

Article

Optimizing a Single-Slope Solar Still for Fresh-Water Production in the Deserts of Arid Regions: An Experimental and Numerical Approach

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Abstract: Solar desalination is a promising sustainable solution to overcome the scarcity of fresh water in the deserts of arid regions. The productivity of a solar still depends mainly on its design parameters and the meteorological conditions of its location (longitude and latitude angles). Therefore, this study aimed to optimize the main design parameters of a single-slope solar still for freshwater production in the arid climate of the central region of Saudi Arabia (24°4' N, 32.89° E). Experiments were conducted on four identical solar stills, with the same basin surface area and air gap distances (d) of 14, 16, 18, and 20 cm, respectively. The stills operated using three basin water depths (h) of 0.5, 1, and 1.5 cm on clear sunny days. The performance and productivity of the four stills were evaluated. The results showed that reducing the air gap distance (d) and water depth (h) significantly enhanced the distillate freshwater yield, and the optimum ratio of the length/width is 2 and of the back/front wall height is 3.65. Specifically, at a low water depth (h) of 0.5 cm, the daily distillate yield of the solar still increased by about 11% when the air gap distance (d) decreased from 20 to 14 cm. For the lowest air gap distance (d) of 14 cm, the distillate yield increased by about 23% when h decreased from 1.5 to 0.5 cm. Using the measured parameters, several numerical correlations have been developed to estimate the desalination rate (m_c) as a function of the solar irradiance (I_s) and ambient temperature (T_{am}). The developed correlations can be used successfully to estimate the values of m_c instead of the prohibitive experimental measurements. The stills showed excellent performance in the arid climate and reduced water salinity from 31,250 to 495 ppm. This should encourage decision-makers to expand investment in solar desalination to sustainably develop the deserts of arid regions.

Keywords: solar desalination; still; water depth; gap distance; arid climate; single slope



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1. Introduction

Freshwater is an essential requirement of life and sustainable development of all sectors in the deserts of the Arabian Peninsula. Freshwater scarcity is the main challenge in the deserts, despite the huge amount of brackish water resources. In the deserts of arid regions, freshwater scarcities are due to the high salinity of water resources and the rapid increase in population and agriculture extension needs. Recently, about 40% of the world's population has been located in remote deserts or islands, which, in most cases, do not have access to clean freshwater [1]. The process of obtaining freshwater by using the available clean, eco-friendly, and sustainable energy (e.g., solar energy) is a promising solution for freshwater scarcity (known as solar-thermal desalination). Moreover, the desalination of saline water by using solar stills is economically profitable because of the low cost and simple design and construction of the stills [2]. Passive solar stills are more convenient and profitable because they depend only on solar energy for heating [3]. The yield of the

low-cost passive solar still depends on several parameters, such as the climatic conditions (solar radiation intensity, wind speed, ambient temperature, etc.), structural design (slope angle of the cover, side walls heights, relative dimensions, absorber specifications, etc.), and operation conditions (water depth and flowrate, surface area of evaporation, etc.) [4,5].

Several studies have tested the effect of operation and design parameters on the performance and production rate of solar stills. The most common parameters in the previous studies are the air gap distance (the average distance between the basin water surface and cover) and the basin-water depth. Regarding the air gap distance, solar stills with various air gaps were examined under the climatic conditions of Ankara (40° N, 33° E), Turkey [6]. Their result showed that the distillate yield increased by 11% when the air gap was reduced from 13 to 8 cm. They [6] reported that under the climatic conditions of Ankara, Turkey, the air gap distance should be 8 cm or lower for desired freshwater production. The effect of the air gap distance on the yield of a solar still was studied under the climate of Tamil Nadu, India [7]. They used a cover slope angle of 10° which is approximately equal to the test site latitude (9.9° N). The results showed that productivity increased by 1.84 times when the air gap distance decreased from 0.45 m to 0.15 m [7]. The effect of two air gap distances (6.6 cm and 26.6 cm) with a water depth of 1 cm was examined at a location of 13° N and 80° E [8,9]. Their results showed that the productivity of the distillate freshwater increased when the average air gap distance of the solar still was decreased. This was due to the high rate of the convective heat transfer between the condensing cover and absorber. For the same absorber dimensions, the effect of changing the elevations of the north and south walls on the productivity of a single-slope solar still have been examined [10]. The results showed a significant increase in the yield of the solar still when the elevation of the north wall increased [10].

A survey in the literature revealed that similar solar stills, having a typical air gap distance, installed in different locations (latitude and longitude) produced different desalination rates. However, in a specific location, such as the central region of the Kingdom of Saudi Arabia (KSA), and under arid climatic conditions, such information is still unclear; therefore, in situ experiments are necessary to show the effect of air gap distance (d) on the performance of a solar still.

On the other hand, the effect of basin water depth (h) on the performance of solar stills has been evaluated in different locations worldwide and under various climatic conditions. A study in Bagdad (33.3° N, 44° E), Iraq [11] found that increasing the basin water depth, from 1 to 10 cm, reduced the still productivity by about 48%, even though increasing the water depth (h) increases the stored heat energy in the basin water during the daytime and makes the production continue even at night. However, increasing the water depth (h) from 1 cm to 7.5 cm decreased the productivity by about 77% [12]. A study in Tamil Nadu (9°11' N, 77°52' E), India examined the effect of increasing h from 1 cm to 5 cm on the productivity of both single- and double-basin solar stills [13]. They reported that the maximum productivity was at the lowest water depth of 1 cm, at which, the double-basin produced 17.38% more than the single-basin stills [13]. The effect of h as 2, 4, 8, and 16 cm on the solar still productivity in summer and in winter were examined under the climatic conditions of Shiraz (29.6° N, 52.5° E), Iran [14]. They reported that the productivity decreased as h increased; however, the nocturnal yield increased. The performance of passive and active solar stills at various h of 0.5, 1.0, and 1.5 cm were tested in the New Delhi (28.3° N, 77.2° E) climate [15]. They reported that increasing h decreased the temperature and internal energy of basin water, and thus the productivity of the solar still decreased. Different water depths, h (2, 3, 4, 5, and 6 cm) for passive and active solar stills were evaluated under the climatic conditions of Andhra Pradesh (16.51° N, 80.52° E), India [16]. They reported that h of 4 cm is optimum for the specific climate of the experimental site, and the active solar still enhanced the yield by about 57.55% compared with the passive solar still.

Based on the previous studies, large numbers of optimum air gap distances (d) and basin water depths (h) were recorded based on the locations of the experimental sites

(latitude and longitude) and the meteorological conditions of these sites (solar radiation intensity, sunshine duration, air temperature, wind speeds, etc.). In addition, the available previous studies conducted under climatic conditions are completely different from the arid climate of the central region of KSA. In arid climates, intensive solar radiation flux, high air temperature, low relative humidity, and long periods of sunshine are common in most of the months of the year [17]. However, a similar study used to determine the optimum air gap distance (d) and basin water depth (h) for single-slope solar stills under harsh, arid climatic conditions of the KSA is still missing and urgently required.

