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Performance enhancement of stepped solar still via different sand beds, cooling coil and reflectors

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ABSTRACT

This study aims at enhancing the freshwater from saline water via stepped solar stills (SSS). Experimental work for different sand beds SSS was conducted to enhance its performance, the sand was used as thermal storage materials. The effects of sand type (black and yellow) and sandy bed height on the performance of stepped solar still (SS) were studied. Also, the effect of internal reflectors and cooling coil on the sand stepped SS performance was investigated. Experimental results revealed that the sandy layer improves the stepped SS productions. At 1 cm height of sand beds the accumulated productivity of the conventional solar still (CSS), SSS, yellow SSS and black SSS were 3,000 and 4,650; 5,150 and 5,750 mL/m^2·d, with improvement of 55%, 71%, and 92%, for the SSS, yellow SSS and black SSS higher than CSS. In addition, the maximum increase in accumulated production of sandy stepped SS with internal, external reflectors and cooling coil was obtained at sand beds height of 1 cm and black sand. In this case, the production of black SSS was increased by 165% over CSS with thermal efficiency 56.6%. In addition, in comparison to the CSS, the cooling system increases black SSS productivity by 31%. The environmental parameter of black SSS with vapor withdrawal and reflectors was 24 tons·CO_2/y.

Keywords: Solar stills; Stepped solar stills; Thermal storage materials; Sand; Reflectors

1. Introduction

Due to the rapidly rising demand and the limited supply of resources, freshwater scarcity is one of the most significant issues that humanity is currently dealing with. Water needs are anticipated to rise by 130% and 400% from home and manufacturing consumption, respectively, by 2050, notwithstanding the stability of global water resources. It was reported that exclusively 0.01% of the earth's water can be reachable [1]. Solar still (SS) is suggested for smaller requirements due to its cheapness and simplicity [2]. Because of their low production, solar distillers are small units of desalination devices that can be utilized to meet the freshwater needs of small families. So, various shapes of SS systems have been tested under different design and operating conditions such as conventional solar still (CSS), stepped SS [3], pyramid SS [4], pyramidal absorber SS [5], conical absorber SS [6], tubular SS [7], drum tubular SS [8], convex tubular SS [9], trays SS [10], corrugated trays SS [11], finned trays SS [12], hemispherical SS [13]. and half barrel SS [14]. Also, phase change material [15], various wick materials [16], sensible heat storage [17], nanoparticles [18], wire mesh absorber SS [19], reflectors [20], elevated basin SS [21], solar collectors SS [22], hybrid SS [23] cords SS [24], rotating wick SS [25], rotating discs SS [26], rotating drum SS [27], fan SS [28], parabolic solar concentrator SS [29] and ultrasound waves SS [30].

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The water depth in the SSs inversely affects the production of the SSs. Maintaining the minimum depth in the SS is very difficult. For maintaining minimum depth, wick [31], plastic water purifier [32] and stepped SS [33] were utilized. Studies have found that a decrease in the SS's salinity depth increases output, primarily because the basin's water is warmer. The performance of the modified stepped solar stills (SSS) with reflectors (internal and external) studied by Omara et al. [34]. The results indicated that, freshwater production of SSS enhanced by about 125% over conventional SS, with mirrors and external condenser. An experimental study of SSS with external condenser and reflectors (internal and external) was conducted by El-Samadony et al. [35]. The results indicated that, production of SSS enhanced by about 165% over conventional SS. Kabeel et al. [36] studied effect of varying both widths and depths and of trays on the performance of stepped SS. The step width was constant and equal 100 mm. They found that, at a tray depth 5 mm and tray width 120 mm the maximum production of SSS is achieved, which is about 57.3% over conventional SS.

The solar still efficiency is dependent on the energy of sun. The sun is most intense between 12:00 and 13:00. As a result, SS ought to produce more fresh water between 12:00 and 13:00. However, the water temperature inside the SS remains greater, and water vapour formation is also higher, because to the increased amount of solar rays impacted on the basin water at this time. So, the temperatures of the mixture of air vapor increased and which increases the glass cover temperature. The productivity of SS depends on the difference of temperature between temperature of glass cover and temperature of saline water, so due to higher glass cover and temperature of saline water, improvement in production is not increased. The use of thermal energy storage materials, which store surplus thermal energy and release it during non-sunny hours, enables an increase in production and thermal efficiency, is thus necessary to make use of the extra energy. Omara and Kabeel [37] investigated conventional solar still with sand beds in detail, taking into account numerous characteristics such as depth and sand type. They found that black sand was the most efficient of the different sands tested Murugavel et al. [38]. Velmurugan et al. [39] utilized pebbles, sponges, sand and black rubber in the finned SS for enhancing the daily productivity. They indicated that sand in the SSs improves the SS productivity by around 14%. Srithar [40] utilized sand, pebble and sponge to improve the daily distillate of the traditional SS. The experimental results indicated that maximum daily production of 32.3% improvement was obtained with sponge and sand. Mohammed et al. [41] conducted experimental study to evaluate the influence of inclined rectangular perforated fins, hollow cylindrical perforated fins, and nanocomposites on the yield of a pyramid solar stills. The results indicated that, inclined rectangular perforated fins and hollow cylindrical perforated fins, improving the productivity by 55.9% and 31.3%, respectively, compared to that of the conventional PSS. Additionally, utilizing nanocomposites with inclined rectangular perforated fins improved the daily yield by 82.1%.

