Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21193

84 (2017) 1–7
July

Experimental analysis of stepped basin pyramid solar still integrated with mini solar pond

M. Appadurai[a], V. Velmurugan[b,*]

[a] *Department of Mechanical Engineering, Dr. Sivanthi Aditanar College of Engineering, Tiruchendur, Tuticorin, India, Tel. +91 97860 48985; email: appadurai86@gmail.com*
[b] *Department of Mechanical Engineering, SCAD College of Engineering and Technology, Tirunelveli, India, Tel. +91 98421 19667; email: svvvelmurugan@gmail.com*

Received 17 December 2016; Accepted 7 July 2017

ABSTRACT

Many research works were carried out in the proper selection of design and operational parameters which plays an important role in the performance of a basin-type solar still. This experimental analysis was conducted to improve the design parameters such as condensing glass surface area, inlet brine water temperature, incident solar intensity rate, the gap between the basin water and glass. The pyramid glass cover increased the condensation area of the solar still. The mini solar pond was used to preheat the inlet brine water and the two external mirrors reflect more solar radiation into the still. The gap between the basin water and glass was less in the stepped basin. The results indicated that the daily productivity increased in mini solar pond integrated with the stepped basin solar still having mirrors. The productivity of the modified solar still was 4,920 mL per day, which was 66.2% higher than the conventional solar still.

Keywords: Pyramid solar still; Mirror; Stepped basin; Mini solar pond

1. Introduction

Nature's wonderful gift is water, which plays an important role in the development of an economy and in turn for the welfare of a nation. About 97% of the water is salty and non-drinkable which is at sea and oceans. Remaining 3% is fresh water; of these 2% is stored as icebergs in polar regions. And only 1% is fresh water, which is used directly for human needs and industrial purposes. The fresh water is contaminated by industrialization and civilization. The demand of drinking water is one of the major problems in the developing and underdeveloped countries of the world. Water distillation is one of the sustainable methods to overcome this problem. Solar still can be used for the distilling of brackish and saline water for the drinking purposes.

Several researchers studied the design and operational parameters of the solar still thoroughly [1–4]. They had expressed the parameters affecting the performance of the solar still. An experimental analysis on a solar still was examined by Khalifa and Hamood [5] for different brine depths and showed that the still productivity could be influenced by the brine depth by up to 48%. Sathyamurthy et al. [6] analyzed the effect of water depth and wind velocity on the performance of the triangular pyramid solar still (PSS). They found that the still productivity increased by 8% and 15.5% due to the effect of wind speed from 1.5 to 3 m/s and 3 to 4.5 m/s, respectively. Xiao et al. [7] stated that the solar radiation intensity, wind velocity, ambient temperature, cover angle, material coated on the basin, water depth, temperature difference between the water and glass cover and the insulation affect the still productivity. Velmurugan et al. [8] found that 29.6% productivity increased when wick-type solar still was used, 15.3% productivity increased when sponges were used and 45.5% increased when fins were used. Velmurugan and Srithar [9] and Velmurugan et al. [10] integrated the mini solar pond with conventional solar still to increase its productivity. The fins were integrated with mini solar pond and still basin to increase

* Corresponding author.

the convective heat transfer rate from basin to water was analyzed by Appadurai et al. [11]. They showed that 50% higher productivity was observed when fin type mini solar pond was integrated with fin type solar still. El-Naggar et al. [12] investigated a solar still with finned basin liner experimentally and theoretically. The finned basin enhanced the convective heat transfer coefficient by 3.6 times the basin without fin.

The external solar collectors, mirrors, thermal energy sources and condenser can be used to increase the productivity of the solar still. Ibrahim and Elshamarka [13] constructed a modified basin type solar still with an air-cooled condenser at reduced pressure. They found that the modified solar still had better performance than that of the conventional one. Dehghan et al. [14] used a thermoelectric module in solar still to raise the temperature difference between evaporating and condensing zones. Tanaka [15] investigated the theoretical analysis of a basin type solar still with internal and external reflectors and concluded the optimum external reflector inclination for each month for a solar still with a glass cover inclination for better distillation of water. Tanaka and Nakatake [16] fabricated a tilted-wick solar still with an inclined flat plate external reflector. They concluded that the daily distillate water production would be about 15% or 27% greater when the reflector's length was half of or the same as the still's length. Senthil Rajan et al. [17] conducted an experiment to utilize the thermal energy from biomass heat source to the saline water in the still by heat exchanger at a constant current rate using the circulation pump. They found that the sensible heat storage materials produce 48% more productivity and evaporative materials produce 19% more productivity than the conventional still under the same meteorological conditions. Arunkumar et al. [18] studied a compound conical concentrator solar still and compound parabolic concentrator tubular solar still and found that the daily yield is about 18,000 and 6,100 mL, respectively. A stepped solar still integrated with solar air heater was investigated by Abdullah [19]. The hot air from solar air heater is used to heat the stepped still basin. The productivity was increased by 112% over conventional still. Sathyamurthy et al. [20] investigated the effect of water mass on the performance of triangular PSS with and without latent heat storage in an experimental mode. They found that the distillation of the solar still with and without latent heat energy storage was 5.5 and 3.5 L/m^2 d, respectively.

