Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1085917

57 (2016) 17167–17181
August

Taylor & Francis
Taylor & Francis Group

Performance analysis of single and double basin-inclined solar water distillation systems with and without black-fleece wick

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Received 31 March 2015; Accepted 12 August 2015

ABSTRACT

The aim of this study is to design and to test the double basin-inclined solar water distillation (DB-ISWD) system and compare it with the single basin-inclined solar water distillation (SB-ISWD) system under the northern Cyprus environmental conditions. The SB-ISWD and the DB-ISWD systems have the ability to produce both freshwater and hot water at the same time. In the SB-ISWD system, the feeding water falls down on the bare plate (BP) through the distribution pipe. The DB-ISWD system has two sections: the lower section and the upper section. In the lower section, the feeding water falls down on the BP through distribution pipe. In the upper section, the feeding water falls down on the transparent glass through distribution pipe. These systems are tested by two variants: BP and with black-fleece wick. It is observed that both systems show higher production rate of freshwater when the black-fleece wick is used. Also, the hot water production by both systems is hot enough for domestic appliances. In comparison of these two systems, the amount of condensate water and hot water produced by the DB-ISWD system is more than that of the SB-ISWD system.

Keywords: Solar distillation; Solar hot water; Wick

1. Introduction

Energy and water are two significant issues in environmental point of view. Both of them are playing a vital role in the improvements of economy over the entire world. Potable water is a basic human need and it is adversely affected by the pollutants made by human. Most of the water exists in the form of seawater and only limited sources of freshwater can be found in the surface of the earth, or deep in the earth, or as natural aqueducts. Most of the water sources contain salt, bacteria, and pollutants. To obtain fresh and potable water for drinking and domestic uses, the impure water is in a need to be distilled and processed. These inappropriate conditions lead to apply a method to purify water from impurities and salts to obtain potable and drinking water.

To produce potable water, large amount of energy is required. In the arid or semi-arid areas of the world, many people are suffering from the lack of potable water. In these areas, solar energy can be applied to run the desalination systems, and desalination systems

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are used to provide potable and freshwater. Consequently, running desalination systems by utilizing renewable energy such as solar energy is one of the best solutions to resolve the lack of potable and drinking water. A positive point of desalination systems is that they can be installed in the regions where there is no access to electricity or difficult to reach fossil fuels. Renewable energy sources, such as solar, or wind energy, have the potential to be used in order to run the desalination systems. The cost of utilizing solar energy to produce freshwater is reasonable and efficient, and also there is no remained pollutant from the process. The process of solar desalination is similar to the hydrological process of evaporation and condensation water which occurs in nature.

Solar desalination is a system that utilizes the sun energy (solar radiation) for the separation of water and salt. Classification of solar desalination varies depending on the techniques and energy supply. The most common type of solar desalination systems is the solar stills. Solar stills can be categorized into passive solar stills and active solar stills in terms of energy supply. Solar desalination systems can also be categorized by the techniques and design of the systems. These can be categorized as direct collection system or indirect collection system. The direct collection systems are the systems with all parts integrated into one system. The system uses the heat energy from the sun to produce water vapor that is later condensed on the glass cover of the system. The indirect collection systems are the ones with two subsystems. The solar energy is collected in one subsystem and the desalination takes place in the other.

Numerous scientists have been working on the conventional solar still by modifying it in order to increase the efficiency of this system. Different designs of the solar stills can be found in the literature; some of them are: single-basin [1], multi-basin [2], double-basin [3], wick-basin [4], and multi-use environmental type [5]. The efficiency of solar stills depends on many parameters. The effect of those parameters has been investigated in many studies, such as the effect of solar irradiation, ambient temperature, weather conditions, heat loss, and glazing material [6,7], the effect of dye, the effect of reflector [8–10], and the effect of water mass [11–13]. The effect of integrating a solar collector with the basin-type solar still is investigated [14], and the effect of the water heights in the basin is investigated in these systems as well [15]. The effect of floating perforated black plate on the performance of a solar still is investigated [16].

Recently, a falling film approach in solar distillation systems has been considered by several studies [17–21]. The falling film approach studies of Abu-Arabi et al. [17] and Mousa and Abu Arabi [18] have 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 the other researcher's studies [19–21], the film is established on flat plate or on tubes. In the case of flat solar absorber plate, the feed water is spread as a film on the plate which has a glass cover [19]. This way, the amount of water to be heated is reduced. Evaporation takes place from the falling film as it absorbs solar irradiation, and condensation occurs on the glass cover [20]. The heat and mass transfer coefficients of falling film evaporation and condensation are very high, which results in a higher system productivity [21].

Aybar et al. [22] have designed and tested the inclined solar water desalination (ISWD) system, and also Aybar [23] had a study for the mathematical modeling of the ISWD system. Aybar et al.'s [22] experimental work has showed that the freshwater production of ISWD system is about 3 kg/m^2 d. Aybar's [23] theoretical investigation has showed that the system is capable of 3.5–5.4 kg/m^2 d production in a typical summer day. Unlike a conventional solar still, in the ISWD systems, the feed water falls down on the absorber plate, and freshwater and hot water are produced simultaneously.

In order to improve the productivity of the ISWD system, a number of researchers have tested the ISWD system under different climates with different design configurations and operation parameters [24–35]. These modified designs are as follows: improved inclined solar water desalination (IISWD) system with spraying jet, improved inclined solar water desalination system with wire mesh (porous media) (IISWDWM), improved inclined solar water desalination system with wick (IISWDW).

The feed water in the IISWD system uses jets to spray water on the inclined absorber plate allowing the water to run down the absorber plate uniformly, till the whole area of the absorber plate is covered with water [24]. Since, it was first designed in 2005 by Aybar et al. [22], a couple of designs have emerged [25] by varying some specific parameters and various operation conditions in the first design to enhance the performance of the system. These parameters may be summarized as follows: bare plate (BP) and black-cloth wick [26] with regard to the inlet mass flow rate, and inclination angle, charcoal cloth wick on the absorber plate with different input water flow rates [27] in the ISWDS, reinjected hot water into the system as feed water, BP absorber, and various absorber thicknesses, black-cloth wicks (made up of natural cotton), and porous media (wire mesh) on the plate absorber under the different spraying jet numbers [28–31].

The freshwater production increases with low inlet mass flow rates and also inclination angle at 260, preferable for getting more freshwater production [26,27]. It has been observed that the improvement in the efficiency of the system is due to higher retaining capacity of wick, higher retention time for water, and efficient utilization of absorbed temperature [26]. It has been concluded that the black-cloth wick and the charcoal cloth are good materials to be used as an absorber/evaporator and also as a water transport medium to induce the better system performance [26,27]. The results of the above investigations have revealed that the introduction of spray jets to inclined solar water desalination was significant [28] and usage of the spray jet in the ISWDS leads to a better performance of the system [30,31]. The results show that the system productivity increases with two spray jets rather than with four and six jets tested on the system [25,29]. The daily production also increases by cooling the system glazing and by rising the solar radiation intensity, simultaneously. The inclusion of a wick made up of different materials with black color on the absorber plate has a significant effect on the system production [30,31]. It was seen that the wick improved approximately around 20 percent of the daily production of the system [29]. It can be concluded that reinjecting the hot water produced by the system into the feed tank raised the temperature of the inlet (feed) water and hence, improved the system's thermal performance [29]. Using the thicker absorber plate improved the efficiency and daily production [25]. It was seen that the efficiency dropped in winter season to be around 40%, while the daily efficiency was approximately found to be around 50% in summer [24].

