

How to Cite:

Sarkar, N., Tiwari, A. K., & Somwanshi, A. (2022). Enhancement of distillate output of solar still by cooling glass cover: Detailed review. *International Journal of Health Sciences*, 6(S5), 9400–9421. <https://doi.org/10.53730/ijhs.v6nS5.9563>

Enhancement of distillate output of solar still by cooling glass cover: Detailed review

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Abstract--The difference in temperature between the temperature of the basin water and the temperature of the glass cover is the most important regulating factor for getting yield from a solar still. The higher the temperature differential, the more distillate the solar still produces. This temperature difference can be enhanced either by increasing the temperature of basin water by decreasing glass cover temperature or combining both strategies together. A strategy for lowering the temperature of a glass cover is to cool it with air or flowing water. Cooling the glass cover by water not only boosts the production of the still but also cleans it. The presence of dust particles on the glass cover reduces the amount of solar energy impacting on water in basin, which is continuously cleaned by water flowing over it. In present work a detailed review on the various methods used to cool glass cover have been discussed. The decrease in temperature of cover is up to 20°C by cover cooling and the maximum increase in efficiency of solar still by cover cooling is about 20%. Moreover, it is seen that with evaporatively cooled water allowed to flow over glass cover the increase in annual distillate output is about 56.5% which is about 15.2% more when the cover is cooled by ordinary water at ambient temperature.

Keywords--Solar Still, Cover cooling, Distillate output, Efficiency, Economic analysis.

Introduction

Purification of brackish water by solar energy is a realistic and promising technology for creating drinkable water in water-scarce places, particularly in desert climates. Drinking water scarcity is one of the most serious issues confronting both emerging and developing countries throughout the world. According to a report only 3% of fresh water is available in earth out of which about 68.7% are in the form of icecaps and glaciers about 30.1% is ground water, 0.3% is surface water and 0.9% are in other form [1]. The challenge is to make the 3% of fresh water available to us clean and contaminated free that can be used for drinking. Although commercial purification procedures such as membrane distillation, reverse osmosis, multi-stage flash distillation, and electro dialysis are available, solar distillation may be the most cost-effective choice. A solar still is a water purification device that uses solar energy. The biggest issue with solar still is its poor productivity; on a hot day, it produces around 2-3 L/m² of pure water, which is one of the major reasons for its non-commercialization. However, researchers are around the globe is working to enhance the production output of solar distillation system.

Aside from environmental factors, the basin water temperature and the glass cover has an impact on a solar still's performance. The key regulating factor in obtaining output from a solar still is the temperature difference between the basin water and the glass cover. The higher the temperature differential, the more distillate is produced, and vice versa. The output can be enhanced by either raising the temperature of the basin water or lowering the temperature of the glass cover. In the past, black dye was used to boost the basin water temperature by using reflectors, condensers, and heat storing materials (pebbles, metal, chips, and sand bags). Glass cover is cooled using either water, air, a combination of water and air, or a separating condenser unit from still to reduce their temperature.

We have offered a complete review of previous efforts on cooling of glass covers in this paper. Furthermore, a full comparison, productivity, and performance has been provided based on the improvements and suggestions proposed in previous studies connected to cover cooling. The report will undoubtedly aid researchers seeking to improve the distillate yield of solar stills utilising various glass cover cooling strategies. The research will aid in determining the best still parameters for maximising solar still productivity.

1. Various Glass Cover Cooling Techniques

The production output of solar still will increase as the rate of condensation of vapours increases. By lowering the temperature of the glass cover, the rate of condensation will increase. The rate of evaporation of water from a still basin increases as the temperature of the water rises. When the temperature differential between the basin water and the glass cover is the greatest, the highest feasible output will be achieved. The cooling of cover can be accomplished either by flowing water or flowing air over the cover. The distillate of water was 0.10 L/m² when the temperature difference between the basin water and the glass cover was 6°C, however the distillation of water was 0.850L/m²h when the temperature

difference between the basin water and the glass cover was approximately 11°C. A distillate of 0.8 L/m²h was achieved when the basin water temperature was around 70°C and the temperature differential was 10°C, whereas the distillate was around 0.10L/m²h when the basin water temperature was around 30°C [2]. The following is a comparison of various solar stills with cover cooling.

1.1 Water Cooled Cover of Single Slope Solar Still

Tiwari and Rao [3] provided a transient theory of a single basin solar still with water flowing over the glass cover, finding that flowing water at uniform velocity nearly doubles the daily distillate output of the still. Moreover, they analysed the effect of various parameters on performance of solar still. Dhiman and Tiwari [4] extended their previous work by analysing the effect of flowing water on multi wick solar still. Because of the low thermal capacity of water, they provided an analytical model that included the effect of running water over the cover. They concluded that increasing the thickness of the insulation at the bottom had no significant influence on the distillate output. The distillate production increases or decreases as the heat transfer coefficient from the glass cover to the water flowing over it increases or falls. (Shown in figure 1)

To avoid the water wastage due to glass cover cooling Abu Hijleh and Bassam [5] suggested that some part of water after cover cooling recycled as makeup water. Moreover, they investigated the effect of water cooling of glass cover on efficiency of single slope solar still. They concluded that the efficiency of solar still can be increased about 6 % whereas improper combination of film cooling parameters reduces still efficiency. The result indicated that with proper use of film cooling parameters can enhance efficiency of solar still about 6% whereas poor combination of film cooling parameter reduces still efficiency. He moreover concluded that presence of water film over cover neutralises the effect of wind speed and efficiency of solar still.

To determine the effect of thermal capacity of the water mass Lawrence et al. [6] presented a transient analysis of single slope solar still with cover cooling by flowing water. They discovered that efficiency of solar still increases as the flow rate of water flowing over the cover increases, and that the impact is more pronounced when the water mass in the basin has a high heat capacity. They discovered a 7% improvement in efficiency when dye was not added to the water, and a 10% increase in efficiency when dye was added to the water. Sherwood et al. [7] have depicted heat transfer as a result of cooling water evaporation. When a portion of cooled water is used as makeup water of still the output was increased even more. According to their findings, proper use of film cooling combination can increase the still's efficiency by up to 20%.

Janarthan et al. [8] designed a new floating wick single slope solar still. They developed a mathematical model incorporating the effect of flowing water over cover they found significant decrease in temperature of glass cover. They suggested 1.5m/s the optimum mass flow rate of water flowing over glass cover. (Shown in Fig.2) To increase the productivity of still Badran [9] combined asphalt basin and sprinkler to cool cover. He found 51% increase in the production

output of single slope solar still during day time. During night without solar radiation the increase in production of still was about 16%.