The different distillation and solar desalination methods were summarized and reported [42]. The stepped solar distiller performance was improved by using suspended trays [43]. Also, the authors merged the effect of using trays with PCM and vacuum fan to further enhance the performance of distiller. They enhanced the productivity by 55%, and the thermal efficiency was 52.4%. In addition, using the wick material with corrugated and curved absorbers and PCM enhanced the distillate by 170%, where the distillate reached 7 $L/m^2{\cdot}d$ [44]. Besides, Gandhi et al. [45] used the online Sequential Extreme Learning Machine (OSELM) with the stepped solar distiller for haste of energy absorption. The thermal efficacy obtained an increase by 49.21%, using 30% of SiO_2/TiO_2 coating. Moreover, Bamasag et al. [46] used the machine learning technique to predict the performance of a dish solar still with convex stepped absorbers and PCM. The distillate of solar still was enhanced by 178%, and efficiency reached 67.62%. Abd Elaziz et al. [47] used the neural networks (ANN) to predict the performance of solar distiller with nanomaterials. The distillate and efficiency of distiller were improved by 140% and 36.02%, respectively due to using CuO nanomaterials.

From this review, it is very important to conclude that the sand as thermal storage material inside solar stills play a vital role in its performance. In addition, the effect of sand on the stepped solar stills performance is not recognized. So, the aim of this study is to improve the performance of the stepped solar still via exploiting different types of sand as thermal storage material. Given the prior research, the following may be said about this work's novelty:

- Black sand and yellow sand were studied.
- Three heights of the sand beds were investigated.
- The effect of adding internal and external reflectors on the performance of the sand stepped SS.

2. Materials and procedures

2.1. Setup elements

Four solar stills were fabricated; black sand stepped SS (BSSS), yellow sand stepped SS (YSSS), stepped SS (SSS), and CSS to evaluate and compare the tested SSs performance and estimate the influence of install internal and external (top and bottom) reflectors and two type of sand. Figs. 1 and 2 show a photograph and 2D-shematic drawing of the experimental test rig. The SSs were made of galvanized steel and have 0.5 m^2 projected area. The lengths of higher and lower edges of SSs were 15 and 35 cm, respectively. The stepped SS has the same construction and dimension of CSS, in addition the absorber plate is made of 5 steps (10 cm × 100 cm each of size) with trays width of 120 mm. As internal mirrors for SSS,

Fig. 1. Photo of experimental test rig.

reflectors were attached to the trays' vertical sides, Fig. 2. The basin was also covered by a 3 mm glass cover. In order to maximize irradiance absorption, the SSs were painted black. The SSs have been positioned to face south to maximize the sun irradiation. The fan used to extract vapor from the SSS and conduct the condensation process through a copper coil (3 m length and 0.02 m diameter) located inside the feeding tank, so the condensation process takes place, and the feed water temperature is raised utilizing the fan, which lowers the glass temperature. As a result, condensation is enhanced. The fan was integrated with a solar-powered photovoltaic system. The fan used 6 W of power while the PV system produced 10 W. The used fan was an axial fan with a blade diameter of 9 cm and a radial diameter of 10 cm.

2.2. Experiments procedures

In order to measure the solar intensity, temperatures, air velocity, and productivity, all measuring instruments were then attached to the setup. The beginning and ending times of testing were 08:00 and 18:00, respectively. The processes of tests were resumed into: (a) effects of two different types of sand (black and yellow sand) on the performance of SSS were studied, (b) three height of sand bed (1, 2, and 3 cm) with zero water height above the sand beds level were investigated, according to Kabeel et al. [48] the maximal productivity increase was obtained at zero depth of water over sand beds, (c) the effect of adding internal and external (top and bottom) reflectors on the performance of the sand SSS.

2.3. Measuring tools and error analysis

Sunlight intensity, glass and water temperatures, ambient temperatures, wind speed, and water productivity all affect the SS's performance. A solarimeter was used to measure the radiation. As well, the temperatures were measured by thermocouples. The basin water temperatures were measured at all steps then the mean value was taken. Also, air velocity was measured by anemometer. What is more, the yield was recorded by graded bottles. Table 1 provides the unit, accuracy, resolution, and range characteristics of the measuring equipment.

