Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29279

283 (2023) 109–117
January

Performance study of a solar still desalination system coupled with solar air heater

Balaji Ellappan[a,*], Venkata Ramanan Madhavan[b], Mohammed El Hadi Attia[c]

[a]*Department of Mechanical Engineering, Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai 600062, Tamil Nadu, India, email: balaji.dew@gmail.com*
[b]*Department of Mechanical Engineering, Faculty of Energy Studies, College of Engineering, Chennai 600025, Tamil Nadu, India, email: madhavanvenkat@gmail.com*
[c]*Department of Physics, Faculty of Exact Sciences, University of El Oued, 39000 El Oued, Algeria, email: attiameh@gmail.com*

Received 21 June 2022; Accepted 18 December 2022

ABSTRACT

The main aim of the present study is to enhance the output of the solar distiller using hot air produced from the solar air heater (SAH). In this manuscript, two solar stills [conventional solar still (CSS) and CSS-SAH] were fabricated and researched. The performance of the CSS-SAH was experimentally examined at three different water depths (W_d) and compared with the CSS. The SAH act as a water heating element, the heat extracted from the SAH was sent to the basin water of the CSS. The experimental results showed that the maximum daily yield of 4.7 kg/m^2 was achieved for the CSS-SAH at a minimum W_d. The CSS-SAH has produced 0.34 to 1.8 kg higher yield than the CSS. The study also has shown that CSS-SAH produced 38.3% higher yield than the CSS. The payback period of the CSS, CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d is 46, 40, 47, and 58 ds, respectively.

Keywords: Solar still; Hot air; Water; Solar collector; Copper tubes; Heat exchanger

1. Introduction

The demand for drinking water is increasing day by day. Clean water is essential for social and economic development. Most of the world's population will not be able to secure safe drinking water, in the coming years, because the possibility of obtaining clean water quality that meets the standard limits of safe water is extremely limited, especially in the African region. On the other hand, we have that 10,000 tons of oil annually produces 1,000 tons of fresh water per day using desalination techniques. Using oil leads to a deterioration of the climate and the environment [1–3]. Therefore, it became necessary to use new energy sources such as renewable energy (solar energy). The quality of saltwater can be easily improved by solar water desalination technology [4–6]. Conventional solar distillation is a simple device used to clean saltwater using solar energy and convert it into fresh water through evaporation and condensation processes. The maximum yield of conventional solar still (CSS) is around 2–5 L/m^2·d [7–9]. This low productivity does not cover the growing demand for clean water. One of the methods proposed to enhance the productivity of freshwater is by heating the absorbent or cooling the condenser of the distillation device. In this section, some research used reasonable techniques and contributed to improving the productivity of SS.

Mahian et al. [10] studied the SS integrated with a flat plate collector (FPC) using SiO_2 and CuO water-based nanofluids. Nanofluids were get heated in the FPC and sent to SS. They developed a mathematical model and it was validated with experimental results. It was found that CuO water-based nanofluid liquids have a higher evaporation

* Corresponding author.

rate than SiO_2 water-based nanofluids. Joy et al. [11] published the use of hot air to augment the output of a SS. It was reported that the output without and with the air blower was about 2.5 and 7 kg/m²·d. They also concluded that the efficiency was 32% and 65% without and with the use of the blower. Xiong et al. [12] published the multi-stage SS with vacuum tube heat pipe to enhance the system's productivity. Heat pipes absorb solar intensity and heat the water of basins by the vacuum tube collectors. The experimental results showed that the output of the multi-stage SS with the vacuum tube was about 9.61 kg/m²·d. Chen et al. [13] experimentally studied a multi-stage SS made of stainless-steel trays. The other trays stacked in the distillation apparatus were heated by the latent heat emitted from the lower trough. They concluded that the productivity of this system was 8.1 kg/m²·d. Estahbanati et al. [14] studied a four-stage SS made of aluminum trays with a heat exchanger made of copper. The heat is transferred from the heat exchanger to the lower basin of the SS with oil as a heat transfer fluid, and then the latent heat in the tray above is released. They concluded that, over a full day, the system yield is 23.8 kg of drinking water. Shatat and Mahkamov [15] used a vacuum-integrated solar collector in a multistage SS. They concluded that the system's productivity was about 10 L of drinking water per day. Panchal et al. [16] studied SS output using evacuated tubular array collectors in CSS. They concluded that the system yield is 5 kg/d·m². Panchal [17] investigated the effect of evacuated tubular collectors in a double-effect SS system. Evacuated collectors were integrated with the lower basin of the SS. The productivity of freshwater in the solar distillation system reached 20 kg/m²·d. Bhargva and Yadav [18] studied the performance of SS with a heat exchanger circuit made of a copper tube using engine oil as heat fluid. They investigated the modified still at dissimilar water depths of 4, 5, and 6 cm and compared it with a conventional still. It was reported that the output and efficiency were improved when using the heat exchanger at a depth of 4 cm brine, which was 138.9% and 2.1%, respectively, compared to CSS. Shafii et al. [19] reported the SS integrated with evacuated tube collector (ETC) and it was noted that this system had produced a 21.6% higher yield than CSS. Badran and Al-Tahaineh [20]. studied the performance of SS by integrating an FPC and inner reflectors (mirrors). They investigated the modified still at different saltwater depths and reported that the yield of the SS was improved by 36%. Arunkumar et al. [21] studied hemispherical SS containing copper balls filled with Phase Change Material (PCM), integrating with a parabolic concentrator. The experimental results showed that daily output was increased by 26% when balls filled with PCM and parabolic concentrators were used. Singh [22] compared the payback time and cycle conversion efficiency of ETC-integrated single slope SS with PVT and parabolic concentrator – integrated SS. He found that the ETC integrated SS to be the best compared to the others. Singh and Al-Helal [23] repeated the above-mentioned experiments by replacing the CSS with a double slope SS. Singh et al. [24] studied the impact of several evacuated tubular collectors on the performance of CSS when at 3 cm water depth. They have observed that when using 10 ETC operating on a thermosyphon, the maximum output is 3.8 kg/m². Kabeel and Abdelgaied [25] compared a parabolic trough concentrator incorporated SS and a CSS. The output showed an increase in freshwater yields of 140.4% for the modified system. Eltawil and Omara [26] developed a basin still integrated with FPC, solar air heater (SAH), external condenser, and water spraying unit working by PV panels. They noticed that the productivity value of traditional distillation reached a maximum of 4 kg/m², while the productivity of the developed SS was improved by 148% as compared to the productivity of traditional distillation. Kabeel et al. [27] researched a SS with hot air injection (air is heated using a SAH) in basin water and PCM was used to enhance the productivity of SS. It was noticed that the freshwater productivity value of traditional distillation reached 4.5 L/m², while productivity reached 9.36 L/m² using modifications (hot air injection and PCM). A copper tube-type heat exchanger is installed at the bottom of the CSS basin in this experimental investigation, and the air is used as the working fluid in the tube. Studies were conducted on CSS-SAH operating on forced convection at different water depths (1.5, 3, and 4.5 cm). Noval portable SS with a hot air injection system was studied by Fallahzadeh et al. [28] and they have reported that hot air injection to the basin water significantly improves the yield.