Some researchers have been theoretically and experimentally worked 25 trays [32] and 4 trays [33] on the stepped-type basin-inclined solar stills for three variants: different depths, different exposure areas of the trays installed in the basin, and different temperatures of the saline water. In addition, to improve the productivity, small fins were integrated in the basin plate, and sponges were added in the trays [32]. Modifications such as sponges to increase the exposure area, sensible heat materials like sand, and metal scraps to increase the saline water temperature, glass cubes with dry salt, camphor, aluminum scraps, and charcoal to increase both saline water temperature and exposure area showed suitable improvement in the production rate [33]. Helmy et al. [34] has investigated experimentally the performance of a single basin-inclined solar water still with black-cloth wick moving on two rollers driven with a DC motor via a control circuit according to the OFF and ON periods. The clothes wick is immersed in water when the motor is ON and the wet clothes are subjected to solar radiation when the motor is in the OFF period. Results show that an ON period of 30 s is suitable and an OFF period of 25 min yields a maximum thermal efficiency. An inclined solar water distillation system was designed and tested [35] with four variants: BP, shaded bare plate (SBP), black-cloth wick (BCW), and shaded black-cloth wick (SBCW). Using the BCW helped the maintenance of water film on the absorber, and a shaded plate prevented the uppermost 25% portion of the glass surface from taking solar radiation, and a kind of chimney drilled on the glass surface improved the convective heat transfer to the atmosphere to increase the condensed water. The results showed that the use of bare cloth wick, shading plate, and both together increases the system efficiency by 3, 2, and 5%, respectively.

Recently, many authors [36–41] have investigated freshwater productivity in the inclined stepped solar stills. The performance of the weir-type stepped solar stills with and without PCM was studied [36,37]. The daily productivity and overall thermal efficiency with 30° tilted angle of solar still were theoretically found to be 6.7 and 5.1 kg/m^2 d; 64 and 47% for the still with and without PCM, respectively [36]. Total productivity and overall thermal efficiency with 20° tilted angle of the solar still with and without PCM were experimentally found to be 4.85 and 5.14 kg/m^2 d, 38.15 and 36.02%, respectively [37]. An extensive experimental investigation on a stepped solar still augmented with porous medium using flash evaporation with nozzle was carried out [38], and the results show that the unit daily productivity reaches 6.7 L/m^2 d and the average daily thermal efficiency reaches 77.35%. Velmurugan et al. [39] has designed a stepped solar still which consists of 50 trays with two different depths. First 25 trays with 10 mm height and the next 25 trays with 5 mm height are used and analyzed theoretically. In this study, fins, sponge, pebble, and combination of those are used for enhancing the productivity of the stepped solar still, and a maximum increase in the productivity of 98% occurs in stepped solar still when fin, sponge, and pebbles are used in this basin. Abdullah [40] has investigated the performance of a single slope passive solar still (conventional still) and stepped active solar still coupled with a solar air heater and glass cover cooling. Water productivity of stepped still increased by 112% over conventional still, when both of the hot air passing under the base of stepped still and glass cover cooling were used [40]. Three-stepped solar stills with different shapes of the basin surface area with the same overall dimensions are investigated experimentally [41]. The shape of the absorber surface provided in the basins of solar stills was flat, convex, and concave, respectively. When the convex and concave type-stepped solar stills are used, the average daily water production has been found to be 56.60 and 29.24% higher than that of flat type-stepped solar still, respectively [41].

Yeh et al. have worked on a downward-type double-effect solar still [42–45] and upward-type double-effect solar still [46–50], experimentally and theoretically. The studies related to upward-type double-effect solar still have reported the effect of air flow through the second-effect unit of upward-type double-effect solar distillers and the improvement in productivity for open-type distiller. Considerable improvements in productivity are obtained because of the reuse of latent heat, especially for high levels of insolation. The main disadvantage of a downward-type multiple-effect solar distiller is that water vapor must transfer from the lower side of the upper plate down to the upper side of the lower plate for condensation, while releasing the latent heat for reuse. Between the plates, there is a downward concentration gradient which is necessary for transferring water vapor. In the same direction, however, there also exists a temperature gradient which suppresses the free convection and also the mass transfer of the water vapor. Therefore, upward-type multiple-effect solar distiller may be more effective than a downward-type unit because it may create a free convection effect [46–48], while preserving the reuse of energy effect, thereby yielding an improved performance. It was reported that considerable improvements in performance were achieved either by reducing the operating pressure in solar distillers [49], or by creating an air flow through the last-effect unit of a still [44,45].

The main purpose of this study is to design and to test single basin and double basin-inclined solar water distillation systems. Both systems are run under North Cyprus climate conditions to find out the amount of productivity of freshwater and hot water. The effects of the BP and the covering absorber plate with black fleece on the production of freshwater and hot water are also studied.

2. Inclined solar water distillation systems

In this study, the original ISWD system is called as single basin-inclined solar water distillation (SB-ISWD) system hereafter. A new form of the SB-ISWD system is designed and named as double basin-inclined solar water distillation (DB-ISWD) system. SB-ISWD and DB-ISWD systems are constructed to obtain the experimental results of both of them and to compare with each other. The experiments were carried out by two different variants of absorber plate: as BP and covering with black fleece. Both systems are explained briefly in the following subsections.

2.1. Single basin-inclined solar water distillation (SB-ISWD) system

Fig. 1 shows a schematic diagram of the SB-ISWD system. The SB-ISWD system consists of a cavity made of galvanized steel and painted matte black absorber to increase its absorptivity. The length of the cavity is 100 cm, the width of the cavity is 50 cm, and the depth of the cavity is 20 cm, and an ordinary transparent glass with 4 mm thickness covers the cavity. A distribution pipe having length of 50 cm was placed at the top inside the box. There are several holes on the pipe to let the feed water drop on the BP. On the other side of the box, there is a channel located under the glass, to collect the running condensed water under the glazing. There is a hole in the middle bottom of the box to allow the remaining hot water get collected in a separate collector. Theoretically, it is being said that the best angle for a surface to get the most solar radiation is approximately equal to the latitude of the location. North Cyprus is located at 35˚N and 33˚E. The optimum angle for a tilted surface to get the most solar radiation is approximately the same as the latitude of the place, i.e. 35˚ with the horizontal facing the south of Famagusta.

