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Review of different methods employed in pyramidal solar still desalination to augment the yield of freshwater

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ABSTRACT

Water plays a major part in all our regular activities. Requirement for freshwater is growing regularly, because of improved living standards. Some of the earth's regions are under severe stress due to a lack of water. The potable water needs of mankind can only be satisfied if salt water, which is plentiful, can be converted into drinkable water by desalination. Surfaces used for the evaporation and condensation processes play an important role in the performance of solar stills. Compared with basin-type solar stills, pyramid-shaped stills have larger condensation areas. In this review, various research works carried out on pyramid solar stills are discussed. The main objective of this review is that it will motivate researchers to investigate and promote pyramid solar still technology for appropriate development. The daily distilled water production from the passive and active pyramid solar still is in the range between 2–7 L/m^2 and 3–7 L/m^2, respectively.

Keywords: Pyramid solar still; Passive and active mode; Yield enhancement

1. Introduction

A lack of freshwater is an extremely crucial trouble that is constantly growing, due to populace growth and changes in climate conditions. Several countries have plentiful seawater assets and a superior level of solar intensity that could be used to generate pure drinkable water from salt water. Solar stills are one of the best ways to convert seawater to pure, potable water using solar radiation from the sun [1]. Many countries have a critical need for large amount of pure water for consumption and drinking purposes. Brackish water available in rivers, lakes, seas, and ponds cannot be used directly for consumption, because it contains dissolved salts and hazardous microorganisms. According to the WHO, there is a growing need for the production of clean water from salt water. A solar still is an extremely efficient way

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and eye-catching method for distilling potable water from seawater. Solar still desalination is the best system for producing clean water from salt water in isolated locations, which possess an abundance of solar radiation and ample saline water, or scarcity of electrical energy [2–5]. A review of different pyramid solar stills (PSSs) was studied by Nayi and Modi [6]. A review of research and advancement in solar stills was performed by Kabeel and El-Agouz [7]. Srithar and Rajaseenivasan [8] recently reviewed the progress in potable water augmentation techniques in humidification-dehumidification and solar still. Kabeel et al. [9], Omara et al. [10], and Sharshir et al. [11] have performed a comprehensive report on stepped solar still, still incorporated with reflectors and thermal, exergy efficiency analysis of solar still, respectively. Sivakumar and Sundaram [12] published solar still efficiency improvement methods. Thermal models of solar still were studied by Elango et al. [13]. Rajaseenivasan et al. [14] have carried out various design modifications on multi-effect solar still. Ranjan and Kaushik [15] reported the exergy, energy, and thermo-economic of solar still. Different model of still was reviewed by many researchers [16–20]. Different element/parameter affecting the solar still production had been performed by Manokar et al. [21], Muftah et al. [22], and Velmurugan and Srithar [23]. Solar still in active mode has been reviewed by many researchers [24–26]. In this review article, different research works carried out on PSSs are discussed. Based on a detailed survey analysis, recommendations for the extent of upcoming research work in pyramidal stills are given. PSSs are classified as follows:

- Passive pyramid solar still (PPSS)
- PSS with heat storage materials
- Active pyramid solar still (APSS)
- APSS with heat storage materials

2. Passive pyramid solar still

Fath et al. [27] designed a single-slope solar still (SSSS) and a PSS. The thermal performance of both stills was analytically studied, and economic analyses for two stills were also carried out. The annual productivity and efficiency of the stills were derived mathematically. Fig. 1 shows the configuration of the PSS and SSSS. Both the setup was designed with the similar basin area of 1.5274 m^2. For the theoretical analysis, climatic data of Aswan city (Egypt) have been considered. It was concluded that the PSS received a 4% higher daily average annual solar intensity and absorbed more solar intensity than the SSSS, and the PSS liberated 1% higher on