The error analyses are executed regarding the method of Holman [49] and Elminshawy et al. [50]. The error in a result of parameter was found as following.

$$W_R = \left[\left(\frac{\partial R}{\partial X_1}W_1\right)^2 + \left(\frac{\partial R}{\partial X_2}W_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial X_n}W_n\right)^2\right]^{\frac{1}{2}} \quad (1)$$

where W_1, W_2, W_3, …, W_n are the uncertainties of the independent parameters. All calculated errors for the used tools are found in Table 1.

$$\eta_{th} = f\left(m, I_R, \Delta T_{w-g}\right) \quad (2)$$

Then, the efficiency uncertainty is determined by:

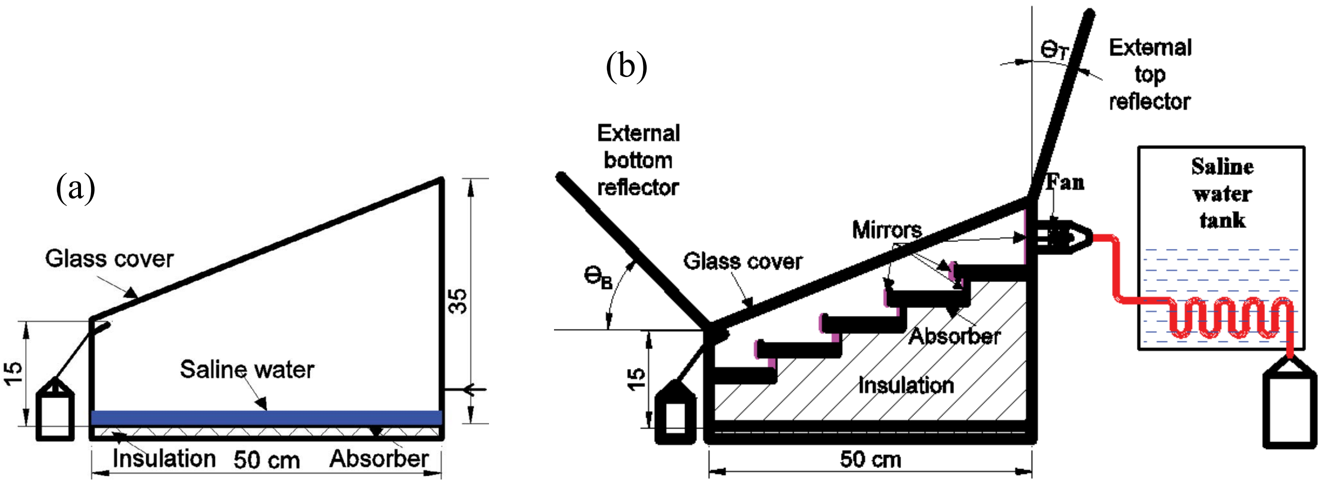

Fig. 2. Schematic drawing of setup. (a) Conventional solar still and (b) black sand stepped solar still with reflectors and fan.

Table 1
Characteristics of the measurement tools

Device	Parameter	Resolution	Accuracy	Range
Solarimeter	Irradiance, W/m^2	0.1	±1	0–5,000
K-type thermocouple	Temperature, °C	0.1°C	±0.5	0–100
Anemometer	Wind velocity, m/s	0.01	±0.1	0.4–30
Graded bottles	Productivity, L	0.5 mL	±5 mL	0–1

$$W_{\eta_{th}} = \left[\left(\frac{\partial \eta_{th}}{\partial m} W_m \right)^2 + \left(\frac{\partial \eta_{th}}{\partial I_R} \right)^2 + \left(\frac{\partial \eta_{th}}{\partial \Delta T_{w-g}} \right)^2 \right]^{\frac{1}{2}} \quad (3)$$

3. Results and discussions

3.1. Performance of solar stills at 1 cm sand height

The average temperature of the sand-water mixture in sand trays, the salinity of the stepped and CSS waters, and the productions all rise with exposure to the sun. Figs. 3 and 4 show that they rise until the afternoon, when they peak, and then decline the rest of the day as the sun's irradiance and surrounding temperature decrease.

Glass and water temperatures of CSS, SSS, YSSS, BSSS and solar climatic conditions were measured at 1 cm trays height, as shown in Fig. 3. The average water temperature of trays of SSS was higher than that of CSS by 0°C–3°C. This can be explained by two factors: (a) Due to the step-wise basin's larger surface area for heat and mass transport than the flat basin, SSS's basin water temperature rises, (b) Compared to a conventional still, the still chamber catches less air, hence the trapped air will heat up much more quickly. Additionally, a stepped solar still's glass temperature rises as a result of increased evaporation and condensation due to the high-water temperature. In addition, from Fig. 3, it can be indicated that the sand-water temperature (average value) of YSSS and BSSS are greater than that of CSS by a range of 0°C–4.5°C and 0°C–6.5°C. This is owing to that sand has a large capacity for storing sensible heat. Furthermore, due of its dark color and the presence of ferromagnetic elements, Fig. 3 shows that the temperature value of the black sand is higher than the yellow sand at all times. Black sand absorbs heat more efficiently than yellow sand. The peak value of sun radiation of 1,100 W/m² was achieved at 12:00. Additionally, at 13:00, the highest sand-water mixture temperature was 67°C, 68.5°C and 70.5°C for SSS, YSSS and BSSS, respectively, while the temperature of saline water of CSS was 64°C.