Hybrid solar still using the solar air-conditioning system was reported by Shukla et al. [29–31]. From the literature, it is known that only a few researchers reported CSS with the SAH. In this work, a copper tube-type heat exchanger is installed at the bottom of the CSS basin, and the air was used as the working fluid in the tube. Studies were conducted on the CSS-SAH operating on forced convection at different water depths (1.5, 3, and 4.5 cm). In April 2021, all experiments were conducted in Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Avadi, Chennai, Tamil Nadu, India, under the same meteorological conditions.

2. Experimental set-up

In this work, the solar still was made of a wooden box with dimensions 50 cm × 50 cm. A copper tube was placed on the still basin, in that hot air is passed using SAH. The experimental device consists of a solar still, SAH, a fan, and a solar panel (Fig. 1). The SAH was made of a wooden box with dimensions (35 cm × 25.5 cm × 8 cm) insulated on all sides with polystyrene covered by aluminum. Inside, a metal plate painted black was inserted into the bottom of the collector. A copper tube with a thickness of 14 mm was painted in black for the passage of the heated air. SAH was covered with transparent 3 mm thick, making the collector incline from the horizon at an angle of 10° (which corresponds to the location of the experiment site in Avadi at Chennai, Tamil Nadu, India). In these conditions, the solar intensity falls on the glass of the collector. When the air passes through the tubes, heat obtained from the SAH by air transfers heat to the basin water of the solar still. A solar panel was connected to the fan to supply it with the power produced by solar radiation. Fig. 2a. Shows a schematic presentation of the SAH and (b) shows a photo of the SAH.

The experimental measurements were carried out from 8:00 AM to 7:00 PM on 10th April 2021. Fig. 3 shows the schematic of the CSS-SAH. Fig. 4 shows the photo of the CSS-SAH. As shown in Fig. 4, a CSS has a basin area of 0.25 m^2 (0.5 m × 0.5 m). The basin of CSS was made of wood 25 mm thick. The low-side and high-side walls have been preserved at 0.06 and 0.14 m elevations, respectively. To avoid any leakage in SS and to improve the absorption of solar radiation, the entire interior surface of the basin is sprayed with black silicone. CSS cover is made of commercial glass, with a thickness of 3 mm and a 10° tilt to the horizontal. A heat exchanger (copper tube with a diameter of 1.4 cm) is attached at the base of the CSS. The air is forced into the SAH by a fan driven by solar panels. The mass flow rate of air is 50 g/s. The SAH warms the air before passing it through the heat exchanger. The exchange of heat between the heat exchanger tubes and the salty water caused by the hot air generated by the SAH increases the heating rate of the basin water, increasing the quantity of evaporation and thus augmenting yield. In the present experimental study, an air heat exchanger consists of a single tube with one pass, the airflow inside the copper tube is 1.4 cm in diameter. The copper tube of the air heat exchanger is placed in the basin of the CSS. The fan is used to pump the air, the air gets warm in the SAH, the air flows into the copper tube, and water continuously gets heat energy. Experiments were conducted on CSS and CSS-SAH at 3 different water depths (1.5, 3, and 4.5 cm).

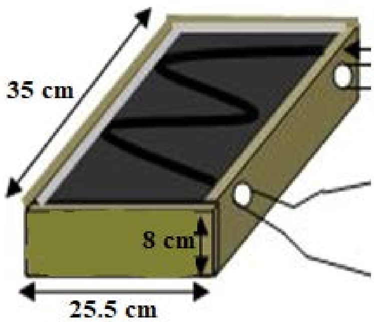
Fig. 1. Solar still with the heat exchanger of the studied system.

In addition, Fig. 5 shows a photo of the CSS and CSS-SAH. In a SAH, a flat plate collector concentrates sun intensity on the receiver copper tube. The receiver consists of an absorber copper tube; it is painted black color 1.4 cm in diameter. The flat plate collector has a dimension of 0.25 m wide, 0.35 m long, and a height of 8 cm it is inclined by 33° to the horizontal, an aluminum reflector is used as a reflective material, and it is placed on the inner walls of the collector, commercial glass with a thickness of 3 mm is used for the collector cover.

