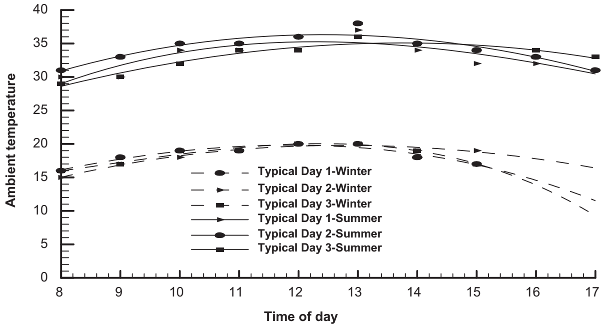

Fig. 4. Hourly variations of ambient temperature for some selected typical days in summer and winter. *Typical Day 1—Winter corresponding to 13 February 2011. *Typical Day 2—Winter corresponding to 14 February 2011. *Typical Day—Winter 3 corresponding to 15 February 2011. *Typical Day 1—Summer corresponding to 29 July 2010. *Typical Day 2—Summer corresponding to 1 August 2010. *Typical Day 3—Summer corresponding to 6 August 2010.

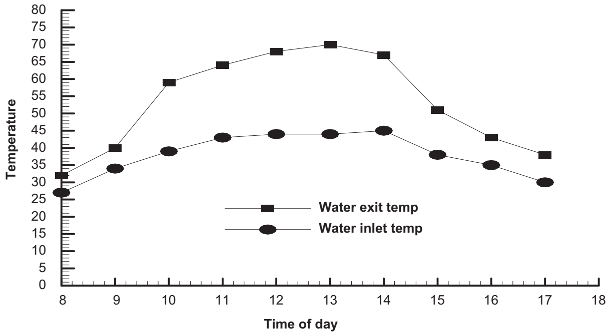

Fig. 5(a). Inlet and outlet temperature on a typical day (1 August 2010) in summer.

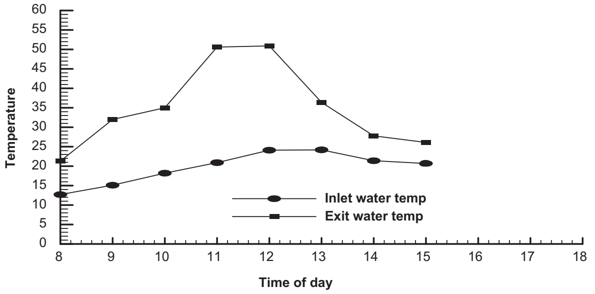

Fig. 5(b). Inlet and outlet temperature on a typical day (14 February 2011) in winter.

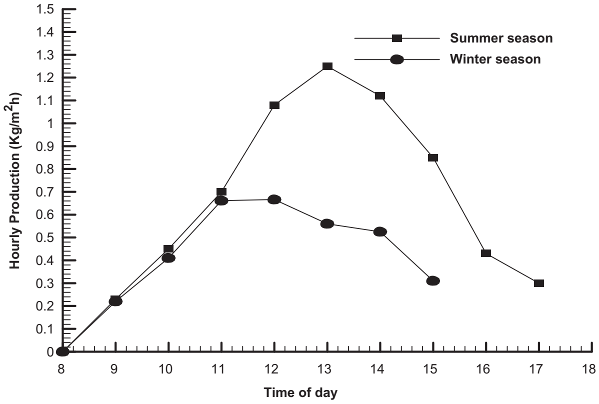

Fig. 6. Variations of hourly productivity with time for a typical day in summer and winter season (with wick system)*. *Typical Day—Summer corresponding to 1 August 2010. *Typical Day—Winter corresponding to 14 February 2011.

temperature of the water, thereby improving the system's efficiency. Fig. 6 shows the hourly production of fresh water from the improved ISWD for summer and winter. The early hour session of the hourly production of the system in summer and winter co-move, as they produced almost the same amount of fresh water; the only explanation for this could be that the effect of the re-injection of the exit water has little effect at this point.

The wide margin in hourly production was noticeable from 12 noon, when the temperature of the exit water had increased substantially for the summer season. The maximum daily production for the two weather conditions were 6.41 and 3.327 kg/m^2, respectively, as compared with Aybar et al. [20], who observed 2.99 kg/d m^2. The hardness of the fresh water produced ranges from 14 to 40 ppm depending on whether the absorber plate or the wick used.

The daily production of the system compared with other kind of solar desalination system is presented in Table 1. Fig. 7 shows the effect of number of jets on the hourly production of the system. Each jet sprays 0.375 L of water per minute into the system, and the use of 2 jets, 4 jets, and 6 jets were tested on the system, meaning that with increasing flow rate, the system produced more hot water than fresh water. The aim of this experiment was to improve the daily production of fresh water, so the hot water advantage had to be given off to increase the daily production.