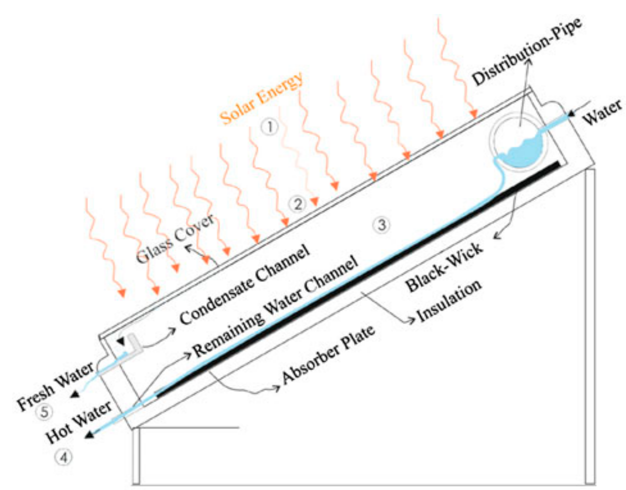

Fig. 1. Schematic view of the SB-ISWD system [22,23].
Notes: (1) ambient temperature measurement, (2) solar intensity measurement, (3) air–vapor mixture temperature measurement, (4) flowrate and temperature measurement of hot water, and (5) flowrate and temperature measurement of freshwater.

2.2. Double basin-inclined solar water distillation (DB-ISWD) system

Fig. 2 shows a schematic diagram of the DB-ISWD. Three sides of the double-inclined solar water distillation system, i.e. a base and inner side of two ends are made of galvanized steel, painted to matte black to absorb more solar radiation. The middle, and the two left and right sides, and also the top are covered with transparent glass having a thickness of 4 mm. DB-ISWD is divided into two sections: lower and upper sections. The lower section has a rectangular shape, the bottom is made of the galvanized steel, the two ends are made of galvanized steel as well, the top and other two sides, i.e. left and right inner sides are covered by glass. The upper section of DB-ISWD has two ends made by galvanized steel, the left and right inner sides, and the bottom and top are covered with a 4-mm thick transparent glass. In both lower and upper sections, there are pipes that have small holes along them to distribute the feeding water on the plate and the glass, and on the other end, there are channels to collect and allow the condensate water vapor get collected in collectors. And also, there are holes connected to the pipe to guide the remaining hot water get collected into separate tanks.

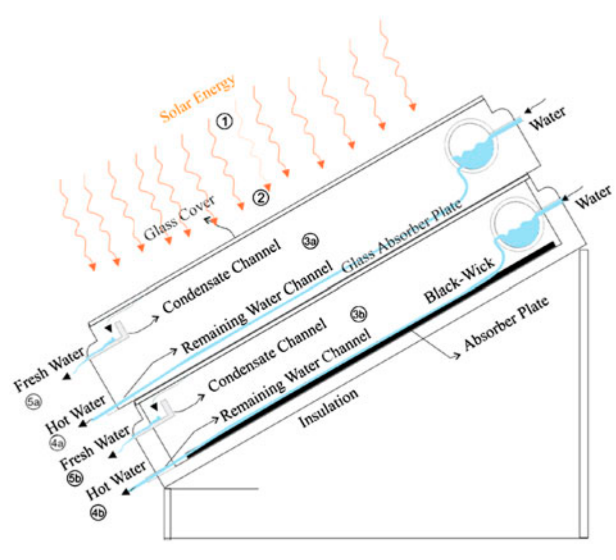

Fig. 2. Schematic view of the DB-ISWD System.
Notes: (1) ambient temperature measurement, (2) solar intensity measurement, (3a) air–vapor mixture temperature measurement in cavity 1, (3b) air–vapor mixture temperature measurement in cavity 2, (4a) flow rate and temperature measurement of hot water in the upper section, (4b) flow rate and temperature measurement of hot water in the lower section, (5a) flow rate and temperature measurement of freshwater in the upper section, and (5b) flow rate and temperature measurement of freshwater in the lower section.

2.3. Description of the thermal process of DB-ISWD system

Fig. 3 shows the definition of the thermal process on the double basin-inclined solar water distillation (DB-ISWD) system. T_a, T_p, T_{g1}, T_{g2}, T_{m1}, T_{m2}, $T_{h\text{-}w1}$, $T_{h\text{-}w2}$, T_{w1}, and T_{w2} in the figure are: ambient temperature, absorber plate temperature, glass cover1 temperature, glass cover2 temperature, air–vapor mixture temperature in the cavity1, air–vapor mixture temperature in the cavity2, hot water1 temperature, hot water2 temperature, feed water1 temperature, and feed water2 temperature, respectively. Q_{evap1}, Q_{evap2}, Q_{cond1}, Q_{cond2}, $Q_{r,g1\text{-}a}$, $Q_{c,g1\text{-}a}$, $Q_{r,g2\text{-}g1}$, $Q_{c,g2\text{-}w1}$, $Q_{r,p\text{-}g2}$, and $Q_{c,p\text{-}w2}$ are evaporation heat flux in cavity1, evaporation heat flux in cavity2, condensation heat flux in cavity1, condensation heat flux in cavity2, the radiation heat transfer from the glass cover1 to atmosphere at the temperature of T_a, the convection heat transfer from the glass cover1 to atmosphere at the temperature of T_a, the radiation heat transfer from the glass cover2 to glass cover1 at the temperature of T_{m1}, the convection heat transfer from the glass cover2 to feed water1 at the temperature of T_{m1}, the radiation heat transfer from the absorber plate to glass cover2 at the temperature of T_{m2}, and the convective heat transfer from the absorber plate to feed water2 at the temperature of T_{m2}, respectively. I_o, $I_1 = \tau_1\alpha_1 I_o$, and $I_2 = \tau_2\alpha_2 I_1$ are the solar insolations radiated on the glass cover1, glass cover2, and absorber plate, respectively.

2.4. Definition of the solar still efficiencies

2.4.1. Instantaneous efficiency

An instantaneous efficiency (η_i) of improved inclined solar water desalination is defined as the ratio

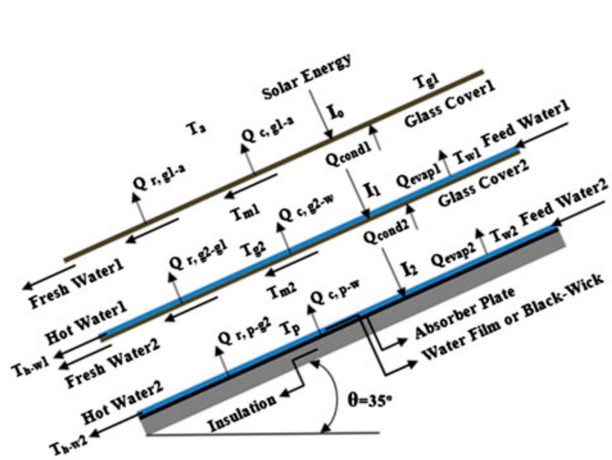

Fig. 3. Thermal process of the DB-ISWD system.

of the energy used for water production to the total solar radiation rate which is given by:

$$\eta_i = \frac{Q_{evap}}{HA_b} \tag{1}$$

where Q_{evap} is the evaporative heat transfer (W), A_b is the absorber plate area (m^2), and H is the total solar radiation falling upon the ISWD surface (W/m^2).

