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Geometrical variations in solar stills for improving the fresh water yield—A review

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ABSTRACT

Water consumption by humanity is one of the major yardsticks to assess its civilization. Humans depend on groundwater sources for drinking. Some of these underground water sources cannot be used for drinking due to pollution. To solve the issues related to drinking water, several methods are employed, and a promising one is solar desalination. This paper communicates a review of different geometrical shapes of solar still. The present study concludes that the geometry in the solar still significantly influences the yield of fresh water.

Keywords: Pollution; Solar still; Geometry; Yield; Potable water

1. Introduction

Solar desalination is the traditional method for converting saline water into potable water and thereby addressing the problem of its shortage. There are two techniques involved in desalination using solar energy: (i) direct and (ii) indirect desalination. Direct desalination utilizes heat from solar radiation directly, and its plant capacities are relatively low. Several low-cost solar stills have been discussed [3–12]. Conversely, an indirect approach uses photovoltaics to generate electricity and the electricity to desalinate water, and is only suitable for larger distillation capacities [1–12].

The principle behind solar desalination is similar to a hydrological cycle and involves the following processes:

(a) Direct solar radiation heats up the water.
(b) Water evaporates.
(c) Water vapor condenses (as clouds or on the still glass).
(d) Water is collected by rain or flowing down the glass.

The basin-type solar still is commonly used for distillation, but the yield is relatively lower than other methods [10]. The shadow from the side walls falls on the surface of the water during morning and evening hours and this phenomenon reduces the yield of fresh water. The use of internal and external reflectors in

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the solar still increases the hourly fresh water yield rate. This increases the initial capital cost, but it can decrease the cost of distilled water. The main objective of the present review is to identify new methods for improving the yield of fresh water from solar stills at low cost. Table 1 compares the different solar still geometries with their major drawbacks and possible solutions. In the following section, solar stills with different geometrical shapes are discussed.

2. Geometry of solar still

2.1. Concave-type solar still with wick

Kabeel [13] investigated the performance of a basin in the shape of a concave structure with a cover on four sides (Fig. 1). A steel frame supports the pyramidal glass surface, and for better evaporation a black cloth was kept inside the concave surface. Experimental studies concluded that the water temperature is less than the wick temperature as the wick absorbs solar radiation and has lower thermal mass than the water, creating a greater driving force for evaporation of water. The efficiency of the solar still was improved by 50% over the conventional solar still. Moreover, the space taken up and insulation thickness were reduced by 50% while using a concave basin of solar still.

2.2. Stepped solar still

Comparing with conventional solar still Kabeel et al. [14] studied the experimental and analytical aspects of modified stepped solar still (Fig. 2). The evaporation of saline water depends on contact time of water with solar radiation and thermal characteristics of the other elements of solar still. For enhancing freshwater yield, a wick material is placed on the

Table 1
Comparison of yield from different geometrical variation of solar still

Still no.	Type of solar still	Yield (kg/m^2/d)	Percentage improvement in yield (%)	Remarks
1	Basin type [43]	1.5	Reference	–
2	Concave wick type [13]	4.1	170	Wick material must be frequently replaced to avoid odor and to maintain the drinking water standards
3	Stepped solar still [14]	5.5	270	–
4	Stepped solar still with reflectors [15]	8	430	Reflectors are to be optimized. Yield is higher. But economically, it is not a viable solar still
5	With effluent settling tank [17]	1.65	10	–
6	Solar air heater [18]	5.4	260	Requires electricity to blow heated air from solar collector
7	Continuous flow [19]	5.6	270	Cotton absorber is best for improving the yield and optimized mass flow rate is identified as 1 LPM
8	Weir cascaded solar still [20]	7.5	400	PCM is used to improve the yield
9	Hemispherical [22]	3.6	140	Improvement in the yield was greater with cover cooling
10	Transportable hemispherical [23]	2.1	40	Yield is lower than stationary hemispherical
11	Spherical [25]	1.95	30	–
12	Tubular [28]	1.67	11	The use of polyethylene film reduced the total cost and weight of solar still
13	Concentric tubular [34,47,48]	5	230	Cover cooling improved the yield of tubular solar still with an annulus arrangement
14	Pyramidal [37]	2.8	87	
15	Triangular pyramidal [39]	4.1	170	Continuous flow with extracting the heat from absorber improves the yield
16	Triangular pyramidal with phase change material [41,42,44,50]	5.1	240	PCM appears to be costly

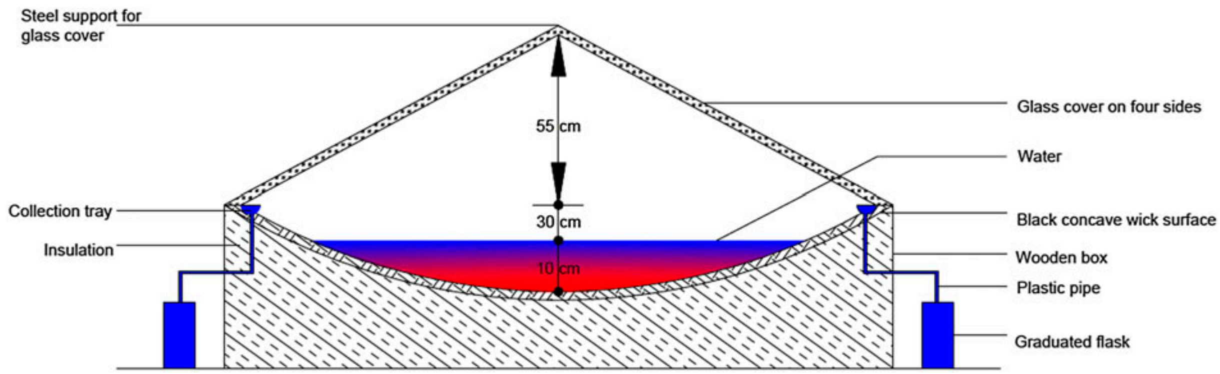


Fig. 1. Schematic diagram of a concave solar still with wick [13].