The glass cover temperature of for SSS, YSSS and BSSS was found to be more than that of conventional SS by 0°C–6.5°C. This is brought on by an increase in SSSs' rates of condensing and vaporizing relative to conventional SS. Moreover, the maximum temperature of glass were recorded at 13:00 where the temperatures of glass cover of SSS, YSSS, BSSS and the conventional SS were 46°C, 48°C, 49.5°C and 43°C, respectively.

Fig. 4 depicts the changes of instantaneous hourly and accumulated yields for the tested solar distiller from 8:00 to 21:00. From Fig. 4, the daily yield of BSSS was greater than that of SSS, YSSS and conventional SS. The figure indicated that, over the CSS, the SSS, YSSS, and BSSS all provided more output immediately. This is because SSSs evaporate at higher rates than ordinary SS do due to their higher evaporation area.

The water temperature in SSSs is also higher than in conventional SS. In comparison to conventional SS, which has an evaporation area of 0.5 m², SSSs have an area of roughly 0.58 m². In comparison to CSS, the area of SSS evaporation was almost 16 percent larger.

Also, from Fig. 4 the water production for sand SSS is superior to that of the CSS. The growth of both sensible heat and the area that absorbs sun irradiation increases the productivity of fresh water. Additionally, sand in SSS reduces the amount of time needed to pre-heat the water in the basin until it evaporates, where the specific heat of saline water (average value 4,050 J/kg·°C) is approximately five times than that of sand (average value 830 J/kg·°C), Therefore, compared to the conventional SS, the sand SSS requires lesser time to heat up before yield for the same depth. Additionally, the BSSS produces more, whilst the output of the conventional SS is consistently lower. Additionally, Fig. 4 indicates the production of the CSS, black SSS, yellow SSS and SSS, were

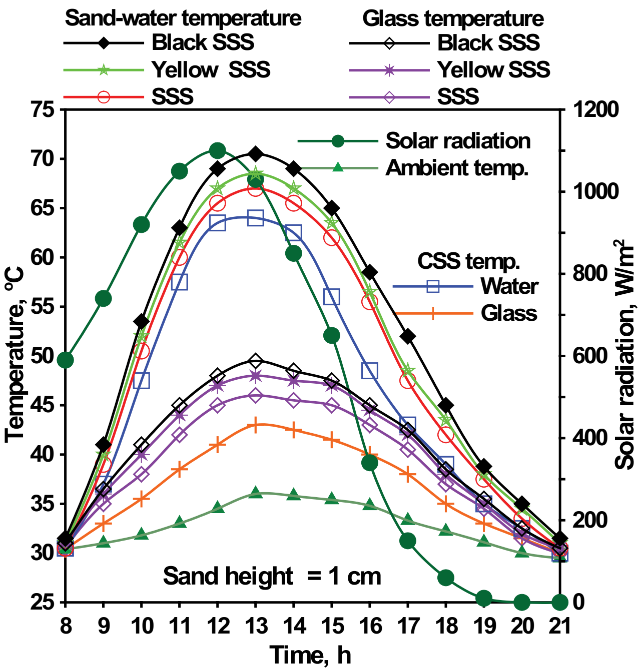

Fig. 3. Temperatures and solar irradiation for solar stills at sand height 1 cm.

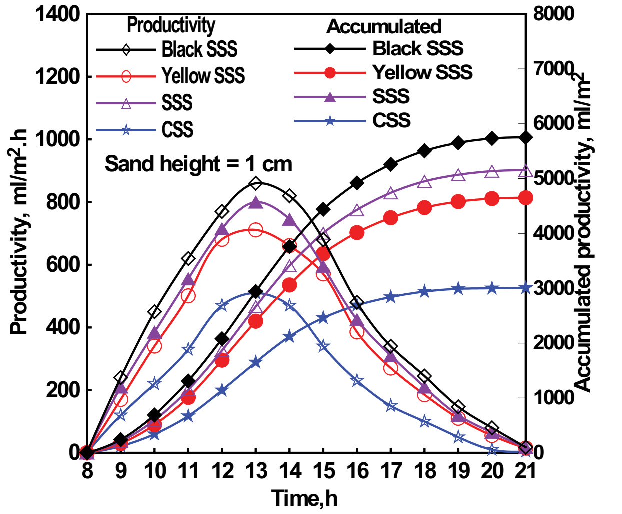

Fig. 4. Changes of total and hourly yields for stills at sand height 1 cm.

3,000 and 5,750; 5,150 and 4,650, mL/m²·d, with improvement of 55%, 71%, and 92%, for the SSS, YSSS and BSSS higher than conventional SS.

3.2. Effect of sand beds height on the stepped SS performance

According to Fig. 5, the measured variations in the daily production increase's percentage (productivity rise, %) for stepped SS, YSSS and BSSS over the CSS with different sand heights. According to Fig. 5, the greater quantity of heat transported and stored within the tested sand beds trays sunlight, results in a drop in daily production rise when the height of the sand beds is increased. The BSSS has greater production for all heights, as shown in the figure, due to its high capacity of heat (rich in iron and its black color). From Fig. 5 at 1 cm sand beds height, the daily productivity rises of freshwater of the SSS, YSSS and BSSS were 55%, 71%, and 92% over CSS. While at 3 cm sand beds height, the daily productivity rises of freshwater of the SSS, YSSS and BSSS were 51%, 66%, and 86%, over CSS.

