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Performance of Conical Solar Distiller at Different Aspect Ratios

Ahmed A. Al-Nagdy[1,*], Swellam W. Sharshir[2], M. Omara[1], E. M. Elhefnawy[1], Gamal B. Abdelaziz[1]
1 Mechanical Department, Faculty of Technology and Education, Suez University, Egypt.
2 Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt.
*** Corresponding author: Ahmed A. Al-Nagdy (ahmed.alnagdy@suezuniv.edu.eg).**

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Abstract: The most popular desalination method is the solar still, but it has poor productivity. In this work, three fixed cone-shaped solar still (CSS) were tested experimentally. Experiments were done simultaneously at three cone heights (H) 25, 50, and 75 cm (CSS-75, CSS-50, and CSS-25), producing three aspect ratios (AR) of 3, 2, and 1, respectively. Experiments were also conducted with different depths of the basin water level (WD = 1, 2, 3 cm) to obtain the optimal water depth. Experiments were carried out based on thermal efficiency, water productivity, and economic studies to confirm its impact on the performance of the presented system. The results indicated that the obtained daily productivity was 5.17, 3.82, and 1.18 L/m^2 at 3, 2, and 1 aspect ratio, respectively, and a water depth of 1 cm. The daily thermal efficiency was 43.1, 37.9, and 30.4% for CSS-75 at WD = 1, 2, and 3 cm, respectively. The cost per liter for CSS-75 was 0.015 USD, lower than that for CSS-25 by about 233 %.

Keywords: Thermal analysis; Economic study; Conical distiller; Desalination; Aspect ratios; Solar still.

1. Introduction

One of the major issues in emerging countries is the rising demand for drinking water. The World Health Organization (WHO) estimated that more than 2.1 billion people lack access to safe drinking water sources, and about 40% of people worldwide experience ongoing freshwater shortages [1].

Additionally, WHO broadcasts that the best feasible stage of affordable saltiness in consuming water is 500 ppm [2]. And for extraordinary cases, it is able to be identical to 1000 ppm. Nevertheless, the maximum of the floor or groundwater to be had on the planet has a salinity of as much as 10,000 ppm. Seawater has a salinity among 35,000 and 45,000 ppm [3]. United Nations World Water Development Report says that if the degradation of the environment and flawed stress on worldwide water assets will increase at the same rate, then 45% of the worldwide gross home product (worldwide GDP) and 40% of global grain manufacturing can be at excessive chance via way of means of 2050. This file additionally states that during numerous growing nations, 3 out of ten people do now no longer have admittance to steady ingesting water [4]. World health organization (WHO) said that globally 2.2 million human beings die each yr. because of intake of infected water. Water makes a good-sized contribution to health; precise fitness is the essence of progress [5]. United states sustainable improvement aim 3 (SDG-3) states that making sure wholesome lives and inspiring wellness at every age is important for sustainable improvement [6]. To fulfil secure consuming water demand, groups use diverse desalination systems, for instance, opposite osmosis, multi-impact desalination, electrodialysis, multi-level flash, ion exchange, solvent extraction, and solar still.

Solar still is easy from a creation factor of view, reasonably-priced and that they may be green with the aid of using offering numerous techniques of development. Furthermore, they necessitate much less repairs, and anyone could make advantages of them. They encompass a basin that has been painted black to take in warmth. It includes salty water and is uncovered to solar rays. The basin is included with an obvious cloth like glass [7]. After that, the water evaporates and condenses at the glass's inside face. Channels gathered sparkling and easy water and saved in bottles or tanks. The important drawback of sun nonetheless is the low productiveness of water in line with day so, it allows access lots traits on it to boom its productiveness.

There are several opinions and studies on paintings performed on solar stills for improvement their productivity [8]. Some scientists studied passive solar still. others researched tilted solar stills [9], design and modeling of solar stills [10], stepped solar stills [11], energy and exergy analysis [12], solar stills with nano-particles [13], floating structure [14], graphene nano ratchet [15], and a hybrid desalination system that includes HDH and solar stills [16], No verifications of the geometry of the solar still have been performed, so this article is a desk overview of the SS geometry, its advantages and theory of operation, and a comparison between these types.

Solar stills are classed into two types: single-effect & multiple-effect, with the heat source used for water evaporation determining whether they are active or passive. Clean water is created simply by solar radiation in passive solar stills, but active solar stills utilize additional thermal energy from a solar collector to generate drinkable water. The authors' study is notable because it demonstrates the advantages of using active approaches and increasing the number of stages in sun stills to increase the rate of evaporation and condensation when compared to standard solar stills. Figure a, shows a schematic representation of several solar still arrangements [17], [18]. Various additional technologies, such as thermal solar collectors, heat exchangers, solar ponds, and hybrid PV/T systems, have been integrated in multiple studies to improve the daily output of solar stills [19]. Several researchers have attempted to cool the condensing surface by using methods such as flowing water over it to enhance the temperature differential between the condensing surface and evaporated water [20]. and lowering the temperature of the glass cover with a layer of continually running water [21], or by utilizing an intermittent flow of cooling water over the lid [22]. Wind velocity also influences surface temperature because greater air movement enhances convective heat transmission from the cover to the atmosphere, which increases evaporation and condensation rates and system output [23].