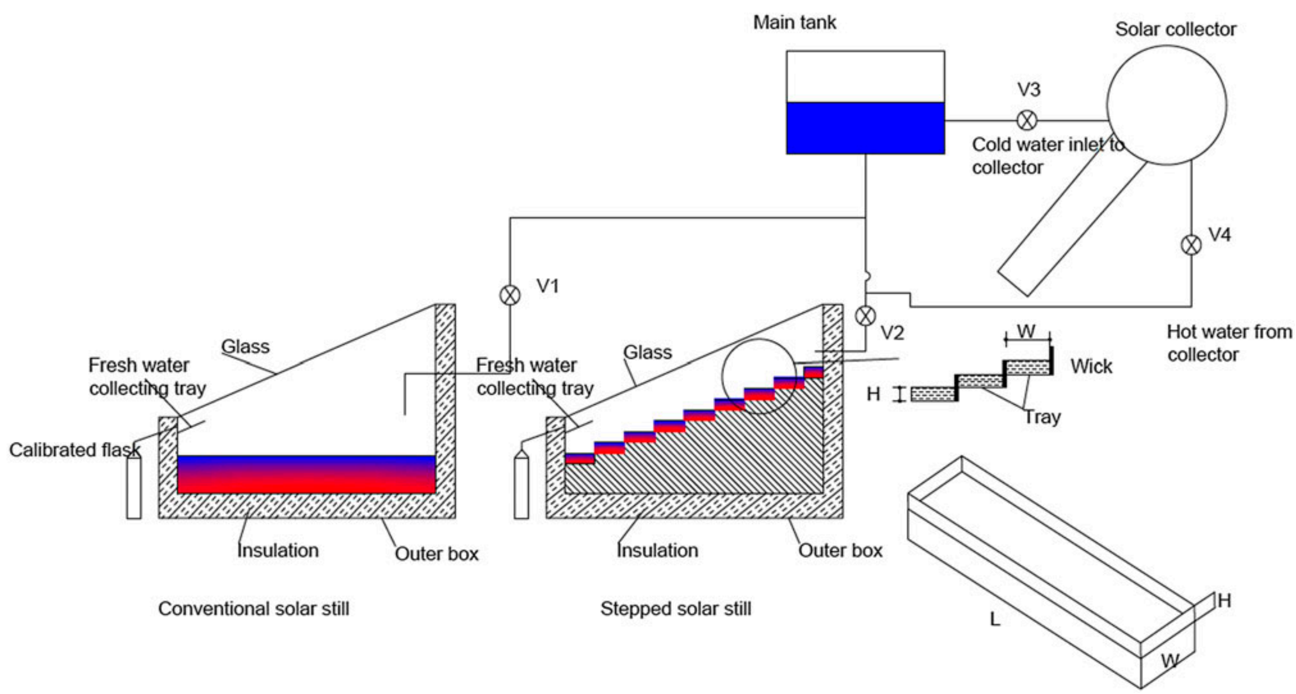
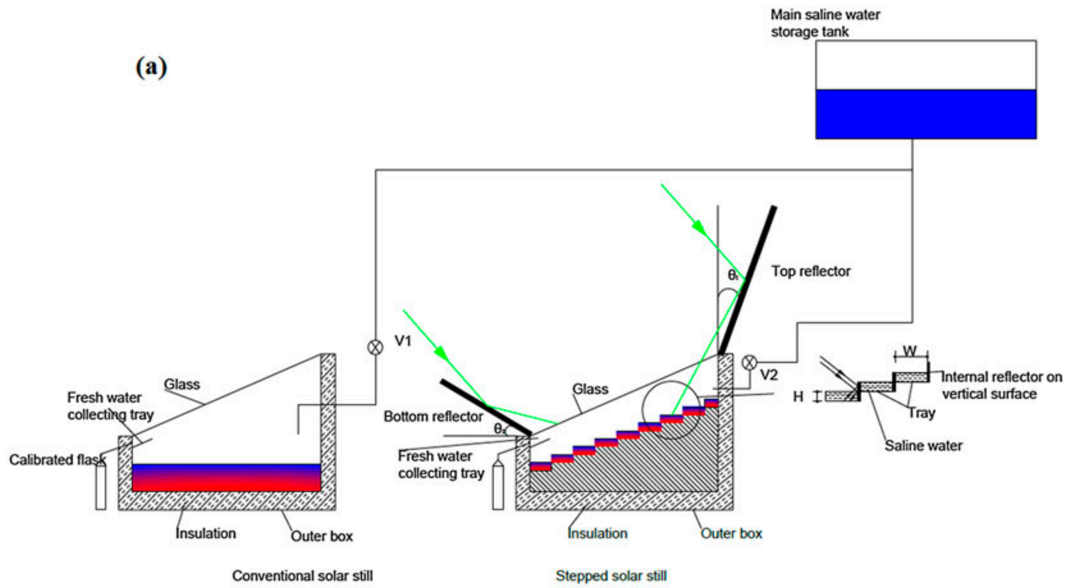


Fig. 2. Schematic diagram of a stepped solar still with wick as absorbing material [14].

vertical surface of the trays. Parameters such as the temperature of the feed water and the depth and width of trays are considered in the theoretical analysis. The results show that evaporation of saline water depends on the width and depth of the trays inside it. From their results, it is identified that the feed water temperature has no effect on augmentation of the yield as it is almost equal to ambient conditions. An additional solar collector can be used to increase the feed water temperature, which mathematically increases the fresh water yield by 66% at a feed water temperature of $T_{fw} = 86^\circ C$.

2.2.1. *With internal and external reflectors*

Omara et al. [15,16] enhanced the performance of a stepped solar still with internal and external reflectors. Figs. 3(a) and 4(a) shows the schematic diagram of a modified stepped solar still with reflectors. The vertical sides of the tray walls are internal reflectors (Figs. 3(a) and 4(a)). External reflectors were placed on the top and bottom of the still, and the upper reflector was held at 25° from vertical and the lower reflector was at 25° from the horizontal. The results show that the accumulated yields of the still with and without



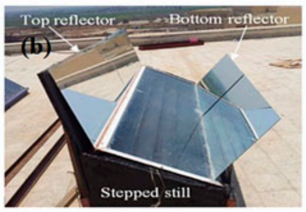


Fig. 3. (a) Schematic diagram of a stepped solar still with reflectors (Internal and External) and (b) experimental picture of a solar still with reflector (internal and external) [15].

reflectors are 8 and 3 l/m^2 d, respectively. Thus, the improvement in output of the still due to reflectors was ~170%. By adding reflectors on the internal and external surface, the temperature distribution is maintained.

2.2.2. With effluent settling tank

Velmurugan et al. [17] analyzed a stepped solar still with an effluent settling tank for industrial effluent desalination (Fig. 5). The effluent tank consists of three layers of materials (pebble, coal, and sand layer), which are used for pre-treatment of effluents from textile industries. Also, major modification such as fins, sponges, and pebbles are used to enhance the freshwater yield. The results show that there are factors such as solar radiation and wind velocity that play a vital role in the output. Theoretical results match well with experimental studies and the deviation was 7.5%. The maximum productivity was found to be 0.7 kg/m^2 d while using Pebbles-Sponge-Fin (PSF). The percentage difference in productivity for fins, PF (Pebbles-Fin), SF (Sponge-Fin), PSF over the solar still without any modifications are found to be 45.45, 49.15, 50, and 57.14%, respectively, with an average intensity of 800 W/m^2. The pebbles act as a sensible heat storage and the sponge as an absorbing material with porosity.

2.2.3. With solar air heater

Abdullah [18] incorporated the effect of integrating a stepped solar still with a solar air heater (Fig. 6). The experiments were conducted under different testing conditions like glass cooling, underneath heating using air heater, and thermal energy storage. The results show that the maximum yield of 0.8 and 0.6 kg/m^2 h for stepped and conventional solar still, respectively, without any modifications during the midnoon of the solar hour. The study also showed that the yield of the solar still with underneath heating during the solar noon was increased by 50%. The hot air increases the water temperature to about 80˚C which is 18% higher than the conventional solar still. Also, water temperature is almost equal to the humid air temperature. The use of thermal energy storage in