The daily thermal efficiency is formulated as:

$$\eta_d(\text{thermal efficiency}) = \frac{\sum \dot{m}(\text{distillate}) \times h_{fg}(\text{latent heat})}{\sum A(\text{area}) \times I(t)(\text{solar radiation})} \quad (4)$$

So, Fig. 6 shows the distiller's daily efficiency at varying sand bed height. Fig. 6 shows that the lowest (41.4%) and highest (42.3%) efficiencies of stepped SS without any sand were found at 3 and 1 cm. Fig. 6 indicated that the daily thermal efficiency declines with raising the height of sand beds for the tested sand beds trays solar still similar to the productivity rise. The thermal efficiency of the yellow SSS at 1 cm and 3 cm was 44.7% and 42.8%. Also from the figure, the black SSS has a higher daily thermal efficiency for all heights of sand beds because it has the highest daily production. At 1 and 3 cm sand beds height, the thermal efficiency of black SSS were 48% and 46.7%. Furthermore, the CSS's efficiency was about 33.5%–34%.

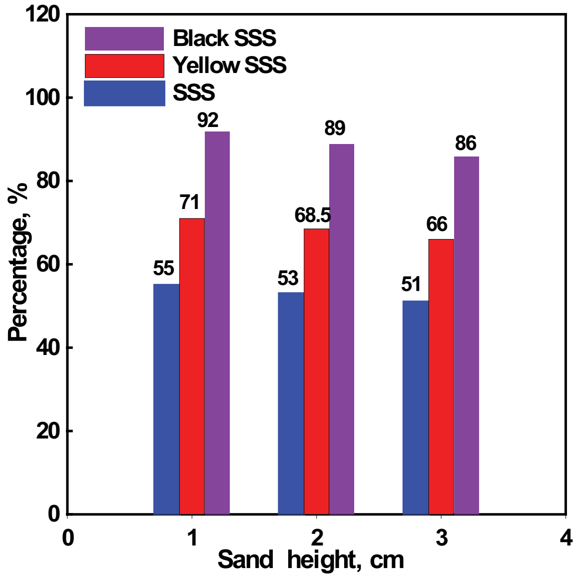

Fig. 5. Production rise of basin stills.

3.4. Performance of the black sand stepped SS with reflectors

The reflectors, whether internal or external, are an effective and affordable improvement to raise the solar radiation directed at the water or basin liner as well as the still's distillate efficiency. The BSSS performance has been investigated by employing external top and bottom reflectors and internal refractors in vertical sides of both of trays and steps. Temperatures of sand–water mixture, glass cover and saline water temperatures and sun irradiation measurements have been indicated in Fig. 7. From the figure at 1 cm water and sand height, the temperature of sand–water mixture

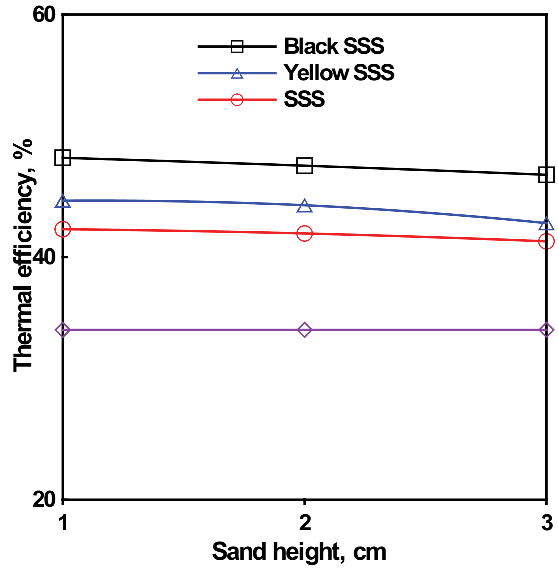

Fig. 6. Efficiency of stills at different sand bed height.

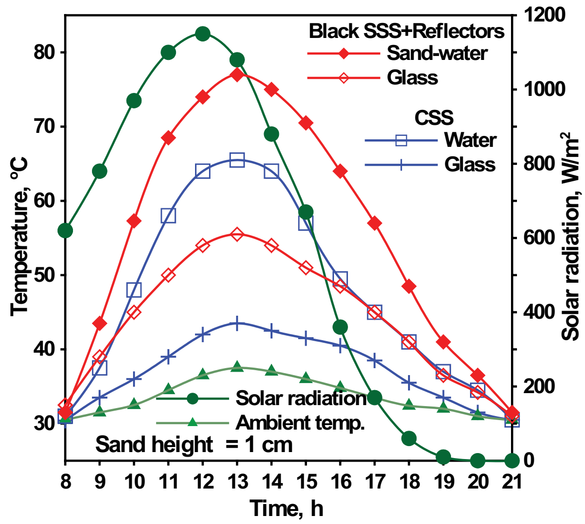

Fig. 7. Solar irradiation and temperatures profiles for BSSS with mirrors.

for black stepped SS is higher than that for CSS by about 0°C–12.5°C with internal and external reflectors. Because, the internal mirrors reflecting the sun radiation on the saline water of trays. Additionally, the internal mirrors reduce the losses of back and sides walls of stepped SS by reflecting the sun radiation onto the saline water. In addition, utilizing external reflectors enhances the diffuse and direct beams transmitted through the glass cover.