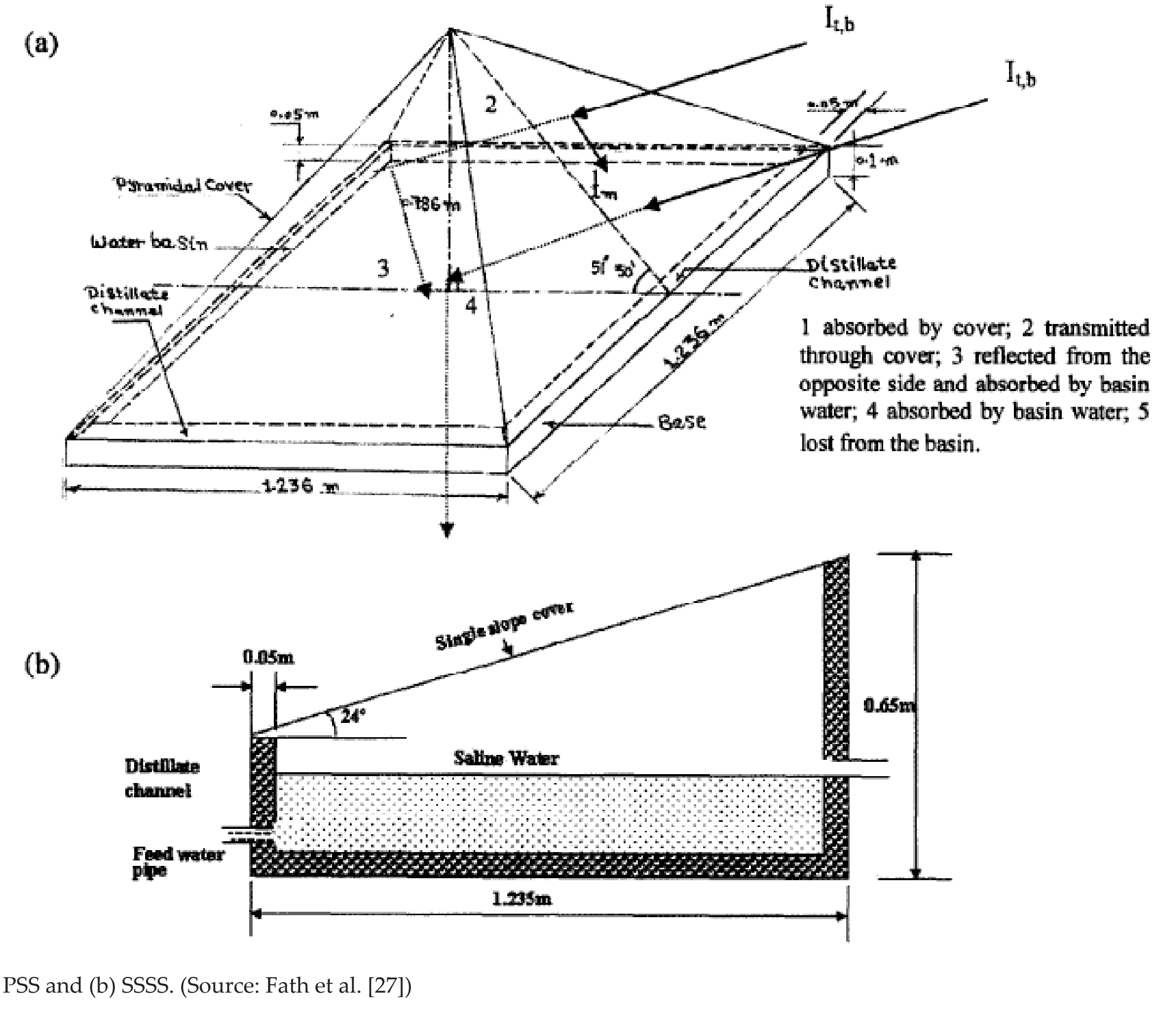

Fig. 1. (a) PSS and (b) SSSS. (Source: Fath et al. [27])

a daily average annual solar radiation than the SSSS. The resultant solar radiation obtained by the SSSS was 8% higher than that obtained by the PSS. Based on Dunkle relations, the monthly yield, average yearly yield, monthly efficiency, and the average yearly efficiency for both stills have been plotted in Fig. 2. The SSSS produced relatively higher productivity and efficiency than the PSS. Both stills produced nearly the same annual average daily outcome of about 2.6 L/m^2 D: the PSS produced 30% annual average daily efficiency and the SSSS produced 33% annual average daily efficiency. From the cost analysis, it was concluded that the annual cost required to produce 1 L of water from the PSS was slightly higher than that required to produce the same from the SSSS.

Kabeel [28] fabricated the glass PSSs with a parallel multi-shelf array in the basin (Fig. 3) with the same shape and dimension. The height and base of the PSS was 160 cm × 100 cm × 100 cm, respectively. The base of the PSS was insulated with 15 cm thickness to decrease temperature losses from the bottom to the atmosphere. Four shelves inside the basin were kept 30 cm apart. In a first PSS, the shelf beds are made of saw wood; and in a second PSS, the shelf beds are made of cloth material. Both the stills are saturated with 30% concentrated calcium chloride solution. The sides of the PSS are opened at nighttime to allow the dry, saturated humid air and closed early in the morning to remove the humidity from the bed by means of solar intensity (Fig. 4). It was concluded that the solution absorption capacity of the cloths bed was 12% higher than that of the saw wood bed. Introducing this novel method produced a yield of around 2.5 L/d m^2. Multi-shelf bed methods produced 90%–95% higher freshwater yield than corrugated or horizontal beds. The cloth bed produced a 5% higher yield than the saw wood bed, because the cloth bed absorbed maximum solution compared with the saw wood bed.

Kabeel [29] fabricated a novel PSS with a curved wick evaporation absorber and a four-sided pyramid-shaped condensation area (Fig. 5). This system has the following main advantages: larger evaporation and condensation areas; and minimum shading effect compared with conventional solar stills (CSSs), because all the sides of concave solar stills are glass. The absorber area of the system is 1.2 m × 1.2 m. A black-painted wick was placed in the absorber to absorb maximum solar intensity. All four sides of the still were covered with 3 mm-thickness normal window glass. It was submitted that the daily distilled water production and efficiency from the system was about 4.1 L/d m^2 and 30%, respectively. The system produced a 20%–40% higher yield than conventional corrugated wick of cloths, and 200% higher than the CSS.