1.2 Cooling by Evaporatively Cool Water

To increase the difference between the temperature of water in basin and glass cover furthermore Somwanshi and Tiwari [10] suggested to use evaporatively cooled water from tank of desert cooler for glass cover cooling shown in fig. 3. They compared the performance of single slope solar still considering two different cases (i) cooling glass cover by flowing water at ambient temperature (ordinary water) (ii) Cooling glass cover by flowing evaporatively cooled water from desert cooler at wet bulb temperature of ambient air. They considered a constant mass flow rate (1.5m/s) of water flowing over cover. They found that water flowing at wet bulb temperature increased yearly production by 56.5 percent, while water flowing at ambient temperature increased annual production by 41.3 percent.

They extended their previous work and suggested to utilise cooled water from garden fountain reservoir to cool glass covers of small single slope solar distillation plant. [11] (shown fig.4) They performed techno economic analysis to determine cost of water produced from plant integrated with reservoir of garden fountain. They found about 37.5% to 39.5% reduction in distillation plant area required with water flown over cover. The cost of distilled water produced by proposed plants was between Rs0.40/l (US\$0.0061/l) and Rs0.41/l (US\$0.0063/l).

1.3 Water Cooled Cover of Double Slope Solar Still

To enhance production output Zeroual et al. [12] (shown in fig.5) recommended to improve the performance of condenser. He suggested either water cooling or by providing shade to avoid direct solar radiation. They found 11.82% increase in daily production of still by water cooling of cover located in North whereas by shading north cover the enhancement in output was about 2.94%. Singh & Tiwari [13] presented mathematical model of a double slope solar still with provision of water flown over glass cover at constant velocity. They discovered that cooling the glass cover boosts solar efficiency dramatically, especially at high water depths in the basin.

1.4 Combining Cover Cooling and Heating Basin Increasing the Temperature of the Water in the Basin While Also Providing a Cooling Cover

The temperature difference between the basin water and the glass cover can be raised by raising the temperature of the water in the basin, lowering the temperature of the glass cover, or doing both. Various active and passive approaches have been used in the past to raise the temperature of basin water. Cover temperature can be decreased by flowing water or air as discussed in previous section. Combining both techniques can give maximum possible temperature difference & hence maximum possible distillate output. Tiwari et al. [14] presented a mathematical model to heat water temperature they proposed to use waste hot water in the basin of single slope solar still. To cool glass cover they suggested to flow water over cover. They performed numerical analysis to investigate the performance of the proposed system. The schematic arrangement

of the proposed system is shown in fig.6. They concluded that the temperature of water flowing over glass cover is nearly equal to ambient temperature and the temperature of glass cover is slightly higher than water temperature. Furthermore, they discovered that the productivity of still increases with increasing input water temperature and declines with inlet water temperature less than the average ambient temperature as the flow rate increases.

Sharshir et al. [15] proposed to utilize graphite and copper oxide micro-flakes mixed in water basin along with cooling glass cover. They found about 44.91% and 53.95% increase in distillate output using copper oxide and graphite micro-flakes, respectively in comparison to conventional single slope solar still. With water cooling of cover the output is increased furthermore about 47.80% and 57.60% with copper oxide and graphite micro-flakes, respectively. The photograph of setup is shown in Fig.7. Moreover, the increase in annual efficiency about 49%. Kumar et al. [16] proposed a hybrid photovoltaic PV/T active solar still and tested it at various water depths (0.05m, 0.10m, and 0.15m), they found that the daily yield is 6 times higher than a traditional solar still. A nickel-chromium heater driven by solar photovoltaic was proposed to achieve high distillate yield. Fig.8 shows a schematic representation of the proposed hybrid solar still.

1.5 Water Cooling of Cover of Regenerative Solar Still

The double basin solar still (shown in fig.9) differs from the conventional still by having another transparent sheet (glass is preferred for well-known reasons) fixed in between the basin liner and glass cover; this sheet serves as the base of an extra basin for saline water. The main advantage of the still is that it makes use of the latest heat of condensation on the underside of the lower glass rather than it being wasted as its case in conventional solar stills. As a result, the entire assembly acts as two single-basin stills stacked one on top of the other, with a lesser area need per unit mass distillate than a single-basin still. On a typical winter day in Delhi, the distillate yield from a double basin solar still proposed by Malik et al. [17] was reported to be roughly 36% greater than from a still with a single glass cover of the same area. Sodha et al. [18][19] investigated the performance of the double basin still in both periodic and transient circumstances, and found that the observed experimental findings were in good accord with the theoretical conclusions acquired from the analysis. The regeneration method of running water over the glass cover can increase the performance of double basin distillation. Apart from boosting still efficiency, it also aids in the regular cleaning of the lower glass cover in double slope solar stills.

Prakash and Kavanthekar [20] conducted research on regenerative solar stills. It was also expanded to include an active distillation system. Waste hot water from the upper basin can either be fed into the lower basin or utilised as hot water for various thermal uses in an active regenerative solar still. Rai and Tiwari [21], Zaki et al. [22], and Fernandez and Chargoy [23] were the first to investigate active regenerative solar stills. The daily volume of distillate and thermal efficiency of a regenerative active solar still were investigated by Singh and Tiwari [24], Fig.10. The regenerative solar system was still operated in thermosyphon mode. The effects of system design and climatic circumstances were taken into consideration

in the basic energy balance equations for each component of the system. The hourly output and efficiency of the system were examined. The flow velocity of water between the glass panes ranged from 0.001 to 0.005 kg/s. They discovered that (i) flowing water over the glass greatly increased performance, and (ii) the amount of accessible hot water due to the regeneration influence had no effect on the daily amount of distillate. Kumar and Tiwari [25] devised a theoretical model for predicting the daily yield from a solar system with an active double effect. For a number of applications, including battery charging, essence extraction, chemical laboratories, and drinking in remote areas of poor countries, it has been discovered that an active double effect solar still generates higher distillate output than a passive distillate system.

1.6 Stepped Solar Still

Abdulla [26] investigated the performance of a stepped solar still with water cooling of glass cover (see fig. 11). The suggested solar still's performance was compared to that of a standard single-slope solar still. The still proposed consists of five steps which acts as absorber plate. Solar radiation and hot air from a solar air heater were used to heat the water in the basin. To store thermal energy, he recommended using energy-storing materials such as aluminium filings on an absorber plate. The flow rate of water flowing over cover was taken as 0.03kg/s. He concluded that the efficiency of the suggested still with hot air and glass cover cooling was raised by 65 percent and 53 percent, respectively, for hot air and glass cover cooling. The efficiency of both procedures was increased by 112 percent when they were combined.

El-Samadony and Kabeel [27] theoretically investigated thermal performance of stepped solar still incorporating the effect of cooled water over cover. They analysed the effects of various parameters like mass flow rate of water flowing, film thickness, temperature of water flowing over glass cover, and wind velocity on the performance of solar still. The results shows that with cover cooling the output was increased by about 8.2% they also concluded that percentage increase in production depends on proper combination of various parameter for film cooling.