Over the last ten years, a great number of studies on various types of single-effect solar still designs have been widely debated in the literature. Among these designs were fan solar stills [24], spherical and pyramidal solar stills [25], wick solar stills [26], solar chimney and condensers [27], rotating wick solar stills [28], rotating disc solar stills [29], and solar stills with revolving drums [30].

Through the review, it can be concluded that the solar desalination method still needs a great deal of research and development to deliver high-yield systems. So, the main objective of this study is to investigate the effect of using a conical solar distiller at three different aspect ratios on thermo-economic performance. In addition, experiments were tested at varying depths of the water level in the basin.

2. Experimental Setup and Procedures

This experimental test seeks to maximize the performance of conical solar stills. The experimental setup is depicted schematically and photographically in Figure 1. The testing apparatus includes a brine water storage tank, a wooden table, a distillation water tank, and three conical solar stills with different aspect ratios (AR = Height/Radius). The three conical solar stills are CSS-75, with a height of 75 cm, CSS-50, with a height of 50 cm; and CSS-25, with a height of 25 cm, producing aspect ratios AR = 3, 2, and 1, respectively.

The three distillers have a projected area of 0.2 m^2. The three conical stills are carried on a wooden table. The solar still basin is a 0.5mm thick sheet of aluminum fully coated with black paint to enhance water absorption further. The tank's bottom and inner side walls are painted with matte black rubber silicone to maximize absorption Incident solar energy capacity [31]. In contrast, the outer side walls are properly insulated with a 10mm thick polyester film to minimize heat loss to the external surrounding. The diameter of the basin is 500 mm and 100 mm in height. In addition, the basin is covered by a conical acrylic cap with a 5mm thickness and 500 mm diameter as a condensing surface. A circular trough is put at the bottom of each distiller's glass cover to collect the condensed water vapor, followed by a bottle of water to collect the distilled water production.

Experimental runs were done in the three proposed conical stills under the same outdoor conditions of Suez (29° 58′ N, 32° 32′ E), Egypt, in July 2022 for 11 hours from 7:00 am to 6:00 pm with the performance of the stills being quantified every 1 hour. The amount of saline water is kept constant (approximately) by feeding the stills manually with an amount of saline water equal to the distillate every half an hour. The temperatures and freshwater productivities of the modified conical stills were measured and compared. During the experiments, type K thermocouples (accuracy ±0.1 °C) were placed at appropriate points in the three solar stills to measure the temperature of the absorption reservoir, the saline water, and the cover acrylic. A data-logging solar meter (accuracy ±1 W/m^2) was employed to log the total solar radiation. Anemometer (accuracy ±0.1 m/s) was used to indicate the wind speed during experiments. In addition, a graduated cylinder (accuracy ±10 mL) was utilized to determine the amount of distillate each hour. All recorded values were completed within one hour.