Algaim et al. [30] performed a comparative study of a PSS and CSS (Fig. 6). Both the systems were designed, fabricated, and tested in Basra city, Iraq. Both stills were manufactured with 4-mm thick transparent glass, and the still basins were manufactured from a black-painted aluminum plate with a surface area of 0.25 m^2. In order to prevent thermal losses from the still basins, wood blocks were used as insulating material. It was submitted that the PSS produced a higher yield than the glass CSS, because the PSS had a larger collector surface. It was reported that the maximum distilled water from the PSS and the CSS was 7,368 and 5,570 mL/m^2 d, respectively. The highest energy efficiency of the PSS and the CSS was 66.5% and 43.4%, respectively. It was concluded that, based on the experimental investigation, the PSS was the best design in the Basra region.

Fig. 3. Photograph of the pyramid desalination system. (Source: Kabeel [28])

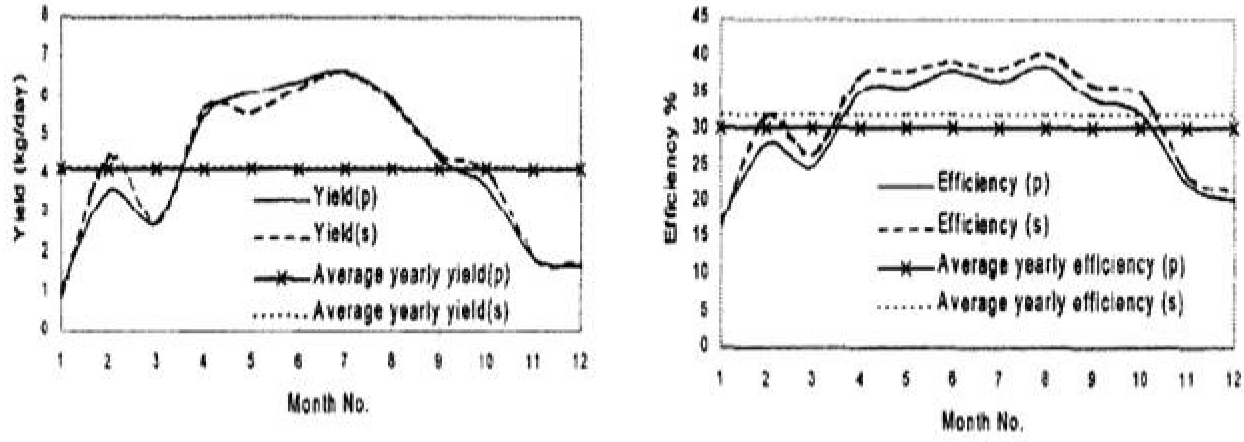

Fig. 2. Monthly average productivity and efficiency for both the PSS and SSSS based on Dunkle relations. (Source: Fath et al. [27])

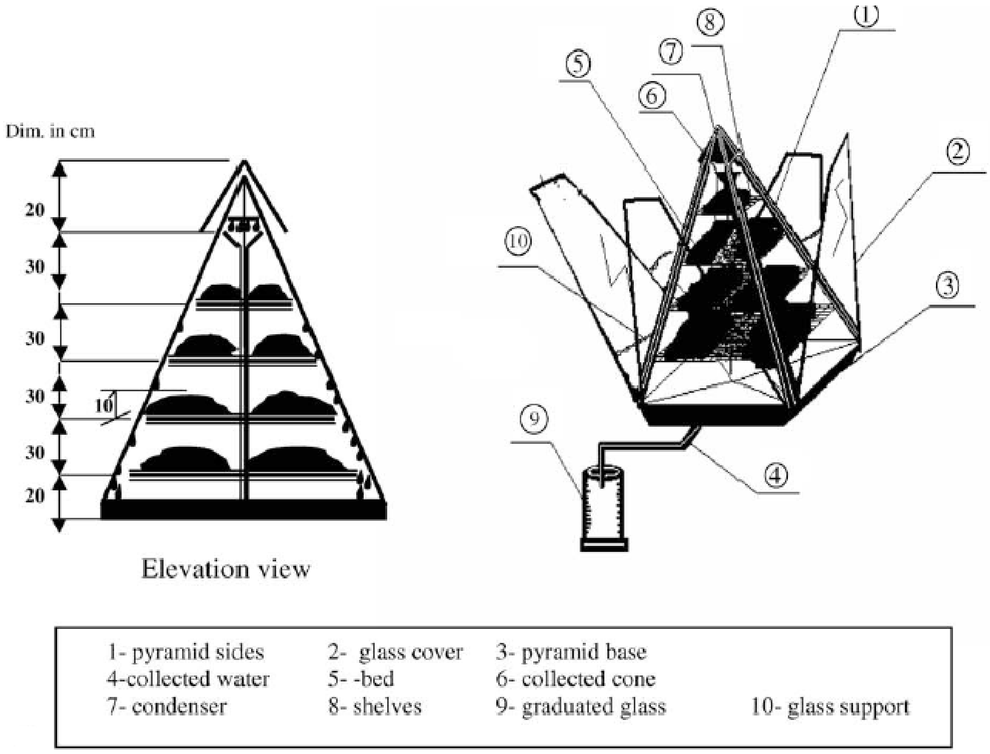

Fig. 4. PSS with collector covers open during nighttime. (Source: Kabeel [28])