3. Results and discussion

3.1. Temperature profile and performance of the CSS and CSS-SAH

Experiments were conducted for 3 clear sunny days. The hourly plots of solar intensity, air, water, and glass temperatures for the CSS and CSS-SAH are shown in Figs. 6 and 7, respectively. During the testing days, air temperature is measured between 27°C to 43°C, solar intensity is measured between 95 to 980 W/m^2. The maximum water temperature of the CSS is 65°C, and CSS-SAH is 69°C. The hot air produced from the SAH is used to enhance the hourly yield by increasing the water temperature. The integration of SAH and the CSS has produced a 2°C–5°C higher water temperature than the CSS. During the operation of CSS-SAH, natural air was drawn from the atmosphere using a D.C fan and it was heated in the SAH system and preheated air was sent to the basin water of the CSS. The everyday average water temperature of the CSS is 51.3°C whereas CSS-SAH is 54.4°C. Integrating SAH with the CSS has improved the daily average water temperature by 5.67% as compared to the CSS. Also, the maximum temperature difference between the CSS basin water and glass is 13°C whereas the temperature difference between the CSS-SAH is 16°C. The reason for the higher temperature difference



(a)

(b)

Fig. 2. Flat solar collector (a) Schematic presentation of SAH and (b) Photo of the SAH.

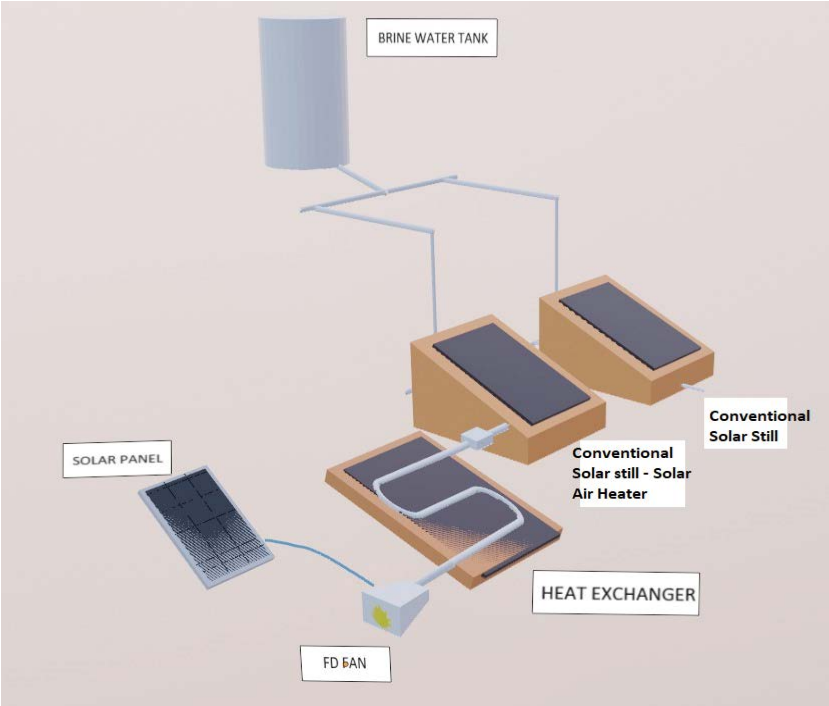


Fig. 3. Schematic of the CSS with heat exchanger and SAH.

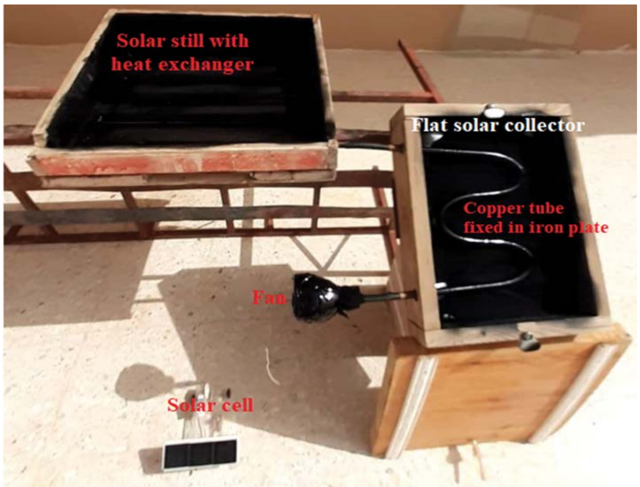


Fig. 4. Photo of the CSS with heat exchanger and SAH.

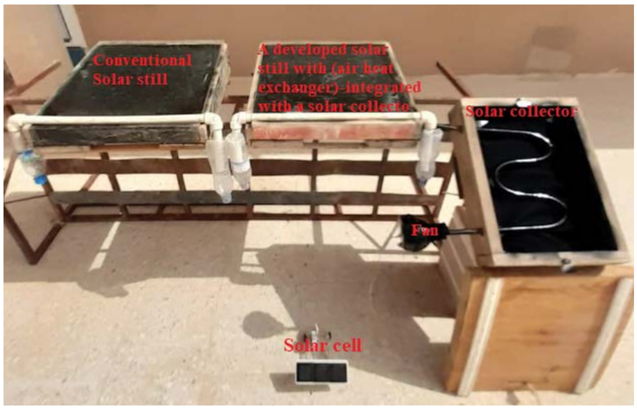


Fig. 5. Photograph of the CSS, CSS with heat exchanger, and SAH.

between CSS-SAH and the CSS is the continuous supply of hot air to the basin water of the CSS-SAH. The hot air produced from the SAH is passed to the copper tube which is placed on the CSS-SAH. This hot air transfers heat to the water so the water temperature of the CSS-SAH is higher.