2.4.2. Daily efficiency

Daily solar still efficiency, η_d, is obtained by summing up the hourly condensate production multiplied by the latent heat of vaporization (L), and divided by the daily average solar radiation over the solar cavity area (this is the same as the length and breadth of the system), and calculated from the following equation:

$$\eta_d = \frac{\int_0^t \dot{m}_{evap} L\, dt}{3600 A_b \int_0^t H\, dt} \tag{2}$$

where t is the time (h), A_b is the area (m^2), L is the latent heat of vaporization (kJ/kg), and $\dot{m}_{evap}$ is the mass of distillate per hour (kg/h). The calculated daily efficiencies of the SB-ISWD and DB-ISWD systems are presented in the following section.

3. Experimental study

3.1. Instruments and accuracy

The errors occurred in the measuring instruments were calculated. K-type thermocouples, digital thermo-hygrometer (MDSSi8 series digital, Omega), and Eppley pyranometer coupled with a solar radiation meter and graduated cylindrical vessel are used for measuring the temperature, air humidity in the cavities, solar intensity, and distillate collection, respectively. The minimum error occurred in any instrument is equal to the ratio between its least count and minimum value of the output measured. The accuracies of various measuring instruments used in the experiments are given in Table 1.

3.1.1. Temperature measurement

Thermo-hygrometer was used to measure the precise amount of temperature or humidity from the desalination systems. K-type thermocouple connected with thermo-hygrometer was used for taking temperature from the systems. A calibration test was carried out on the thermocouple; the result agrees with the stated accuracy from the manufacturer (±0.25). The K-type thermocouples were fixed at different locations within the system for the temperature data. The temperature data were retrieved by a 10-channel digital thermo-hygrometer (MDSSi8 series digital, Omega) with ±0.5℃ accuracy, and frequency of measurement is 30 s for 63% different steps. For the humidity the ranges of measurement are from 2 to 98% RH, accuracy 3% @ 25℃, between 20 and 90% of range 5% @ 25℃, below 20% or above 90% and the response time 30 s for the 30–80% step change. So using this device, the temperature of the freshwater, and hot water, and also the temperature of the cavities, and ambient were measured.

3.1.2. Radiation measurement

To measure the global solar irradiation on the surface of objects in the world, a pyranometer is used. This device has the ability of 180 degrees of view. Thermopile sensor has a black coating, which absorbs the solar radiation. This kind of sensors creates a voltage signal proportional to the solar irradiance and then the solar irradiance is converted to heat in the pyranometer. The pyranometer was located over a glass surface of the single basin and DB-ISWD systems to measure and obtain the irradiance onto the cavity and system's cavity. An Eppley radiometer pyranometer was coupled with a solar radiation meter model HHM1A digital, Omega with a 0.25% basic DC accuracy and a resolution of ±0.5% from 0 to 2,800 W/m^2. The radiation was recorded hourly.

3.1.3. Flow rate measurement

Measuring or graduated cylindrical vessel is a piece of the equipment which is used in the laboratory, and also used to measure the volume of the liquids. Measuring vessels are generally more accurate and precise than beakers and laboratory flasks. However, they are less accurate and precise than volumetric glassware, such as a volumetric pipette or volumetric flask. Usually, the largest measuring vessels are made of polypropylene for its excellent chemical resistance and transparency, making them lighter and less fragile than glass. The typical graduated cylindrical vessel capacities are between 5 ml and 2,000 ml; they have the scale along the length and easily can be read by eye to determine the volume of the liquid. The graduated cylindrical vessel used in this work with an accuracy of ±5 ml had a capacity of maximum 1,000 ml, and used to measure the volumes

Table 1
Accuracies and ranges of the measuring instruments

Sl. No.	Instrument	Accuracy	Range	Error (%)
1	K-type thermocouple	±0.25˚C	0–100˚C	0.10
2	Digital thermo-hygrometer	±0.5˚C	0–200˚C	0.10
		3–5% RH	2–98% RH	0.5
3	Eppley pyranometer	±5 W/m^2	0–2,800 W/m^2	0.25
		DC accuracy: 0.25%		
		Resolution: ±0.5%		
4	Graduated cylindrical vessel	±5 ml	0–1,000 ml	5

of the freshwater and hot water obtained from the inclined and double-inclined solar water distillation systems.

3.2. Experimental procedure

A SB-ISWDS and DB-ISWDS are promising a technique to produce potable or drinkable water and hot water for domestic applications. The experiments were performed under North Cyprus climate and weather condition of the Famagusta. The Famagusta city is located at 35.3˚N latitude and 33.9˚E longitude. For both systems, the absorber of solar collector was tilted by 35˚ angle with horizontal corresponding to the latitude. The SB-ISWDS and DB-ISWDS experiments are conducted from 21 October 2013 to 25 October 2013 for BP, and 27 October 2013 to 31 October 2013 for black fleece from 09:00 am to 04:00 pm. Fig. 4 shows the SB-ISWD and DB-ISWD systems, and the experimental setup of DB-ISWD system.

The water from the reservoir tank through the pipes is distributed in both the SB-ISWD and DB-ISWD systems in both lower and upper sections simultaneously with certain mass flow rate. The feeding water drops from the spots (holes) that are made along the pipes into the cavity and gradually flows on the BP of the SB-ISWD, and the BP of the DB-ISWD, and also on the glass surface of the upper section on the DB-ISWD unit. Sun radiates on both systems, and the water starts to be heated, and water evaporates. Water vapor sticking on the glass gradually starts to be cooled and then water vapors condense on the inner glass which runs down to channels that were provided to collect freshwater. The remaining water that did not become vapor gets heated and collected in a separate tank as hot water. This work has been tested by two variants as explained, the first test was

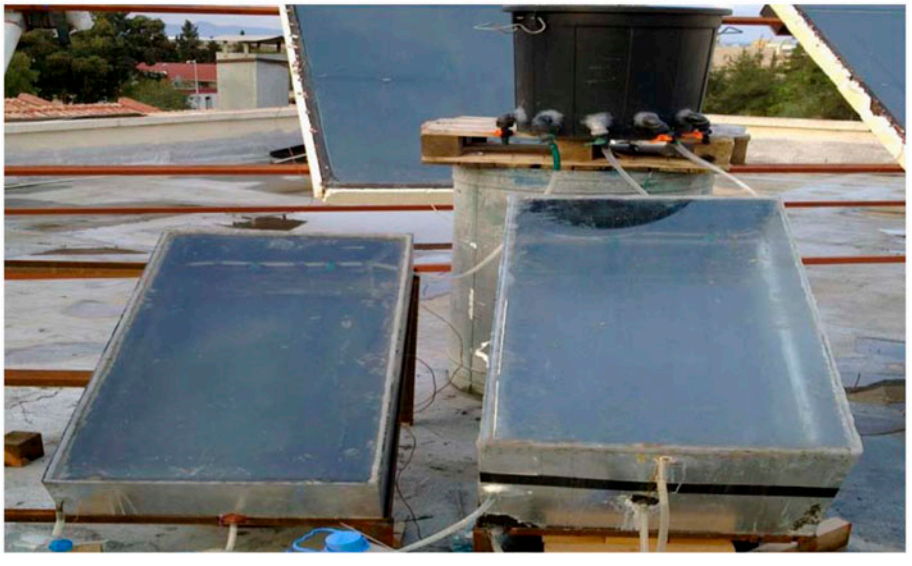

Fig. 4. Pictorial view of SB-ISWD and DB-ISWD systems.

with BP, and the second test was carried out using black fleece covering over the surface of the plates. In the SB-ISWD system, in the second test, some black fleece has put over the surface of the BP on the bottom of the box. The black fleece makes a thicker film of water and the distribution of water became even. So using black fleece, the water kept longer time in the system and promises more vapor production that results in more freshwater.