Accordingly, this study aimed to determine the optimum design parameters of the simplest type and low-cost solar still (i.e., single-slope). These parameters are the air gap distance (d), basin water depth (h), and back/front wall height ratio; these would be optimized for the harsh arid climatic conditions of the Arabian Peninsula. Even though wind stream may have a positive effect on cooling the glass cover and enhancing the still productivity, the effect of wind was excluded because of the very low wind speed over the stills during the days of the experiments. For this purpose, four identical insulated wooden frame single-slope solar stills covered with glass sheets were constructed with different air gap heights (d) of 14, 16, 18, and 20 cm. The stills would be operated, in parallel, for several clear sunny days using various water depths (h) of 0.5, 1.0, and 1.5 cm, one for each day. The experiments would be conducted during the daytime; however, the nighttime period is beyond the scope of this study.

2. Materials and Methods

2.1. Experimental Setup and Measuring Procedure

The experiments were conducted on clear sunny days under solar and thermal irradiance on the roof of the building of the Agricultural Research and Experiment Station at King Saud University (Riyadh, Saudi Arabia, $46^{\circ}47'$ E, longitude and $24^{\circ}4'$ N, latitude). The measurements were carried out in October 2023 from 7:0 to 19:0 for 12 h every day. During the experiments, the wind speed was very low; in addition, the roof of the building was surrounded by an external wall of 2 m height, which was relatively far from the solar stills; therefore, the effect of wind over the still cover was neglected. Four wooden frame single-slope solar stills (designated as A, B, C, and D), with identical cover slope angles of 24.4° (the latitude angle of Riyadh), and different air gap distances (d) of 14, 16, 18, and 20 cm for stills A, B, C, and D, respectively, were constructed. Wood bars of 5 cm $\times$ 5 cm cross section for each were used for constructing the frames. The front wall height (H_o) of the lowest solar still (still A) was decreased as much as possible to allow the cover, trough, basin, and base (h_o) to be installed properly. The air gap distance (d) was estimated according to Figure 1 as $d = (H + H_o)/2 - (h + h_o)$. A schematic diagram showing the layout dimensions (length, $L = 100$ cm, and width, $W = 50$ cm) of the solar still used in the study is illustrated in Figure 1. A black-painted galvanized iron sheet, in the form of a tray, was constructed to be used as an absorber basin; the galvanized iron sheet was also used to perform the trough (Figure 1). The basin surface area (A_s) is 4050 cm², with a dimension of 90 cm length, and 45 cm width (Figure 1); the aspect ratio (length/width) of 2 was recommended by [18] as an optimal ratio to efficiently collect solar radiation in the solar still. A condensing glass cover of 5 mm thickness was fixed and sealed on the top of each solar still cavity, each having a surface area of about 5400 cm². To minimize the heat losses, the outer surfaces of the frame (side walls and base) were insulated using glass wool of 5 cm thickness (thermal conductivity, $k = 0.03$ W m⁻² °C⁻¹). The covers of the solar stills faced to the south direction to collect most of the incident solar radiation during the day. For the stills A, B, C, and D, the layout dimensions are summarized in Table 1. A schematic diagram of the experimental setup, including the four solar stills, is illustrated in Figure 2. Before starting the actual measurements, the experiment was conducted for several days to fix any problems, such as leakage, measuring errors, etc., and to reach steady state operation conditions. During the 9 days of measurements (10–18 October), the water depth (h) in the basin was kept constant for each three consecutive days

of measurements; it was 0.5, 1.0, and 1.5 cm. This was achieved by continuously supplying feed water, equal to the amount of distillate-collected water, to the solar still basin. The working fluid was Red Sea water taken from Duba Coastal, Tabuk, KSA, with a salinity of 31,250 ppm.

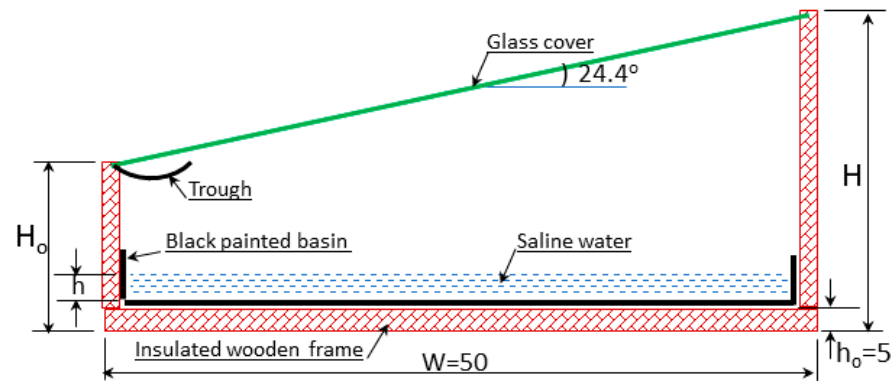


Figure 1. Schematic diagram and layout dimensions in cm, not to scale, for the solar still used in the study.

Table 1. Layout dimensions of the four solar stills used in the study.

Symbol	Definition	Still A	Still B	Still C	Still D	Units
L	(length)	100	100	100	100	cm
W	(width)	50	50	50	50	cm
H	(back wall height)	30.63	32.63	34.63	36.63	cm
H_o	(front wall height)	8.38	10.38	12.38	14.38	cm
h_o	(basin depth)	5	5	5	5	cm
α	(latitude angle)	24.4°	24.4°	24.4°	24.4°	degree
d	(air gap distance)	14	16	18	20	cm

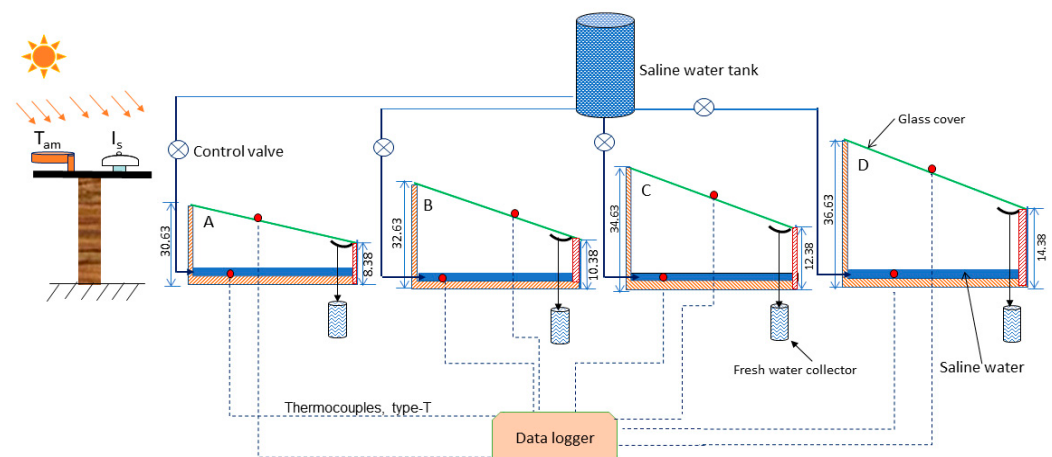


Figure 2. Schematic diagram of the experimental setup including the four solar stills (A, B, C, and D) used in the study. Dimensions in cm, not to scale.

The ambient air temperature (T_{am}) was measured using an aspirated psychrometer. The temperatures of the outer surface of the glass cover (T_g) and basin water (T_w) were measured using type-T copper constantan thermocouples of 0.3 mm in diameter, (Reotemp Instruments Co., San Diego, CA, USA). The thermocouple sensors used to measure T_g were covered with strips of aluminum foil to eliminate the effect of radiation on the thermocouple reading. The global solar radiation flux (I_s) was measured beside the stills, at a height of the covers level, using a CMP3 pyranometer (Kipp and Zonen, Sterling, VA, USA). The

thermocouple sensors and pyranometer used in the experiment were calibrated by the supplier before use to eliminate any expected errors. All the required parameters were measured at every 10 min interval, averaged at every hour, and saved in a data logger (CR3000 Micrologger®, Campbell Scientific Inc., Logan, UT, USA). However, the distillate yield was collected manually and measured every hour. During the experiment, the four solar stills (A, B, C, and D) were operated in parallel, with the same water depth (h) in the four stills, for three consecutive days for each water depth, and the average value of each parameter was obtained. The average air gap distance (d) changes according to the water depth (h); the values of d according to h and the days of measurements are illustrated in Table 2.