The hourly plots of Evaporative Heat Transfer Coefficient (EHTC) and yield for both CSS and CSS-SAH are plotted in Fig. 8. The EHTC and yield increased with time until they reached a maximum value at 3 PM for the CSS and 2 PM for the CSS-SAH. The maximum EHTC of 29.43 W/m^2·K for the CSS and 35.25 W/m^2·K for the CSS-SAH was calculated. The average EHTC of 16.67 and 19.9 W/m^2·K was calculated for the CSS and CSS-SAH, respectively. The maximum yield per hour of 0.61 and 0.9 kg was obtained using the CSS and the CSS-SAH, respectively. The yield produced from the CSS after reaching peak yield (yield during 4 to 7 PM) was 0.65 kg and the yield produced from the CSS-SAH after reaching peak yield (yield during 3 to 7 PM) was 1.73 kg. The yield produced per day from the CSS is 2.9 kg and from the CSS-SAH is 4.7 kg. The yield produced from the CSS-SAH did not decrease drastically due to the hot air produced by the SAH. The difference between the yield for both CSS-SAH and CSS is 1.81 kg. The daily yield of the CSS-SAH is 63% higher than the CSS. The constant flow of hot air into the CSS-SAH water temperature increased and caused the increased yield of CSS-SAH as

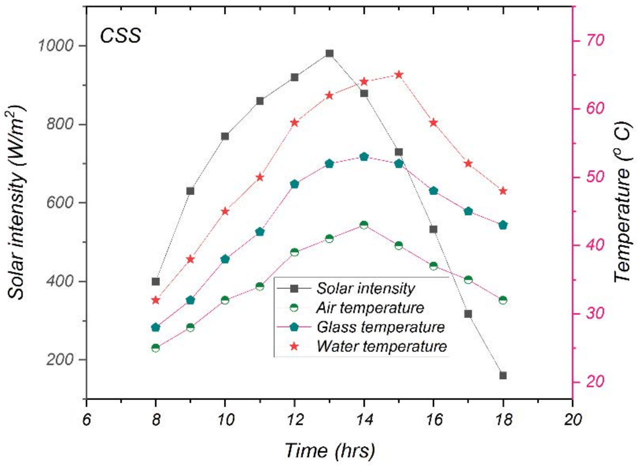


Fig. 6. Hourly plots of CSS temperature profile and input parameters.

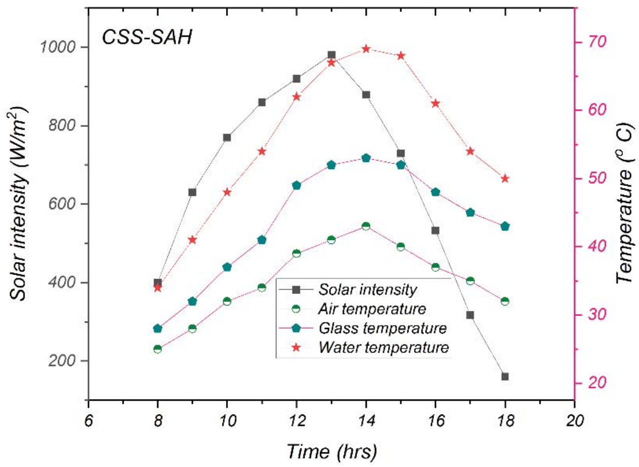


Fig. 7. Hourly plots of CSS-SAH temperature profile and input parameters.

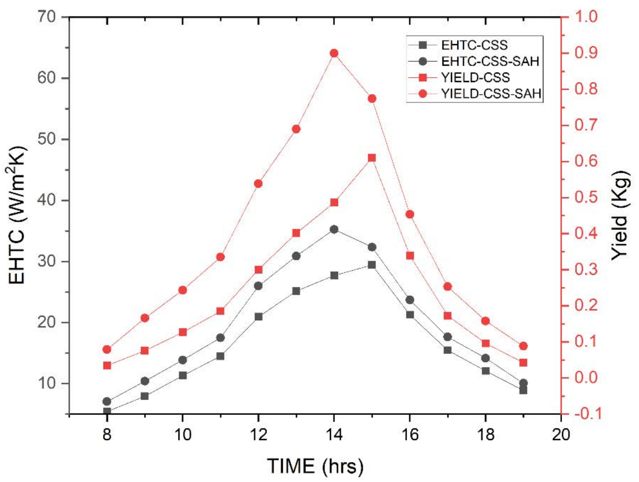


Fig. 8. Hourly plots of EHTC and yield for both CSS and CSS-SAH.

compared to the CSS. The water in the CSS-SAH is warmer as a result of heat transfer from this hot air to the water, so it produced a higher yield than the CSS.

3.2. Effect of water depth on temperature profile and performance of the CSS-SAH

The hourly plots of solar intensity, air, water, and glass temperatures for the CSS-SAH at various water depths (W_d) are shown in Figs. 9–11, respectively. The maximum water temperature of the CSS-SAH at 1.5 cm W_d is 69°C, CSS-SAH at 3 cm W_d is 68°C and CSS-SAH at 4.12 m W_d is 66°C. The hot air created from the SAH is used to enhance the hourly yield by raising the water temperature of the CSS-SAH. The peak water temperature of the CSS-SAH at 1.5 cm W_d is 3°C higher than the peak water temperature of the CSS-SAH at 4.5 cm W_d. The daily average water temperature of the CSS-SAH at 1.5 cm W_d is 54.4°C, CSS-SAH at 3 cm W_d is 53°C and CSS-SAH at 4.5 cm W_d is 52°C. The maximum temperature difference between the CSS basin water and glass of the