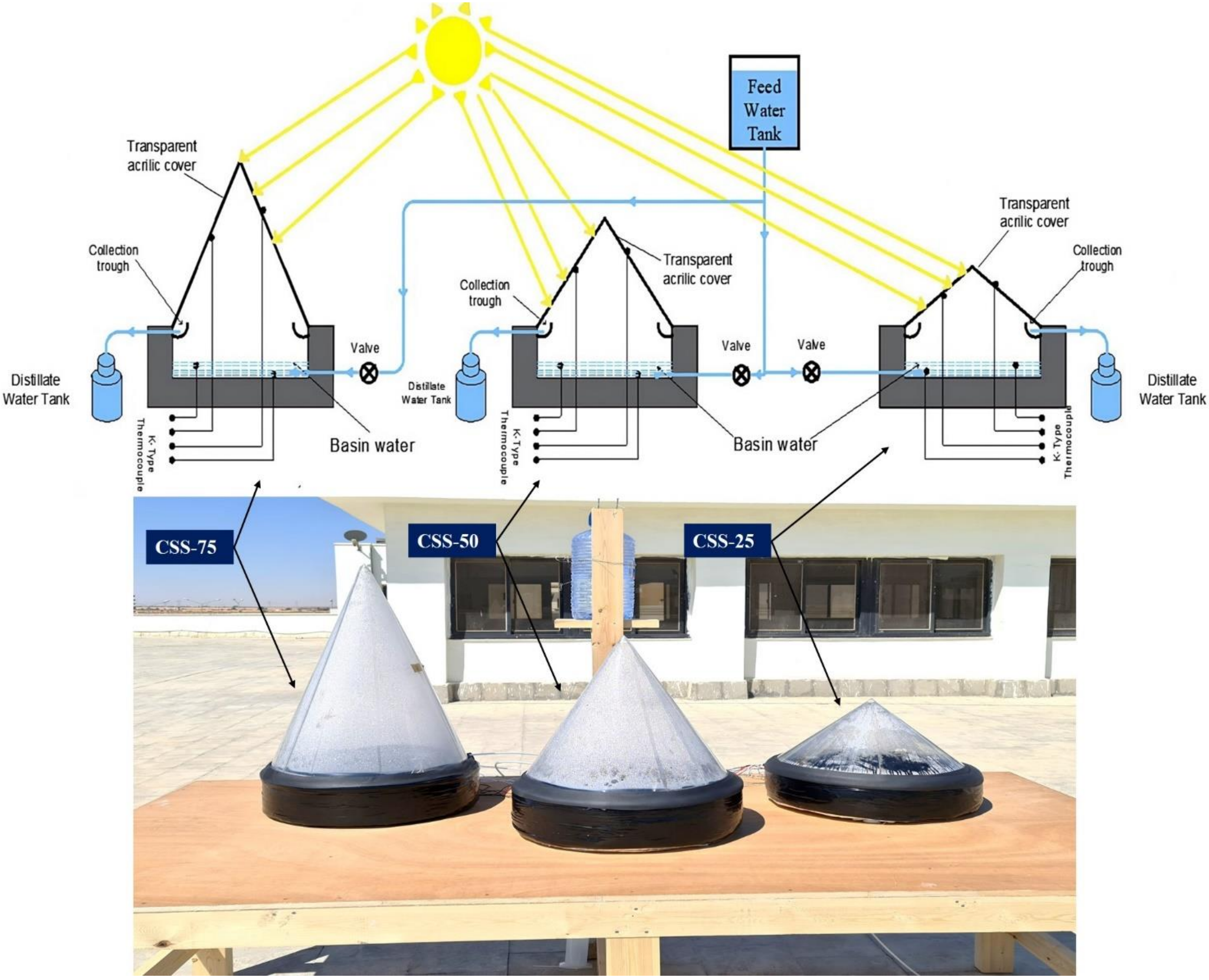

Fig. 1 Schematic diagram and photograph view for different aspect ratios of conical distillers.

3. Results and discussion

3.1 Performance of conical solar stills at 1 cm water depth

Figure 4(a) depicts the ambient temperature, solar radiation, and wind speed variables for the CSS-75, CSS-50, and CSS-25 on July 18, 2022. The graphic shows that the ambient temperature and the intensity of solar radiation peak around midday (about 12:00 pm), then fall to their lowest point at the end of the day at 6:00 pm. The air-speed, however, has varied between 4 and 8.4 m/s. The water basin temperature of the CSS-25 was higher than that of the CSS-75 and CSS-50, as shown in Fig. 4(b). This is because the CSS-25 has a closer glass cover to the basin, increasing the exposure of the basin water to sunlight. However, Because of the modest size of the cover and hence the small surface area of condensation, the CSS-25 was not the most productive. The largest water basin temperatures of the CSS-25, CSS-75, and CSS-50 at 12:00 pm were 72 °C, 60.9 °C, and 59.6 °C, respectively, as shown in Fig. 4(b).

The hourly and accumulated freshwater outputs from CSS-75, CSS-50, and CSS-25 are shown in Fig. 4(c). The immense hourly freshwater value of 689 mL/m^2 was achieved for the CSS-75 at 12:00 pm, while low productivity of 619 mL/m^2.h for the CSS-50 and 241 mL/m^2.h for the CSS-25 simultaneously. In addition, the significant amount of accumulated freshwater for CSS-75 was 5.17 L/m^2, 3.82 L/m^2 for CSS-50, and 1.18 L/m^2 for CSS-25. The results suggest that CSS-75 had a higher hourly and cumulative freshwater content than CSS-50 and CSS-25. Accordingly, the use of AR = 3 as a modification in the CSS-75 increased freshwater output by approximately 35.3% compared to the CSS-50 and 338% compared to the CSS-25 due to more massive heat transfer from the condensation surface's surface area to brackish water in the basin by increasing the size of the glass cover surface area.