Table 2. Values of d and h and the days of measurements for the solar stills.

Date of Experiments	Height (cm)	Still A	Still B	Still C	Still D
(10,11,12) October 2023	d	14	16	18	20
	h	0.5	0.5	0.5	0.5
(13,14,15) October 2023	d	13.5	15.5	17.5	19.5
	h	1	1	1	1
(16,17,18) October 2023	d	13	15	17	19
	h	1.5	1.5	1.5	1.5

2.2. Theoretical Approach

To evaluate the solar still, a mechanism to describe the evaporation process (heat and water vapor exchanges) is required. The key factors in this process are the evaporative and convective heat transfer coefficients (h_e and h_c). Once these coefficients were determined, the production rate (yield) of a solar still can be estimated theoretically without the need for measurements. Several analytical expressions (models) have been reported in the literature for these coefficients; we have selected three of them to calculate h_e and h_c (i.e., Dunkle [19], Kumar and Tiwari [20], and Zheng et al. [21]). For simplicity, among these models, several assumptions have been considered such as (i) the heat loss from inside to outside the solar still was neglected, (ii) there is no heat generation in the solar still, (iii) the basin-water depth is fixed as having a uniform temperature of T_w , (iv) all thermophysical properties of the humid air in the still are calculated at the mean temperature of the basin water surface (T_w) and condensation surface (T_g) of the solar still, and (v) the evaporation rate (m_{ev}) is equal to the condensation rate (m_c) which is completely collected to be as the production rate of the solar still.

The maximum evaporation or desalination rate of a solar still, (kg s^{-1}) can be calculated as follows:

$$m_{ev} = m_c = \frac{q_e}{h_{fg}} \quad (1)$$

where h_{fg} is the latent heat of vaporization of water (J kg^{-1}), and q_e is the evaporative heat transfer rate (W) and is given by the following:

$$q_e = h_e(T_w - T_g) \quad (2)$$

where h_e is the evaporative heat transfer coefficient ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$), T_w is the basin water temperature ($^\circ\text{C}$), and T_g is the inner surface temperature of the glass cover ($^\circ\text{C}$). An expression to estimate h_e is given by [19] as follows:

$$h_e = 0.016273 \times h_c \times \frac{P_w - P_g}{T_w - T_g} \quad (3)$$

where h_c is the convective heat transfer coefficient ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$), P_w (N m^{-2}) is the partial pressure of the humid air at the basin water temperature (T_w), and P_g (N m^{-2}) is the partial pressure of the humid air at the glass cover temperature (T_g).

In Equation (3), the convective heat transfer coefficient (h_c) is estimated using a semi-empirical expression proposed by the following numerical models:

(i) Dunkle model [19]

$$h_c = 0.884(\Delta T)^{1/3} \quad (4)$$

where ΔT ($^{\circ}\text{C}$) is the temperature difference between the basin water and glass cover surface and is given by [19] as follows:

$$\Delta T = \left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right] \quad (5)$$

The partial pressures of water vapor in Equation (5) are given by [19] as follows:

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right) \quad (6)$$

$$P_g = \exp\left(25.317 - \frac{5144}{T_g + 273}\right) \quad (7)$$

(ii) Kumar and Tiwari model [20]

They considered the characteristic length of N_u as the average air gap distance (d) to express h_c in the following form:

$$N_u = \frac{h_c * d}{K} = c(Gr * Pr)^n \quad (8)$$

where Gr , Pr , d , and k are the Grashof number, Prandtl number, average air gap distance, and thermal conductivity of the humid air, respectively. The numerical constants c and n are dependent on the boundary conditions and the flow regime. Dunkle [19] has suggested that for humid air enclosed in a horizontal space, the numerical constants are $c = 0.075$ and $n = 0.333$ for $(3.22 \times 10^5 < Gr < 1 \times 10^7)$. Hollands et al. [22] suggested that for $Ra > 5.5 \times 10^6$, the corresponding values are $c = 0.055$ and $n = 0.333$. Gr and Pr dimensionless numbers are defined as follows:

$$Gr = \frac{g \beta \Delta T d^3}{\mu^2 / \rho^2}, \quad Pr = \frac{C_p \mu}{K} \quad (9)$$

where g is the gravitational acceleration (m s^{-2}), ρ is the humid air density (kg m^{-3}), β is the thermal expansion factor ($=1/T$, T is the humid air temperature in degree K), C_p is the specific heat of the humid air ($\text{J kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$), and μ is the dynamic viscosity of the humid air in the still (N s m^{-2}).

(iii) Zheng et al. model [21]

$$h_c = 0.2 \times (R_a)^{0.26} \left(\frac{K}{d} \right), \quad (10)$$

$$R_a = \frac{\rho \beta g d^3}{\mu \alpha} \left[T_w - T_g + \frac{P_w - P_g}{\frac{M_a P_t}{M_a - M_w} - P_w} \times (T_w + 273) \right] \quad (11)$$

where α is the thermal diffusivity ($\text{m}^2 \text{s}^{-1}$), M_a is the molecular weight of dry air (kg mol^{-1}), M_w is the molecular weight of water vapor (kg mol^{-1}), and P_t is the total pressure of the

humid air in the solar still (N m^{-2}). For conventional passive solar still, the overall daily efficiency (η_d) is given by [23] as follows:

$$\eta_d = \frac{\int_{t_1}^{t_2} m_c(t) h_{fg} dt}{\int_{t_1}^{t_2} I_s(t) dt} \quad (12)$$

where t_1 and t_2 are the sunrise and sunset time; $m_c(t)$ is the rate of distilled water at a specific time t ($\text{kg s}^{-1} \text{m}^{-2}$), and $I_s(t)$ is the global solar radiation flux over the solar still (W m^{-2}). The physical properties of the humid air in the solar still, such as specific heat (C_p), density (ρ), thermal conductivity (k), viscosity (μ), latent heat of vaporization (h_{fg}), and thermal expansion factor (β), were estimated as a function of the glass and basin water mean temperature, T_m [$T_m = (T_g + T_w)/2$], using well-known correlations reported in [24].

3. Results and Discussions

3.1. Evaluation of the Solar Stills

(i) Effect of water depth (h) and air gap distance (d)

In order to optimize the most important parameters of a single-slope solar still (basin water depth, h and air gap distance, d), four identical solar stills (A, B, C, and D) having different d values (14, 16, 18, and 20 cm) were operated, in parallel, for nine days using different h values (0.5, 1, 1.5 cm); measurements were conducted for three consecutive days using constant water depth, and the measured parameters were averaged as one day for each water depth. The daily production for each solar still (in kg per m^2 of basin water surface) was collected for the three cases of h (0.5, 1, 1.5) and is illustrated in Figure 3. Based on the resulting yields in Figure 3, still A ($d = 14$ cm) showed the highest production rate (5.4 kg m^{-2}) at a water depth of 0.5 cm compared to the other three stills (B, C, and D). The proper design/construction considerations (e.g., well insulation, high transparency of the glass cover, clear sunny weather) that were considered have enhanced the desalination yields of the solar stills to reach 5.4 kg m^{-2} (for still A) and 4.7 kg m^{-2} (for still D) at a constant water depth (h) of 0.5 cm.

