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Experimental investigation of a novel passive solar still with additional condensation on sidewalls

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ABSTRACT

In common solar stills, a portion of the produced vapor undesirably condenses on the sidewalls and runs down to be mixed with saline water in the basin. This results in lower distillate output of the system. The aim of this study was to improve the condensation process of a solar still without complicating its structure to collect the water condensed on sidewalls. The proposed solar still was made of two containers nested one inside the other such that the smaller container, containing saline water, fitted easily into the larger container. There was a thin gap between the two in which condensed liquid on sidewalls, ran down and was collected from the bottom of the larger container. The results showed that the daily efficiency reached 55.5% in the current system from the 29.72% corresponding to conventional solar still. On average, 38.5% of the yield was collected from the gap between sidewalls and the rest was obtained from the glass cover. The amount of daily yield and its cost per liter (CPL) were 5.85 kg/m^2 and 0.0069 \$/L m^2, respectively. Additionally, the placement of fins on the system's outer surfaces showed no improvement from both economical and performance standpoints.

Keywords: Desalination; Passive solar still; Enhanced condensation

1. Introduction

The supply of freshwater is one of the major global challenges in recent years. It has been estimated that two-third of the world population will face water crisis by 2025 [1]. Population growth and usage of modern devices have led to an increase in demand for freshwater and consequently energy consumption. The energy needed for majority of existing desalination methods such as reverse osmosis, multistage flash, multiple effect boiling, and electrodialysis is obtained from fossil fuels. Using these fuels, in addition to exacerbating the energy crisis, leads to environmental pollutions [2,3].

Solar desalination is a suitable option to alleviate both the freshwater and energy crises. A summary of the solar-assisted desalination systems has been discussed in Li et al. [4]. Among the various desalination methods, due to simplicity, low cost, low environmental impact, and the ease in maintenance, solar distillation presents specific advantages to be used specially in remote areas where fossil fuel sources do not exist or are costly to use. It has been reported that for capacities lower than 200 L per day, solar stills are more economical than other methods [5]. Despite this, the major disadvantage of solar stills is their low output. On average, a conventional solar still, yields 2.5 L/m^2 freshwater each day [6]. The operating principal of solar stills lies in the absorbance of solar radiation by saline water and its vaporization and subsequently condensation of produced vapor and collection of it as freshwater.

A great deal of research has been conducted to improve the performance of solar stills. Based on these, solar stills can be categorized into two groups: passive and active systems. In passive systems, solar energy is the only source of the energy while in active systems extra thermal energy is obtained. This extra energy may be obtained from a solar collector or any other external source of the energy [7–10]. A thorough review

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of active solar stills is proposed by Sampathkumar et al. [11]. In general, the main disadvantage of active solar stills is their complexity and high cost; whereas, passive systems have a lower cost and are structurally simpler. A review was performed by Muthu Manokar et al. [12] on studies concerning the parameters affecting the vaporization and condensation rates in passive solar stills.

The efficiency of solar stills is a function of the temperature difference between the condensation surface and the saline water in the basin. Throughout the day, as the water and condensation surface warms up, the temperature difference between them decreases, which leads to a drop in system efficiency [13]. Therefore, various researchers have tried to find the ways to further increase water temperature and decrease condensation surface temperature. The results demonstrate an increase in yield as the water depth drops in the basin [14–16]. Low water depth speeds up the temperature increase and consequently causes an increase in water evaporation rate. Rajaseenivasan and Srithar [17] investigated the effect of placing fins in the saline water basin theoretically and experimentally. They concluded that placing fins leads to better heat transfer to the saline water and consequently results in performance increase. The effect of adding various absorber materials to the basin to further increase water temperature was studied by Abdallah et al. [18]. The results showed 28% and 43% increase of yield for coated and uncoated metallic wires, respectively.