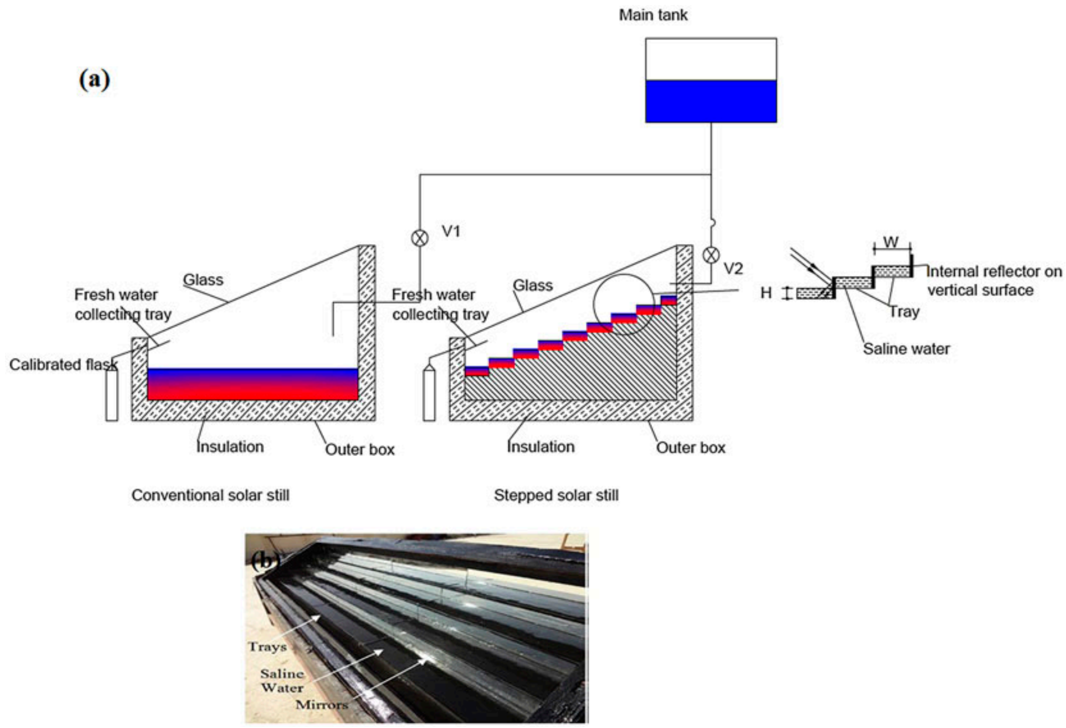


Fig. 4. (a) Schematic diagram of a stepped solar still with reflectors (internal) and (b) experimental picture of a solar still with reflectors (internal) [16].

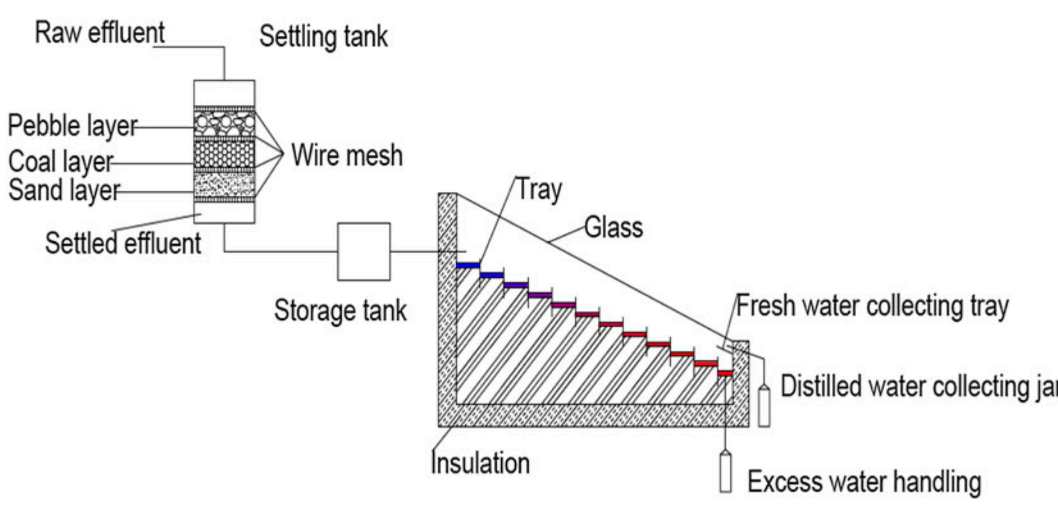


Fig. 5. Schematic diagram of a stepped solar still integrated to solar pond [17].

the form of aluminum filings inside the stepped basin increased output by 83.3%. The overall increase in the yield of fresh water from conventional, stepped still without modification, pre-heated air, and the thermal energy storage found to be 34, 48, 52, and 55%, respectively.

2.2.4. With continuous water flow

El-Agouz [19] compared the performance of a conventional and stepped solar still with continuous water flow (Fig. 7). From the stepped solar still, saline water absorbs the heat for evaporation inside the basin by absorbing the heat from absorber while

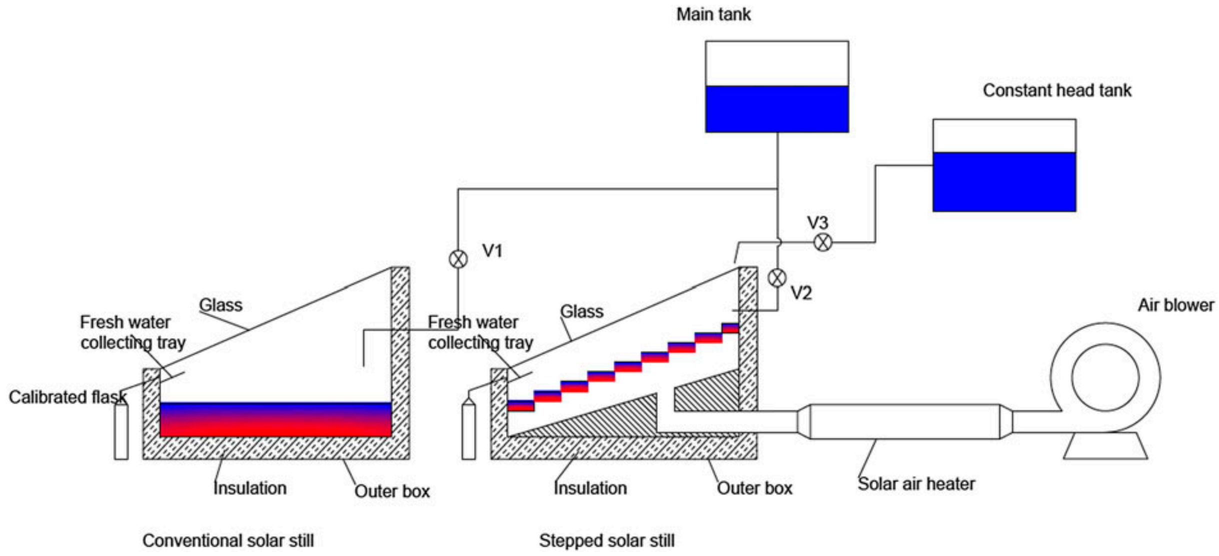


Fig. 6. Sectional view of a stepped solar still with solar air heater [18].