1.7 Triple Basin Solar Still

Srithar et al. [28] investigated the performance of a stand-alone triple basin solar system that included a triple basin glass solar still, parabolic dish concentrator, cover cooling arrangement, and photovoltaic panel (Figs. 12 and 13). They considered water flow rates as 20, 25, 30, 35, and 40 mL/s. in order to enhance rate of heat transfer they suggested using fins and energy storing materials. For investigation they considered a triple basin solar still, triple basin solar still with cover cooling, triple basin solar still with parabolic dish concentrator and triple basin solar still with cover cooling and parabolic dish concentrator. For each analysed configuration, other characteristics were considered, such as using fins without any storage material, fins with river sand, and fins with charcoal. The distillate of a triple basin glass solar still with charcoal and a triple basin glass solar still with river sand was found to be 34.2 percent and 25.6 percent higher than that of a standard triple basin glass solar still, respectively. In addition,

when compared to the usual type, the glass temperature of the triple basin glass solar still with cover cooling was reduced by roughly 8°C. They also discovered that a flow rate of 40 mL/s produced the most distillate. Furthermore, cover cooling increased overall output by 32.8 percent.

1.7 Hemispherical Solar Still

Arun Kumar et al. [29] developed a hemispheric glass cover solar still with provision of cooling cover by flowing water over the glass. The hemispherical still has a larger surface area than a conventional still. Figures 14 and 15 show the proposed designs of hemispherical solar still. To allow uniform water flow they suggested to connect the water tank to pressure head. The flow rate of water considered was 10 mL/min. They found that the thermal efficiency with cooling cover was about 42 % and without cover cooling it was around 34%.

1.8 Vertical Still

The daily distillate produced by the system is highly influenced by ambient temperature, solar isolation and orientation, according to Boukar and Harmim [30]. The still's daily distillate ranges from 0.5 to 2.3 L/ m² day, depending on the sponged cloth area. As demonstrated in fig. 16, the difference between water film and glass for glass cover cooling is large, with daily productivity ranging from 1.02 to 1.91 L/m² day and thermal efficiency varying from 18.6 percent to 33.19 percent for solar radiation ranging from 13.14 to 13.68 MJ.

2 Cooling Of Glass Cover By Air

Decrease in temperature of glass cover can be accomplished either by flowing water or it can be cooled by flowing air. Some of the past research works on glass cover cooling includes work by Al- Garni [31] he utilised a fan to cool glass cover of single slope solar still. The slope of glass cover was taken as 35°. He found that the distillate output of still was more at low water depths. Experimentally he found an increase in productivity of solar still about 250% when external electric heater 500W was used to heat basin water. With external cooling fan increase in productivity was 5.2 and 10.3 % with fan speed of 7 and 9 m/s respectively.

3 Cooling Of Glass Cover By Water And Air

Suneesh et al. [32] studied experimentally a "V" type still with a cotton gauze top Cover cooling without and with air flow above the glass, as shown in Figs. 17 and 18. They tested stills with cotton gauze over the glass cover, cotton gauze with air flown above it, and bare glass cover. Because the flowing water above the naked glass cover did not distribute properly throughout the width of the glass cover, cotton gauze was used to distribute the flowing water evenly above the glass cover. The rectangular basin measured 2m 0.75 m 0.05 m in size. A control valve was linked to an external water tank to allow cold water to flow over the glass cover. The water was run over the cover at a rate of 150 mL/min. With water flowing above the glass and no Cotton Gauze Top Cover Cooling, the daily distillate production of the solar still was 3.3 L/m². With the use of Cotton Gauze Top Cover Cooling, daily distillate output increased to 4.3 L/m² per day, and with

Cotton Gauze Top Cover Cooling and air flow, it increased to 4.6 L/m² per day. Arun kumar et al. [33] designed and tested a tubular still having rectangular basin with provision of circulating air and water above the glass. A visual illustration of a tubular solar still is shown in Fig. 19. The daily productivity of that design was boosted by lowering the temperature of the water and air flowing above it (top cover cooling system). Without the cooling flow, the daily amount of distillate was 2.05 L/day. The daily distillate was enhanced to 3.05 L/day with the cooling air, and it was further increased to 5 L/day with the cooling water flow. In their review publications, Kabeel et al. [34] and Muthu et al. [35] studied the effects of top cover cooling on several solar stills. They discovered that with increase in mass flow rate of water/air above the glass cover the daily distillate increases.

4. Increasing Condensation Area (Cover Area) With Water Cooling

The more condensation area will enhance the production of solar still, increase in area decreases the temperature and hence increases the out of still some of the work related with increasing the condensation area are discussed below:

Bhardwaj et al. [36] increased the condensation area to increase the still's water production. The test rig is depicted schematically in Figure 20. Both inside and outside the lab, the experiments were conducted. Still, by raising the condensation area by 7.5 times and running at a constant energy of 625 W/m², production was raised by around 65 percent in the lab. When compared to a control group operating under the same conditions as the lab experiments, productivity increased by 50% outside the lab.

Belhadj et al. [37] evaluated the performance of a double slope solar still connected with a condensation cell, as shown in Fig. 21. Some of the ensuing vapour condenses on the inner side of the glass cover, while the rest condenses on the outside of metal plate. The prototype's daily productivity was 7.15 L/m². Over conventional and capillary film, a 60 percent increase in still output was achieved.

Conclusions

From the past research works on glass cover cooling as discussed in previous sections the following conclusions can be drawn:

1. Cooling of glass cover by water/air increases the temperature differential between water in basin and cover, this increases the amount of distillate output produced by solar still.
2. The cooling film of water over glass cover neutralizes the effect of wind velocity flowing over cover thus will not affect the efficiency of solar still
3. By the proper combination of cooling film parameters, the thermal efficiency of solar still increases by about 20%.
4. The right cooling film parameters, the still efficiency can be increased by up to six percent. A bad choice of settings, on the other hand, would result in a reduction in still efficiency. The optimal cooling film parameters were 2.5×10^{-4} m film thickness, 5×10^{-7} m³/s m cooling water volumetric flow rate per unit width, and 2 m glass cover length.

5. For right combination of water film cooling parameters productivity of stepped basin solar still increases about 8.2%.
6. The best combination of film thickness and volumetric flow rate for stepped basin solar still is 2.5×10^{-4} to 5.5×10^{-4} m and 4×10^{-5} to 8.5×10^{-5} m³/s respectively.
7. With flow of evaporatively cooled water at wet bulb temperature increase in annual productivity of single slope solar still is about 56.5%.
8. By increasing condenser area, the distillate output of solar still can be increased.