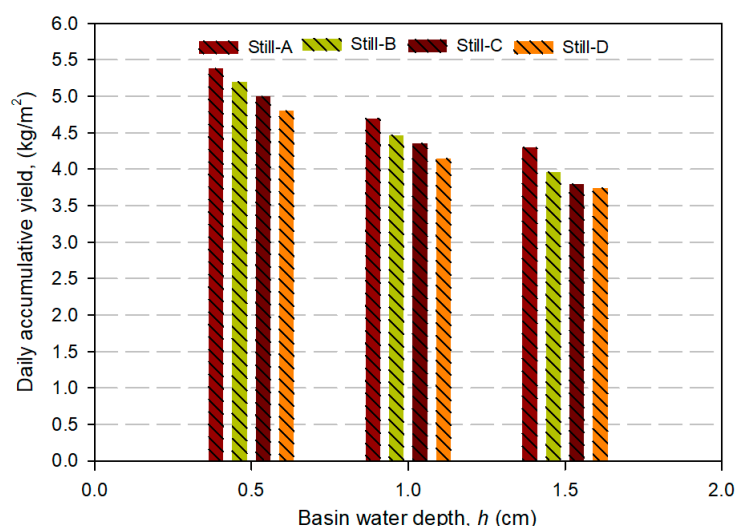


Figure 3. Daily accumulative yields (kg m^{-2}) at different basin water depths for the four solar stills tested in the study (10–18 October 2023).

For more clarification on the effects of d and h on the still performance, the daily yields of the four solar stills (A, B, C, and D) were estimated (in kg per m^2 of basin surface area) and are plotted in Figure 4a against the basin water depth (h). Under the same conditions of solar irradiance and ambient temperature, still A (having the lowest air gap distance of 14 cm) showed the highest daily yield compared to the other stills having higher air

gap distances. In each solar still, the daily yield decreases as the water depth increases (Figure 4a). This is because for the same solar irradiance, increasing water depth would increase the amount of water in the basin and reduce the water temperature; thus, the distillate freshwater yield would decrease.

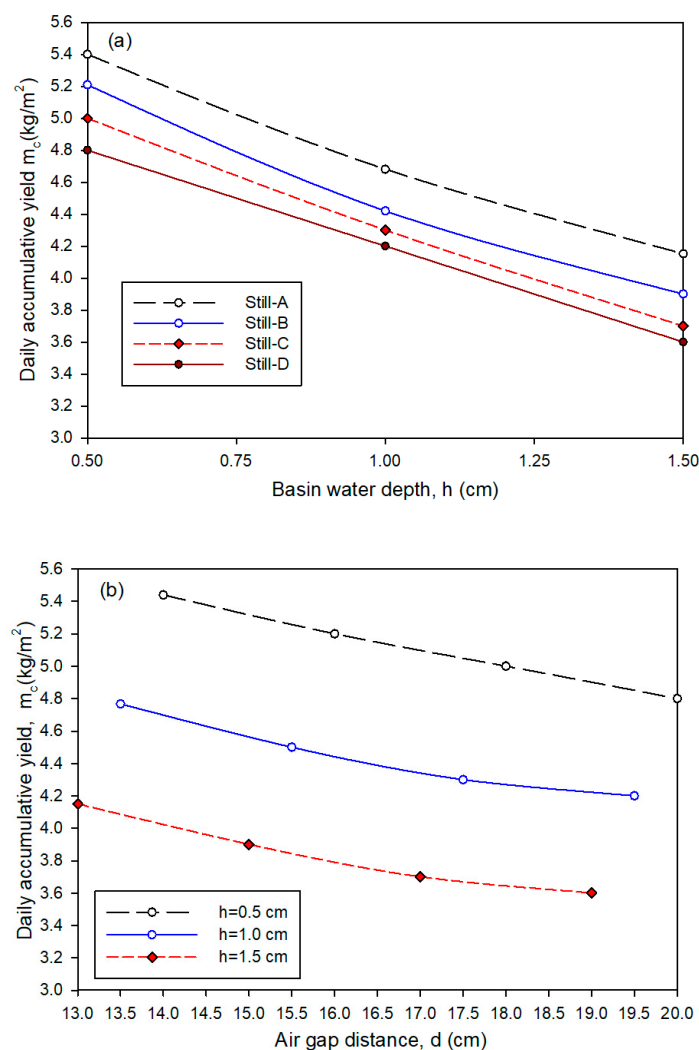


Figure 4. The daily accumulative distillate yields as affected by (a) the water depth (h), and (b) air gap distance (d) for the tested solar stills A, B, C, and D (10–18 October 2023).

On the other hand, increasing the basin water depth would attenuate the transmitted solar irradiance to reach and be absorbed by the absorber surfaces (i.e., the black-painted inner surface of the basin). For any water depth (h), the reduction in the air gap distance (d) improves the distillate yield, as shown in Figure 4b. The decrease in the air gap height would eliminate the shading effect of the side walls on the basin surface, allowing more solar irradiance to be absorbed by the basin water, and the evaporation as well as the desalination rate increases. Based on Figure 4a,b, the daily distillate yield of the solar still at a water depth (h) of 0.5 cm increased by about 11% when the air gap distance decreased from 20 to 14 cm. For an air gap distance (d) of 10 cm, the distillate yield increased by about 23% when the water depth decreased from 1.5 to 0.5 cm. This indicated that, during the daytime, the effect of basin water depth, h , on the still productivity, m_c , is much higher than the effect of the air gap distance, d .

The basin water depth (h) is an operator choice, whereas the air gap distance (d) is a designer choice; it depends on the still base dimensions (L , W , H , and H_0); d should be reduced as much as possible to enhance the still performance. To calculate the optimum

value of d , designers should go through the following steps: (i) selecting L and W ($L/W = 2$, recommended) based on the requirements of customers (i.e., the amount of the freshwater), (ii) selecting the lowest height of the front wall (H_o) and the basin depth (h_o) based on the lower limit of design considerations, (iii) determining the cover slope angle (α), i.e., equal to the latitude angle of the location, and (iv) determining the back wall height (H) as $H = H_o + W \times \tan(\alpha)$. Then, the optimal air gap distance (d) can be calculated. In addition, an optimum value of the back-to-front wall height (H/H_o) of 3.65 should be taken into account. A proper design of a solar still would produce at least 5 kg m^{-2} per day, and according to the World Health Organization [25], a solar still having a basin surface area of $10\text{--}20 \text{ m}^2$ is required to meet the needs of one person per day. Scaling up of the proposed design is possible; the only limitation is the breakability of the glass cover. To avoid this, rigid supports (e.g., rigid plastic or stainless-steel bars) should be used below the glass cover to carry the weight of the cover; for a glass cover of 1 m width, one bar for every 1–1.5 m interval of glass span length is suggested based on our observations on the present experiments.