The glass cover temperature of CSS shows fewer measures than that for black SSS with reflectors 0°C–11°C. The rapid rate of evaporation caused by mirrors and the high salinity of the water was the cause of the high temperature of the glass cover of BSSS. Additionally, the highest temperatures of water/glass were 78°C/55°C and 65.5°C/44°C for black SSS and CSS, respectively at 1:00 pm.

The results indicated that the black SSS with reflectors produced more instantaneous and total yield over the CSS, Fig. 8. This is as a result of BSSS has faster rate of evaporation than CSS due to their higher evaporation area. Also, BSSS has a higher temperature of sand-water over CSS. The area of evaporation of BSSS higher than that of CSS. Additionally, the internal mirrors decrease the losses of heat from the vertical walls of the stepped SSs by reflecting the sun radiation on the sand-water of trays. The use of external auxiliary reflectors considerably boosted the radiation falling on the solar still. The daily yield of freshwater of the CSS black SSS were 3,300 and 7,720 mL/m²·d, with enhancement of 134%, respectively for the black SSS higher than CSS. The daily efficiency in this instance is approximately 51.2% and 34% for the black SSS, yellow SSS, stepped SS, and CSS, respectively.

3.5. Performance of the black sand stepped SS with vapor withdrawal and reflectors

The afore-mentioned experiments showed that when using mirrors, a significant volume of vapour was produced from the black stepped SS. This caused a 0°C–11°C increase in the black SSS glass cover temperature compared to the CSS. As is well known, the high glass temperature has a

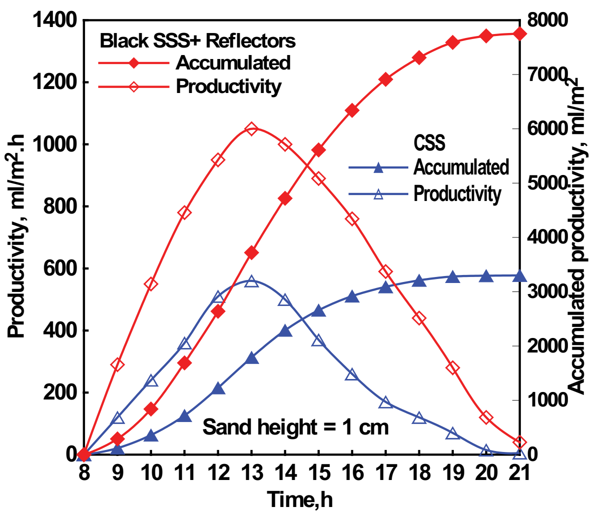

Fig. 8. Total and hourly yields for tested stills at sand height 1 cm with mirrors.

detrimental effect on the rate of condensation in the solar still. A small fan was put at the vertical wall of the black stepped SS distiller to extract some of the created vapour so it could be condensed and collected into an external container by a condensing apparatus. We employed the black stepped SS's low-temperature water as the fan's first cooling medium for the vapour pulled in by the fan. To finish the condensation process of the withdrawn vapour, the vapour then travels through the feed water tank. A copper tube served as the condensation coil's construction. This arrangement helped to lower the temperature of the black-stepped SS glass while boosting the temperature of the water. As a result, the evaporation and condensation rates of the black stepped SS with fan were improved. According to the testing findings, the temperature of the glass of the black stepped SS with vapour withdrawal was between 0°C and 5°C higher than that of the CSS. This means that employing the vapour withdrawal resulted in a decrease in the glass's temperature from 0°C–11°C to 0°C–5°C, which has a beneficial impact on the black stepped SS's performance and condensation rate.

Additionally, according to the trial results, the black SSS with vapour withdrawal was more productive overall than the conventional CSS. This is because the evaporation and condensation of black SSS are improved when a fan with a cooling serpentine design is used. Due to heat transfer between the water in the basin and the vapour inside the cooling coil, the distiller's elevated water temperatures increased the rate of evaporation. Additionally, the pressure inside the solar still was decreased by using the fan. The pressure dropped, which led to a drop in the water's saturation temperature. The productivity and evaporation of the distiller consequently increased. Additionally, the fan draws non-condensable gases outside the distiller, as previously noted [51,52]. As a result, the solar still's production increased. According to the trial results, the freshwater usage rates for CSS and black stepped SS with cooling coil and mirrors, respectively, were around 3,650 and 9,550 mL/m²·d. As a result, the black SSS's freshwater production was boosted over the CSS by around 165% when the fan and mirrors were used. Therefore, it can be determined that the rise in productivity of the black SSS with vapour removal is 31% greater than that of the black SSS. The daily thermal efficiency of black SSS and CSS in this case is roughly 56.6% and 34.5%, respectively.