Improving the condensation process by use of an internal or external condenser appears to be a very promising solution to increase yield and efficiency of the solar still. In this regard, using an additional area for condensation which is 7.5 times larger when compared with a reference still without an additional area of condensation was investigated by Bhardwaj et al. [19]. Their results revealed that the production of water increased by more than 50% in the case of increased area of condensation. In fact, the lack of suitable glass cover cooling and its large thermal resistance cause an increase in the system's total thermal resistance and subsequently a rise in its temperature. Belhadj et al. [20] investigated a double-slope solar still coupled with a capillary film condenser in a numerical study. In their investigated system, a fraction of the resulting vapor is condensed on the inner glass cover plate (first slope) and the rest on the outer metal plate (second slope-capillary film). As a result, the system's yield was 60% more than that of the conventional solar still. The condensation of a portion of vapor in an air cooled condenser equipped with fins and the remainder of it on a solar still cover was studied by Ibrahim and Elshamarka [21]. The results of their mathematical model introduced a relation for evaluating the annual performance of the solar still. Monowe et al. [22] numerically investigated the existence of a sun tracker and using a fan to transfer the existing vapor in the solar still to an external condenser. By preventing latent heat loss and preserving it, the system efficiency increased to 68%.

One of the major disadvantages of solar stills, even when they have external condensers, is the condensation of a portion of the vapor on the sidewalls and its return to the saline water basin. Vinoth Kumar and Kasturi Bai [23] investigated a solar still in which the condensation occurs not only on the glass cover but also on the four sidewalls. Sidewalls are cooled by water through circulation tubes attached on them for efficiency enhancement. Results indicated a maximum daily yield of 1.4 L/m^2 and a maximum efficiency of 30%.

Ahsan et al. [24] studied the performance of a tubular solar still in which the water basin was inside a huge horizontal pipe. Therefore, all the condensed water could be collected from the bottom of the pipe and daily yield could reach 5 kg/m^2. Arunkumar et al. [25] combined the compound parabolic concentrator with tubular solar still and studied the effect of the outer pipe wall cooling on the performance of the system. The results showed an increase in daily yield up to 3.5 L/m^2 by cooling the inner surface of the pipe by water.

The purpose of this study was the experimental investigation of a simple novel passive solar still that could collect the condensed water on the sidewalls and prevent it from flowing back to the saline water basin. In other words, the condensed water, in addition to the glass cover, could be collected from the sidewalls separately, which improved the amount of total yield; whereas in the conventional solar still, a portion of the solar-produced vapor undesirably condenses on the sidewalls and runs down to be mixed with saline water in the basin. This results in lower distillate output and efficiency of the system. The proposed novel solar still was made of two containers nested one inside the other such that the smaller container, containing saline water (basin), fitted easily into the larger container. There was a thin gap between the two in which condensed liquid on the sidewalls, ran down and was collected from the bottom of the larger container. The fact that condensation took place on both sidewalls and glass cover improved the total yield of the system. In this study, the amount of water yield from the glass cover and the sidewalls and also the effect of the placement of fins on the external surface of the sidewalls for better cooling were investigated.

2. Experimental setup

All the tests were conducted in Tehran (latitude: 35.42, longitude: 51.35 and altitude: 1,172 m). The experimental setup was a single-slope solar still in which the saline water poured into a small basin placed in a bigger basin. The dimensions of the bottom of the big and small basins were 59 cm × 97 cm and 51 cm × 89 cm, respectively. Therefore, the distance between the sidewalls of these two basins was 4 cm. The produced freshwater from the sidewalls, passed through the gap between the two basins and was directed out from the bottom. The outside wall of the inner container was covered with polyurethane insulation with a thickness of 1 cm. A picture of the fabricated setup and a schematic diagram of how it operates are provided in Fig. 1. The evaporation process starts by the absorption of solar radiation by blackened interior surface of the inner container and its saline water. As the saline water is heated, its vapor pressure is increased. A portion of the resultant water vapor is condensed on the underside of the glass cover and runs down into the troughs and gets collected at the lower ends of the top cover. The remaining vapor in the basin condenses on the inner sidewalls of the larger container and along the gap. The resultant condensed liquid is drawn separately from the bottom of the larger container through an exit channel. The glass cover at the top of the system was positioned at an angle equal to the latitude of the Tehran. It is worth noting that the results of various researches show that the optimum angle for the placement of the glass cover is equal to the latitude of the experiment location [26]. Additionally, the containers were made of steel and plastic gaskets were used to ensure air sealing around edges of the glass cover.