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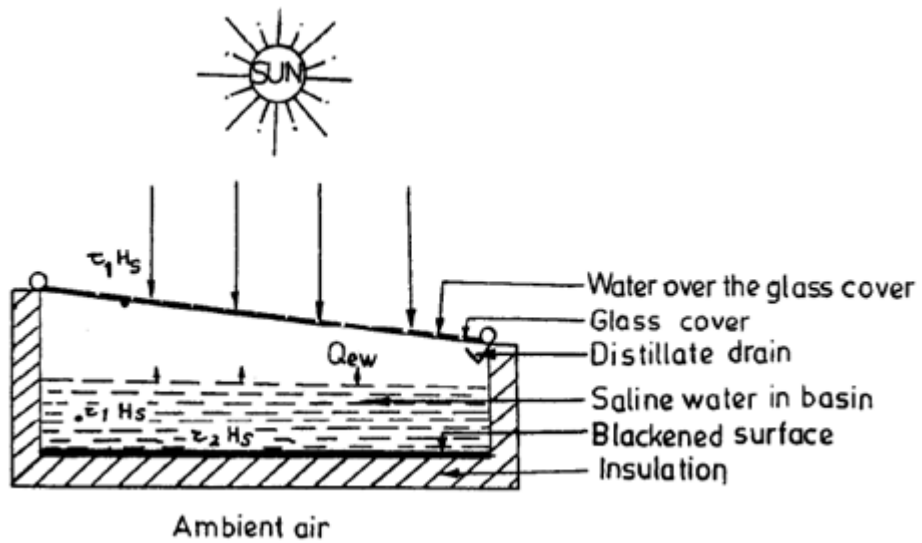


Fig.1: Schematic diagram of conventional still with water flowing over the glass cover [14]

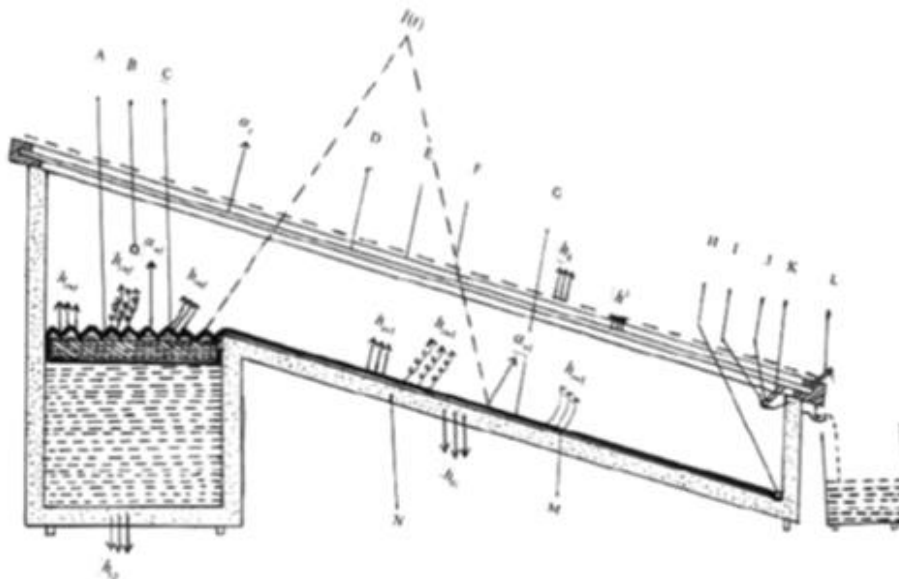


Fig.2: Sectional graph of the still with water flowing above the glass cover [8]

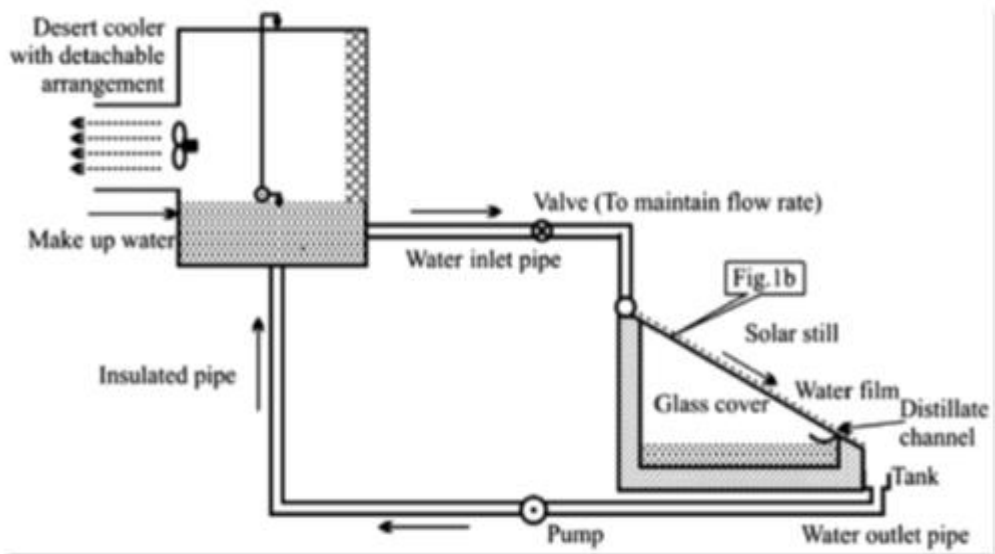


Fig. 3: Schematic graph of a basin still associated to a desert cooler [10]