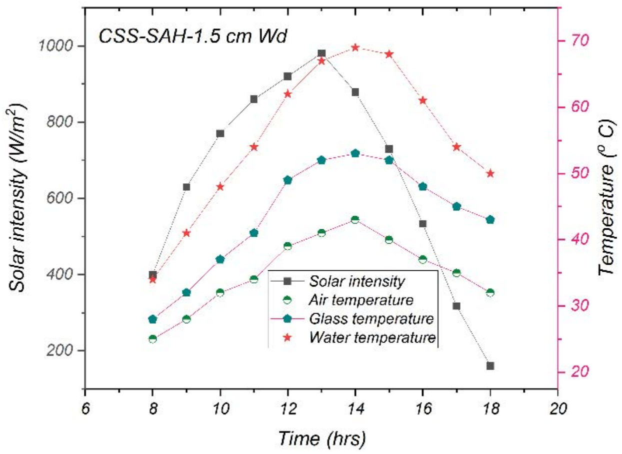


Fig. 9. Hourly plots of CSS-SAH at 1.5 cm W_d temperature profile and input parameters.

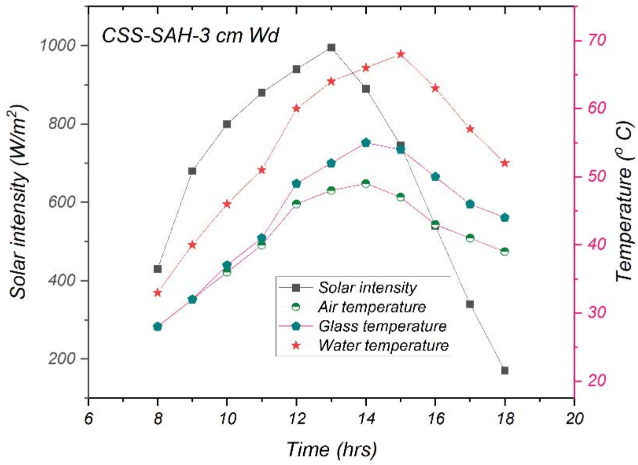


Fig. 10. Hourly plots of CSS-SAH at 3 cm W_d temperature profile and input parameters.

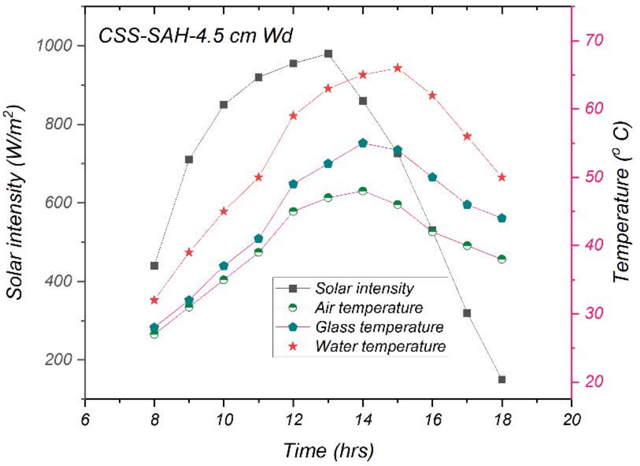


Fig. 11. Hourly plots of CSS-SAH at 4.5 cm W_d temperature profile and input parameters.

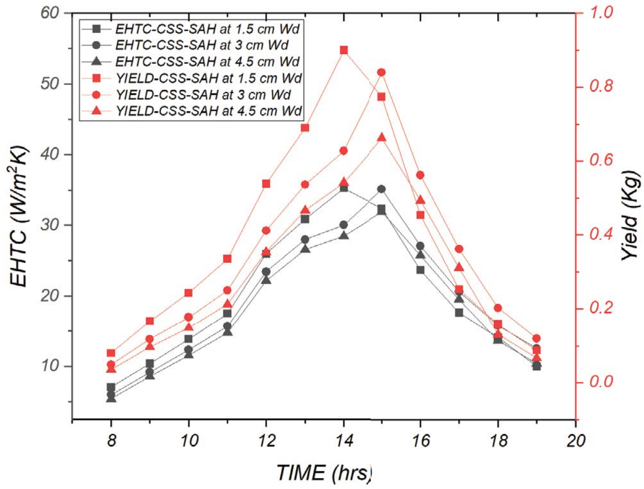


Fig. 12. Hourly plots of EHTC and yield for CSS-SAH at various W_d.

CSS-SAH at 1.5 cm W_d is 16°C, CSS-SAH at 3 cm W_d is 14°C, and CSS-SAH at 4.5 cm W_d is 12°C. When the W_d increased from 1.5 to 3 cm, the water temperature decreased from 1 to 3°C, and W_d increased from 1.5 to 4.5 cm, the water temperature decreased from 2 to 4°C. When the W_d is minimum inside the CSS-SAH, it has maximum water temperature as compared to the water temperature of the CSS-SAH at 3 and 4.5 cm W_d. The CSS-SAH at 1.5 cm easily heated the water and produced more yield than the CSS-SAH at 3 and 4.5 cm W_d. When the water volume inside the CSS-SAH is minimum, it gains more heat energy from the solar intensity and hot air produced by the SAH. During the operation of the CSS-SAH, it was found that SAH significantly improves the water temperature as compared to the CSS.

The hourly plots of EHTC and yield for CSS-SAH at various W_d are plotted in Fig. 12. The EHTC and yield increased with time until it reached a maximum value at 2 PM for the CSS-SAH at 1.5 cm W_d, 3 PM for the CSS-SAH at 3 cm W_d, and 3 PM for the CSS-SAH at 4.5 cm W_d. The maximum EHTC of 35.25 W/m²·K for the CSS-SAH at 1.5 cm W_d, 32.1 W/m²·K for the CSS-SAH at 3 cm W_d, and 30.1 W/m²·K for the CSS-SAH at 4.5 cm W_d was calculated. The daily average EHTC of 19.9, 18.4, and, 16.5 W/m²·K was calculated for the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d, respectively.