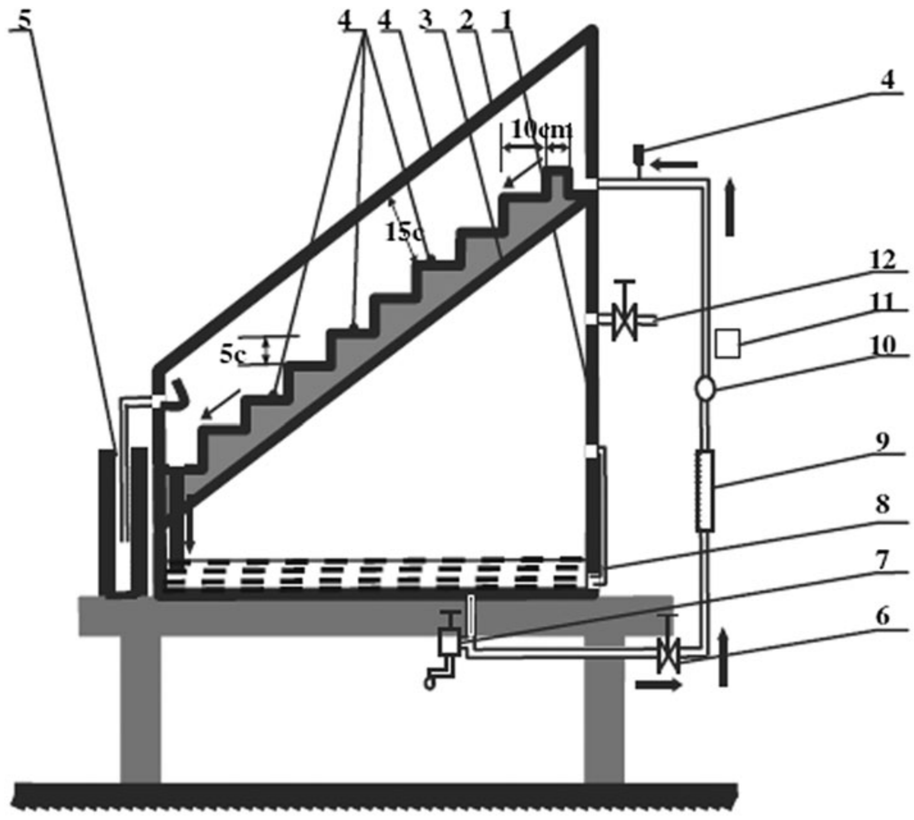


Fig. 7. Schematic diagram of the experimental setup [19].
Notes: (1) Solar still frame, (2) glass cover, (3) absorber plate, (4) digital thermometer, (5) water vessel, (6, 12) control valve, (7) water drain, (8) graduate level, (9) flow meter, (10) water pump, and (11) control timer.

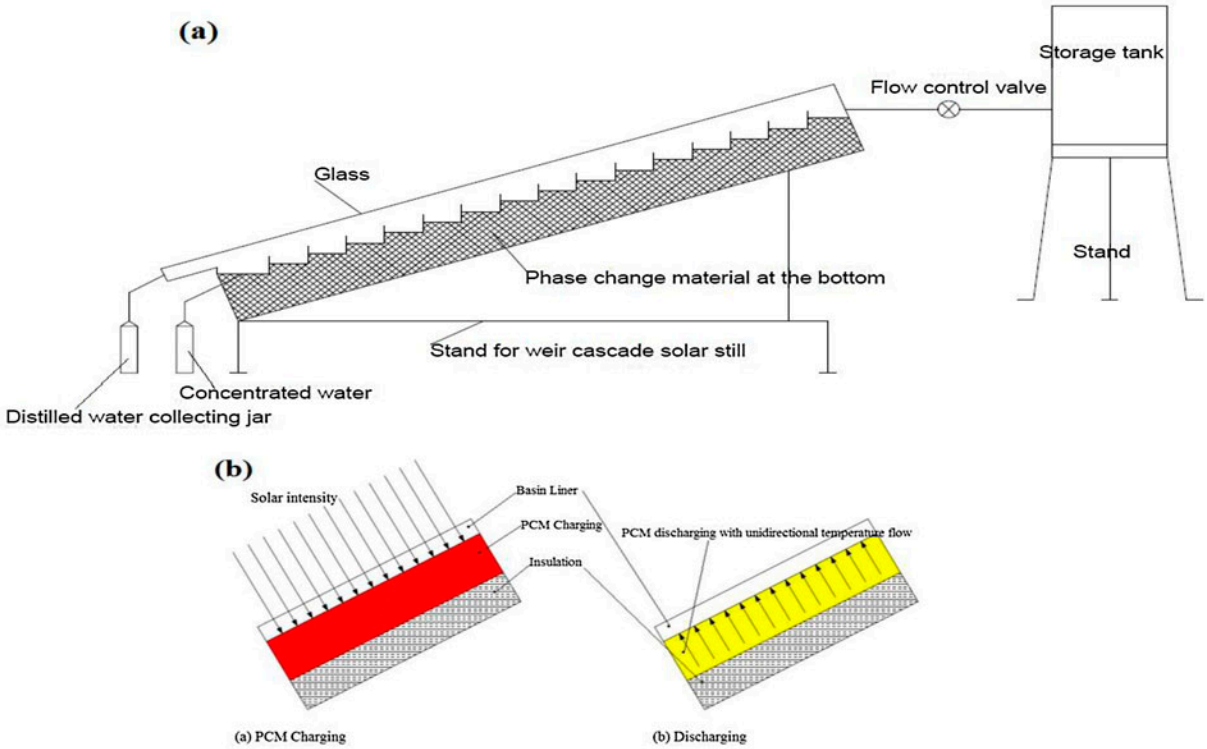


Fig. 8. Schematic diagram of (a) weir cascaded solar still with PCM [20] and (b) heat flow from PCM in charging and discharging modes.

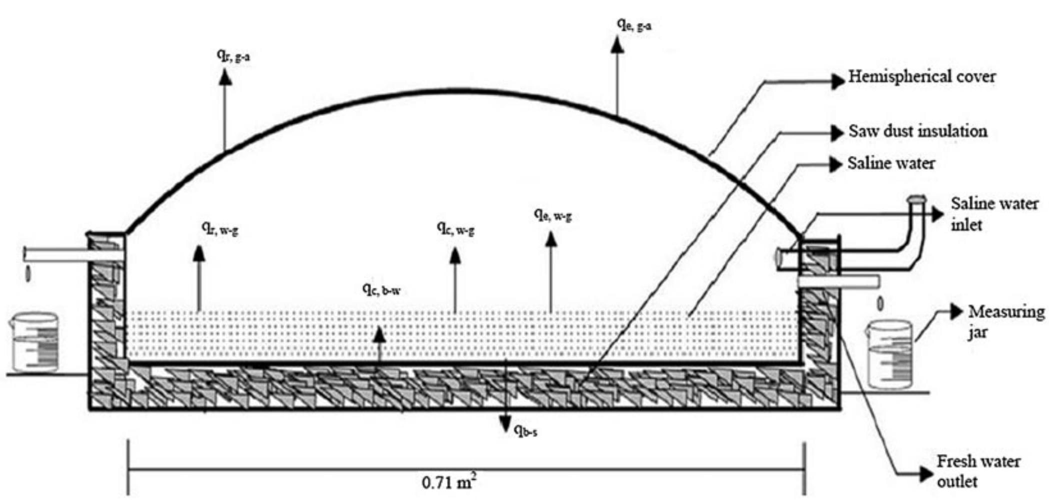


Fig. 9. Schematic diagram of a hemispherical cover solar still [22].

flowing. In practical cases, all flowing water is not completely converted into fresh water. The saline water absorbs the heat not only from solar radiation, but also from the heat stored in the absorber plate. The water with stored heat is kept in a separate chamber and, with the help of a pump, the water is fed into the solar still. Experiments were conducted with black and cotton absorbers on conventional and stepped solar stills. The results show that the efficiency increases with 1 liter per minute (LPM) and 3 LPM for sea and salt water, respectively, with separate storage. With different absorber materials, their