3.6. Exergy analysis

Exergy analysis can be used to determine the energy quality for thermal devices. The ratio between the exergy output and exergy input is called the exergy efficiency (η_{ex}) [53]:

$$\eta_{ex} = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{E_{x_{evap}}}{E_{x_{sun}}} \quad (5)$$

The daily overall exergy gain can be evaluated as follows [54]:

$$E_{x_{output}} = E_{x_{evap}} = \sum_{t=1}^{t=n} \left(h_{ew} A_g \left[\left(T_w - T_g\right) - \left(T_a + 273\right) \ln\left(\frac{T_w + 273}{T_g + 273}\right) \right] \right) \quad (6)$$

Moreover, the exergy input $\left(E_{x_{\text{sun}}}\right)$ depends mainly on the solar irradiance [53]:

$$E_{x_{\text{sun}}} = A_b \times I(t)\left[1 - \frac{4T_a}{3T_{\text{sun}}} + \left(\frac{T_a}{T_{\text{sun}}}\right)^4\right] \quad (7)$$

where A_b, $I(t)$, T_a, and T_{sun} are the distiller area (m^2), sun irradiance (W/m^2), temperature of ambient (K), and sun temperature (6,000 K), respectively.

Furthermore, according to the above results, the exergy efficiency of the black sand stepped SS with vapor withdrawal and reflectors was about 3.1%.

4. Economic analysis of freshwater

Economic analysis is done to ensure the comparability of distillers' performance is accurate. Table 2 shows the specifics of the fixed costs for CSS and black SSS with IR and fan. The formulae in Table 3 are utilized to calculate the expenses of the desalinated water based on the previously mentioned information. Additionally, Table 4 lists the presumptions and estimates for a few factors used in the economic analysis. Some of these assumptions include the system lifetime, the number of working days in a year, the interest rate and costs of annual maintenance and cleaning. So, the costs of freshwater are 0.026 and 0.016 \$/L for CSS and black SSS with IR and fan.

5. Environmental analyses

The environmental analyses of the proposed system are evaluated. It is well known that the world, recently, is paying close attention to the environmental analyzes of the systems in order to know the greenhouse gas emissions that come out of these systems especially CO_2 and life cycle assessment (Mousavi and Mehrpooya [56]). This interest came because the use of fossil fuel sources leads to disasters and environmental risks including the emission of greenhouse gases to the surroundings. This helped the scientists and decision makers to utilize the renewable energy sources for the systems instead of the fossil fuel sources in order to obtain the goals of preservation of environmental and sustainability. The governing equations stating the mitigation and emission of CO_2 by SS are proposed as following.

The solar distiller annual energy output (kW·h/y) is:

$$E_{\text{out}} = \frac{365 \times \dot{m}(\text{hourly yield}) \times h_{\text{fg}}(\text{latent heat of vaporization})}{3,600} \quad (8)$$

Table 2
Fixed costs of fabricated conventional solar still and black SSS for 1 m^2

Unit	Conventional solar still (\$)	Black SSS (\$)
Iron sheet	30	30
Tray's sheet	–	15
Glass sheet	10	10
Paint	10	10
Support legs and ducts	25	25
Fiber glass (insulation)	7	7
Production	20	45
Mirrors	–	15
Fan and cooling coil	–	30
Total fixed cost (F)	102	187

Table 3
Calculations for cost analyses [55]

No.	Description	Relation
1	Fixed annual cost	FAC = F(CRF)
2	Capital recovery factor	$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$
3	Sinking fund factor	$\text{SFF} = \frac{i}{(1+i)^n - 1}$
4	Annual salvage value	ASV = S(SFF)
5	Salvage value	S = 0.2F
6	Total annual cost	TAC = FAC + AMC – ASV
7	Costs of annual maintenance	AMC = 0.15(FAC)
8	Distilled water cost	CPL = TAC/M

Table 4
Premises utilized in the economic analyses

No	Variable	Mean	Value	Unit
1	*N*	Working days of year	340	d
2	*I*	Interest rate	15	%
3	*n*	System lifetime	20	y
4	*F*	System fixed cost	187 for black SSS + IR + Fan 102 for conventional solar still	\$
5	*M*	Average yearly productivity	2,550 for black SSS + IR + Fan 1,080 for conventional solar still	L/m^2·y
6	CPL	Costs of the desalinated freshwater	0.016 for black SSS + IR + Fan 0.022 for conventional solar still	\$

Table 5
Embodied energy of the components of the system

Component	Materials	Energy density (kW·h/kg)	Mass of component (kg)	Embodied energy, E_{in} (kW·h)
Body	Galvanized iron	13.88	10	138.8
Trays	Galvanized iron	13.88	6	83
Cover	Glass	4.16	6.1	25.4
Insulation	Fiberglass	2.6	0.4	1.1
Coating	Black paint	25	0.2	5
Valves	Brass	17.22	0.22	3.8
Total				257

The yearly amount of CO_2 emitted in kg/y is (Parsa et al. [57]).

$$CO_{2,\text{emitted}} = \frac{2 \times E_{in}}{n} \quad (9)$$

where E_{in} is the embodied energy of components.