Fig. 5. Photograph of the fabricated concave wick solar still. (Source: Kabeel [29])

Ahmed et al. [31] did a comparative study of three solar stills, namely SSSS, double-slope solar still (DSSS), and PSS (Fig. 7). All three solar stills were manufactured with 1 m^2 basin area and 1.2 m^2 collector surface area. The experiments were conducted in natural environmental conditions in the south of Kuwait City. Fig. 8 shows the accumulated yield of all three solar stills with respect to time. The daily yield produced from the SSSS, DSSS, and PSS was 3.613, 3.957, and 4.245 L/d, respectively. The PSS produced a 17.5% higher yield than the SSSS, and the DSSS produced a 9.5% higher yield than the SSSS. The PSS received more direct solar radiation than the other two stills, so it produced a higher yield than the others.

Kabeel et al. [32] researched a square PSS with three different collector cover inclination angles of 30.47°, 40°, and 50° (Fig. 9). In this research work, three PSSs with different collector cover angles were designed, fabricated, and tested under Egyptian conditions. During the experimentation, it was observed that the solar stills with 30.47°, 40°, and 50° cover inclination angles produced maximum temperatures of 78°C, 75.8°C, and 74.4°C, respectively. It was reported that the PSS received maximum solar energy input when the collector cover inclination angle was equal to the latitude of the place (30.47°), and solar intensity input to the PSS decreased when the inclination angle (40° and 50°) was higher than the latitude of the place (30.47°).

The accumulated yield for different types of square PSS is shown in Fig. 10. From the graph, it was clear that the 30.47° cover inclination (System A) produced a higher accumulated yield than the 40° cover inclination (System B) and the 50° cover inclination (System C). The accumulated yield produced from System A, System B, and System C was 4.14, 3.5, and 2.93 L/m^2, respectively. System A produced a 41% higher yield than System C, and an 18% higher yield than System B. It was concluded that a still collector cover angle equal to the latitude of the place produced a higher yield, and increasing the still collector surface angle above the latitude angle resulted in a decrease in still productivity.

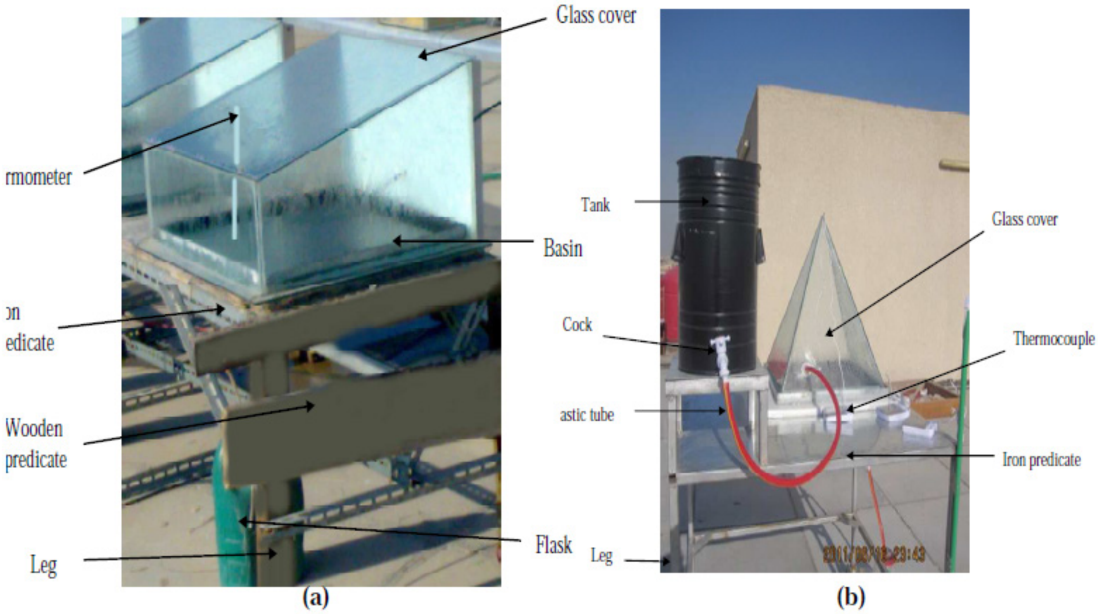

Fig. 6. (a) Photograph of the CSS and (b) schematic diagram of the PSS. (Source: Algaim et al. [30])

Fig. 7. The three stills configurations in situ. (Source: Ahmed et al. [31])