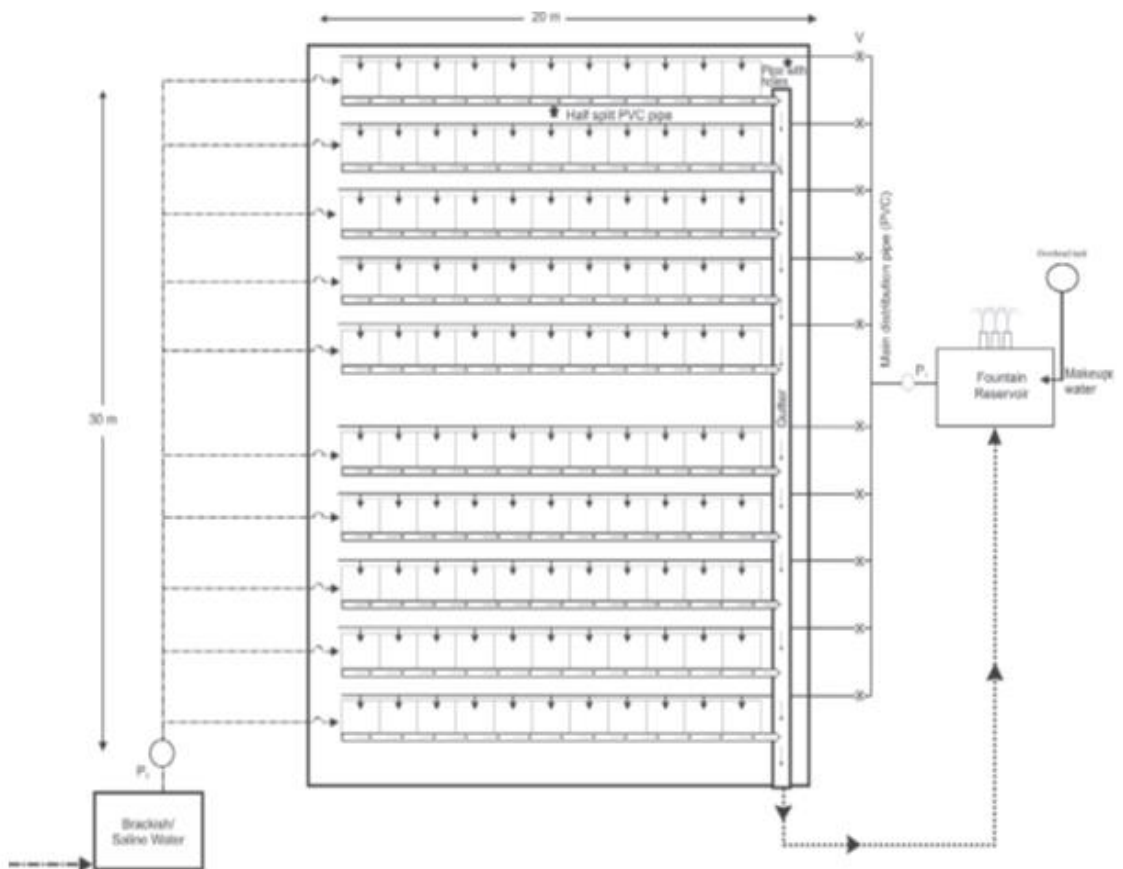


Fig. 4: Pilot distillation plant connected to garden fountain reservoir [11]



Fig.5: Zeroual's solar stills [12]

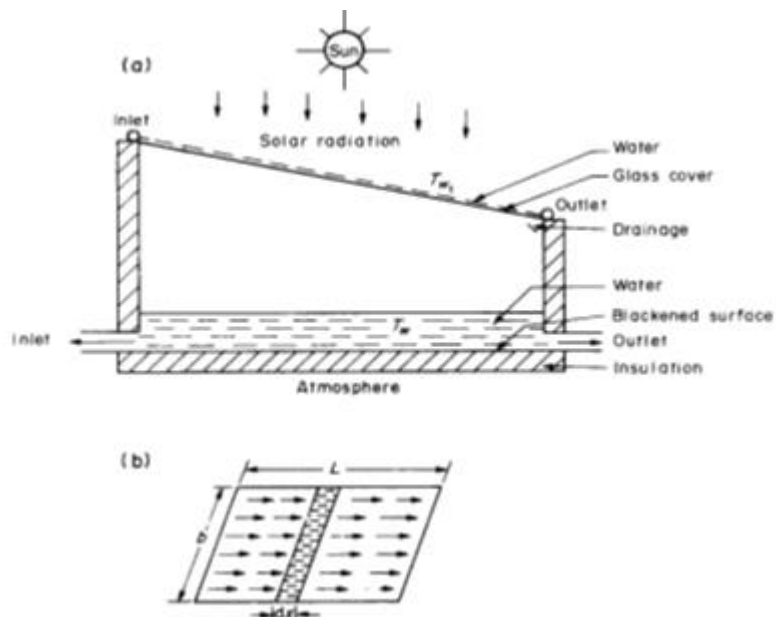


Fig.6: a) Schematic representation of single basin solar still with an intermittent flow of waste hot water in the basin b) Side view of the flowing water system [14]

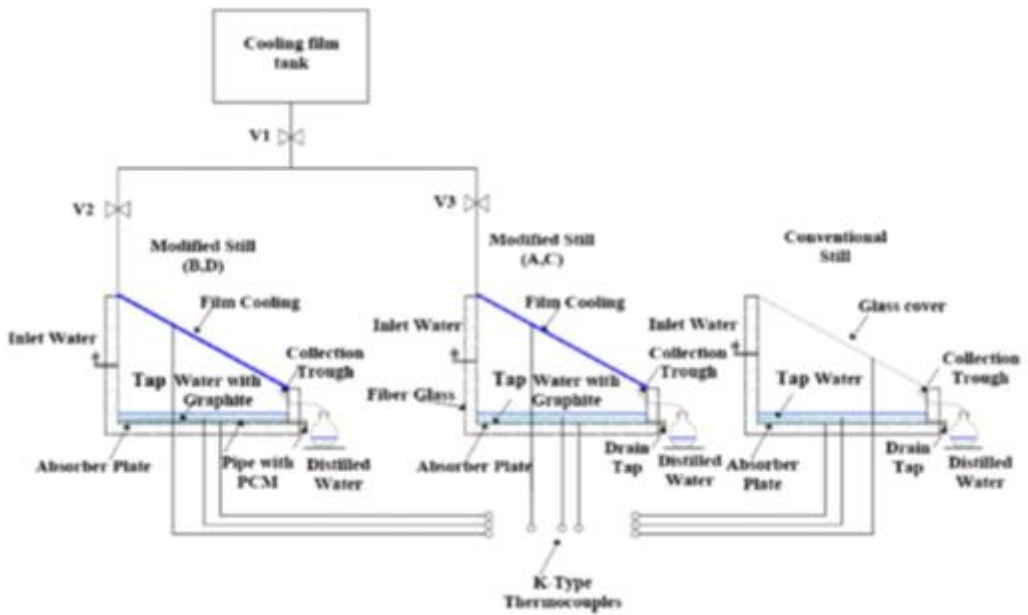


Fig. 7: Schematic diagram of the experimental setup [15]

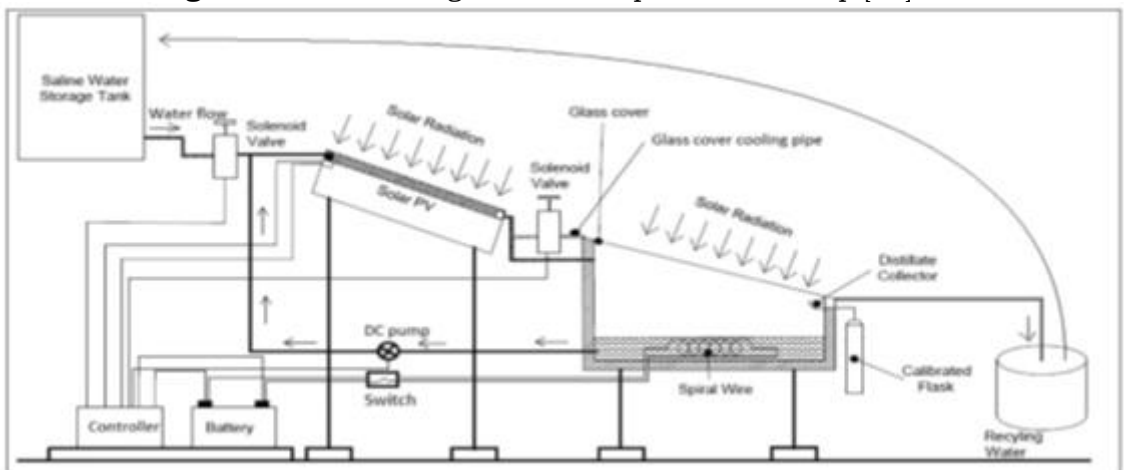


Fig.8: Schematic view of the proposed hybrid (PV/T) active solar with NiCr spiral wire heater [16]