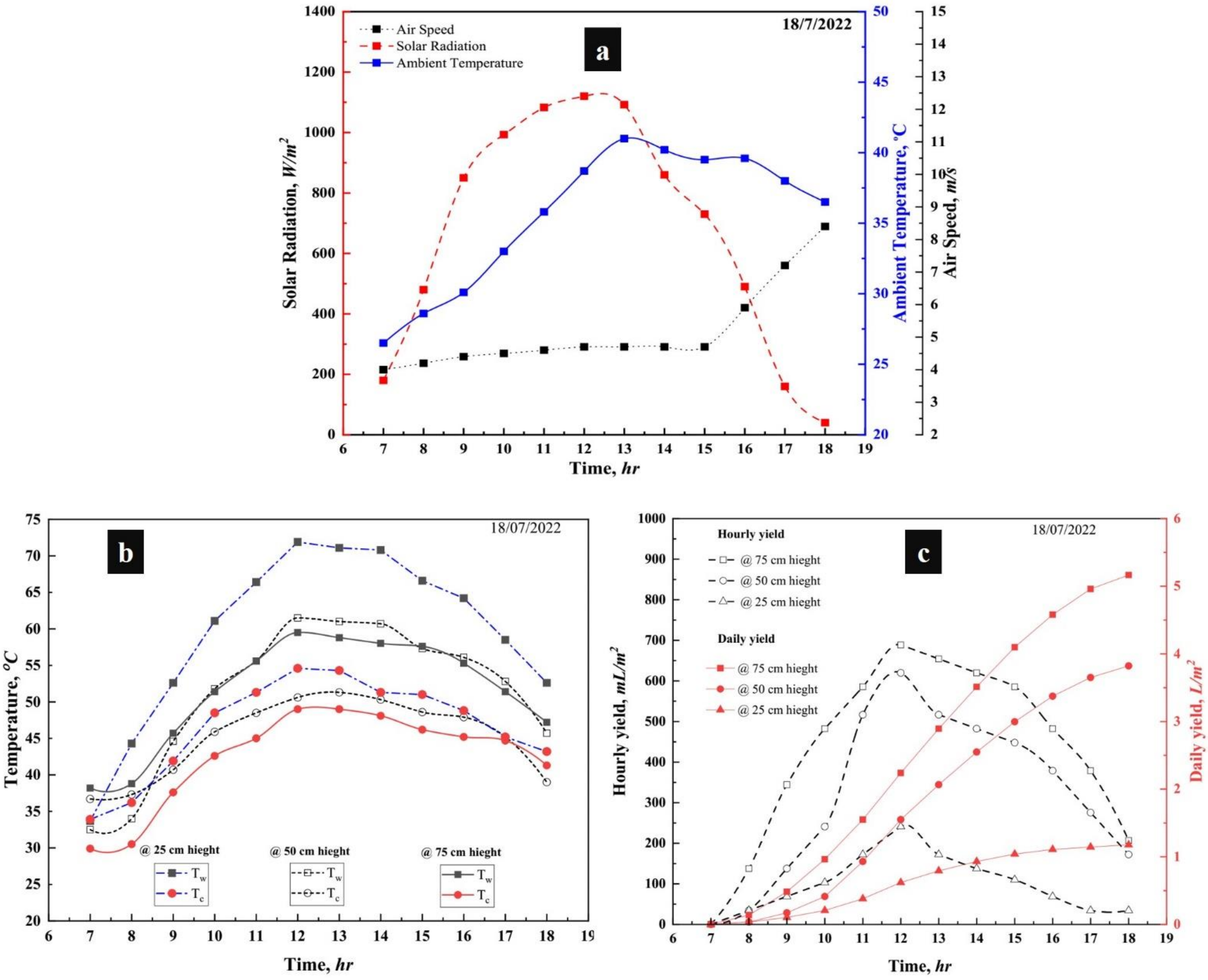

Fig. 2 Thermal performance of conical solar stills at 1 cm water level (a) ambient temperature, solar radiation intensity, and wind speed, (b) water and cover temperatures, and (c) hourly and daily freshwater production.

3.2 Performance of conical solar stills at 2 cm water depth

On July 24, 2022, Figure 4(a) illustrates the ambient temperature, solar radiation intensity, and airspeed variables for the CSS-75, CSS-50, and CSS-25. The graphic depicts the air temperature and solar radiation intensity peak around midday (12:00 pm) and then falling to their lowest point at the end of the day at 6:00 pm. The airspeed, on the other hand, has ranged between 4 and 8.3 m/s. The CSS-25's water basin temperature was higher than the CSS-75 and CSS-50, as shown in Fig. 4(b). This is because the CSS-25 has a closer glass cover to the basin, exposing the basin water to more sunlight. However, due to the small size of the cover and thus the small surface area of condensation, the CSS-25 was not the most productive. The greatest water basin temperatures of the CSS-25, CSS-75, and CSS-50 at 1:00 pm were 69.7 °C, 57.4 °C, and 56.7 °C, respectively, as shown in Fig. 4(b).

The hourly and accumulated freshwater outputs from CSS-75, CSS-50, and CSS-25 are shown in Fig. 4(c). At 1:00 pm, the CSS-75 obtained an enormous hourly freshwater value of 690 mL/m^2, whereas the CSS-50 and CSS-25 recorded lower values of 585 mL/m².h and 172 mL/m², respectively. In addition, the significant amount of accumulated freshwater for CSS-75 was 4.34 L/m², 3.23 L/m² for CSS-50, and 0.79 L/m² for CSS-25. According to the results, CSS-75 had more extensive hourly and cumulative freshwater content than CSS-50 and CSS-25. Accordingly, Due to more efficient heat transfer from the condensation surface's surface area to the brackish water in the basin by expanding the size of the glass cover surface area, the CSS-75's use of the 75 cm conical height as a modification increased freshwater output by roughly 34.3% compared to the CSS-50 and 449.3% compared to the CSS-25.