In the second test of DB-ISWD, the BP in the lower section was covered with black-fleece wick. Same procedure which was used in SB-ISWD system was conducted in the DB-ISWD system and nothing changes for the upper section in the middle side of the DB-ISWD system.

Every hour, the amount of freshwater and hot water produced by the single basin and DB-ISWD systems was measured. Also, the solar intensity, air temperature in the cavity, and the temperatures of the fresh and hot water, and also the ambient temperature in front of the sun and the shade were measured. The same measurements were done for both lower and upper sections of DB-ISWD system.

4. Results and discussion

The experiments were conducted under Famagusta climate condition in Northern Cyprus in the EMU at the Mechanical Engineering Department roof. Famagusta is located at 35.3˚N latitude and 33.9˚E longitude. In the experiments of both systems, namely SB-ISWD and DB-ISWD are run simultaneously. The first experiment was carried out from 21st to 25th of October 2013 from 09:00 am to 04:00 pm using BP for SB-ISWD, and DB-ISWD in the lower section, and glass surface for the upper section. The second test was conducted from 27st to 31th of October 2013 from 09:00 am to 04:00 pm using black-fleece wick for SB-ISWD, and DB-ISWD lower section, and glass surface for the upper section of DB-ISWD. During the experiments, solar intensity, ambient temperature, cavity air temperature, hot water temperature, and the amount of produced freshwater are measured. The results of five repeated experimental runs for each case are averaged. The main aim of these tests is to compare the performance of the SB-ISWD system with the DB-ISWD system in terms of freshwater productivity, hot water temperature, and daily efficiencies of these two systems together. In this study, the results are presented using graphs and the systems' performances (efficiencies) were evaluated using the amount of produced freshwater.

4.1. Effect of solar radiation and ambient air temperature

Different parameters are affecting the amount of water production in solar stills. These parameters include solar radiation and ambient air temperature. Of course, there are some other parameters which affect the solar still production, but in this study, the solar radiation and ambient air temperature are measured. The ambient temperatures and the solar radiation were measured for both single basin and DB-ISWD system. Figs. 5 and 6 show the hourly average of ambient temperatures and solar intensity during the experiments with BP and with black-fleece wick, respectively. The maximum solar radiation occurs at noon time and the solar radiation intensity plays a vital role in the output of these systems.

The vertical axes in the left-hand side and the right-hand side of graph show hourly average solar intensity and ambient temperatures, respectively, for SB-ISWD with BP, DB-ISWD with lower section with BP, and DISWD with upper part with glass surface of DB-ISWD system. The ambient temperature and solar intensity vary hourly as expected corresponding to the duration of the experiment. Fig. 5 shows that the maximum ambient temperature and solar intensity occur at 01:00 pm for both systems in the first test.

The vertical axes in the left side and the right side of graph show the average solar intensity and ambient temperatures, respectively, for SB-ISWD with black-fleece wick, DB-ISWD with lower part with black-fleece wick, and DB-ISWD with upper part which is the glass surface of DB-ISWD system. The ambient temperature and solar intensity vary hourly as expected due to the duration of the experiment. Fig. 6 shows that the maximum ambient temperature and solar intensity occur at 01:00 pm for both systems in the second test.

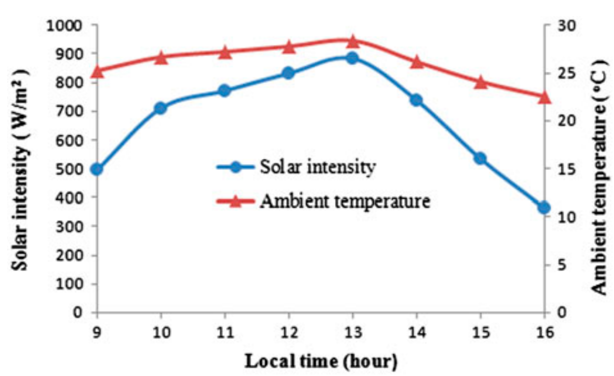

Fig. 5. The average solar intensity and the average ambient temperatures from the repeated experiments of 21st to 25th of October 2013 (both systems are run with BP).

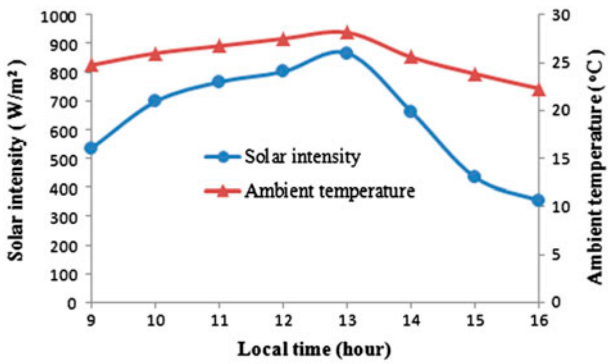

Fig. 6. The average solar intensity and the average ambient temperatures from the repeated experiments of 27th to 31st of October 2013 (both systems are run with black-fleece wick).

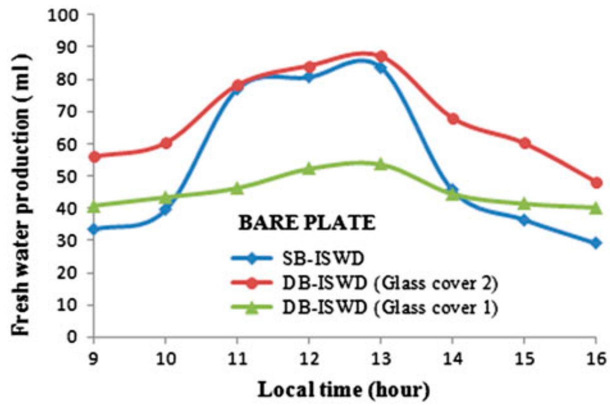

Fig. 7. The freshwater production of both systems. Both systems are run with BP.