Then, the amount of CO_2 emitted through the system lifetime is:

$$CO_{2,\text{emitted}} = 2 \times E_{in} \quad (10)$$

Besides, the amount of CO_2 mitigated in kg/y through the year is:

$$CO_{2,\text{mitigated}} = \frac{2 \times E_{out}}{n} \quad (11)$$

Also, the amount of CO_2 mitigated through the system lifetime in kg is:

$$CO_{2,\text{mitigated}} = 2 \times E_{out} \times n \quad (12)$$

Finally, the environmental parameters (ϕ_{CO_2} and Z') are evaluated as following.

$$\phi_{CO_2} = \frac{2 \times \left(\left(E_{out} \times n \right) - E_{in} \right)}{1{,}000} \quad (13)$$

and

$$Z' = z_{CO_2} \times \phi_{CO_2} \quad (14)$$

where Z_{CO_2} is the carbon cost in the international market (14.5 $/ton) [57].

The embodied energy of the system components, Table 5, following the above equations. Additionally, the enviroeconomic and environmental analyses for lifetime 20 y and 365 d are obtained in Table 5. So, the environmental parameter of black SSS with modifications (vapor withdrawal and reflectors) was 24 ton·CO_2/y. Also, the enviroeconomic parameter (Z') was 348 per year for the black SSS with modifications, for lifetime 20 y and 365 operating days, Table 6.

Table 6
Environmental and enviroeconomic analysis for 365 d and lifetime 20 y

Type of solar still	CPSD-B
Embodied energy = E_{in} (kW·h)	257
E_{out} yearly (kW·h)	620
E_{out} for lifetime (kW·h)	12,400
Environmental parameter, (ϕCO_2·y)	24
Enviroeconomic parameter, (Z'·y)	348

6. Conclusions and recommendations for future research

The production of the sand's SSs is improved by incorporating sandy beds over the trays and basin plate of SSS. The sandy beds are regarded as a practical heat-storage media, so the freshwater production is increased. The aforementioned findings and justifications lead to the following conclusions.

- The daily distillate of the sand stepped SS was inversely proportional to the heights of sandy beds.
- The highest daily production of sandy stepped SS is obtained at 1 cm height of sand beds
- At 1 cm height of sand beds the daily yield of freshwater productivity of the CSS, SSS, yellow SSS and black SSS were 3,000 and 4,650; 5,150 and 5,750 mL/m^2·d, with improvement of 55%, 71%, and 92%, for the SSS, yellow SSS and black SSS higher than CSS.
- With internal mirrors, at 1 cm height of sand beds the daily yield of freshwater for SSS, yellow SSS and black SSS were enhanced by 69%, 88%, and 111%, respectively over CSS. The daily efficiency for black SSS, yellow SSS, SSS and CSS are about 50.7%, 47.2%, 44.35% and 34%, respectively.
- Using the cooling coil and reflectors together in the black stepped SS enhanced the fresh-water production by around 136% over the CSS with daily efficiency 54.4% and 34.5%, respectively.
- The anticipated cost of 1 L of the freshwater for black SSS and CSS are around $0.016 and $0.026.
- The environmental parameter of black SSS with vapor withdrawal and reflectors was 24 tons·CO_2/y.
  Scope for further research
- Optimizing the sand beds thickness to give the highest yield.

- A study of the effect of other types of sand on the performance of the stepped SS.
- The tracking system of sun is more effective than a fixed system and it is capable of improving the production of the stepped still with sand beds.

Symbols

A	—	Area, m^2
E_{in}	—	Embodied energy, kW·h
E_{out}	—	Energy output, kW·h
$\dot{m}$	—	Water production, kg/s
h_{fg}	—	Vaporization latent heat, J/kg
i	—	Interest rate, %
$I(t)$	—	Solar radiation, W/m^2
M	—	Average annual yield, L/y
n	—	Life time, y
P	—	Capital cost of solar still, $
S	—	Salvage value, $
t	—	Time, s
T	—	Temperature, °C
z_{CO_2}	—	Carbon cost, $/ton
Z'	—	Enviroeconomic parameter
η_d	—	Daily efficiency, %

Abbreviations

AMC	—	Annual maintenance and operating costs, $
ASV	—	Annual salvage value, $
BSSS	—	Black sand stepped solar still
YSSS	—	Yellow sand stepped solar still
CPL	—	Cost of fresh water, $/L
CRF	—	Capital recovery factor
CSS	—	Conventional solar still
FAC	—	Fixed annual cost, $
SFF	—	Sinking fund factor
SS	—	Solar still
SSS	—	Stepped solar still
TAC	—	Total annual cost, $

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