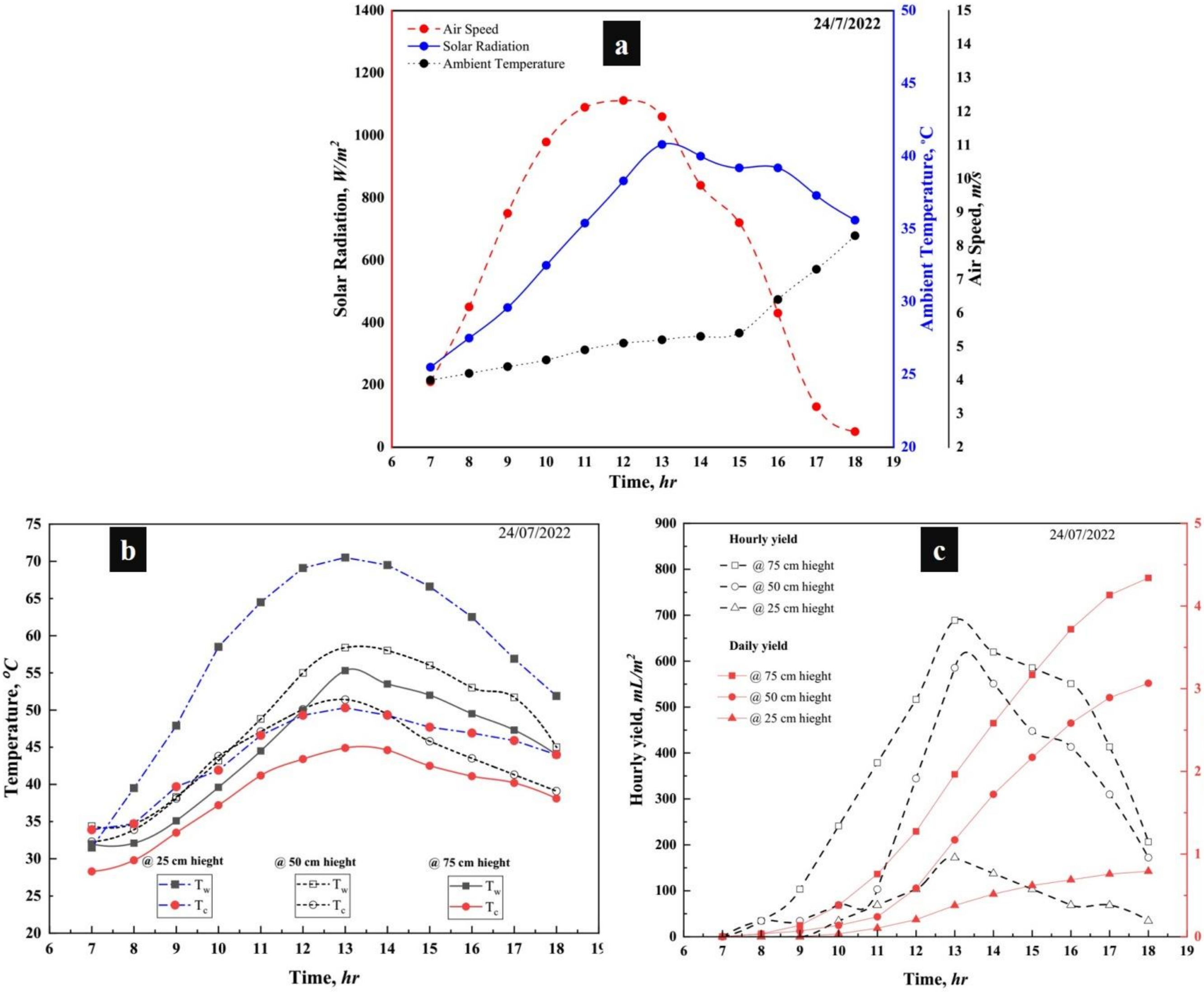

Fig. 3 Thermal performance of conical solar stills at 2 cm water level (a) ambient temperature, solar radiation intensity, and wind speed, (b) water and cover temperatures, and (c) hourly and daily freshwater production.

3.3 Performance of conical solar stills at 3 cm water depth

On July 26, 2022, Figure 4(a) illustrates the weather condition (ambient temperature, solar radiation intensity, and airspeed) for the CSS-75, CSS-50, and CSS-25. The picture depicts that the ambient temperature and solar radiation intensity peak about midday (approximately 12:00 pm) and subsequently descend to their lowest point at the end of the day at 6:00 pm. The airspeed, on the other hand, has ranged between 3.6 and 5.1 m/s. The CSS-25's water basin temperature was higher than the CSS-75 and CSS-50, as depicted in Fig. 4(b). This is because the CSS-25 has a closer glass cover to the basin, exposing the basin water to more sunlight. The CSS-25, on the other hand, was not the most productive due to the small size of the cover and hence the small surface area of condensation. As indicated in Fig. 4(b), the largest water basin temperatures of the CSS-25, CSS-75, and CSS-50 at 1:00 pm were 6.36 °C, 58.6 °C, and 53.5 °C, respectively.

Figure 4(c) monitors the hourly and accumulated freshwater outputs from CSS-75, CSS-50, and CSS-25. At 2:00 pm, the CSS-75 obtained an enormous hourly freshwater value of 654 mL/m^2.h, while the CSS-50 and CSS-25 recorded lower values of 447 and 172 mL/m^2.h, respectively. Furthermore, for CSS-75, the significant amount of accumulated freshwater was 3.51 L/m^2, 2.33 L/m^2 for CSS-50, and 0.68 L/m^2 for CSS-25. According to the results, CSS-75 had more extensive hourly and cumulative freshwater content than CSS-50 and CSS-25. Accordingly, The CSS-75's use of the 75 cm conical height as a modification increased freshwater output by roughly 50.6% in comparison to the CSS-50 and 416.1% in comparison to the CSS-25 because the larger surface area of the condensing cover allowed for more efficient heat transfer from the condensation surface to brackish water.