3. Measurement instruments

In Tehran, more than 80% of solar intensity occurs between 8:00 am and 17:00 pm. Therefore, all the tests were performed in this period during July and August 2015. The solar radiation was measured using a pyranometer (SP-apogee sensor 110) on an hourly basis. At the same time, the variation in saline water temperature T_W, the bottom temperature of the smaller container T_B, inner and outer temperatures of the glass cover $T_{G,I}$ and $T_{G,O}$ and also the inner and outer wall temperatures of the larger container $T_{SW,I}$ and $T_{SW,O}$ were measured every hour using K-type thermocouples and were recorded by Lotrun BTM-4208SD data logger with a reading accuracy of 0.1°C. Locations of measured temperatures are designated in Fig. 1. Furthermore, the amounts of produced water from the glass cover and the sidewalls were measured separately by two graduated cylinder with a reading accuracy of 5 mL. The uncertainty corresponding to the solar radiation, temperature and water yield rate were 10.06 W/m², 1.006°C and 5.8 mL, respectively.

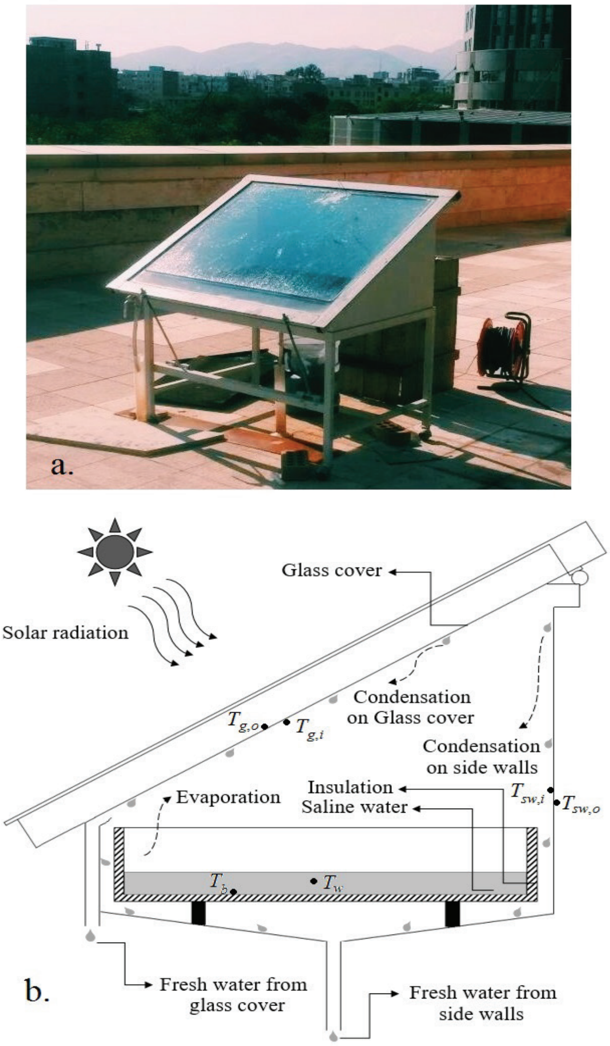

Fig. 1. (a) Experimental setup and (b) schematic of the setup and its processes.

4. Results and discussion

The saline water depth in the basin is one of the most important parameters affecting the performance of solar stills. Therefore, to investigate system performance, first, the optimum value of saline water depth was studied. Three tests were performed to determine the optimum depth with depths of 1, 2 and 3 cm. The tests were done in three consecutive days and therefore had similar solar radiation conditions. In Fig. 2, the hourly yield from the glass cover and the sidewalls as well as the total hourly yield for all three tests are presented. As can be seen, the highest yield for both the glass cover and the sidewalls corresponds to the 1 cm depth during the day. The reason for this is the rise in water thermal capacitance by increasing depth which leads to lower yield. It is worth mentioning that decreasing the initial water depth to less than 1 cm leads to a decrease in system output due to the occurrence of dry-out and the absence of water for desalinization for the rest of the day.