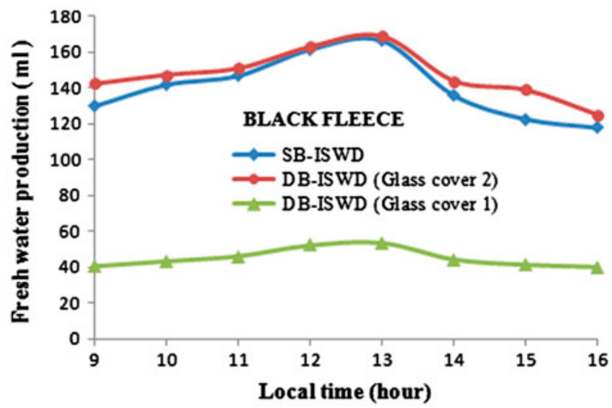

Fig. 8. The freshwater production of both systems. Both systems are run with black-fleece wick.

4.2. Freshwater production

The freshwater produced by SB-ISWD (BP), DB-ISWD lower section with BP, and DB-ISWD upper section with the glass surface of the first test was measured and the hourly average of freshwater production was plotted in Fig. 7. As it can be seen in this figure, the amount of freshwater produced by DB-ISWD lower section (BP) is more than that of SB-ISWD (BP) and DB-ISWD upper part (glass surface) in the first test. The averages of the highest amount of freshwater produced by SB-ISWD (BP), DB-ISWD lower (BP), and DB-ISWD upper (glass surface) parts in the first test were 83.7, 87.2, and 53.6 ml/hr, respectively.

The freshwater produced by SB-ISWD (black fleece), DB-ISWD lower section with black fleece, and DB-ISWD upper section with glass surface of the second test was measured and the hourly average of freshwater production was plotted in Fig. 8. As it can be seen in this figure, the amount of freshwater produced by DB-ISWD lower section (black fleece) is more than the amount of freshwater produced by SB-ISWD (black fleece) and DB-ISWD upper part (glass surface). The averages of the highest amount of freshwater produced by SB-ISWD (black fleece), DB-ISWD lower (black fleece), and DB-ISWD upper (glass surface) in the second test were 166.4, 169 and 53.18 ml/hr, respectively.

When these figures (i.e. Figs. 7 and 8) are compared, it is observed that freshwater production was increased with black-fleece wick. The black-fleece wick keeps more water on the absorber plate and makes a thicker water film which caused the higher evaporation rate and thus a higher rate of freshwater production. The amount of freshwater production in the lower section of DB-ISWD system is very close to the amount of freshwater production in the SB-ISWD system for the case of black-fleece wick (see Fig. 8). In the case of BP (Fig. 7), they are close. For both the cases (i.e. Figs. 7 and 8), the DB-ISWD system produces more freshwater than the SB-ISWD system. For example, at 11:00 local time in Fig. 7, the freshwater production of DB-ISWD system is about 50% more than SB-ISWD system.

4.3. Hot water temperature

Using thermocouples, the temperature of hot water was measured. Fig. 9 shows the hourly average variation of the hot water temperatures of SB-ISWD and DB-ISWD systems in Test 1 as follows. This figure reveals the hourly average of hot water temperature for SB-ISWD (BP), DB-ISWD lower (BP), and DB-ISWD upper (glass surface) in the Test 1. The highest amount of hourly average of hot water

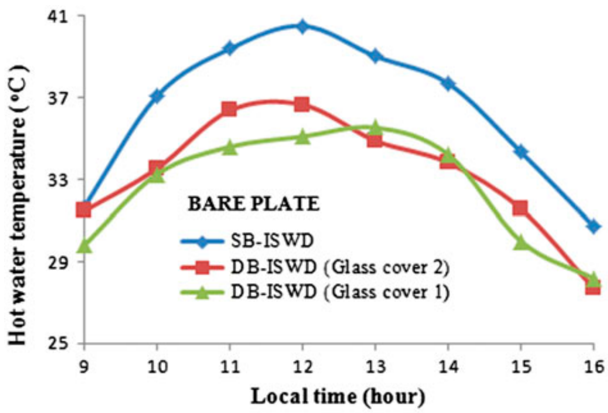

Fig. 9. The hot water temperature of both systems. Both systems are run with BP.

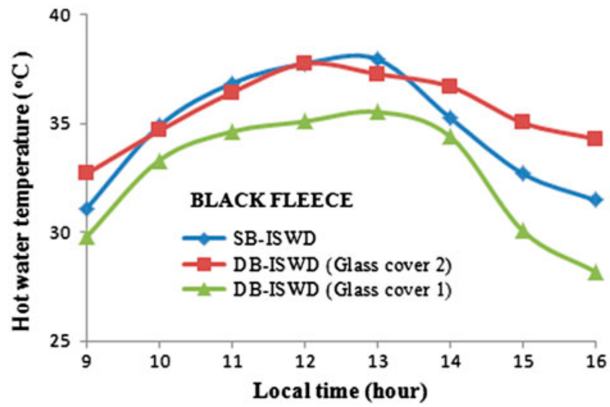

Fig. 10. The hot water temperature of both systems. Both systems are run with black-fleece wick.

temperatures of SB-ISWD (BP), DB-ISWD lower (BP), and DB-ISWD upper (glass surface) was 40.52, 36.66, and 35.54°C respectively.

Fig. 10 shows the hourly average variation of the hot water temperatures of SB-ISWD and DB-ISWD systems in the Test 2 as follows. This figure reveals the hourly average of hot water temperature for SB-ISWD (blackfleece), DB-ISWD lower (black fleece), and DB-ISWD upper (glass surface) of the Test 2. The highest amount of hourly average of hot water temperatures of SB-ISWD (black fleece), DB-ISWD lower (black fleece), and DB-ISWD upper (glass surface) is 37.96, 37.76, and 35.24°C respectively.

Both systems produce hot water as well. The maximum average of hot water temperature is 40°C for SB-ISWD system and 36°C for DB-ISWD system. In case of black-fleece wick, the maximum average of hot water temperature is about 37°C for both systems.

4.4. Daily still efficiency

Fig. 11 shows the hourly average of efficiencies of SB-ISWD and DB-ISWD systems in Test 1 and Test 2 as follows. The still efficiencies were calculated by Eq. (2). This figure reveals the hourly average of efficiencies of SB-ISWD and DB-ISWD obtained using BP and black fleece in both systems on the covering of the following days: from 21 October to 25 October for the Test 1 and from 27 October to 31 October for the Test 2 in 2013.