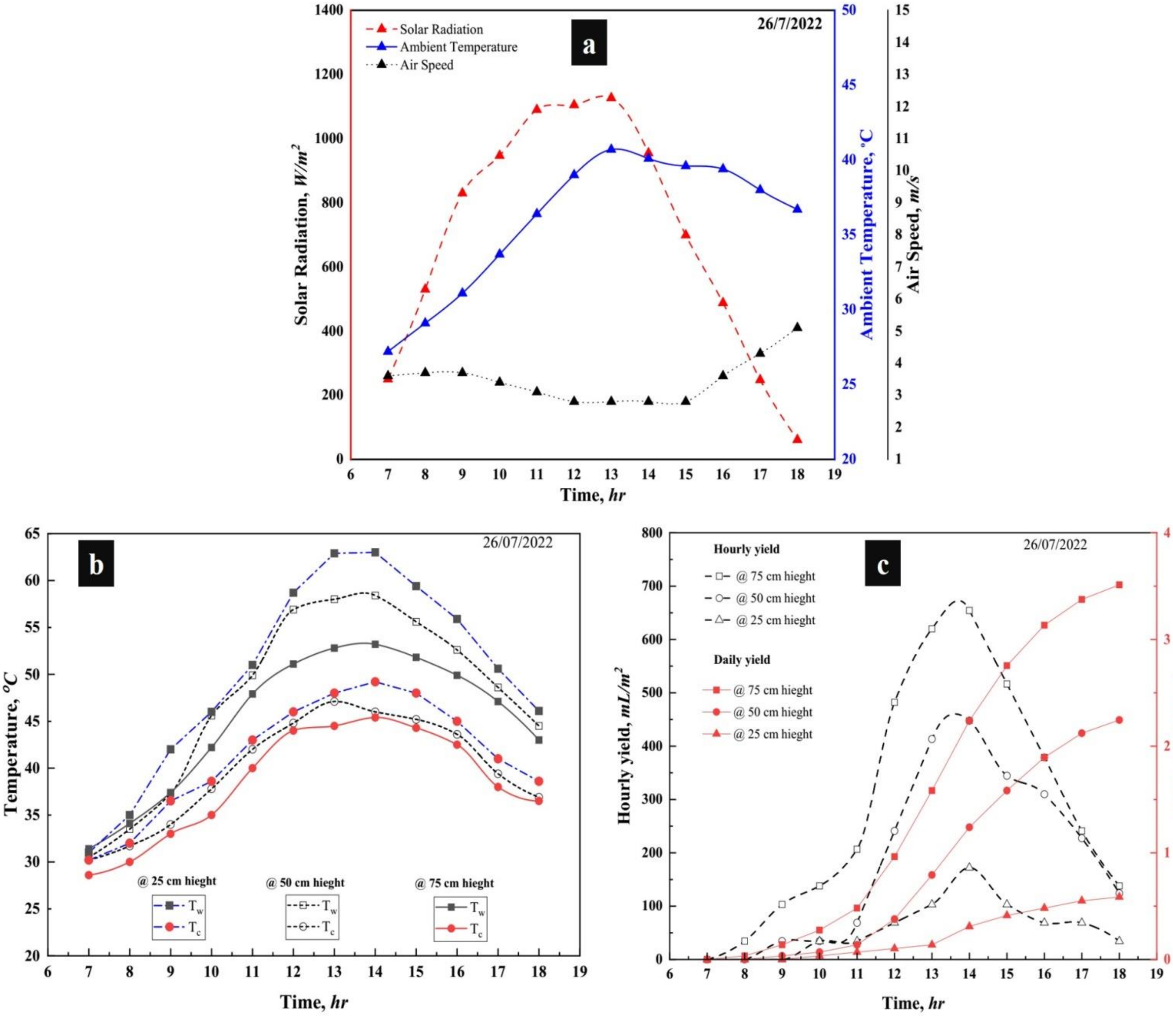

Fig. 4 Thermal performance of conical solar stills at 3 cm water level (a) ambient temperature, solar radiation intensity, and wind speed, (b) water and cover temperatures, and (c) hourly and daily freshwater production.

3.4 Effect of basin water depth on SS performance

According to the above results, the lower the water depth in the basin, the better the performance significantly. We also notice from Figs. (2b-4b) when the water depth was 1 cm, we obtained the highest value for the water temperature at 12 pm, and at a depth of 2 cm, we got the highest water temperature at 1 pm. At a water thickness of 3 cm, the highest water temperature was within the limits of 2 pm. This is because the more significant the thickness of the water inside the basin, the higher the amount of heat required to work on evaporation [32]. Figure 5a shows the total water production and efficiency of the conical solar stills of different heights at different water thicknesses. The results revelated that the SS with a height of 75 cm (AR = 3) achieved the best performance with daily yields of 5.17, 4.34, and 3.51 L/m² for 1 cm, 2 cm, and 3 cm water levels, respectively.