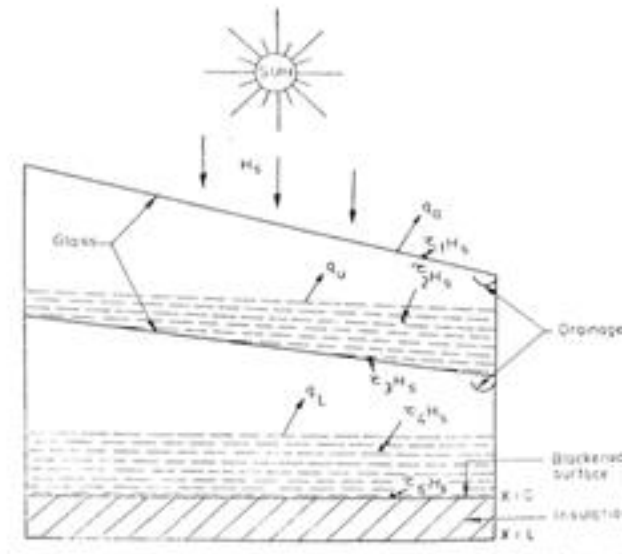


Fig. 9: Double basin solar still [18]

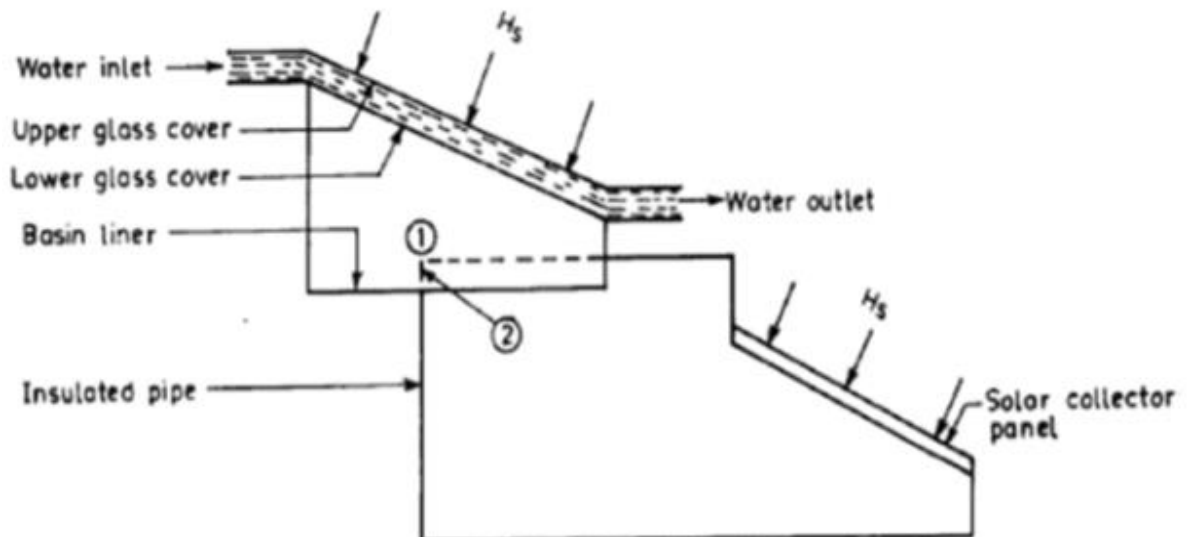


Fig. 10: The active regenerative solar distillation system [24]

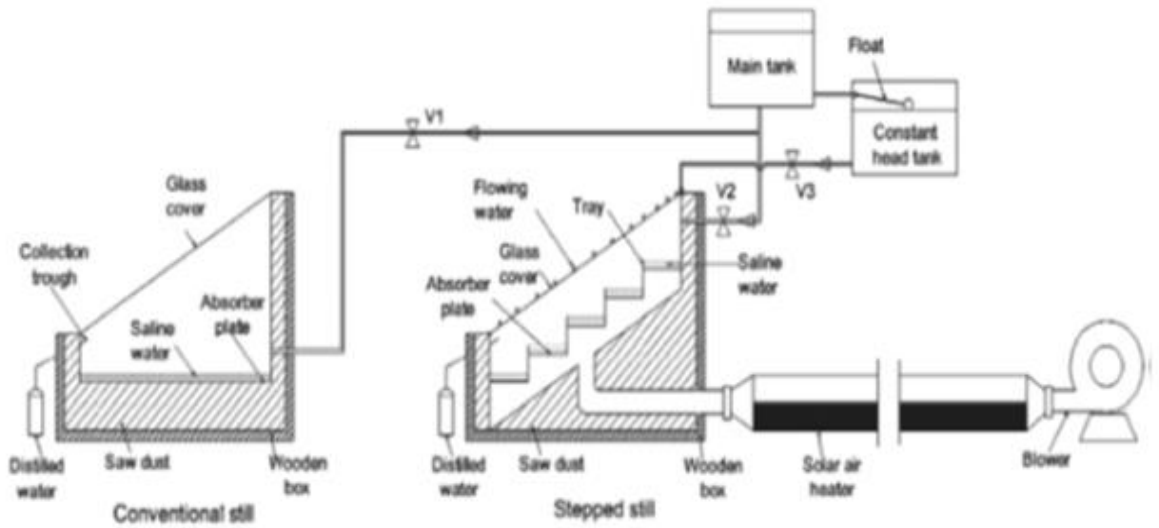


Fig. 11: Cross-sectional view of the stepped still incorporated with solar air heater [26]