(ii) *The still daily overall efficiency, η_d*

The daily overall efficiency (η_d) of the four solar stills was calculated at the three water depths of 0.5, 1, and 1.5 cm using Equation (12), and the resulting values are depicted in Figure 5. The results showed that for a water depth of 0.5–1 cm, the solar still-A showed a higher daily overall efficiency ($\eta_d = 46\text{--}53\%$) compared to the other stills tested. This result emphasizes that under the arid climatic conditions of Riyadh area, a water depth (h) of 0.5–1 cm and an air gap distance (d) of 14 cm or lower are the desired dimensions to design/construct a single-slope solar still; this can produce about 5 kg/m^2 of freshwater per day. On the other hand, values of η_d are quite low for the four solar stills (A, B, C, and D); this is because Equation (12) is the measure of how much the incident solar radiation over the still cover is absorbed by the basin water and converted to water vapor and then condensed on the cover surface. This hypothesis combined the cover transmittance with all the thermal losses from the still to the surroundings and considered the solar still as a solar collector. However, if Equation (12) was divided by the cover transmittance, then the resulting efficiency should be defined as the daily conversion efficiency of a solar still. In the worst case, by considering the cover transmittance of 85%, the resulting daily conversion efficiency (η_{co}) would increase by 17.6% for the four solar stills in Figure 5.

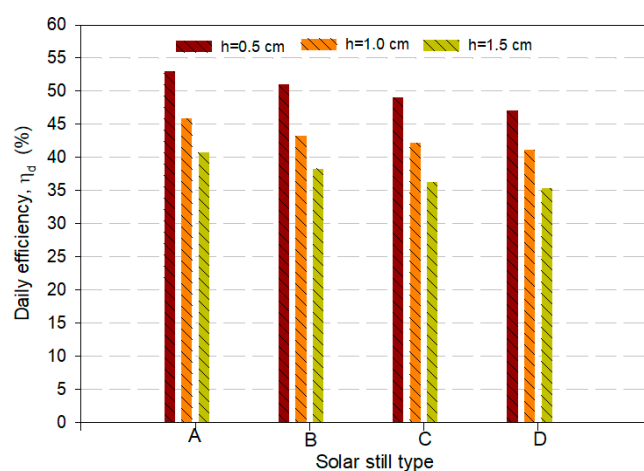


Figure 5. Daily overall efficiency of the tested solar stills (A, B, C, and D), estimated at the three water depths (h) of 0.5, 1, and 1.5 cm.

It is well known that the evaporation, as well as the desalination rate, of a solar still depends mainly on the intensity of solar irradiance and the design configuration of the still. In order to predict the desalination rate simply without the need for experiments, which is mainly induced by solar irradiance, the hourly distillate yields of the tested solar stills (A, B, C, and D having air gap distances of 14, 16, 18, and 20 cm, respectively) were

obtained for the basin water depths of 0.5, 1, and 1.5 cm. All the yield data were gathered and plotted against the corresponding values of the hourly average solar radiation flux in Figure 6a (for the data before noon, from 7:0–12:0) and in Figure 6b (for the data after noon, from 13:0–19:0). Applying the regression analysis to the data in Figure 6a,b, the hourly distillate yields (m_c in kg m^{-2}) could be correlated before noon ($R^2 = 0.92$, standard error of estimate, $\text{SEE} = 0.057$, and $p < 0.0001$) and after noon ($R^2 = 0.91$, $\text{SEE} = 0.072$, and $p < 0.0001$) as a function of solar radiation flux (I_s in W m^{-2}) in the following form:

Before noon

$$m_c = -0.397 + 0.003(I_s) - 5.99 \times 10^{-6}(I_s)^2 + 4.4 \times 10^{-9}(I_s)^3, R^2 = 0.92 \quad (13)$$

After noon

$$m_c = 0.05 + 0.0009(I_s) - 7.1 \times 10^{-8}(I_s)^2, R^2 = 0.91 \quad (14)$$

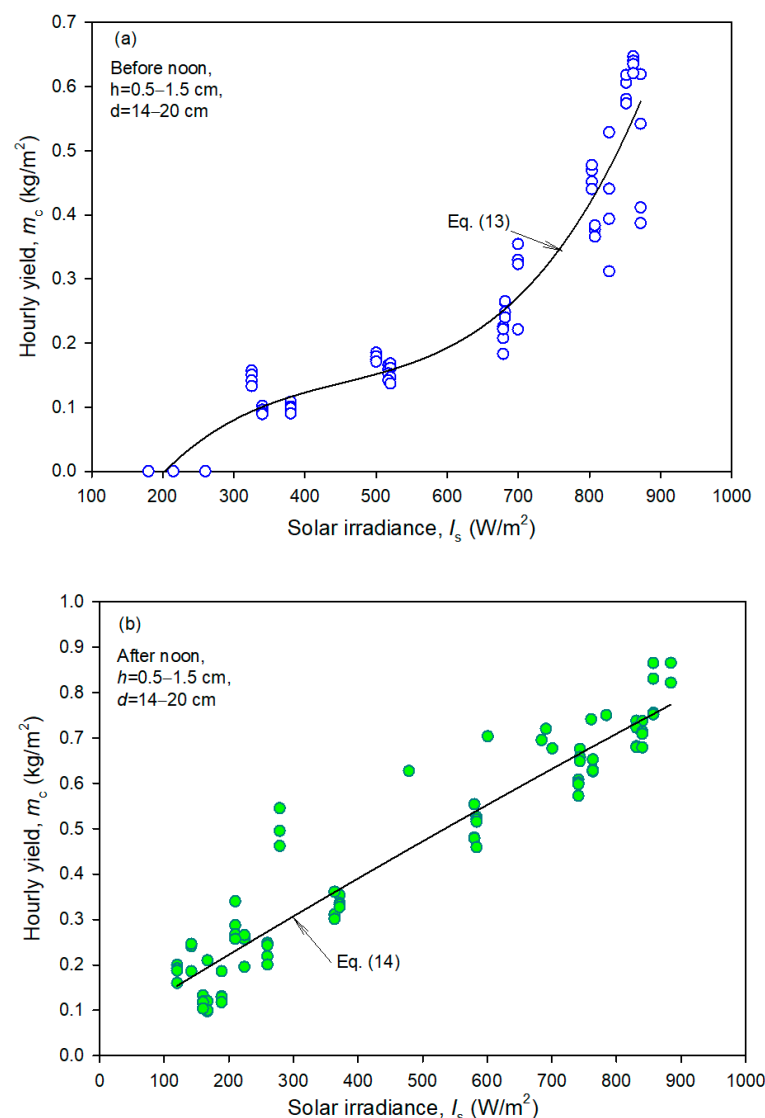


Figure 6. The hourly yields of the four solar stills (A, B, C, and D) as affected by solar irradiance intensity, estimated before noon (a), and after noon (b) for the three water depths (h) of 0.5, 1.0, and 1.5 cm (10–18 October 2023).

Equations (13) and (14) are valid for basin water depth of 0.5–1.5 cm and air gap distance of 14–20 cm and can be used, as a useful and easy tool, to estimate the expected

freshwater yield, with a maximum possible error $\leq 8\%$ (before and after noon) in the arid area of the Arabian Peninsula as a function of the solar irradiance intensity (W m^{-2}), which is easily can be obtained from any meteorological station in this area. Based on such quick estimation, designers can perform feasibility studies and put the outline dimensions of a solar desalination project with a proper expectation of the outcomes.