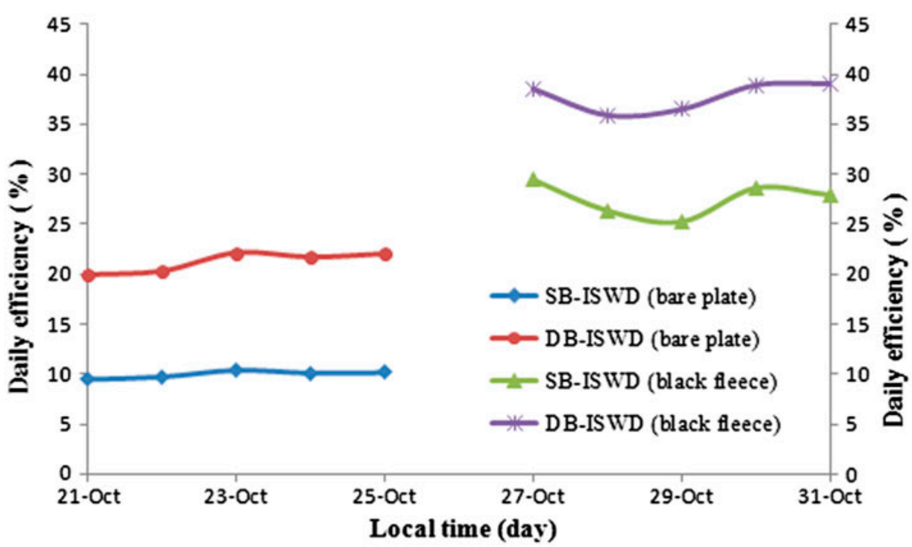

Fig. 11. Daily efficiencies of both SB-ISWD and DB-ISWD systems with BP and black fleece.

Table 2
Summaries of some studies

System type	Daily/hourly production $(kg/m^2\ d)/(kg/m^2\ h)$	η_d (%)	Explanation	Refs.
ISWD	3.23/0.461 (without COGT)	–	Distilled time: 9 am to 16 pm	[17]
	4.2/0.6 (with COGT)	–	Absorber plate: with cloth wick	
			Feed water flow type: falling down	
ISWD	2.6/0.26 (without COGT)	–	Distilled time: 10 h/d	[18]
	6.0/0.6 (with COGT)	–	Absorber plate: with black-cloth wick	
			Feed water flow type: falling down	
ISWD	2.995/0.428 (with BFW)	–	Distilled time: 9 am to 16 pm	[22]
	1.705/0.243 (with BCW)	–	Feed water flow type: falling down through the	
	1.290/0.184 (with BP)	–	distribution pipe	
ISWD	3.5–5.4/0.292–0.45 (with BP)	–	Distilled time: 12 h/d	[23]
		–	Water flowing type: falling down	
IISWD	6.41/0.534 (in summer)	52.4	Distilled time: 7 am to 19 pm in summer	[24]
	3.327/0.475 (in winter)	43.6	8:30 am to 15:30 pm in winter	
			Absorber plate: cloth wick	
			Feed water flow type: two spraying jets	
ISWD	2.22/0.37 (with BP)	7.66	Distilled time: 9 am to 15 pm (BP)	[26]
	4.8/0.8 (with BCW)	19.2	10 am to 16 pm (BCW)	
			Feed water flow type: falling down	
ISWD	4.78/0.683 (with CC)	53	Distilled time:10 am to 17 pm	[27]
			Feed water flow type: falling down	
IISWD	6.41/0.712 (with CW)	59.41	Distilled time: 8 am to 17 pm in summer	[29]
	5.13/0.57 (with BP)	48.3	Feed water flow type: two spraying jets	
			System glazing: cooling	
ISWD	3.25/0.361	40.1	Distilled time: 8 am to 17 pm	[25,28]
			[25,28,30] and [31] obtained the results for the Ref. [22]	[30,31]
			to control systems	
IISWD	5.46/0.607 (with BP)	48.3	Distilled time: 8 am to 17 pm	[25,28]
			Feed water flow type: two spraying jets	[30,31]
IISWDW	6.41/0.712 (with CW)	50.3	Distilled time: 8 am to 17 pm	[25,28]
			Feed water flow type: two spraying jets	[30,31]
IISWDWM	3.03/0.337 (with WM)	32.6	Distilled time:8 am to 17 pm	[25,28]
			Feed water flow type: two spraying jets	[30,31]
ISWD	1.01/0.126 (SSS)	–	Distilled time: 9 am to 17 pm	[32]
	1.76/0.22 (with FT)	–	Absorber plate: with trays on the SGAP	
	1.62/0.203 (with ST)	–	Feed water flow type: falling down on the absorber plate	
	1.98/0.248 (F and ST)	–	through the distribution pipe	
ISWD	1.24/0.155 (CSS)	34.46	Distilled time: 9 am to 17 pm	[33]
	1.78/0.223 (with sponges)	44.11	Absorber plate: four trays on the stepped glass absorber	
	1.94/0.242 (with sand)	42.70	plate	
	2.25/0.281 (charcoal)	43.07	Feed water flow type: falling down through the	
	2.48/0.31 (metal scraps)	44.8	distribution pipe	
	2.72/0.34 (camphor)	46.52		
	2.98/0.372 (dry salt)	48.24		
ISWD	0.58/0.072 (OF period 5 min)	39	Distilled time: 8 am to 16 pm	[34]
		45	Distilled time: 8 am to 16 pm	
	0.65/0.081 (OF period 10 min)	46	Distilled time: 8 am to 14 pm	
		40	Distilled time: 8 am to 14 pm	
	0.5/0.083 (OF period 15 min)	36	Distilled time: 9 am to 15 pm	
		47	Distilled time: 8 am to 16 pm	

(*Continued*)

Table 2 (*Continued*)

System type	Daily/hourly production (kg/m^2 d)/(kg/m^2 h)	η_d (%)	Explanation	Refs.
	0.73/0.122 (OF period 20 min)	38	Distilled time: 8 am to 15 pm	
	0.44/0.073 (OF period 30 min)	24	Distilled time: 8 am to 16 pm	
	0.92/0.115 (OF period 40 min)			
	0.58/0.083 (OF period 50 min)			
	0.25/0.031 (OF period 60 min)			
ISWD	2.01/0.223 (with BP)	33.8	Distilled time: 9 am to 18 pm	[35]
	2.144/0.238 (with SBP)	37.2	Feed water flow type: falling down through the	
	2.718/0.302 (with BCW)	39.2	distribution pipe	
	2.798/0.310 (with SBCW)	39.4		
ISWD	5.1/0.392 (without PCM)	47	Distilled time: 8 am to 21 pm	[36]
	6.7/0.515 (with PCM)	64	Absorber plate: stepped absorber plate	
			Feed water flow type: falling down	
ISWD	6.7/0.744 (PM)	77.35	Distilled time: 9 am to 18 pm	[37]
			Absorber plate: stepped absorber plate	
			Feed water flow type: spraying jets	
ISWD	1.66/0.207 (CSS)	–	Distilled time: 9 am to 17 pm	[38]
	2.54/0.317 (with fin)	–	Absorber plate: with trays on the SGAP	
	2.74/0.342 (with F and P)	–	Feed water flow type: falling down through the	
	2.8/0.35 (with F and S)	–	distribution pipe	
	3.30/0.412 (with F, P and S)	–		
ISWD	3.4/0.142 (CSS)	34	Distilled time: 24 h/d	[39]
	4.35/0.181 (with BP)	48	Absorber plate: stepped absorber plate	
			Feed water flow type: falling down through	
	5.4/0.225 (with AF)	55	the distribution pipe	
	5.6/0.233 (with GCC)	59		
	6.3/0.262 (with AH)	52		
	7.2/0.3 (with AH and GCC)	72		
ISWD	1.06/0.151 (with FS)	–	Distilled time: 10 am to 17 pm	[40]
	1.37/0.196 (with concave S)	–	Absorber plate: stepped absorber plate	
	1.66/0.237 (with convex S)	–	Feed water flow type: falling down	
ISWD	4.85/0.693 (without PCM)	36.02	Distilled time: 10 am to 19 pm	[41]
		38.15	Absorber plate: stepped absorber plate	
	5.14/0.734 (with PCM)		Feed water flow type: falling down	
SB-ISWD	0.85/0.121 (with BP)	9.976	Distilled time: 9 am to 16 pm in winter	Present
	2.245/0.321 (with BF)	27.518	Feed water flow type: falling down	study
DB-ISWD	1.808/0.258 (with BP)	21.248	Distilled time: 9 am to 16 pm	Present
	3.086/0.441 (with BF)	37.784	Absorber plate: lower section with BP	study
			or BF; upper section with transparent glass	
			Feed water flow type: falling down	