Daily efficiency was used as a dimensionless parameter to compare the overall system performance at the end of the day. It is defined as [27]:

$$\eta_{\text{daily}} = \frac{\sum_{8\ \text{a.m.}}^{17\ \text{p.m.}} (m_g + m_{sw}) h_{fg}}{\sum_{8\ \text{a.m.}}^{17\ \text{p.m.}} IA} \tag{1}$$

In which m_g and m_{sw} are the amount of produced water per hour from the glass cover and the sidewalls in kg,

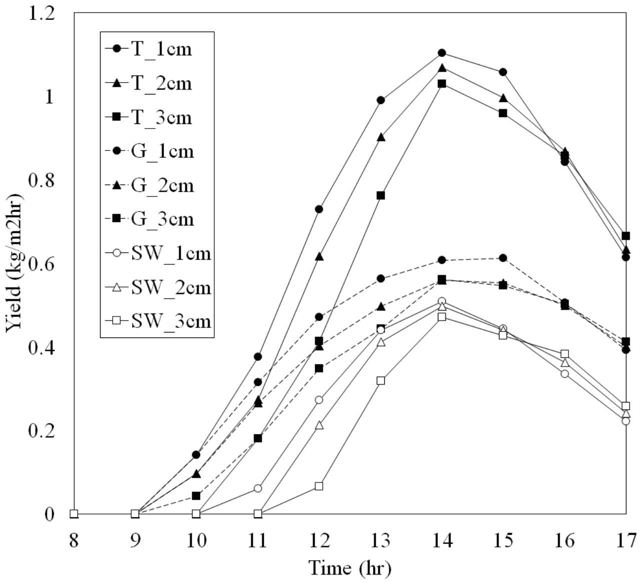

Fig. 2. Effect of water depth on total (T), glass (G) and sidewalls (SW) yield vs. time.

respectively; h_{fg} is the latent heat of vaporization in kJ/kg, I is the solar intensity in W/m^2 measured on horizontal surface and A is the area of the saline water basin. The highest daily efficiency was achieved with 1 cm depth and was equal to 55.5%. Additionally, the efficiencies for the depths of 2 and 3 cm were 52.52% and 47.62%, respectively. Therefore, all the tests were performed with a 1 cm depth for the remainder of the experiments. In Fig. 3, total yield, yields from the glass cover and from the sidewalls and also the variation in solar intensity with respect to time are presented for 1 cm depth of saline water. The maximum hourly yield is equal to 1.1 kg/m^2 at 14:00 pm. As can be seen, the maximum of water production happens with an 1-h delay from the solar intensity maximum. This is due to the thermal capacitance of the saline water inside the basin [28]. Furthermore, the water production maximums for the glass cover and the sidewalls are obtained as 0.61 and 0.51 kg/m^2 h, respectively.

As can be seen in Fig. 3, the amount of produced water from the sidewalls is less than that of the glass cover at any time of a day. As solar radiation normal to the horizontal surface increases, the yields form both glass cover and sidewalls increase as well. As can be seen in Fig. 3, water production from sidewalls begins at 10 am with a time delay of 1 h with respect to the starting production time from the glass cover (which occurs at 9 am). As the day goes on and solar intensity drops, total yield also drops. Regarding the hourly produced water, the significance of the production share of the sidewalls becomes prominent. The total yield in a day is equal to 5.85 kg/m^2 and 38.5% of that was from the sidewalls.

In order to compare the current system with the conventional solar stills, a separate test was performed. In this test, the gap between the two containers was filled with polyurethane and the path for vapor penetration into the distance between the walls of the two containers was blocked. Therefore, similar to conventional solar stills, water production was only possible from condensation on the glass cover. Hourly efficiency was used as a criterion for comparing the performance of the system in different hours throughout the day. This parameter is defined for a passive solar still as [29]:

$$\eta_{\mathrm{hourly}} = \frac{(m_g + m_{\mathrm{sw}})h_{\mathrm{fg}}}{IA} \tag{2}$$

where the parameters are similar to those that were explained for daily efficiency. A comparison of the hourly yield and hourly efficiency of the current system with the conventional solar still (CSS) is provided in Fig. 4. It can be observed that from the start of the test, the current system's total yield is higher than that of the conventional solar still and as the day goes on, the rise in yield and hourly efficiency is evident. As the normal solar radiation decreases in the afternoon, both values drop. Hourly yield reaches the maximum values of 0.55 and 1.1 kg/m^2 h for the conventional solar still and current system, respectively. Additionally, the maximum hourly efficiency for the conventional solar still is 40% which reaches 81% in the current system.