The maximum yield per hour of 0.9, 0.74, and 0.66 kg was obtained using the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d, respectively. The yield produced during the morning (8 AM to 2 PM) from the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d was 2.97, 2.05, and 1.68 kg, respectively. Similarly, the yield produced after morning hours (3 to 7 PM) from the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d was 1.7, 2, and 1.6 kg, respectively. The yield produced during morning hours is higher in CSS-SAH at 1.5 cm W_d whereas the yield produced after morning hours is higher in CSS-SAH at 3 cm W_d. Also, it is observed that yield production after morning hours is almost equal for CSS-SAH at 1.5 cm W_d and CSS-SAH at 4.5 cm W_d. It is due to heat energy stored in the water particles. The yield produced per day from the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d was 4.7, 4.03, and 3.2 kg, respectively. The yield produced from the CSS-SAH at 4.5 cm W_d has produced 31.1% lesser yield than the CSS-SAH at 1.5 cm W_d and 10.4% lesser than the CSS. The difference between the yield for CSS-SAH at 1.5 cm W_d and CSS is 1.8 kg, CSS-SAH at 3 cm W_d and CSS is 1.13 kg, and CSS-SAH at 4.5 cm W_d and CSS is 0.34 kg. The integration of SAH and CSS at 1.5 cm W_d, 3 cm W_d, and 4.5 cm W_d produced 1.8, 1.13, and 0.34 higher yields than the CSS. Similarly, the daily yield of CSS-SAH at 1.5 cm W_d, 3 cm W_d, and 4.5 cm W_d is 38.3%, 28.1%, and 10.4% higher than the daily yield of the CSS. The integration of SAH and CSS resulted in higher water temperature due to the transfer of heat from hot air to the basin water, it resulted in higher EHTC and yield as compared to the CSS.

3.3. Comparison of similar studies

Table 1 shows the comparison of similar studies. From Table 1 it is found that four-stage SS published by Estahbanati et al. [14] produced a maximum yield of 23.8 kg. Also, 10 ETC integrated with SS operating on a thermosyphon mode published by Singh et al. [24] produced a minimum yield of 3.8 kg. The present study has produced yield per day from the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d was 4.7, 4.03, and 3.2 kg, respectively. At 1.5 cm W_d, 3 cm W_d, and 4.5 cm W_d, the daily yield of CSS-SAH are 38.3%, 28.1%, and 10.4% higher than the daily yield of the CSS, respectively.

3.4. Economic analysis

Table 2 provides a detailed view of the manufacturing cost of a CSS and CSS-SAH and elicits the number of days to recover the net cost of the two devices. From the comparative cost analysis of the CSS and CSS-SAH, it was found that the payback period of the CSS is 46 d, CSS-SAH at 1.5 cm W_d is 40 d, CSS-SAH at 3 cm W_d is 47 d, and

Table 1
Comparison of similar studies

S. No.	Author's name and year	Experimentation detail	Yield ($kg/m^2·d$)
1	Joy et al. [11]	Hot air to augment the output of a SS	7
2	Xiong et al. [12]	Multi-stage SS with vacuum tube heat pipe	9.61
3	Chen et al. [13]	Multi-stage SS	8.1
4	Estahbanati et al. [14]	Four-stage SS	23.8
5	Shatat and Mahkamov [15]	Vacuum integrated solar collector in a multi-stage SS	10
6	Panchal et al. [16]	Evacuated tubular array collectors in CSS	5
7	Singh et al. [24]	10 ETC integrated with SS operating on a thermosyphon mode	3.8
8	Eltawil and Omara [26]	SS integrated with FPC, SAH, external condenser, and water spraying unit	4
9	Kabeel et al. [27]	SS with hot air injection (air is heated using a SAH) to basin water and use of PCM	4.5
10	Present study	CSS-SAH at 1.5 cm W_d	4.7
		CSS-SAH at 3 cm W_d	4.03
		CSS-SAH at 4.5 cm W_d	3.2

Table 2
Comparison of the cost of manufacturing CSS and CSS-SAH. 1$ = 74.57 INR, 1€ = 83.86 INR

	CSS	CSS-SAH at 1.5 cm W_d	CSS-SAH at 3 cm W_d	CSS-SAH at 4.5 cm W_d
Physical cost of solar still (PCSS) (INR)	4,000	4,000	4,000	4,000
Price of tube copper (PTC) (INR)	–	600	600	600
Physical cost of a solar collector (PCSC) (INR)	–	1,000	1,000	1,000
Maintenance cost (MC) (INR)	50	50	50	50
Total cost (TC) (INR)	4,050	5,650	5,650	5,650
Amount of yield produced per day, (AYP) ($kg/m^2·d$)	2.9	4.7	4	3.24
Cost of 1 L of yield (COLY) (INR)	30	30	30	30
Price of yield per kg (PY) (INR)	87	141	120	97.2
Payback period (PP) (ds)	46	40	47	58

CSS-SAH at 4.5 cm W_d is 58 d. The payback period of the CSS and CSS-SAH at 1.5 cm W_d is quicker as compared to the CSS-SAH at 3 cm W_d and CSS-SAH at 4.5 cm W_d. This indicates that the best economic solar still is CSS-SAH at 1.5 cm W_d as the payback period is 40 d. The economic feasibility presented that the utilization of the conventional solar still with the solar air heater by the water depth at 1.5 cm W_d (CSS-SAH at 1.5 cm W_d) reduced the number of days to recover of distillates produced from conventional solar distillers by 7 d compared to the CSS.