(iii) *Diurnal variation of the desalination rate, m_c*

The results in the previous figures (Figures 3–5) revealed that operating the solar still-A, having the lowest air gap distance (d) of 14 cm, at the lowest water depth (h) of 0.5 cm is more efficient, giving higher freshwater production than the other solar stills and water depths. To show the daily behavior of the still A, the hourly yield of the still at three different water depths is illustrated in Figure 7a. The hourly distillate yield of the solar still A at $h = 0.5$ cm was the highest over all the solar stills and depths throughout the experiment, (Figure 7a). This is due to the highest solar energy absorbed (because d is the lowest), as well as the highest temperature of the basin water, T_w (because h is the lowest). Specifically, at $d = 14$ cm (still-A), when the basin water depth (h) decreased from 1.5 to 0.5 cm, the cumulative distillate yield increased by about 26% (Figure 7b).

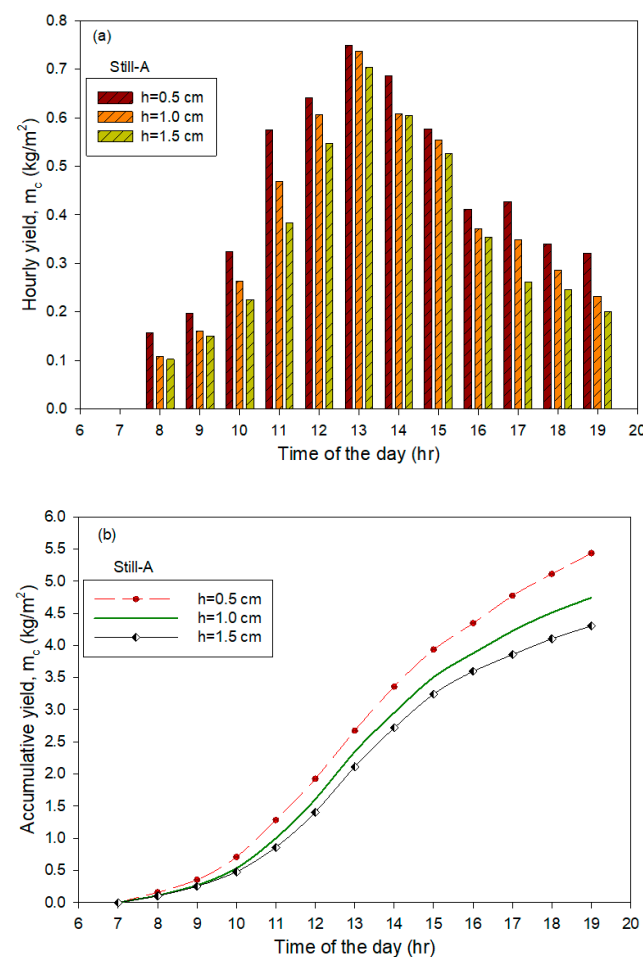


Figure 7. Diurnal variation of the hourly yield (a), and the accumulative yield (b) for the solar still A at different water depths (h), during the period of the experiment (10–18 October 2023) in Riyadh climate.

3.2. Analytical Expressions to Estimate the Desalination Rate, m_c

The desalination rate (m_c) can be predicted by conducting experiments on a real solar still, or by using analytical expressions (i.e., theoretical models, Section 2.2). Numerical expressions, as in Equations (13) and (14), provide a quick, less expensive, and more fixable and repeatable way compared with the expensive and time-consuming experimental

prediction. Several analytical expressions have been developed in the past to predict m_c , and the input parameters to these expressions are the glass cover and basin water temperatures (T_g and T_w). In addition to Equations (13) and (14), another attempt was made to estimate m_c by using Equations (1)–(11). Therefore, the three selected models used to estimate the values of m_c without the need for measurements need evaluation to examine their validity for arid climates. For this reason, during all the experiments, the measured values of T_w (i.e., mainly depends on the solar irradiance, I_s , because of the frame insulation) were plotted against the corresponding values of I_s in Figure 8a for the before noon (7:0–12:0) and in Figure 8b for the after noon times (13:0–19:0). Applying the regression analysis to the data in Figure 8a,b, two expressions could be obtained for the before noon time (Equation (15), $R^2 = 0.97$, SEE = 3.68, and $p < 0.0001$), and after noon time (Equation (16), $R^2 = 0.91$, SEE = 4.68, and $p < 0.0001$) as follows:

$$T_w = 20.45 + 0.0353(I_s) + 3.2 \times 10^{-5}(I_s)^2, \quad R^2 = 0.97 \quad (\text{before noon}) \quad (15)$$

$$T_w = 20.87 + 0.129(I_s) - 7.72 \times 10^{-5}(I_s)^2, \quad R^2 = 0.91 \quad (\text{after noon}) \quad (16)$$

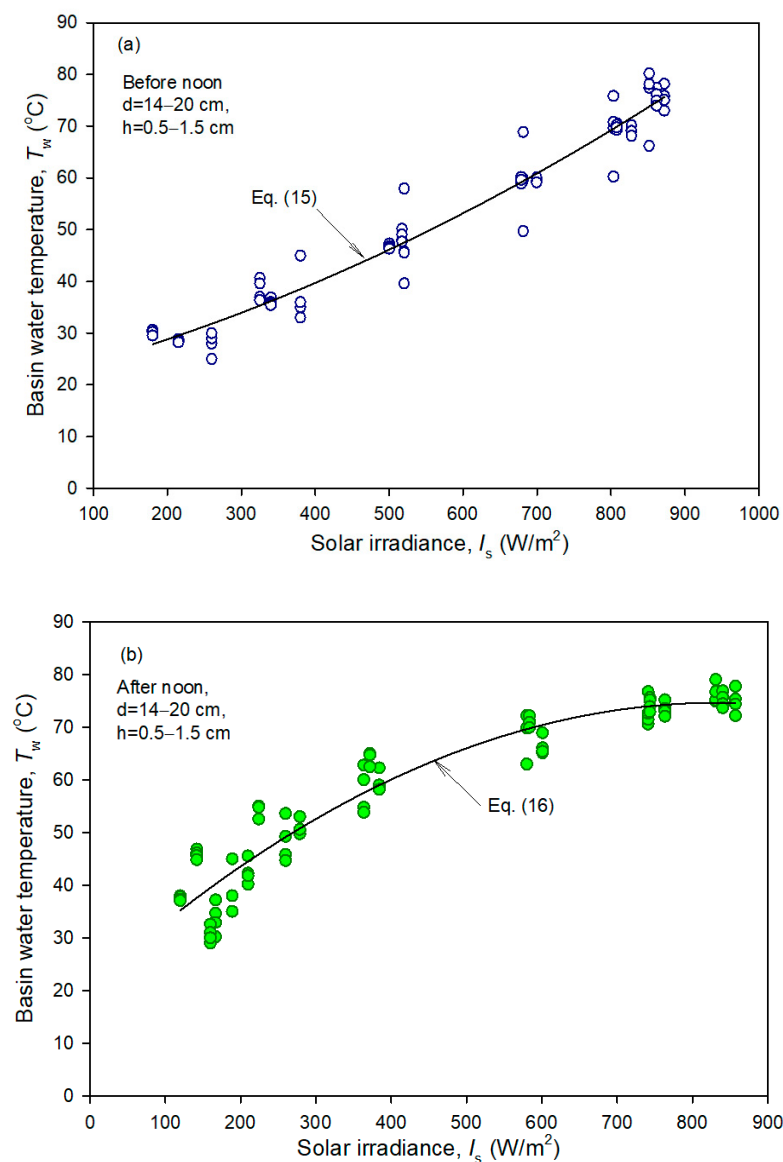


Figure 8. Basin water temperature (T_w) as affected by solar radiation flux (I_s) in the before noon (a) and after noon (b) times for the tested solar stills A, B, C, and D (10–18 October 2023).