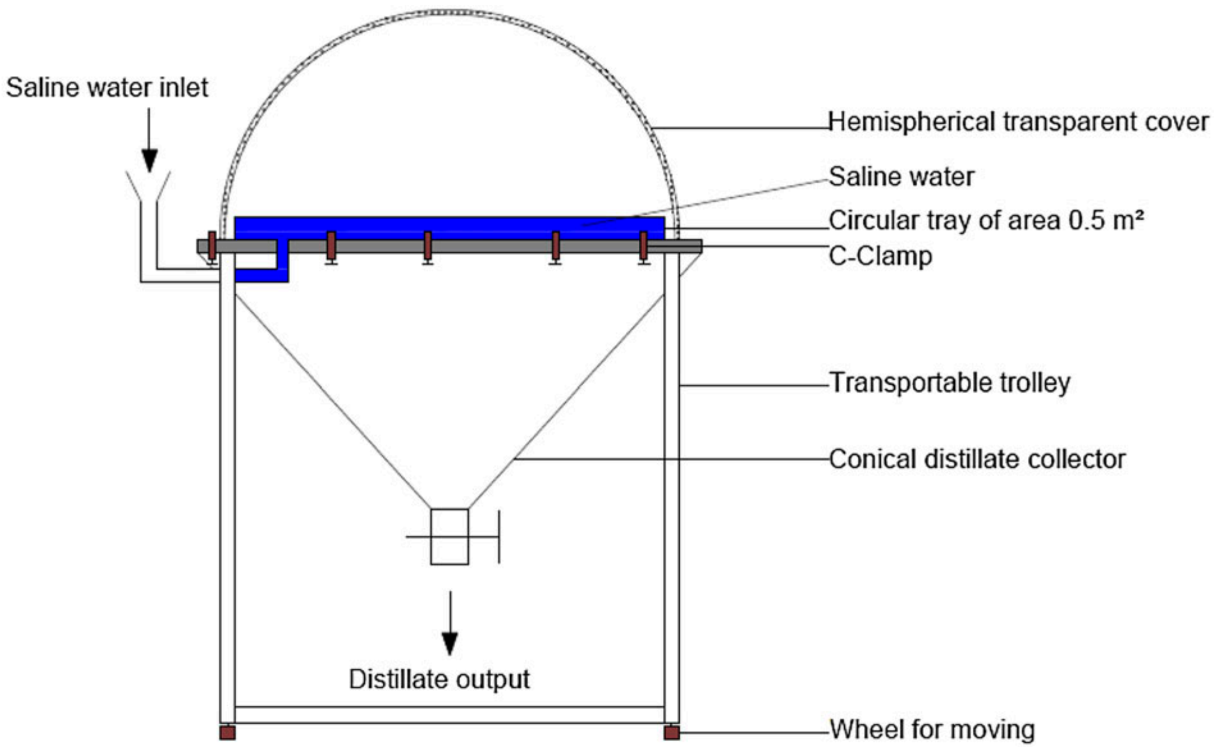


Fig. 10. Schematic diagram of a transportable hemispherical cover solar still [23].

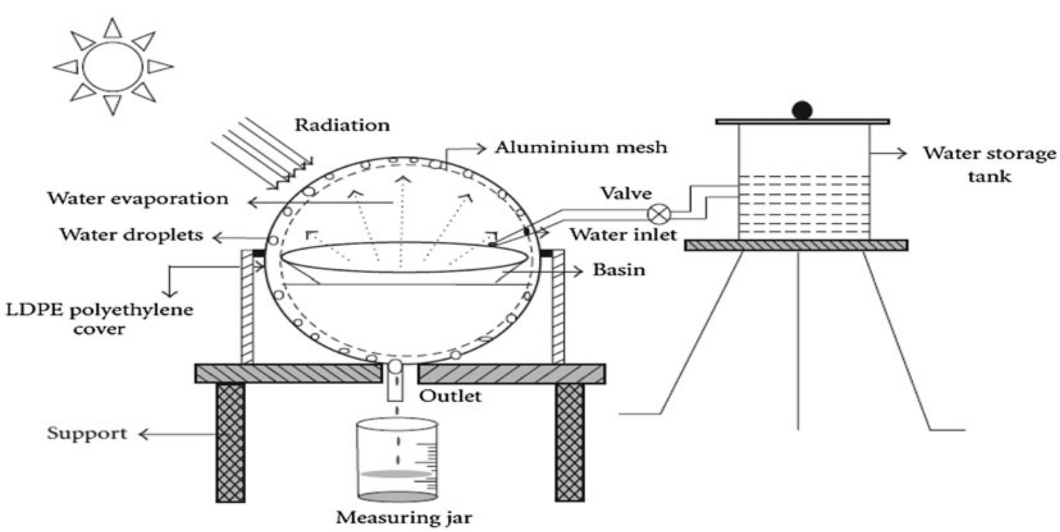


Fig. 11. Schematic diagram of a spherical solar still [24].

results showed that at the lower water storage, daily efficiency is almost the same. Also, it was observed that the efficiency of the cotton absorber with 60 and 80 kg for sea water was 56 and 55%, respectively, with 1 LPM. The efficiency dropped by 9.09% when the flow rate increased to 4 LPM. It was also identified that the daylight efficiency is increased by 3.27% over the modified solar still while using cotton as absorber material due to the absorptivity and porosity of cotton material water is absorbed.

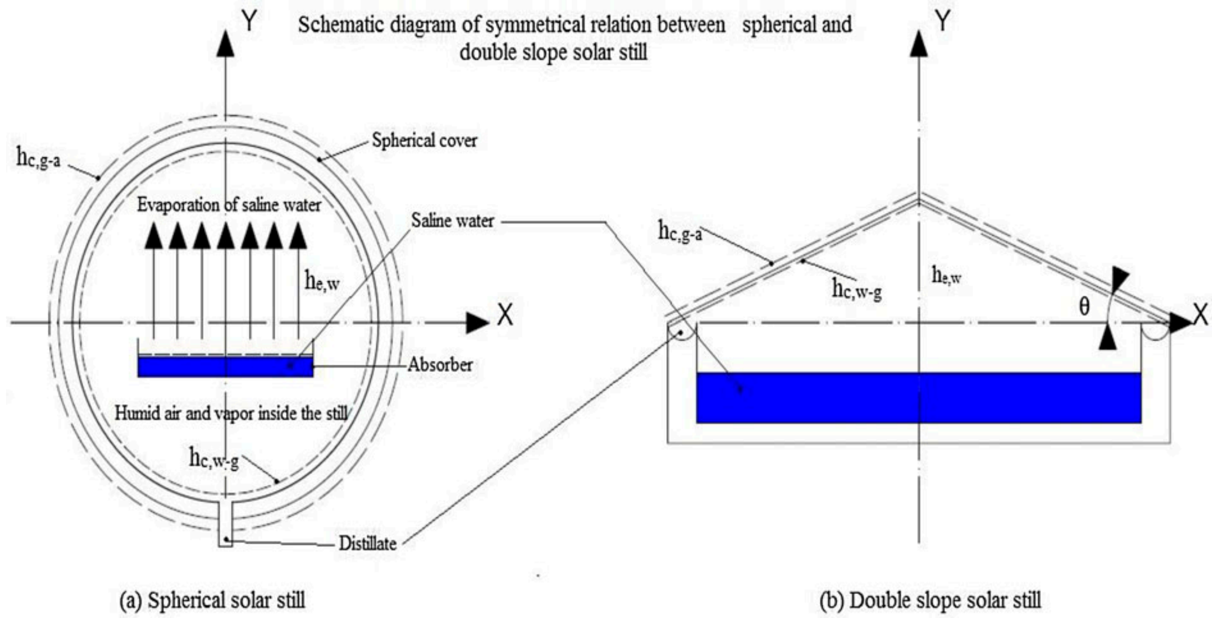


Fig. 12. Mode of heat transfer and condensation in (a) spherical and (b) double slope solar still with axis symmetry.