Equations for the calculation of payback period:

$$TC = PCSS + PTC + PCSC + MC \tag{1}$$

$$PY = AYP \times COLY \tag{2}$$

$$PP = \frac{TC}{PY} \tag{3}$$

where PCSS: physical cost of solar still; PTC: price of tube copper; PCSC: physical cost of a solar collector; MC: maintenance cost; TC: total cost; AYP: amount of yield produced per day; COLY: cost of 1 L of yield; PY: price of yield per kg; PP: payback period.

4. Conclusion

A CSS integrated with SAH was fabricated and experimentally researched its performance at various W_d.

- The experimental results showed that the daily yield produced from CSS-SAH is higher than that of the CSS. The maximum yield per hour from the CSS and CSS-SAH was 0.61 and 0.9 kg.
- The maximum daily yield of 4.7 kg/m^2 was obtained from the CSS-SAH at 1.5 cm W_d, while its value was 2.9 kg/m^2 for the CSS. The percentage increase in yield from the CSS-SAH at 1.5 cm W_d was 38.3% higher than the CSS.
- The W_d of the CSS-SAH was increased from 1.5 to 3 cm and from 1.5 to 4.5 cm, the yield was decreased by 14.1% and 31.15%, respectively.
- The CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d provided daily yields of 4.7, 4.03, and 3.2 kg, respectively.

- The yield produced from the CSS-SAH at 1.5 cm W_d, CSS-SAH at 3 cm W_d, and CSS-SAH at 4.5 cm W_d was 1.8, 1.13, and 0.34 kg higher than the CSS.
- Using a heat exchanger in the CSS, the heat exchanger heats the basin water, enhancing evaporation rate and productivity.

Authors contributions

Venkata Ramanan – Conceptualization, Methodology; Balaji Ellappan – Data collection; Writing – Original draft preparation; Mohammed El Hadi Attia – Review and Editing.

Funding

There is no funding received for the research work carried out.

Competing interests

The authors declare that there is no competing interest.

References

[1] A. Muthu Manokar, Experimental study on effect of different mass flow rate in an inclined solar panel absorber solar still integrated with spiral tube water heater, Desal. Water Treat., 176 (2019) 285–291.
[2] M. El Hadi Attia, A. Elnaby Kabeel, E. Elaloui, M. Abdelgaied, A. Abdullah, Experimental study on improving the yield of hemispherical distillers using CuO nanoparticles and cooling the glass cover, Sol. Energy Mater. Sol. Cells, 235 (2022) 111482, doi: 10.1016/j.solmat.2021.111482.
[3] M.M. Thalib, M. Vimala, A.M. Manokar, R. Sathyamurthy, M. Sadeghzadeh, M. Sharifpur, Energy, exergy and economic investigation of passive and active inclined solar still: experimental study, J. Therm. Anal. Calorim., 145 (2021) 1091–1102.
[4] A.M. Manokar, M. Vimala, D.P. Winston, R. Sathyamurthy, A.E. Kabeel, Effect of Insulation on Energy and Exergy Effectiveness of a Solar Photovoltaic panel Incorporated Inclined Solar Still—An Experimental Investigation, A. Kumar, O. Prakash, Eds., Solar Desalination Technology, Springer, Singapore, 2019, pp. 275–292.
[5] A.R. Prasad, M. El Hadi Attia, W. Al-Kouz, A. Afzal, M. Manokar Athikesavan, R. Sathyamurthy, Energy and exergy efficiency analysis of solar still incorporated with copper plate and phosphate pellets as energy storage material, Environ. Sci. Pollut. Res., 28 (2021) 48628–48636.
[6] M. El Hadi Attia, A. Elnaby Kabeel, M. Abdelgaied, A. Abdullah, A comparative study of the effect of internal reflectors on a performance of hemispherical solar distillers: energy, exergy, and economic analysis, Sustainable Energy Technol. Assess., 47 (2021) 101465, doi: 10.1016/j.seta.2021.101465.
[7] M. El Hadi Attia, A. Elnaby Kabeel, M. Abdelgaied, A. Bellila, B.M. Abdel-Aziz, Optimal concentration of high thermal conductivity sensible storage materials (graphite) for performance enhancement of hemispherical distillers, Desal. Water Treat., 231 (2021) 263–272.
[8] M. El Hadi Attia, A. Muthu Manokar, A. Elnaby Kabeel, Z. Driss, R. Sathyamurthy, W. Al-Kouzg, Comparative study of a conventional solar still with different basin materials using exergy analysis, Desal. Water Treat., 224 (2021) 55–64.
[9] M. El Hadi Attia, A. Elnaby Kabeel, M. Abdelgaied, M.M. Abdel-Aziz, A. Bellila, A. Abdullah, Optimal size of black gravel as energy storage materials for performance improvement of hemispherical distillers, J. Energy Storage, 43 (2021) 103196, doi: 10.1016/j.est.2021.103196.
[10] O. Mahian, A. Kianifar, S.Z. Heris, D. Wen, A.Z. Sahin, S. Wongwises, Nanofluids effects on the evaporation rate in a solar still equipped with a heat exchanger, Nano Energy, 36 (2017) 134–155.
[11] N. Joy, A. Antony, A. Anderson, Experimental study on improving the performance of solar still using air blower, Int. J. Ambient Energy, 39 (2018) 613–616.
[12] J. Xiong, G. Xie, H. Zheng, Experimental and numerical study on a new multi-effect solar still with enhanced condensation surface, Energy Convers. Manage., 73 (2013) 176–185.
[13] Z. Chen, J. Peng, G. Chen, L. Hou, T. Yu, Y. Yao, H. Zheng, Analysis of heat and mass transferring mechanism of multi-stage stacked-tray solar seawater desalination still and experimental research on its performance, Sol. Energy, 142 (2017) 278–287.
[14] M.K. Estahbanati, M. Feilizadeh, K. Jafarpur, M. Feilizadeh, M.R. Rahimpour, Experimental investigation of a multi-effect active solar still: the effect of the number of stages, Appl. Energy, 137 (2015) 46–55.
[15] M.I. Shatat, K. Mahkamov, Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling, Renewable Energy, 35 (2010) 52–61.
[16] H. Panchal, R. Sathyamurthy, A.K. Pandey, M. Kumar, T. Arunkumar, D.K. Patel, Annual performance analysis of a single-basin passive solar still coupled with evacuated tubes: comprehensive study in climate conditions of Mahesana, Gujarat, Int. J. Ambient Energy, 40 (2019) 229–242.
[17] H.N. Panchal, Enhancement of distillate output of double basin solar still with vacuum tubes, J. King Saud Univ.-Eng. Sci., 27 (2015) 170–175.
[18] M. Bhargva, A. Yadav, Experimental comparative study on a solar still combined with evacuated tubes and a heat exchanger at different water depths, Int. J. Sustainable Eng., 13 (2020) 218–229.
[19] M.B. Shafii, M. Shahmohamadi, M. Faegh, H. Sadrhosseini, Examination of a novel solar still equipped with evacuated tube collectors and thermoelectric modules, Desalination, 382 (2016) 21–27.
[20] O.O. Badran, H.A. Al-Tahaineh, The effect of coupling a flat-plate collector on the solar still productivity, Desalination, 183 (2005) 137–142.
[21] T. Arunkumar, D. Denkenberger, A. Ahsan, R. Jayaprakash, The augmentation of distillate yield by using concentrator coupled solar still with phase change material, Desalination, 314 (2013) 189–192.
[22] D.B. Singh, Energy metrics analysis of N identical evacuated tubular collectors integrated single slope solar still, Energy, 148 (2018) 546–560.
[23] D.B. Singh, I.M. Al-Helal, Energy metrics analysis of N identical evacuated tubular collectors integrated double slope solar still, Desalination, 432 (2018) 10–22.
[24] R.V. Singh, S. Kumar, M.M. Hasan, M.E. Khan, G.N. Tiwari, Performance of a solar still integrated with evacuated tube collector in natural mode, Desalination, 318 (2013) 25–33.
[25] A.E. Kabeel, M. Abdelgaied, Observational study of modified solar still coupled with oil serpentine loop from cylindrical parabolic concentrator and phase changing material under basin, Sol. Energy, 144 (2017) 71–78.
[26] M.A. Eltawil, Z.M. Omara, Enhancing the solar still performance using solar photovoltaic, flat plate collector and hot air, Desalination, 349 (2014) 1–9.
[27] A.E. Kabeel, M. Abdelgaied, M. Mahgoub, The performance of a modified solar still using hot air injection and PCM, Desalination, 379 (2016) 102–107.
[28] R. Fallahzadeh, L. Aref, V.M. Avargani, N. Gholamiarjenaki, An experimental investigation on the performance of a new portable active bubble basin solar still, Appl. Therm. Eng., 181 (2020) 115918, doi: 10.1016/j.applthermaleng.2020.115918.
[29] D. Shukla, K. Modi, Hybrid solar still as a co-generative system and desalination system - an experimental performance evaluation, Cleaner Eng. Technol., 2 (2021) 100063, doi: 10.1016/j.clet.2021.100063.