It was also noticed that with increase flow rate (6 jets), the exit hot water temperature dropped, compared to when the flow rate (2 jets) was low. A major difference in the integrated ISWD with the jets system included a thicker absorber plate and the spray jet. The thickness of the absorber plate, 4 mm as compared to 2 mm used by Aybar et al. [20], played a major role in retaining heat energy and the spray jets' even and uniform distribution of the feed water to optimally utilize the thermal area. The efficiency of the improved ISWD system was at maximum at 13:00 h.

Fig. 8 shows the hourly production of the system with a wick on the absorber and without a wick on the absorber plate which is in agreement with similar studies in literature [17,20]. The efficiency of the improved ISWD system with a wick was the highest, followed by the efficiency of the system with the bare plate absorber, given as 50.3 and 47.2%, respectively. One major difficulty encountered in the system was the high glazing temperature; this problem was minimized by cooling the glass surface with water in order to increase the condensation under the glazing. The experiments were performed between the hours of 8:00 am and 5:00 pm from 25 July to 10 August 2010 when the summer weather in Famagusta was mostly sunny with clear skies. In winter time, the experiments were performed between 13 February and 20 March 2011, when sunshine was limited.

Table 1
Experimental results of selected solar desalination systems

No.	Name of system	Place	Ambient mean temperature (°C)	Production (kg/m^2 day)	Reference
1	Double condensing chamber unit	India	13	1.439	[27]
2	Double stepped plastic solar still	Italy	30	1.800	[28]
3	Single-basin solar still with deep basin	Egypt	28	2.045	[29]
4	ISWD with wick	N. Cyprus	30	2.995	[20]
5	Single-slope solar still	Jordan	25	3.560	[30]
6	Double-basin solar still with insulation	Bahrain	39	3.910	[31]
7	Single-slope solar still, asphalt cover	Jordan	29	4.120	[32]
8	Triple-basin solar still	Jordan	27	4.896	[33]
9	Distiller with a film in capillary motion	Algeria	40	5.190	[34]
10	Solar still coupled to outside condenser	Turkey	30	6.520	[35]
11	Improved ISWD bare absorber plate	N. Cyprus	34	6.410	
12	Improved ISWD with wick	N. Cyprus	34	5.130	
13	Improved ISWD with wick	N. Cyprus	19	3.327	

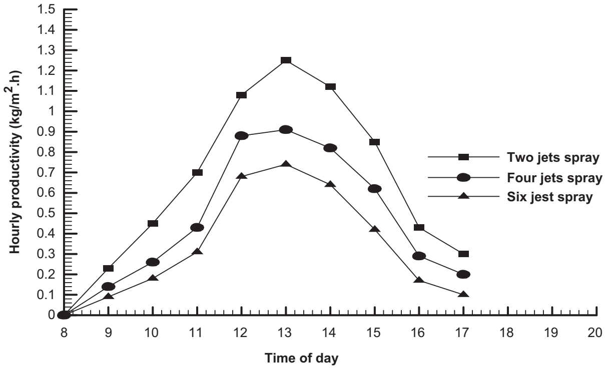

Fig. 7. Hourly production of the system with varied number of the spray jets (1 August 2010).

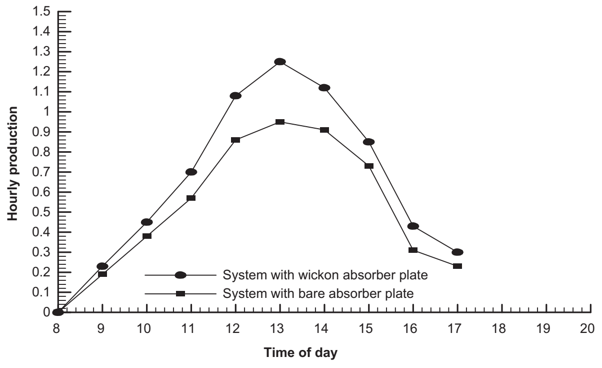

Fig. 8. Hourly production of the system with wick on the absorber plate and the system without wick for a typical summer day (1 August 2010).

4. Conclusion

This work investigated the performance of an integrated ISWD system experimentally, considering the effects of factors such as feed water flow rate, solar radiation, ambient temperature, absorber plate temperature, cavity air temperature, glass cover temperature, variation in number of spray jets, and inlet and outlet temperature of the feed water on the daily production of the system under the climatic condition of Famagusta, Northern Cyprus. It was found that the system, when tested with a wick on the absorber plate produced 6.41 kg/d m^2 of fresh water, while it produced 5.13 kg/d m^2 of fresh water when tested without the wick on the absorber plate. The glazing temperature was intermittently cooled with the brackish water to aid condensation. The number of jets was also varied to test for optimum performance of the system. The system is better in comparison to most other solar desalination systems, especially when in direct comparison with the work of Aybar et al. in 2005.

Acknowledgement

The authors gratefully acknowledge the technical and financial support of Research Center of College of Engineering, Deanship of Scientific Research, King Saud University.

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