2.3. *Weir cascade solar still with phase change material (PCM) storage*

Tabrizi et al. and Dashtban [20,21] theoretically calculated the thermal performance of a weir cascade solar still with and without PCM storage. Experiments were also conducted on solar stills during summer and winter conditions. Furthermore, extensions are made to study the thermal performance of PCM storage during sunny and cloudy conditions. Fig. 8(a) shows the sectional view of a cascade solar still with PCM storage. Their results indicate that the solar still with PCM has lesser performance during the sunny conditions as the heat energy is stored by changing phase from solid to liquid at the bottom of the basin. When the solar intensity is lower, the PCM discharges its heat to the basin water. Since the bottom of the solar still is insulated the flow of heat discharged from the PCM is largely unidirectional (Fig. 8(b)).

Due to the change in geometry, the internal evaporative heat transfer coefficient is higher than Dunkle's prediction [26]. The output of the solar still with and without PCM was 5.5 and 4.7 kg/m^2 d, respectively, under an average solar radiation of 600 W/m^2 at a flow rate of 0.06 kg/min. An achievable yield of 0.75–0.8 kg/m^2 d for a solar still with PCM is possible at night.

2.4. *Hemispherical solar still*

Fig. 9 shows a schematic diagram of a hemispherical solar still. Arunkumar et al. [22] studied the effect of cooling water over the hemispherical cover of a solar still. The driving force of solar still depends on the temperature difference between water and glass. The cover can be cooled by flowing air or water over the cover. Due to the higher heat capacity of water, the cover temperature can be decreased more easily. This reduced temperature of the cover increases the driving force for evaporation. Feeding a fixed flow of 10 ml/min over the cover increases the efficiency from 34 to 42%. Field experiments show that the yield increases with a decrease in cover temperature and increase in driving force for enhanced condensation and evaporation. Fresh water yield from the hemispherical cover instead of a flat inclined cover was improved by 1.25 times. The average output from the solar with and without cooling was found as 4.2 and 3.5 kg/m^2 d.

2.5. *Transportable hemispherical solar still*

Ismail [23] reported on a transportable hemispherical solar still (Fig. 10). The clamps on sides were provided so that the cover can be opened for absorber plate maintenance. The results show that the average

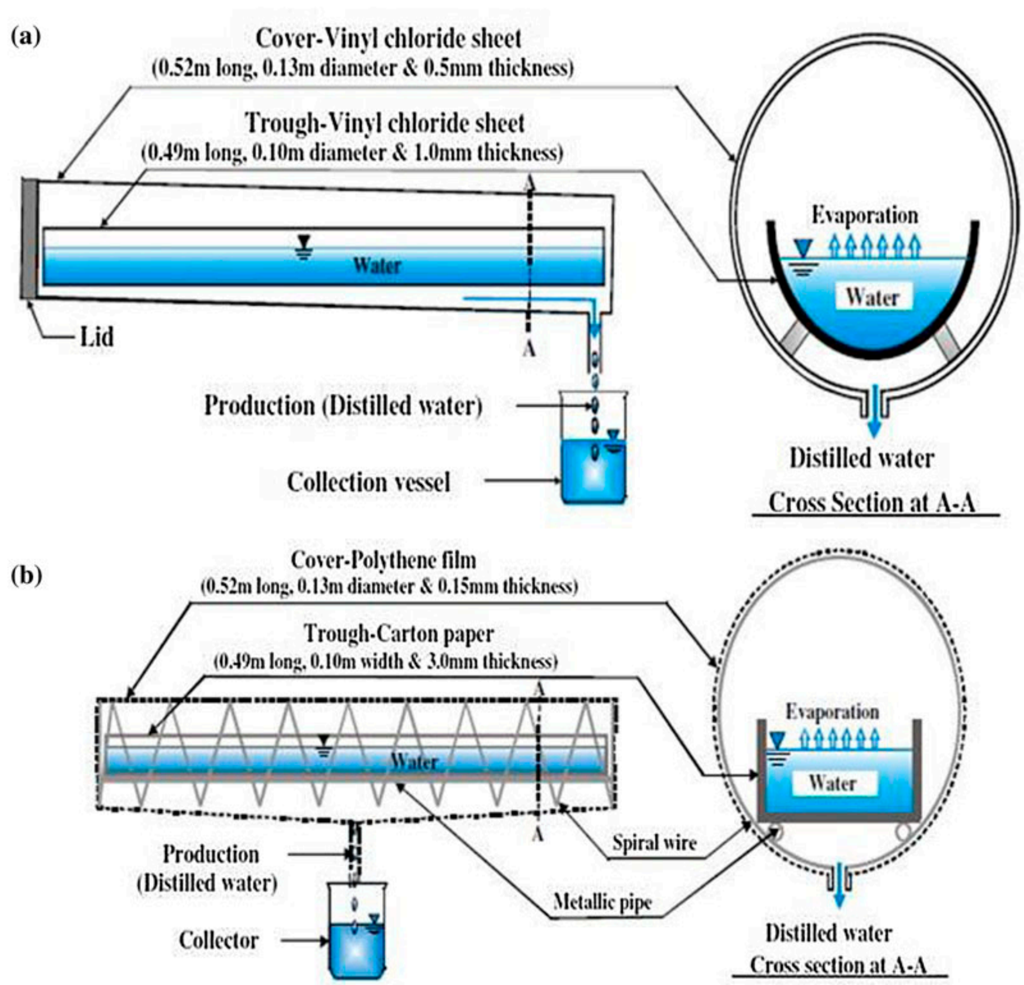


Fig. 13. Schematic diagram of a tubular solar still (a) semicircular trough (b) rectangular trough [29].

distillate per day from the solar still is about 2.8–5.7 kg/m^2 with a solar efficiency of 33%. As the depth of water inside the basin of solar still was increased from 12 to 18 mm, the efficiency decreased by 8%.

2.6. Spherical solar still

Arunkumar et al. [24] experimentally investigated the performance of a spherical solar still. The results indicate that the daily yield of the solar still is 2.3 kg/m^2, which is 39.1% higher than a conventional still. Pictorial and schematic diagrams of the spherical solar still are shown in Fig. 11. Dhiman [25] communicated the transient analysis of a spherical solar still. The analysis was completely based on Dunkle's model, and the calculated empirical relation is validated over the experimental results predicted by Menguy et al. [27]. Fig. 12 shows the symmetrical relation between Dunkle's [26] and Menguy et al. [27]. Also, the results show that the absorptivity of absorber plays a vital role in distillate output. The efficiency of still increased by 30% above the conventional solar still.