[30] K.V. Modi, D.L. Shukla, Regeneration of liquid desiccant for solar air-conditioning and desalination using hybrid solar still, Energy Convers. Manage., 171 (2018) 1598–1616.
[31] D.L. Shukla, K.V. Modi, Hybrid solar still–liquid desiccant regenerator and water distillation system, Sol. Energy, 182 (2019) 117–133.
[32] G.N. Tiwari, V. Dimri, A. Chel, Parametric study of an active and passive solar distillation system: energy and exergy analysis, Desalination, 242 (2009) 1–18.

Appendix 1

1.1. Error analysis

The experiment parameters are calculated using thermocouples, pyrometers, and graduated flasks. The errors committed are mentioned in Table 3.

Appendix 2

From saline water to glass cover, the EHTC is computed as follows: Tiwari et al. [32],

$$h_{e,w-g} = 16.273 \times 10^{-3} \times h_{c,w-g} \left[\frac{P_w - P_{gi}}{T_{b.w} - T_{gi}} \right]$$

Table 3
Standard uncertainties

Instrument	Accuracy	Range	Standard uncertainty
Solar power meter	±10 W/m²	0–1,999 W/m²	5.72 W/m²
Thermocouple	±0.1°C	100°C–500°C	0.07°C
Graduated flask	±1 mL	0–550 mL	0.6 mL

The coefficient of convective heat transfer from saline water to the glass cover is determined by Tiwari et al. [32],

$$h_{c,w-g} = 0.884 \left[\left(T_{b.w} - T_{gi} \right) + \frac{\left(P_w - P_{gi} \right)\left(T_{b.w} + 273 \right)}{\left(268.9 \times 10^{-3} - P_w \right)} \right]$$

The partial vapour pressure in saline water is computed as follows: Tiwari et al. [32],

$$P_w = \exp\left(25.317 - \left(\frac{5,144}{273 + T_{b.w}} \right) \right)$$

The partial vapour pressure at the glass surface is computed using the following formula: Tiwari et al. [32],

$$P_{gi} = \exp\left(25.317 - \left(\frac{5,144}{273 + T_{gi}} \right) \right)$$