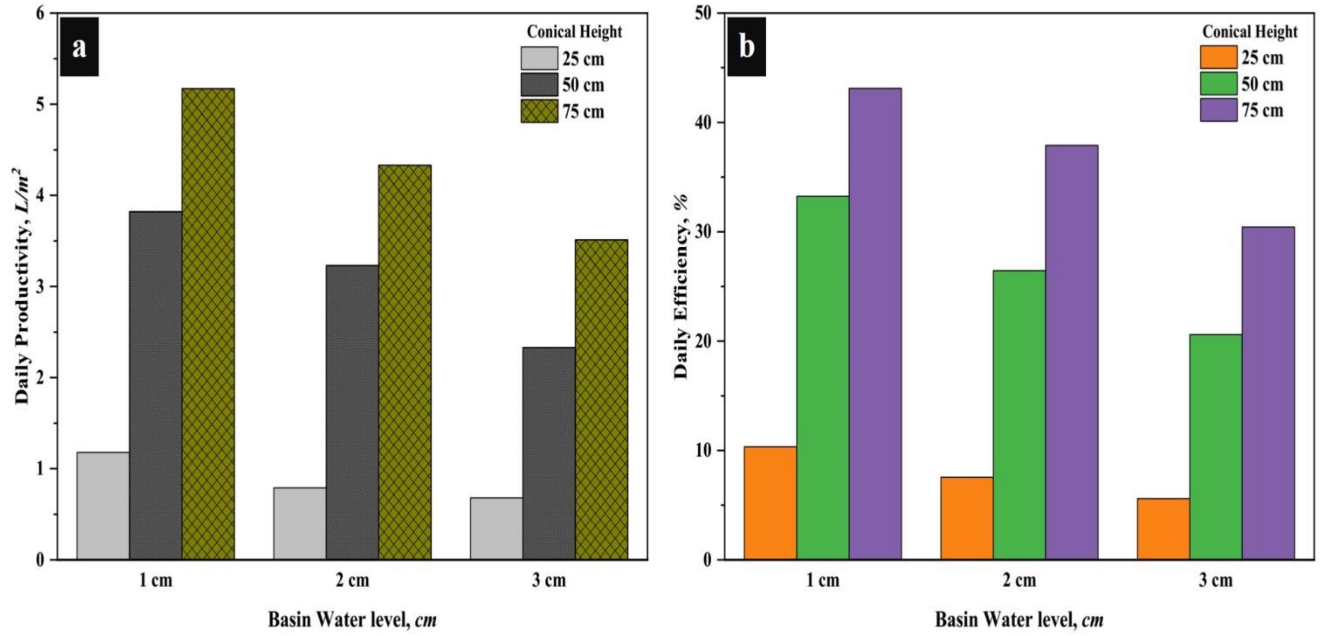

Fig. 5 Performance of CSS (a) Daily productivity vs. basin water level (b) Daily efficiency vs. basin water level.

3.5 Thermal efficiency of conical solar still

The daily thermal efficiency of CSS is calculated by [30][33];

$$\eta_{\mathrm{d}} = \frac{\Sigma \dot{\mathrm{m}} \times \mathrm{h_{fg}}}{\Sigma \mathrm{A} \times \mathrm{I}} \tag{1}$$

Where:

η_d - is the daily thermal efficiency (%).

$\dot{m}$ - is the hourly yield (kg/m².h).

h_{fg} - is the latent heat of vaporization (kJ/kg).

A - is the system area (m²).

I - is the daily average solar radiation (W/m²), and the water temperature T_w (°C) is used to calculate h_{fg} as follows [34];

$$h_{fg} = 3.1625 \times 10^{6} + [1 - (7.616 \times 10^{-4} \times T_w)] \text{ for } T_w > 70°\mathrm{C}$$

Or

$$h_{fg} = 2.4935 \times 10^{6}[1 - (9.4779 \times 10^{-4} \times \mathrm{T_w}) + (1.3132 \times 10^{-7} \times \mathrm{T_w^2}) - (4.7974 \times 10^{-9} \times \mathrm{T_w^3})] \text{ for } \mathrm{T_w} < 70°\mathrm{C} \tag{2}$$

The thermal efficiency of CSS is shown in Figure 5b for various cone heights. The figure indicates that daily efficiency exhibits the same pattern as daily production growth. The CSS-75's daily thermal efficiency was

43.12% at 1 cm of water thickness, the highest value recorded. Additionally, as shown in Figure 5b, at the same water thickness, CSS-50 had a thermal efficiency of 33.24%, and CSS-25 had a thermal efficiency of 10.34%.

3.6 Economic analysis

The economic analysis of CSS-75, CSS-50, and CSS-25 desalinated water was evaluated. The exact fixed costs of three conical distillers are provided in Table 1. Table 2 provides the values of the economic analysis parameters for desalinated water for all distillers. The economic analysis's equations and calculations are written in Table 3. Based on the presumed values of economic analysis parameters (Table 2) and utilized function and calculations (Table 3), the cost values of distilled water are plotted in Fig. 6. From Fig. 6, the cost per distillate water are 0.015, 0.018, and 0.051 USD at 1 cm water level for CSS-75, CSS-50, and CSS-25, respectively.