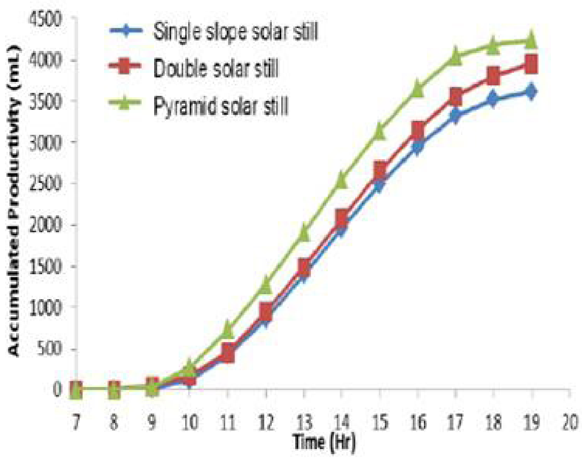

Fig. 8. Comparisons between yields of the three stills configurations. (Source: Ahmed et al. [31])

Arunkumar et al. [33] researched the yield and efficiency of a hemispherical solar still (HSS) and a PSS. The PSS was made of an acrylic sheet with a basin area of 1 m^2. The distillate yield from the HSS and the PSS was 3.3 and 2.73 L/m^2 d, respectively. The daily efficiency of the HSS and the PSS was 32.02% and 26.59%, respectively. It was concluded that the HSS produced more yield than the PSS, because the HSS received solar radiation from all sides of the collector surface.

Nagarajan et al. [34] researched the PSS under natural convection mode. It was found that the PSS produced productivity of 4.3 L/m^2 d with a 40% higher yield than the CSS. Sathyamurthy et al. [35] researched the effect of water depth and wind velocity on the performance of a PSS. Research was conducted with varying water depths of 0.02, 0.04, 0.06, 0.08, and 0.1 m. It was reported that minimum water depth produced maximum yield. The freshwater production from the PSS at 0.02, 0.04, 0.06, 0.08, and 0.1 m was 4.3 2.3, 1.2, 0.9, and 0.5 kg/m^2, respectively. Similarly, experiments were conducted with varying wind speed from 1.5 to 3 and 4.5 m/s. It was found that maximum wind speed produced maximum yield. The freshwater production from the PSS at 1.5, 3, and 4.5 m/s was 3,020, 3,408, and 3,510 mL/m^2 d, respectively.

3. PSS with heat storage materials

Ravishankara et al. [36] researched a triangular-shaped PSS with phase change materials (PCM) and without PCM (Fig. 11). In this research work, paraffin wax was loaded at the bottom of the basin with a 10 mm thickness. The PCM

Fig. 9. Photograph of the experimental setup. (Source: Kabeel et al. [32])

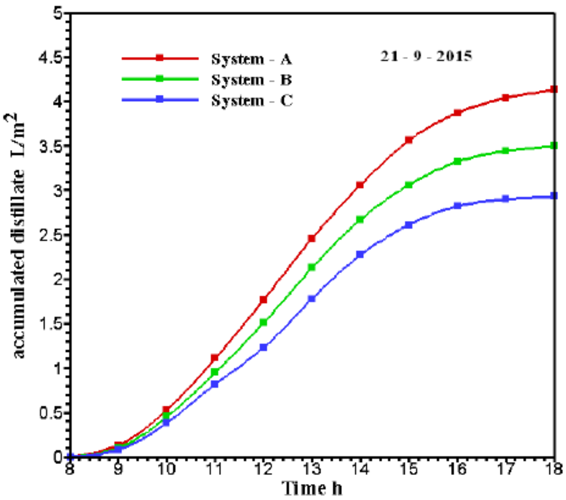

Fig. 10. The daily distillate yield for the PSSs. (Source: Kabeel et al. [32])

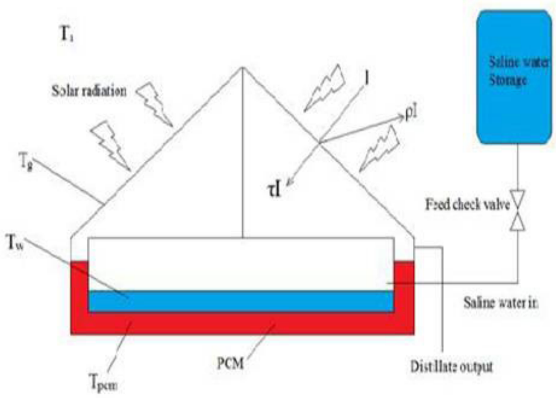

Fig. 11. Schematic diagram of the triangular PSS. (Source: Ravishankara et al. [36])

Fig. 12. Pyramid-type distiller. (Source: Sathyamurthy et al. [37]).

stored heat energy and was used to increase productivity during the evening hours. The yield produced from the PSS with and without PCM was 5.3 and 4.2 L/m^2 d, respectively. The daily efficiency of the PSS with and without PCM was 60% and 45%, respectively. The PSS with PCM produced a 20% higher productivity than the PSS without PCM.

Sathyamurthy et al. [37] did experimental studies on the varying the water mass in the PSS using PCM as energy storage (Fig. 12). In this research work, solar stills were filled with two different water masses (20 and 50 kg) to optimize the water depth in the PSS. From the experimentation, it was observed that the water and basin temperatures in the PSS with 20 kg of water mass in the basin were higher than those in the PSS with 50 kg of water mass. The maximum daily yield of the PSS with and without PCM was 5.5 and 3.5 L/m^2 d at 20 kg of water mass. The still with PCM produced a 35% higher yield than the still without PCM at minimum water mass (20 kg).