2.7. Tubular solar still

Ahsan et al. [28–33] experimentally investigated a tubular solar still with a semi-circular and rectangular absorber (Fig. 13(a) and (b)). From the discussions, it was observed that the evaporation and convection in the inner chamber of the solar still depend on humid air properties, and the cover material plays a vital role in the freshwater yield. Two otherwise identical solar stills had polyvinyl chloride vs. polythene films as the cover material. From their study, it is observed that the use of polyethylene film as cover material reduced the weight of solar still by 62%. Also, the hourly yield

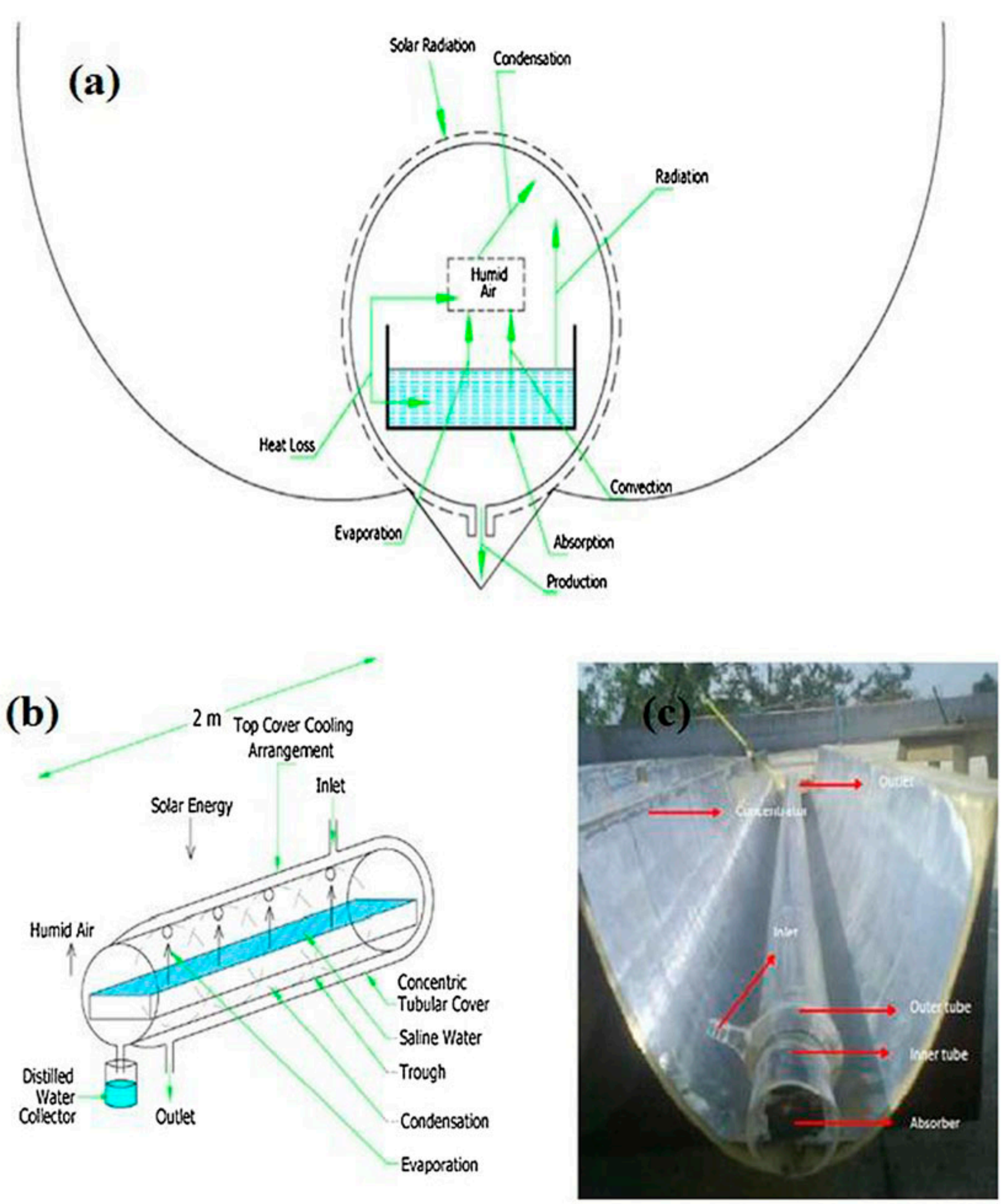


Fig. 14. Schematic diagram of concentric tubular solar still (a) Cross-section, (b) 3D View, and (c) Experimental photograph of concentric tubular solar still [34].

increased from 0.85 to 1.2 kg/m^2 h for polyethylene with a temperature difference of 14–16°C. The new tubular solar still was less expensive and light weight.

2.8. Concentric tubular solar still

Cooling of the external surface of a concentric tubular solar still is one of the difficult tasks in improving the fresh water yield. Productivity in the solar still depends not only on the heat supplied, but the cover temperature and lowering this temperature increases the driving gradient for condensation. Feeding a constant flow of air or water over the entire surface is the best method to reduce the cover temperature. Arunkumar et al. [34–36] proposed a new method of fixing an outer cover in the form of a concentric tube for cooling the external surface of tubular solar still. The schematic diagram of a

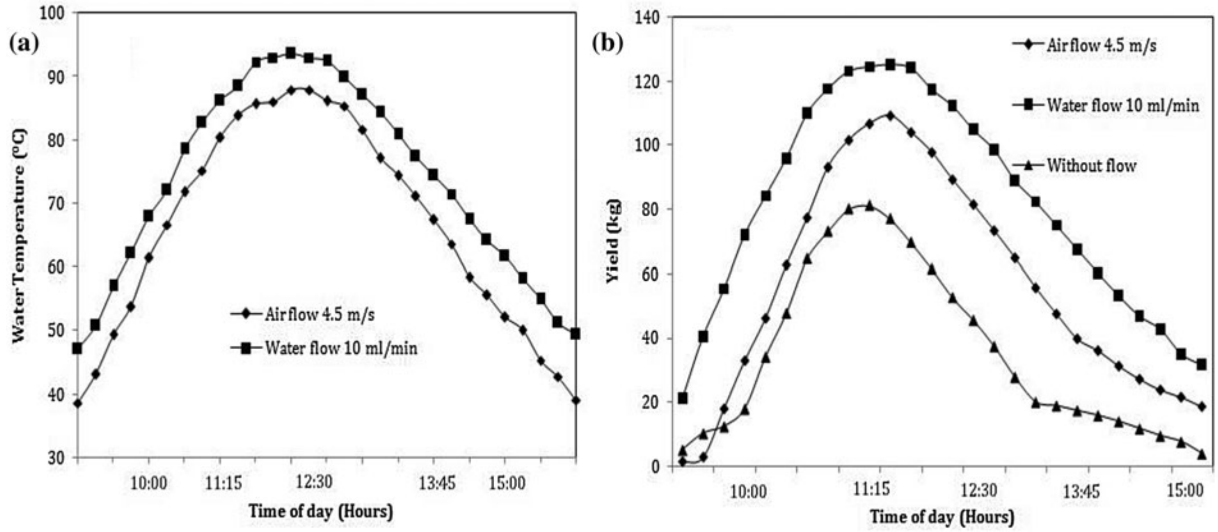


Fig. 15. (a) Effect of water temperature with water flow and air flow and (b) effect of productivity without any fluid medium with air flow, water flow.