As a general comparison of the conventional and current setup, the results showed that the daily efficiency of the solar still reaches from 29.72% for the conventional solar still to 55.5% for the current setup due to the condensation on the sidewalls. Therefore, the use of two nested containers increases the daily efficiency by approximately 87%.

The temperature variations of various points in the system with respect to solar intensity values throughout the day are illustrated in Fig. 5. It can be seen that during the day, as the solar intensity increases, the temperatures of various points increase as well. The solar intensity maximum occurs at around 13 and its value is 925 W/m^2. After that as the solar intensity decreases, the temperatures at various points decrease. Since a portion of the vapor condenses on the sidewalls between two containers, it is expected that lowering the walls' temperatures would lead to an increase in condensation rate. The most important purpose of this study was improving the passive solar still efficiency without complicating its structure. Therefore, to enhance heat transfer from vapor to the ambient air, some fins were attached on the outer surface of the larger container as shown in Fig. 6. Three tests

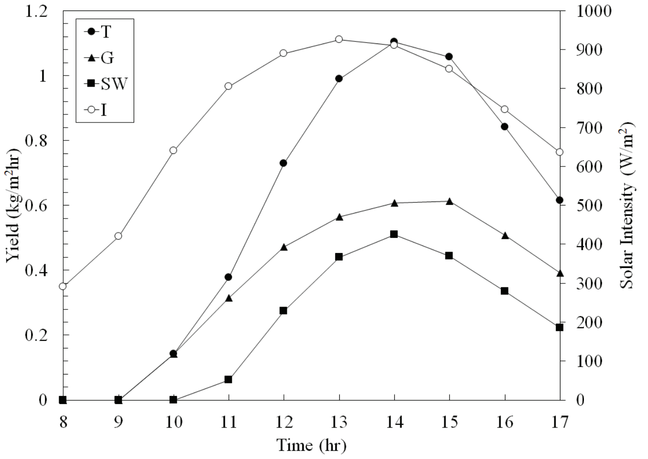

Fig. 3. The variations of total (T), glass (G), sidewalls (SW) yields and solar intensity (I) vs. time.

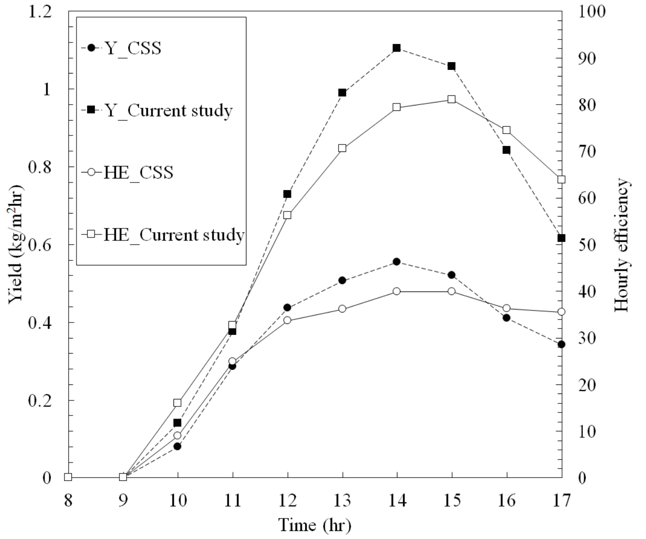

Fig. 4. Yield and hourly efficiencies of current study and CSS vs. time.