Sathyamurthy et al. [38] also performed experimental investigation on triangle pyramid solar still with and without PCM during both summer and winter seasons. It was concluded that the PSS with and without PCM produced a yield of 4.5 and 3.5 L/m^2 d, respectively, during summer, and 3.4 and 2.3 L/m^2 d respectively, during winter.

4. Active pyramid solar still

Kianifar et al. [39] fabricated two solar stills, namely PPSS and APSS. In the APSS, a small fan with minimum power consumption was placed at the side wall of the experimental setup. The illustrative diagram of the APSS is shown in Fig. 13. Polyethylene was used for fabricating the still. The area of the basin is 0.9 m^2, the height is 0.25 m, and the cover inclination is 36°. In this research work, the effect of water depth, productivity, exergy, and economic analysis has been carried out. Experiments were conducted on both the stills by maintaining water depth at 4 and 8 cm, respectively. It was concluded that the maximum productivity of the PPSS is 2.72 and 1.64 L/m^2, at an 8-cm water depth, during summer and winter, respectively. The maximum yield of the APSS is 3.14 and 1.88 L/m^2, at an 8-cm water depth, during summer and winter respectively. The authors reported that the 8-cm water depth produced higher yield for all the cases because of higher solar radiation and not higher water depth. The yield from the lower water depth (4 cm) still will be higher if both the 4-cm and 8-cm water depth stills receive the same amount of solar radiation. The maximum exergy efficiency of the PPSS is 3.06% and 2.43%, at a 4-cm water depth, during summer and winter seasons, respectively. The maximum exergy efficiency of APSS is 3.31% and 2.44%, at a 4-cm water depth, during summer and winter seasons, respectively. The daily productivity of the APSS is 15%–20% higher than the PPSS. The freshwater production cost of the present PPSS and APSS was compared with that of the weir-type solar still, HSS, SSSS, thermoelectric solar still, and sun-tracking solar still. And it was concluded that the PPSS and APSS have lower productive costs in comparison with the other stills, excluding the SSSS. It was reported that the production cost of freshwater in the APSS is 8%–9% lower than that in the PPSS.

Taamneh and Taamneh [40] researched the PSS with and without fans at the collector surface. In this study, two PSSs with the same basin area of 0.95 m^2 were fabricated (Fig. 14). In the first solar still, a PSS without a fan was used. In the modified solar still (a PSS with fan), a low power consumption fan operated by photovoltaic panels was mounted on one of the collector surfaces. It was used for circulating air in the interior of the solar still.

The variations of productivity of both solar stills based on free and forced convection effects are shown in Fig. 15. From the graph, it is very clear that the accumulated yield produced from the PSS with fan is higher than that produced from the PSS without fan. The daily yield of the PSS with and without fan was 2.99 and 2.485 L/d, respectively. Due to the circulation of the air in the interior surface, the PSS with fan produced a 25% higher yield than the PSS without fan. The daily efficiency of the PSS with and without fan was 50.5% and 40.2%, respectively.

Arunkumar et al. [41] experimentally investigated the PSS (Fig. 16) and a PSS integrated with concentrated coupled collector (CPC-PSS) (Fig. 17). In this research work, the PSS

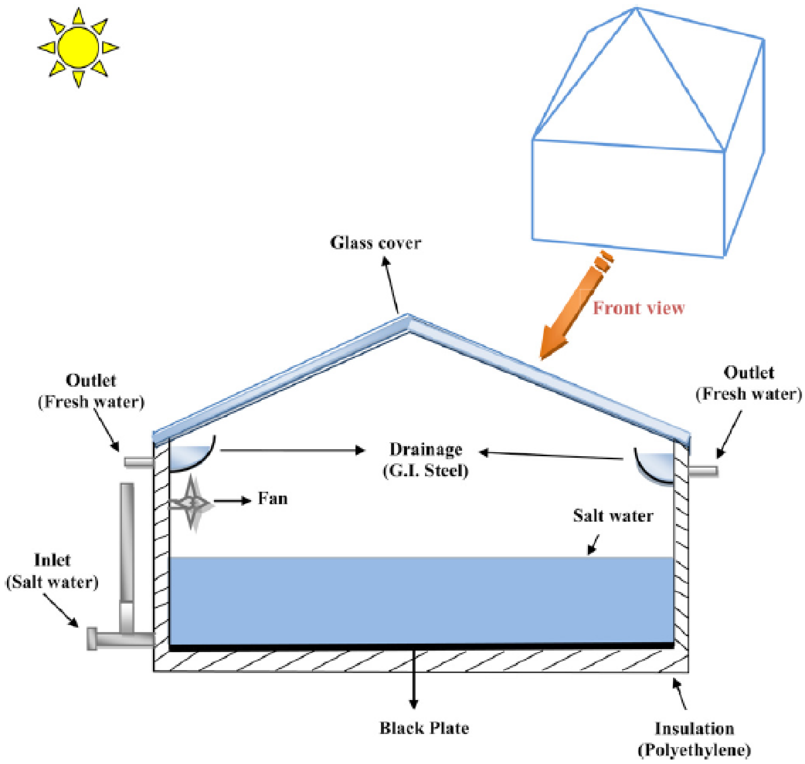

Fig. 13. Schematic of the active solar still. (Source: Kianifar et al. [39])