Unlike the basin water temperature (T_w), the glass cover temperature (T_g) depends on the solar radiation flux as well as the ambient air temperature (T_{am}) because the glass cover is exposed directly to the ambient air and exchanges energy with it. In a similar manner to Equations (15) and (16), the measured data of T_g , T_{am} , and I_s for the stills A, B, C, and D were gathered for the three water depths, h (0.5, 1, and 1.5 cm), and then the values of T_g vs. I_s and T_{am} were plotted, as three dimensions, in Figure 9a for the data before noon and in Figure 9b for those after noon.

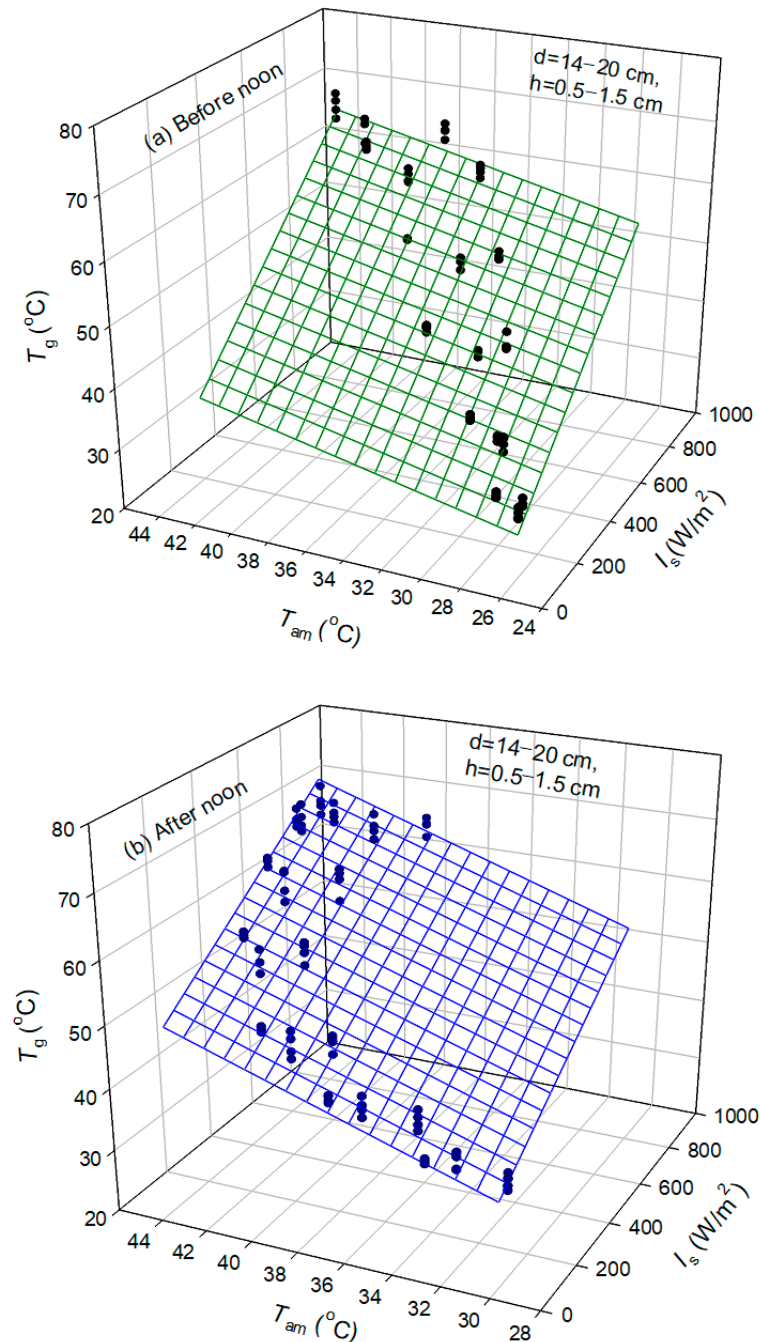


Figure 9. Glass cover temperature (T_g) as affected by solar radiation flux (I_s) and ambient air temperature (T_{am}) in the before noon (a) and after noon (b) times for the tested solar stills A, B, C, and D (10–18 October 2023).

Applying regression analysis to the data in Figure 9a,b, two numerical expressions could be obtained for the before noon time (Equation (17), $R^2 = 0.97$, SEE = 2.26, and

$p < 0.0001$) and the after noon time (Equation (18), $R^2 = 0.97$, $SEE = 2.23$, and $p < 0.0001$) in the following form:

$$T_g = -2.86 + 0.0457I_s + 0.0668T_{am}, \quad R^2 = 0.97 \quad (\text{before noon}) \quad (17)$$

$$T_g = -9.47 + 0.032I_s + 1.185T_{am}, \quad R^2 = 0.97 \quad (\text{afternoon}) \quad (18)$$

Most of the numerical models in the literature used to estimate the desalination rate (m_c) mainly used T_w and T_g as input parameters to the simulation. In order to make these models applicable, T_w and T_g (in $^{\circ}\text{C}$) were correlated in Equations (15)–(18) as a function of solar irradiance (I_s , in W/m^2) and ambient air temperature (T_{am} , in $^{\circ}\text{C}$). Then, an empirical model can be used easily to determine m_c , once the meteorological conditions are predetermined.

To validate the selected numerical models (Equations (1)–(11)), used for estimating the desalination rate (m_c), the values of T_w and T_g were calculated (Equations (15)–(18)), and then these values were substituted into Equations (1)–(11). The resulting values of m_c are depicted in Figure 10 as accumulative yields with time. In addition, the measured values of m_c (under the same conditions of $h = 0.5$ cm and $d = 14$ cm) are also depicted in Figure 10 for comparison. Overestimation errors are observed in Figure 10 on the predicted values of m_c , resulting from the three models, especially in the after noon time. This is mainly attributed to the assumptions allocated with these models; for example, the models have assumed that the evaporation rate is equal to the collected condensation rate ($m_c = m_{ev}$), and the condensed droplets that fall into the basin water were neglected. In addition, Kumar and Tiwari's model [20] and Zheng et al.'s model [21] are more convenient than Dunkle's model [19] to predict the values of m_c theoretically. Eventually, once the ambient air temperature (T_{am}) and solar radiation flux (I_s) were measured, the desalination rate (m_c) in kg per m^2 of basin surface can be calculated.

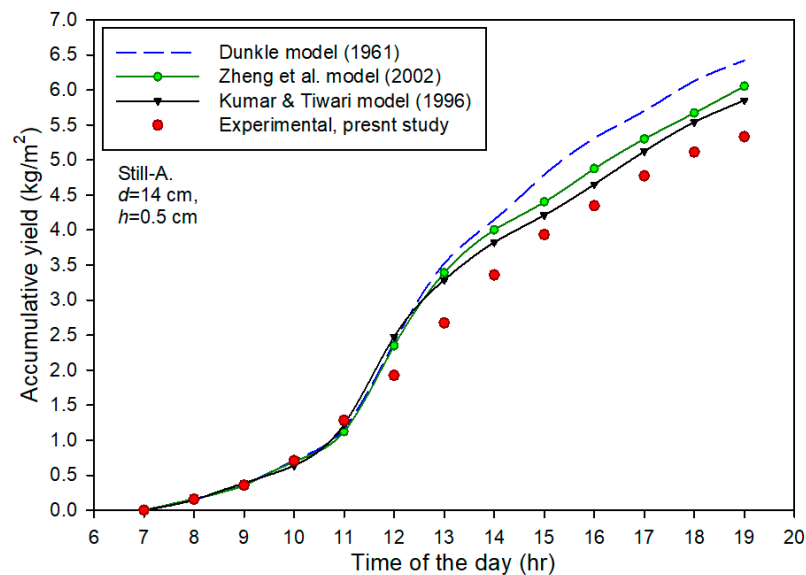


Figure 10. Time evolution of the measured accumulative distillate yield compared with those calculated using three models [19–21] for the solar still A ($h = 0.5$ cm, and $d = 14$ cm).