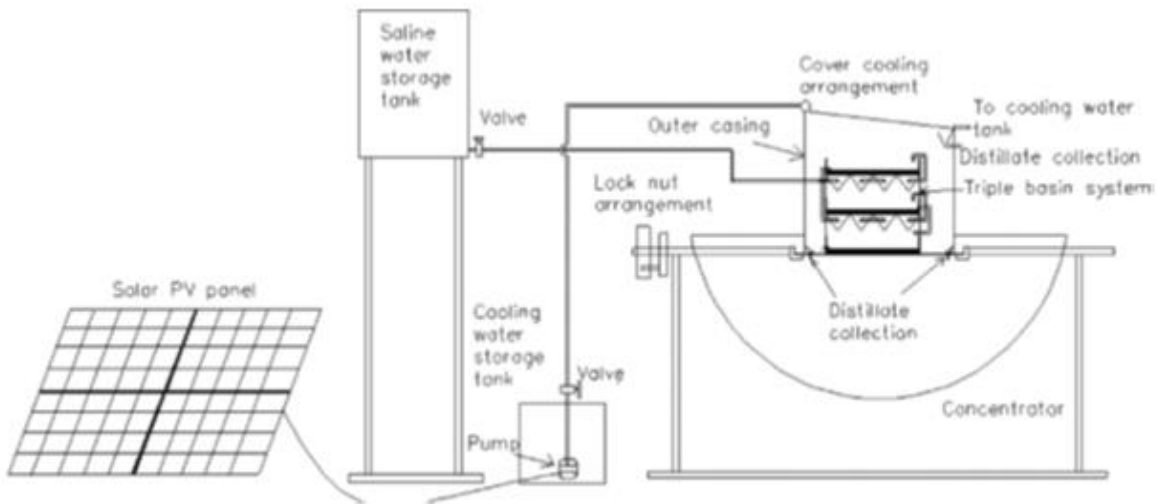


Fig. 12: Schematic view of the triple basin solar system [28].



Fig. 13: Photo of the triple basin solar system [28].

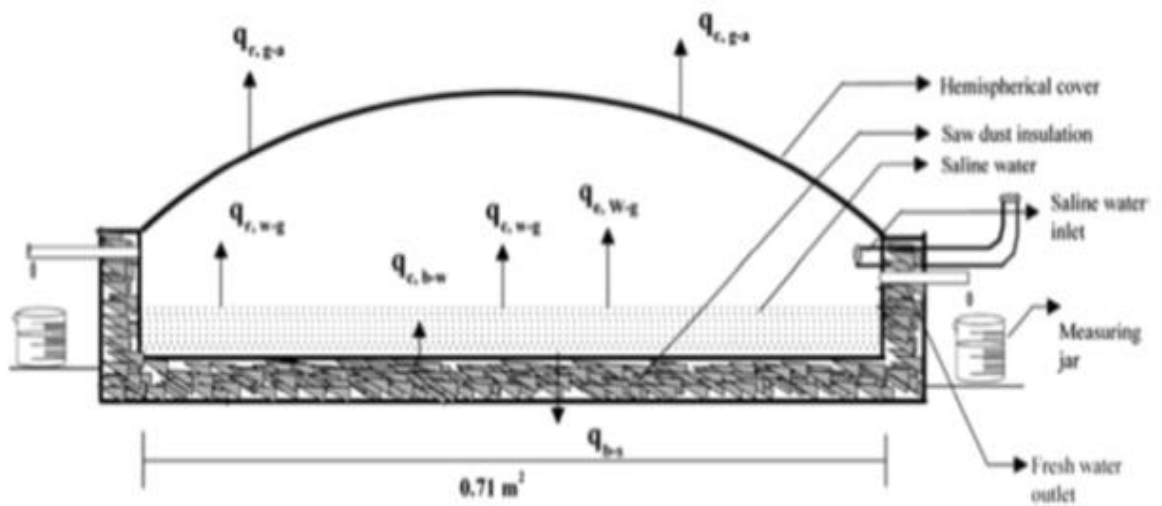


Fig. 14: Cross-sectional view of the hemispherical solar still [29]

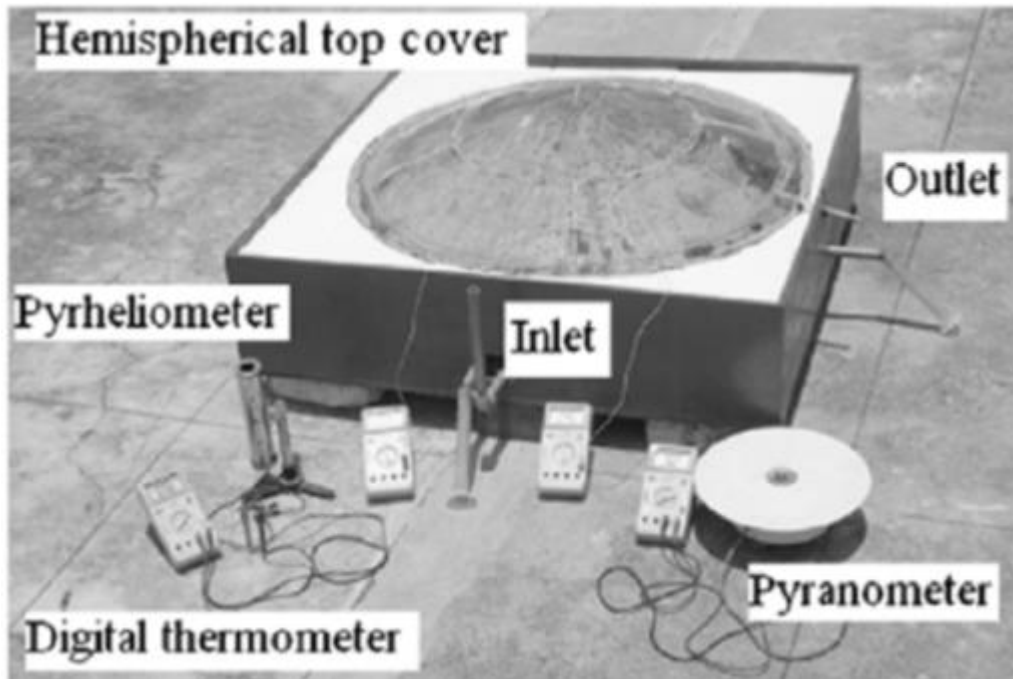


Fig. 15: Photograph of the hemispherical solar still [29]



Fig. 16: Photographic view of vertical solar still [30]

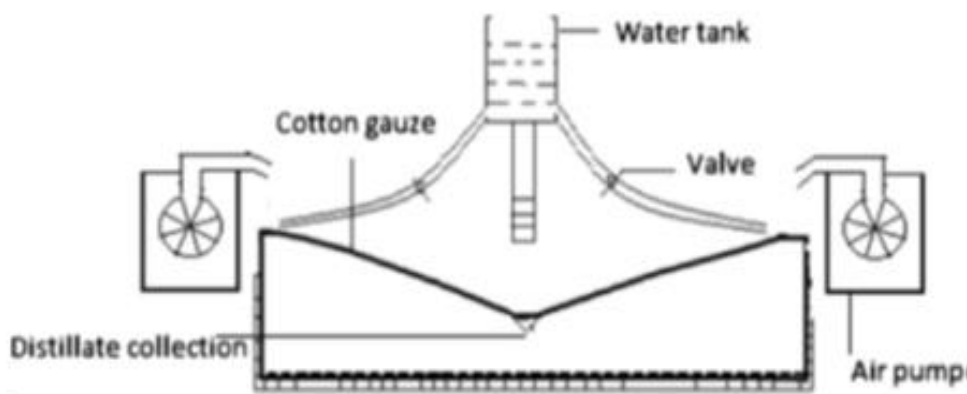


Fig. 17: Schematic view of the "V" type solar still [32]