was made of glass materials. It had 1.21 m^2 of collector area and used sawdust as an insulating material. The condensation rate of the CPC-PSS was enhanced by the flowing of cold water at a constant rate of 10 mL/min over the still collector. In the PSS-CPC, basin water temperature was increased by integrating the CPC, and, additionally, by solar radiation. It was concluded that the flowing of cold water over the PSS increases the yield, and still production mainly depends on the higher temperature difference between water temperature and condensate collector temperature. The productivity from the PSS and the CPC-PSS was 3,300 and 6,928 mL/m^2 d, respectively.

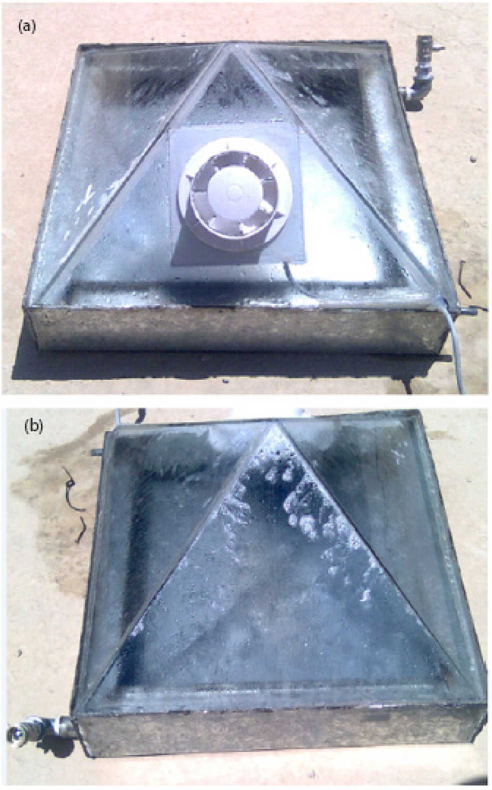

Fig. 14. PSSs (a) with fan and (b) without fan. (Source: Taamneh and Taamneh [40])

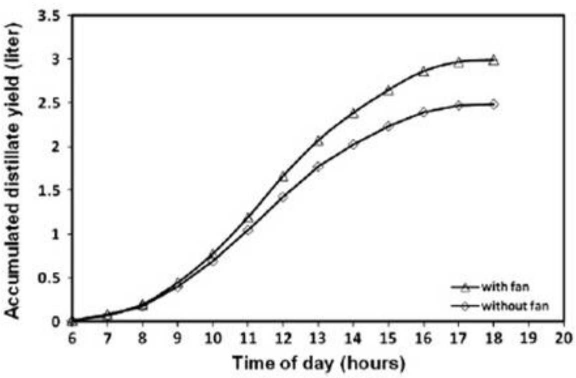

Fig. 15. The distilled yield produced from PSS with and without fan. (Source: Taamneh and Taamneh [40])

5. APSS with heat storage materials

Rajan et al. [42] augmented the distilled water of a PSS by utilizing a biomass heat source (Fig. 18). The PSS was manufactured of 1.4-mm thick mild steel with the size and height of 0.81 m × 0.82 m × 0.75 m and 0.3 m, respectively. The main novelty of this research work was that the input feedwater was preheated using a boiler. The boiler used biomass as fuel, and a heat exchanger was used to circulate the water from the boiler to still. By using biomass as a heat source, the feedwater temperature can reach up to 75°C. The investigation was conducted by a minimum water depth (2 cm),

Fig. 16. Pictorial view of the PSS. (Source: Arunkumar et al. [41])

Fig. 17. Pictorial view of CPC-PSS design. (Source: Arunkumar et al. [41])

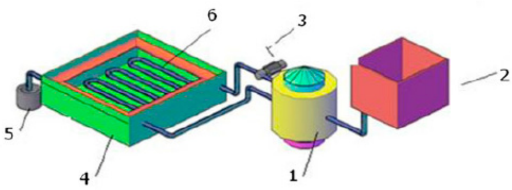

Fig. 18. 3D view of experimental setup. (Source: Rajan et al. [42])