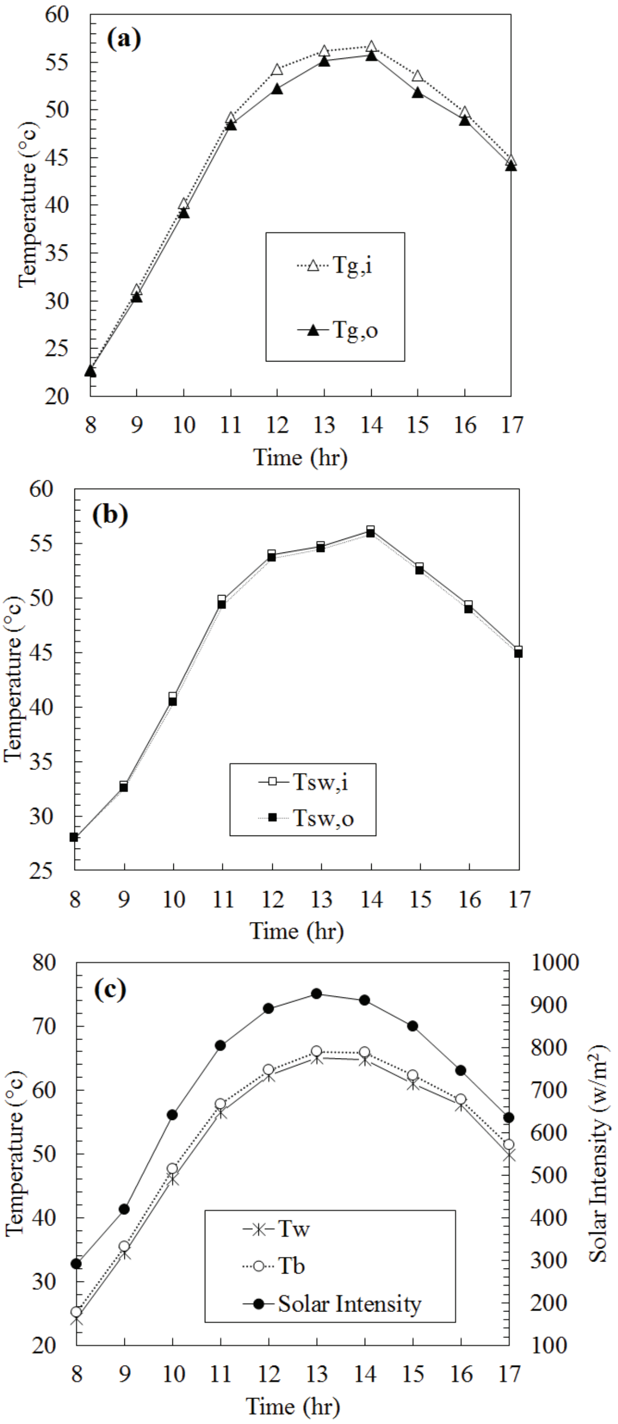

Fig. 5. Variations of the measured temperatures and solar intensity vs. time.

Fig. 6. Fin configuration on the sidewalls of the solar still.

were carried out to evaluate the effect of fins on the distillate output. In two of these tests, the fins covered 16% and 38% of the outside surface of the larger container. In the third test, 38% of the surface area was covered with fins and the outer surface was shaded with a piece of cloth to prevent sun rays from hitting the fins. The amount of water yield from the sidewalls, produced water from the glass cover, total yield and daily efficiency for all three tests with and without fins are provided in Table 3. As can be seen, by increasing the number of fins, heat transfer is improved on the sidewalls and the ratio of the water produced from the sidewalls to the total produced water, increases. The highest water yield from the sidewalls corresponds to the case in which 38% of the surface area is covered with fins and shaded. On the other hand, it can be observed that as the amount of produced water from the sidewalls increases due to better cooling by fins, the amount of produced water from the glass cover decreases.

It can be seen that contrary to what was expected, daily efficiency for the case in which the fins were not used is more than those of all the three cases in which fins were applied. Therefore, the current system, even without any fins, is superior to the finned setups from daily efficiency, simplicity and cost standpoints. Although the reason for this matter is not clear, it is speculated that diversion of vapor flow toward the gap due to the cooling improvement of the sidewalls reduces vapor flow toward glass cover and its condensation rate.

In Table 2, a comparison is provided on daily efficiencies for several solar stills of previous studies. It can be seen that the current system is among the most efficient systems. Additionally, in similar operating conditions, the current system has the highest efficiency improvement (87%) compared with those of the recently investigated desalination systems.