The highest amount of hourly average efficiencies of SB-ISWD (black fleece) and DB-ISWD (black fleece) is 29.44% on the 27 October, and 39.07% on the 31 October in 2013, respectively, while the highest amount of hourly average of efficiencies of SB-ISWD (BP) and DB-ISWD (BP) is 10.40 and 22.16% on the 23 October in 2013, respectively.

The overall daily still efficiency in each design increased with an increase in the accumulated yield due to an increase in the daily total solar radiation received by the water in the cavity, and also with the effect of the design improvements on the solar stills, which are SB-ISWD and DB-ISWD designs used BP and black fleece. Hence, the design improvements lead to well-contacted water on the absorber plate with the heat supplied from the sun in the glazing cavity.

Table 2 shows the system type, average daily/hourly production, average daily efficiency, and description of the systems in comparison with other solar desalination systems. The double basin-inclined solar water desalination (DB-ISWD) systems in comparison with other single basin solar desalination systems, as shown in the table, placed the design among the best solar desalination systems.

5. Conclusion

The present work proposes an experimental study to distill the brackish water using SB-ISWD and DB-ISWD systems with two different variants (BP and black fleece). The study was carried out under the climate conditions of Famagusta; Northern Cyprus, from 21st of October to 25th of October 2013 for the Test 1, and from 27th of October to 31st of October 2013 for the Test 2.

One of the most important factors that affects the productivity of an inclined solar water distillation system and double-inclined solar water distillation system is solar radiation. As the solar radiation increased, the productivity of freshwater also increased.

According to the results obtained from the first test, the average of the highest amount of freshwater produced by SB-ISWD and DB-ISWD was measured as 83.7 and 140.8 ml/h, respectively. In the first test, the highest hourly average efficiencies for SB-ISWD and DB-ISWD systems were evaluated as 10.40 and 22.16%, respectively. Therefore, the freshwater production rate and the efficiency of DB-ISWD system were greater than SB-ISWD system, DB-ISWD was the preferred system. According to the results obtained from the second test, the average of the highest amount of freshwater produced by SB-ISWD and DB-ISWD was measured as 166.4 and 222.18 ml/h, respectively. In the second test, the highest hourly average efficiencies for SB-ISWD and DB-ISWD systems were evaluated as 29.44 and 39.07%, respectively. Hereby, the freshwater production rate and the efficiency of DB-ISWD system were greater than SB-ISWD system, DB-ISWD was the preferred system.

Nomenclature

A_b	—	absorber plate area (m^2)
H	—	total solar radiation falling upon the surface (W/m^2)
I_o	—	insolation received by glass cover1 (W/m^2)
I_1	—	insolation received by glass cover2 (W/m^2)
I_2	—	insolation received by bare plate (W/m^2)
L	—	latent heat of vaporization (kJ/kg)
$\dot{m}_{evap}$	—	Evaporation mass flow rate (kg/s)
Q_{cond1}	—	condensation heat flux to glass cover1 (W)
Q_{cond2}	—	condensation heat flux to glass cover2 (W)
Q_{evap1}	—	evaporation heat flux from glass cover2 (W)
Q_{evap2}	—	evaporation heat flux from bare plate (W)
$Q_{c\ g1\text{-}a}$	—	convection heat transfer from glass cover1 to atmosphere (W)
$Q_{r\ g1\text{-}a}$	—	radiation heat transfer from glass cover1 to atmosphere (W)
$Q_{c,g2\text{-}w}$	—	convection heat transfer from glass cover2 to water (W)
$Q_{r\ g2\text{-}g1}$	—	radiation heat transfer from glass cover2 to glass cover1 (W)
$Q_{c,p\text{-}w}$	—	convection heat transfers from bare plate to water (W)
$Q_{r,p\text{-}g2}$	—	radiation heat transfers from bare plate to glass cover2 (W)
T	—	time (h)
T_a	—	temperature of the air (℃)
T_{g1}	—	temperature of glass cover1 (℃)
T_{g2}	—	temperature of glass cover2 (℃)
$T_{h\text{-}w1}$	—	temperature of hot water1 (℃)
$T_{h\text{-}w2}$	—	temperature of hot water2 (℃)
T_{m1}	—	temperature of cavity1 (℃)
T_{m2}	—	temperature of cavity2 (℃)
T_p	—	temperature of absorber (ºC)
T_{w1}	—	temperature of feed water1 (℃)
T_{w2}	—	temperature of feed water2 (℃)

Greek symbols

η_i	—	instantaneous efficiency
η_d	—	daily efficiency
τ_1	—	transmissivity of glass cover1
τ_2	—	transmissivity of glass cover2
α_1	—	absorptivity of glass cover1
α_2	—	absorptivity of glass cover2
θ	—	inclination angle of double basin

Subscripts

a	—	ambient
b	—	bare (absorber) plate
c	—	convection
cond	—	condensation
d	—	daily
evap	—	evaporation
g	—	glass
i	—	instantaneous
m	—	mixture
p	—	plate

w — water
1, 2 — material numbers

Abbreviations

AF — aluminum filling
AH — air heater
BF — black fleece
BFW — black-fleece wick
BP — bare plate
BCW — black-cloth wick
CC — charcoal cloth
COGT — controlling other glass temperature
CSS — conventional solar still
CW — cloth wick
DB-ISWD — double basin-inclined solar water distillation
F — fin
FS — flat surface
GCC — glass cover cooling
ISWD — inclined solar water desalination
IISWD — improved inclined solar water desalination
IISWDW — improved inclined solar water desalination with wick
IISWDWM — improved inclined solar water desalination with wire mesh
P — pebble
PCM — phase change material
PM — porous medium
S — sponge
SBP — shaded bare plate
SBCW — shaded black-cloth wick
SB-ISWD — single basin-inclined solar water distillation
SGAB — stepped glass absorber plate
WM — wire Mesh

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