Table 1
Different research works made in pyramid solar still

S. No.	Author name	Testing place and latitude	Experimental work done	Productivity (L/m^2 d or mL/m^2 d)	Efficiency (%)	Performance of the still
1	Fath et al. [27]	Egypt 24°N	Theoretical studies on SSSS and PSS	2.6	30	SSSS produced relatively higher productivity and efficiency than PSS
2	Kabeel [28]	Egypt 30.47°N	PSS with a parallel multi-shelf arrangement in the basin	2.5		Multi-shelf bed methods produced 90%–95% higher freshwater than corrugated or horizontal beds
3	Kabeel [29]	Egypt 30.47°N	Novel concave wick PSS	4.1	30	Concave solar still produced 20%–40% higher yield than conventional corrugated wick of cloths and 200% higher than CSS
4	Algaim et al. [30]	Mashhad, Iran 36°36′N	Experimental analysis on passive and active PSS	PPSS: 2.72 APSS: 3.14		The daily productivity of APSS is 15%–20% higher than PPSS
5	Ahmed et al. [31]	Tafilah, Jordan 30°N	Experimental studies on PSS with fan and without fan	PSS with fan: 2.99 PSS without fan: 2.485	PSS with fan: 50.5 PSS without fan: 40.2	PSS with fan produced 25% higher yield than PSS without fan due to the spread of the air in the interior of the solar still
6	Kabeel et al. [32]	Coimbatore, India 11°N	Experimental investigation on PSS and CPC-PSS	PSS: 3,300 CPC-PSS: 6,928		Integrating PSS with CPC increased the still productivity by almost double
7	Arunkumar et al. [33]	Basra, Iraq 30°N	Comparative study of PSS and SBSS	PSS: 7,368 SBSS: 5,570	PSS: 66.5 SBSS: 43.4	PSS produced higher yield and efficiency than SBSS
8	Nagarajan et al. [34]	Kingdom of Bahrain 26°	Comparative study of SSSS, DSSS, and PSS	SSSS: 3.613 DSSS: 3.957 PSS: 4.24		PSS produced 17.5% higher yield than SSSS, and DSSS produced 9.5% higher yield than SSSS
9	Sathyamurthy et al. [35]	Ramanathapuram 30°	PSS integrated with utilizing biomass heat source	PSS with seashell, metals, and stones: 3,625, 2,405, and 2,173		Sensible heat storage materials produced 84% higher yield than CSS

(*continued*)

Table 1 (*continued*)

S. No.	Author name	Testing place and latitude	Experimental work done	Productivity (L/m² d or mL/m² d)	Efficiency (%)	Performance of the still
10	Ravishankara et al. [36]	Egypt 30.47°N	Performance analysis of square PSS with three different collector cover inclination angles of 30.47°, 40°, and 50°	System A: 4.14 System B: 3.5 System C: 2.93		System A produced 41% higher yield than System C and 18% higher yield than System B
11	Sathyamurthy et al. [37]	Chennai 13°	Experimental investigation of the triangular-shaped PSS with PCM	PSS with PCM: 5.3 PSS without PCM: 4.2	PSS with PCM: 60 PSS without PCM: 45	Still with PCM produced 20% higher yield than still without PCM
12	Arunkumar et al. [41]	Chennai 13°	Effect of water depth and wind velocity on the performance of PSS	PSS at 0.02m water depth: 4.3 PSS at 4.5 m/s: 3,510		The freshwater production from PSS at 0.02, 0.04, 0.06, 0.08, and 0.1 m were 4.3, 2.3, 1.2, 0.9, and 0.5 kg/m², respectively

SBSS — Single basin solar still.

and the use of sensible heat and latent heat storage materials, effect of using evaporative surfaces, and the effect of glass cover cooling technology have been carried out.

Sensible heat storage materials such as stones, seashells, and metals were used in the solar still. The daily productivity of the PSS with seashells, metals, and stones was 3,625, 2,405, and 2,173 mL/m², respectively. The sensible heat storage materials produced an 84% higher yield than CSSs. Among the materials tested, seashells produced a higher yield because of its higher calcium content, and it absorbed more heat energy than the other materials. Latent heat storage materials such as water and wax were also used in solar stills. The daily productivity of the PSS with water and wax was 2,005 and 2,145 mL/m², respectively. The latent heat storage materials produced a 69% higher yield than the CSS. Compared with water, wax has a higher heat storage capacity, so it produced more yield. Evaporative materials such as wick and sponge were also used in solar stills. The daily productivity of the PSS with sponge and wick was 1.685 and 1,520 mL/m², respectively. The evaporative materials produced a 61% higher yield than the CSS. The sponge and wick materials absorbed more water due to higher exposure areas and capillary action. The PSS with and without cover cooling was also experimentally investigated. The productivity of the PSS with and without cover cooling was 1,482 and 1,125 mL/m², respectively. The productivity of the PSS with cover cooling increased 24% than the PSS without cover cooling. The enhancement in the yield with cover cooling is due to the temperature difference between the collector cover and the water, which increased condensation rate as well.

6. Conclusion

Table 1 summarizes all the PSS modifications described in this article.

Suggestions for the scope of future research work on PSSs are as follows:

1. In future investigations, the evaporation rate of PSSs can be improved by using nano coating in the still basin.
2. The condensation rate of PSSs can be increased by using Peltier cooling technology.
3. Theoretical study and pyramid dimensions can be optimized.
4. Investigating the system performance using different heating methodologies process.
5. New research could be carried out in APSSs using external condensers.
6. The sun tracking system is more efficient, so it can be integrated with PSS.
7. It is concluded that further investigations are indicated for PSS/hybrid systems, particularly waste heat revival from other resources for water and power cogeneration, because both are important in isolated areas.

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