5. Economic analysis

The economic analysis of the current system was carried out according to Fath et al. and Dev et al. [34,35]. The corresponding details are provided in Table 3. It can be seen that the cost per liter (CPL) value for the fabricated passive solar still is equal to 0.00697 \$/L m^2 with a daily yield of 5.85 kg/m^2. The current system is structurally simpler compared with the passive system with corrugated absorber (CPL = 010121 \$/L m^2) and the passive system with pulsating heat pipe (CPL = 0.0064 \$/L m^2). The possibility of improving the efficiency and hence, lowering the CPL of the current design while maintaining simplicity and fabrication cost will be investigated in the near future.

Table 1
Comparison of the effects of attaching fins on the sidewalls on the water yield and daily efficiencies

	No fin	16% Fin	38% Fin	38% Fin (shaded)
Glass yield (kg/m^2 h)	3.57	2.54	2.23	1.93
Sidewalls yield (kg/m^2 h)	2.28	2.34	2.66	2.78
Total yield	5.85	4.88	4.89	4.71
Daily efficiency (%)	55.50	52.83	51.29	50.31

Table 2
Daily efficiency of different solar stills

Percentage of improvement (%)	Daily efficiency of the CSS (%)	Daily efficiency (%)	Type	Solar system	Reference
79	33	59	Passive	Corrugated absorber solar still with double-layer wick and reflectors	[27]
20	34	41	Active	Solar still coupled with solar photovoltaic, flat plate collector	[30]
12	34	38	Active	Solar still coupled with solar photovoltaic, flat plate collector with hot water spray	[30]
5	34	35.5	Active	Solar still coupled with solar photovoltaic, flat plate collector with hot water jet	[30]
40	27	37.8	Passive	Solar still with a sensible storage medium	[31]
65	34	56	Passive	Stepped solar still performance using internal reflectors	[32]
49	37	55	Active	Stepped solar still with continuous water circulation	[33]
87	29.72	55.5	Passive		Current study

Table 3
Economic analysis of the current study

Parameters	Dev et al. [35]	Current study
Principle cost (*P*), $	135.3	112
Salvage value (*S*) (10% of principle value), $	13.5	11.2
Life of the still (*n*), years	20	20
Interest rate (*i*), %	10	10
Capital recovery factor (CRF)	0.117	0.117
Sink fund factor (SFF)	0.017	0.017
Annual first cost (CRF × P), $	15.9	13.104
Annual salvage value (SFF × S), $	0.24	0.1904
Annual maintenance cost (0.15 annual first cost), $	2.38	1.9656
Annual cost = (annual first cost + annual maintenance cost − annual salvage value), $	18.04	14.8792
Average daily yield, kg/m^2	4.1	5.85
Annual yield of the still (average daily yield × 365), kg/m^2	1496.5	2,135.25
Annual useful energy (annual yield × latent heat of vaporization (= 0.65 kWh/kg)), kWh/m^2	972.7	1,387.91
Annual cost of distilled water per kg (annual first cost/annual yield), $	0.0106	0.0061
Annual cost of distilled water per kWh (annual first cost/annual useful energy), $	0.0163	0.0094
Cost per liter per unit area of still (CPL = annual cost/annual yield of still), $/L m^2	0.0121	0.0069

6. Conclusion

A novel solar still with additional condensation on the sidewalls was experimentally studied. The fabricated double-wall basin was made of two containers nested one inside the other such that the smaller container, containing saline water, fitted easily into the larger container. There was a thin gap between the two in which condensed liquid ran down and was collected from the bottom of the larger container. The fact that condensation took place on both sidewalls and glass cover improved the total yield of the system. The obtained results are as follows:

- The only fundamental structural difference between the current system and the conventional solar still is the addition of an internal basin. Therefore, the current system is extremely simple and compact and is easily applicable in remote areas.
- Daily water yield was equal to 5.85 kg/m^2 and the highest hourly water yield was equal to 1.1 kg/m^2
- Daily efficiency reached 55.5% in the current system from the 29.72% value reported for the conventional system.
- The highest hourly efficiency of the current system was obtained as 81% with an optimum depth of 1 cm.
- On average, 38.5% of the total produced water was generated by the sidewalls and 61.5% was obtained from the glass cover.
- Placing fins on the system's outer surfaces led to an increase in water yield from the sidewalls but on the other hand, caused a drop in water yield from the glass cover and as a result the overall daily efficiency of the system decreased.
- The cost of freshwater production for this system was estimated to be 0.0069 $/L m^2.

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