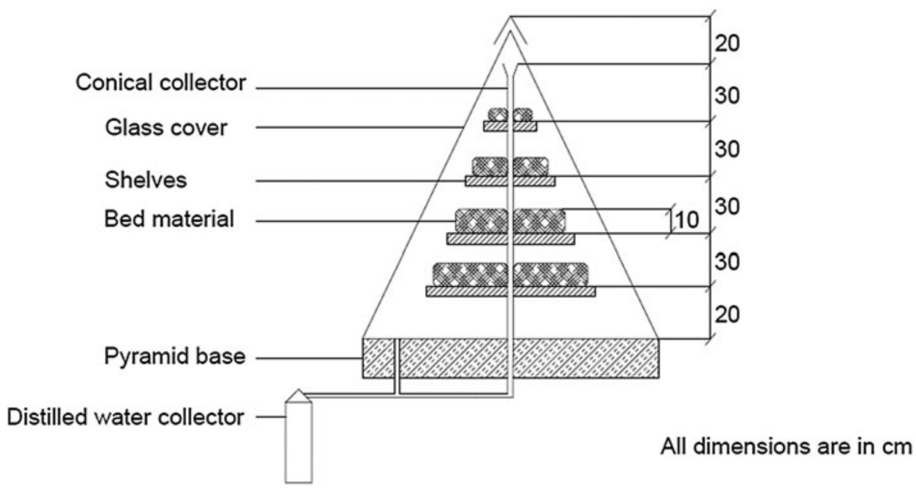


Fig. 16. Schematic diagram of pyramidal multi shelf solar still [37].

concentric tubular solar still is shown in Fig. 14(a) and (b), and the experimental photograph of the tube arrangement is shown in Fig. 14(c). The experiments were conducted in such a way that both water and air can be used for cooling the external surface of the inner tube. The effect of water (10 ml/min) and air (4.5 m/s) on basin water temperature are shown in Fig. 15(a). It was observed that when water is used as the cooling medium, the increase in temperature of basin water temperature is found to be 12.5% lower than with air. Also, the variation in hourly yield of the concentric tube with water flow is higher than the air flow as shown in Fig. 15(b). This is due to the greater specific heat capacity and thermal conductivity of water. The total yield from the solar still without any flow, with air flow, and with water flow are found to be 2.05, 3.05, and 5 kg/d, respectively. From their study, it was found that adding additional baffle configurations on the inner surface of the tube may be provided to increase heat transfer.

2.9. *Pyramidal solar still*

The pyramidal solar still is the next evolutionary step in solar stills, which is discussed by Kabeel [37]. The schematic diagram of a multi shelf pyramidal solar still is shown in Fig. 16. Two identical solar stills

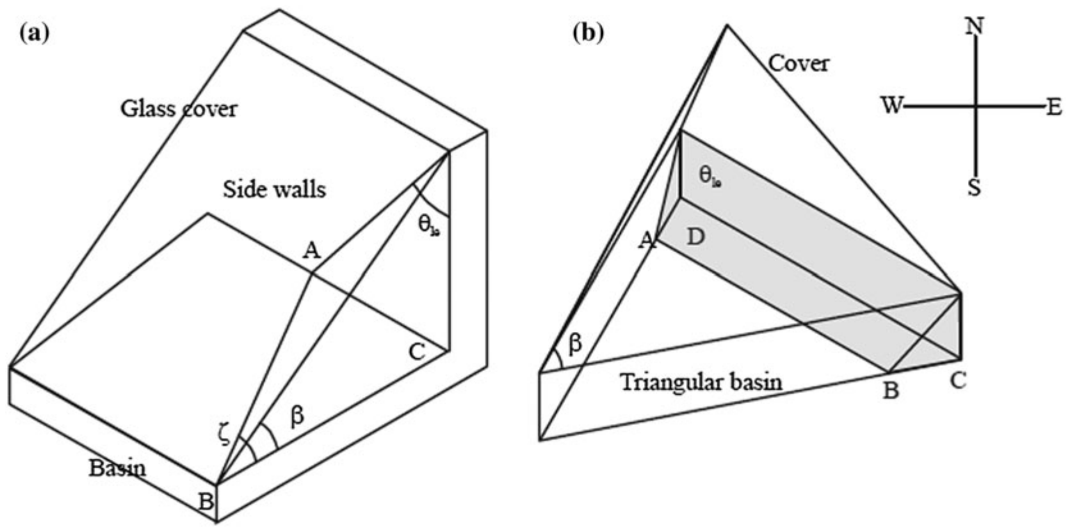


Fig. 17. Schematic diagram of a triangular pyramid solar still [39].

were fabricated and the distance between each shelf was maintained at 30 cm. Each solar still with bed material as sawdust and cloth material are placed on the shelves. The glass was made in such a way that it can be opened during the night hours and the moisture in the air is absorbed by absorbing materials. The results show that the area of the upper basin is lesser than the lower consecutive shelves, and hence the temperature of the upper layer is higher and gradually decreasing. It was also reported that the use of cloth as absorbing material increases the productivity by 3.2% relative to sawdust because the cloth is more absorptive. The maximum productivity during the midnoon was found to be 0.45 and 0.38 kg/m^2/h for cloth bed and sawdust, respectively. Recommendations discuss that better absorbing material and distance between each shelf improves the productivity of freshwater.

Taamneh and Taamneh [38] experimentally studied a pyramidal solar still under forced and natural convection. Experiments were carried out in the outdoor conditions of Tafila city (Jordan), and the performance of solar still with and without a fan show that the reduced temperature of the glass increases the condensation with the larger temperature difference. The solar still yield during midnoon on an experimental day with and without fan found to be 0.4 and 0.35 kg/m^2/h, respectively, and the maximum efficiency of the solar still was increased from 40 to 50% with the fan as a cooling source. Water evaporated from the water surface releases its heat through the glass surface as it condenses. Hence with the help of a solar PV-powered fan, the external surface of the glass cover is cooled for better condensation of vapor.

2.10. Triangular pyramid solar still

Sathyamurthy et al. [39] and Nagarajan et al. [40] investigated the performance of a triangular pyramid solar still (Fig. 17). The results show that the yield of solar still is 4.2 kg/m^2/d for the least water mass of $d_w = 2$ cm. The convective and evaporative heat transfer from the solar still is equal to Dunkle's prediction and solar radiation follows the similar curve of water temperature. The results demonstrate that the water temperature is directly proportional to solar radiation. The water temperature throughout the basin is equally maintained, and this is due to the reduction of the shadow of side walls falling in the solar still. The yield was increased by 50% relative to the conventional solar still. From the economic and space points of view, the new model is more efficient—75 and 50% respectively—relative to the conventional solar still.

Ravishankar et al. [41,42,44,50] investigated a triangular pyramid solar still with phase change material as storage. The results show that the use of latent heat energy storage improved the fresh water yield by 35% relative to the solar still without any storage. The water temperature of the solar still without any storage during the sunshine hours was higher than the solar still with energy storage because some of the heat is stored during the charging mode. The temperatures of the basin and water are very close, and the temperature difference for both stills is higher than the conventional solar still. Similarly, during winter conditions, the yield reduces by 20.9% than summer conditions with energy storage.

3. Conclusions

From the present study following conclusions are made:

(1) The highest yield stills are the stepped with reflectors and weir cascaded solar stills, but their cost remains high.
(2) A serpentine array of tubes from automobile radiators as a solar collector may be used to increase the brine temperature. The theoretical characterization of ethylene glycol nanofluids of automobiles at minimum mass flow shows a higher heat transfer rate [45,46].
(3) A method for improving the yield of conventional solar still is increasing the surface area of water by adding specified dimensions of sensible heat energy storage in the basin [49].
(4) The use of heat exchangers from condensers in the air conditioning system will improve the inlet feed water temperature for better evaporation in the solar still.
(5) A new shape of a triangular basin single slope solar still increases the contact area of water with solar radiance by reducing the shadowing effect from the side walls during morning and evening hours.
(6) For the triangular pyramid solar still, cooling water may be circulated through the side walls, which takes away the heat which is returned as feed water into the basin.

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