Fig. 18: Top cover cooling arrangement of V type solar still [32]

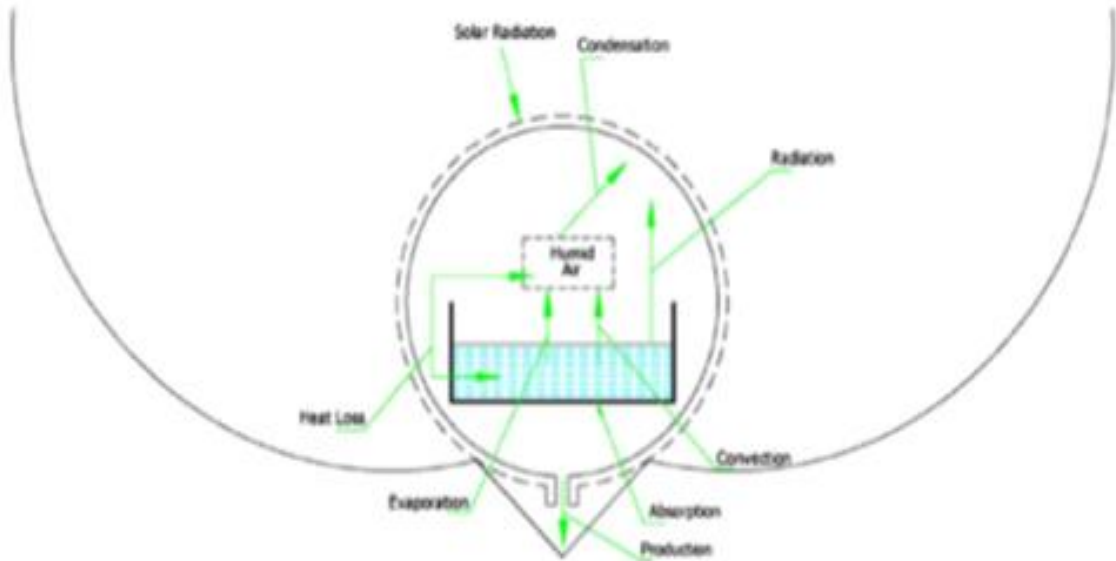


Fig. 19: Cross-sectional view of reflector shape for tubular absorber [33]

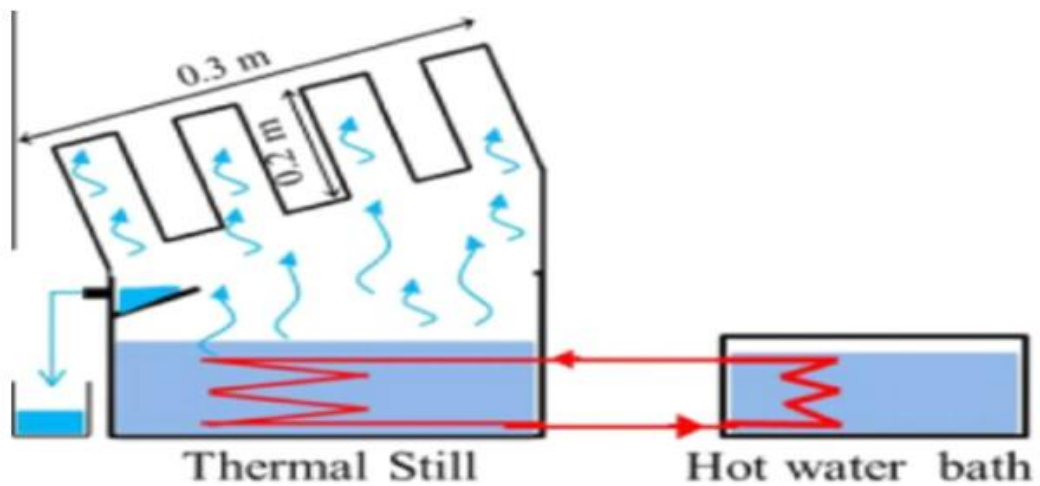


Fig. 20: The solar still with an additional area of condensation [36]

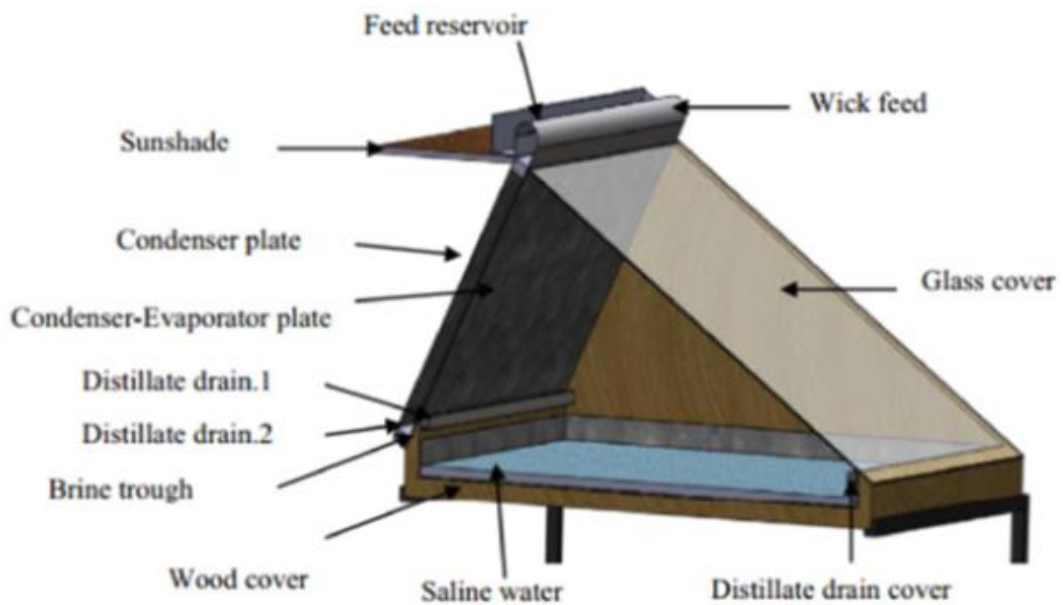


Fig. 21: A condensation cell integrated with a double slope still [37].