3.3. Distilled Water Analysis

The saline water used in the experiments was taken from the Red Sea (Duba Coastal, Tabuk, KSA). Two samples of seawater and the output distilled water were tested in the central laboratory, King Saud University. The total dissolved solids (TDS) in the seawater and distilled water were about 31,250 and 495 ppm, respectively. This is very acceptable because the maximum acceptable solids in the drinking water, according to

the STD reference [25], is about 1200 ppm. Other chemical parameters were measured for the two samples and the results are illustrated in Table 3, and showed promising results, emphasizing that the distilled water can be used as drinkable water according to the STD [25]. However, iron (Fe) in the distilled water was higher than in the seawater; this may be attributed to the corrosion that occurred in the galvanized iron trough during the experiments. Therefore, anti-corrosive materials are highly recommended to make the trough. The distilled water can be remixed with brackish water (adjusting ppm of the mixture up to 1000) to be used for irrigation and greenhouse evaporative cooling in summer. This can solve the main challenge facing greenhouse growers in these regions, especially in summer, which is blocking the wet pad because of using brackish water for cooling the pad in the wet-pad fans system [26]. Solving this issue would significantly enhance the cooling performance of wet-pad fan systems, increase the lifetime of the pads, and reduce the fixed and operating costs of the greenhouses.

Table 3. Chemical analysis of distilled water and seawater.

Composition, ppm	Sample-1 (Seawater)	Sample-2 (Distilled Water)	STD [25]
Carbonates (CO ₃)	560.504	zero	—
Chloride (Cl [−])	21,442	71	500
Phosphates (PO ₄)	54.299	Not detected	0.3
Calcium (Ca)	537.072	16.032	200
Magnesium (Mg)	233.38	4.86	150
Iron (Fe)	0.0567	0.1008	1
Manganese (Mn)	Not detected	Not detected	—
Sodium (Na)	132.0029	22.6480	200
Potassium (K)	109.1886	2.8609	—
pH	6.18	6.23	6.5–9.2
Total dissolved solids (TDS)	31,250	495.36	1200

4. Conclusions and Recommendations

This study evaluated four solar stills to examine the effect of air gap distance (d) and basin water depth (h) on the performance and freshwater productivity (m_c) of these stills in the arid climate of Riyadh area. Based on the measured parameters, different analytical expressions have been developed to estimate the desalination rate (m_c) as a function of the meteorological parameters (i.e., solar radiation flux, I_s , and ambient air temperature, T_{am}). According to the obtained results, the main conclusion could be summarized as follows:

The solar radiation flux is the main power that induces the evaporation process and the solar still freshwater productivity; therefore, selecting the appropriate location to install solar stills is important.

Both the basin water depth and the air gap distance, between the water surface and glass cover, have a considerable effect on the distillate freshwater yield; the highest collected distilled yield could be obtained at the lowest air gap distance and lowest water depth due to the rapid evaporation and condensation rate as affected by the reduction in the still side walls. Low side walls reduce shading on the basin water and consequently increase the water temperature. Therefore, transparent side walls are recommended, in future work, to reduce the shading effects on the basin water, and enhance productivity. Moreover, the effect of wind speed over the glass cover on enhancing the still performance and productivity should be evaluated.

Based on our observation during the experiments, the trough, used to collect the condensed water, should be made from anti-corrosive materials to avoid corrosion. Hydrophilic paint is also recommended to be applied carefully on the inner surface of the

glass cover, without jeopardizing the cover transmittance, to achieve film condensation and eliminate dropwise condensation on the cover.

Scaling up for the proposed design of solar still is possible to meet the requirements of any activity. Due to the breakability of glass cover, rigid supports (e.g., plastic or stainless-steel bars) are recommended below the glass cover to carry its load.

The values of the glass cover temperature (T_g) and basin water temperature (T_w) could be correlated as functions of the solar intensity (I_s), and ambient air temperature (T_{am}) with high R^2 values of 0.97. Thus, values of T_w and T_g can be used as input parameters for analytical models to finally estimate the desalination rate (m_c) theoretically instead of using expensive measurements. Other two simple correlations could be obtained to estimate m_c as a function of I_s (before and afternoon) with a maximum error of <8%; this will be useful for the feasibility studies of solar desalination projects in arid areas.

A high desalination rate per unit area of basin surface was achieved under the highly intensive solar radiation in the central region of Saudi Arabia; therefore, this climate is promising for solar energy applications, such as desalination and power generation.

The solar stills reduced the TDS from 31,250 ppm (sea water) to 495.36 ppm (drinkable water); the distilled water can be remixed with sea water up to ~1000 ppm to be used successfully for evaporative cooling and irrigation in the greenhouses.

More research is required for the night period and how to enhance the desalination rate in the absence of solar radiation by implementing phase change materials (PCM) and storage materials with high thermal capacities on the basin.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

A_s	Basin surface area of the solar still (m^2)
C_p	Specific heat capacity ($J\ kg^{-1}\ ^\circ C^{-1}$)
d	Air gap distance (m)
g	Gravitational acceleration ($m\ s^{-2}$)
H	Back wall height (m)
H_o	Front wall height (m)
H	Basin water depth (m)
h_c	Convective heat transfer coefficient between water and glass cover ($Wm^{-2}\ ^\circ C^{-1}$)
h_{ev}	Evaporative heat transfer coefficient ($Wm^{-2}\ ^\circ C^{-1}$)
h_{fg}	Latent heat of vaporization of water ($J\ kg^{-1}$)
h_o	Basin thickness (m)
I_s	Solar radiation intensity (Wm^{-2})
K	Thermal conductivity ($Wm^{-1}\ ^\circ C^{-1}$)
M_a	Molecular weight of dry air ($kg\ mol^{-1}$)
M_w	Molecular weight of water vapor ($kg\ mol^{-1}$)
m_c	Desalination rate ($kg\ s^{-1}$)
m_{ev}	Evaporation rate ($kg\ s^{-1}$)
P_T	Total pressure of the mixture of air and water vapor in still (Pa)

P_w	Partial pressure of the vapor at water temperature (Pa)
P_g	Partial pressure of the vapor at glass temperature (Pa)
SEE	Standard error of estimate
T_{am}	Ambient air temperature ($^{\circ}\text{C}$)
T_g	Glass cover temperature ($^{\circ}\text{C}$)
T_w	Basin water temperature ($^{\circ}\text{C}$)
<i>Greek symbols</i>	
α	Slope angle of the glass cover (degree)
β	Thermal expansion factor ($1/\text{k}$)
η_d	Daily overall efficiency
ΔT	Temperature difference between water and glass ($^{\circ}\text{C}$)
μ	Dynamic viscosity (Ns m^{-2})

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