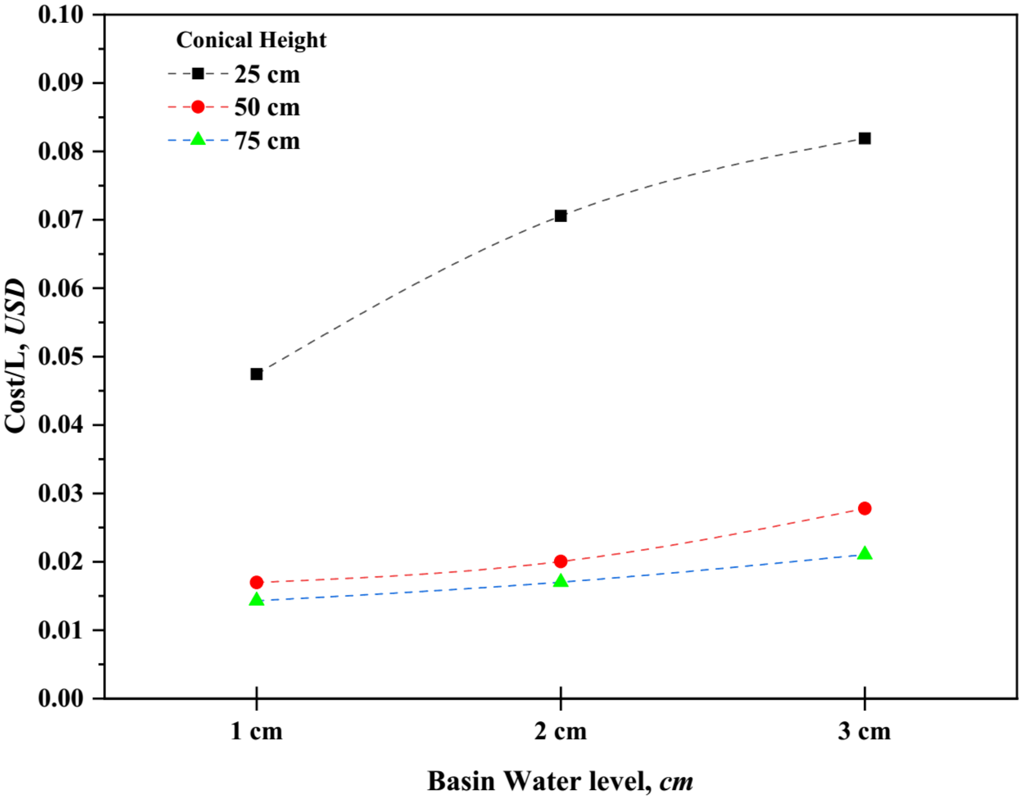

Fig. 6 Cost of distilled water for different solar stills.

Table **1.** Fixed costs of the conical distillers.

Unit	**Cost**		
	CSS-75	**CSS-50**	**CSS-25**
Aluminum basin	15	15	15
Glass cover	45	35	25
Paint	3	3	3
Insulation (fiberglass)	5	5	5
Production	30	25	20
Saline and freshwater bottles	15	15	15
Valves and pipes	10	10	10
Total fixed price (F)	**123**	**108**	**93**

Table 2. Parameters of economic analysis of desalinated water for current work.

No	Parameter	Description	Value	Unit
1	n	System Lifetime	10	Years
2	i	Interest rate	15	%
3	F	System fixed price (see Table 1)	80 for CSS-75 65 for CSS-50 50 for CSS-25	$
4	M	Annual average productivity	1757 for CSS-75 1298 for CSS-50 399 for CSS-25	L/m^2.year

Table 3. Calculations of economic analysis [35]

Relation	Eq. No	Description	Reference
$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$	(3)	Capital recovery factor	[35]
$FAC = F(CRF)$	(4)	Fixed annual price	
$SFF = \frac{i}{(1+i)^n - 1}$	(5)	Sinking fund factor	
$S = 0.2F$	(6)	Salvage value	
$ASV = S\ (SFF)$	(7)	Annual salvage value	
$AMC = 0.15(FAC)$	(8)	Annual salvage value	
$TAC = FAC + AMC - ASV$	(9)	Total annual cost	
$CPL = TAC/M$	(10)	Cost of distilled water	

4. Conclusions

This work investigates the effect of changing the condensation surface height of conical distillers at different depths of the basin water surface level. The tests were conducted simultaneously at three different aspect ratios in Suez, Egypt. The main conclusions remarks are summarized as follows:

- The results showed that increasing the aspect ratio AR = 3 (CSS-75) works to enhance the performance of the solar conical still, as it enhances productivity and energy efficiency by about 338 and 317%, respectively, compared with CSS-25 (AR = 1).
- The water depth in the basin has an apparent effect on the performance of conical distillers.
- In comparison, the daily yield and energy efficiency of the CSS-75 were 5.17 L/m^2 and 43.12% at WD = 1 cm, 3.82 L/m^2 and 37.9% at WD = 2 cm, and 1.18 L/m^2 and 33.44% at WD = 3 cm, respectively.
- The comparative cost analysis results for the various investigated systems indicate that the CSS-75 system achieves the lowest price per liter of distilled freshwater (0.015 USD) with a reduction of 233% compared to the CSS-25 system at optimal water depth.

Nomenclatures

Latin Symbols

A	Area, m^2
I	Solar heat flux, W/m^2
$\dot{m}$	Hourly mass flow rate, kg/s
t	Time, h.
T	Temperature, °C
n	Life expectancy, year
i	Interest rate, %
F	Fixed cost, USD
M	Average yearly productivity, $L/m^2.year$
CRF	Capital recovery factor
FAC	Fixed annual cost
SFF	Sinking fund factor
S	Salvage value
ASV	Annual salvage value
AMC	Annual salvage value
TAC	Total annual cost
CPL	Cost of distilled water
h_{fg}	Latent heat of vaporization, kJ/kg

Greek Symbols

η	Efficiency, dimensionless

Subscripts

c	Glass cover
w	Water

Acronyms

AR	Aspect Ratio (H/R)
SS	Solar Still
CSS	Conical solar still
WHO	World Health Organization
WD	Water Depth

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