Various experiments have been performed to increase condenser glass surface area of the solar still. Taamneh and Taamneh [21] constructed the pyramid-shaped solar still with a fan work to cool the glass cover. The fan was operated by the photo voltaic solar panel. They found that the evaporation rate was enhanced and hence the freshwater production was high. The daily productivity of freshwater was increased up to 25% when compared with a free convection solar still. Senthil Rajan et al. [17] fabricated a PSS heated with biomass heat source along with sensible, latent heat storage materials and evaporative surface material. They found that sensible heat storage materials yield 48% more productivity and evaporative materials yield 19% more productivity than conventional still. The theoretical analysis of a triangular PSS integrated to an inclined solar still with baffles is done by Naveen Kumar et al. [22]. They concluded that day time water distillation is decreased by 6%–46% and night time water distillation is increased by 46%–86% on higher mass content in still basin.

The present work designed to improve the design parameters such as condensing glass surface area, inlet brine water temperature, incident solar intensity rate, the gap between the basin water and glass. The pyramid shaped glass cover was used by several researchers. But in this work gap between the pyramid shape glass cover and basin is decreased by using stepped conical basin, the external reflectors are used to boost up the incident solar radiation for enhancing the evaporation rate of water in the stepped still basin. So the evaporation rate and the productivity are increased.

2. Experimental setup

2.1. Conventional solar still

Fig. 1 shows the conventional single basin solar still (CSS). The CSS consists of the basin, insulated box, glass cover and collecting channel. The basin of the solar still was made up of galvanized iron (GI) sheet having a thickness of 2 mm with the dimensions of 1 m × 1 m area and depth of 0.12 m. The still basin was painted in matte black colour in order to increase the absorbance of solar radiation. The solar still basin was enclosed by the insulation box which was made up of plywood having dimensions 1.2 m × 1.2 m area, thickness 0.02 m and height 0.1 m. The inner walls of the wooden box were painted in white colour in order to reflect more solar radiation to the basin water. The gap between the wooden box and still basin was filled with sawdust to reduce the heat losses from the basin to the surroundings. The plain glass having a thickness of 5 mm was used as the condensing cover. The glass was kept at the latitude angle of 10° as per the geographical conditions in Tirunelveli, India. The outer walls of the wooden box were covered by the GI sheet of 2 mm thickness in order to protect the insulation box from the environmental impacts.

2.2. Pyramid solar still

Fig. 2 shows an arrangement of PSS. The reservoir was made up of plastic with 50 L capacity used as a brine storage tank in order to eliminate the corrosion. The brine from the reservoir reaches the still via flexible plastic tubes of 5 mm diameter. The dimension of the still basin was 1 m × 1 m and painted in matte black colour. It was placed inside the wooden box. The gap between the wooden box and still basin was filled with sawdust for better insulation. A pyramid shaped glass cover was placed over the wooden box. The four glass pieces were inclined at an angle of 45° to form the pyramid shape. The surface area of the pyramid glass cover was 2.04 m^2. The collecting channels were placed in all four directions to collect the yield from the PSS. The productivity was measured every hour to evaluate the PSS performance.

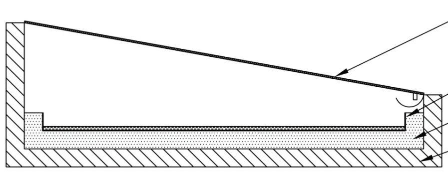

Fig. 1. Constructional details of the conventional solar still and pyramid solar still.

2.3. Stepped basin pyramid solar still with mirrors

Fig. 3 shows an arrangement of stepped PSS with an external mirrors. The basin looked like an inverted truncated cone shape. The five rectangular strips were welded on the pyramid basin with uniform distance by gas welding. The stepped basin had low water depth throughout the still and also a little gap between the basin and glass. A cotton wick was placed over the steps of the basin. The two external mirrors of dimensions 0.5 m × 1 m were placed on the left and right sides of the still at 45° inclinations to reflect more solar radiation on the still basin.

2.4. Stepped basin pyramid solar still having mirrors integrated with mini solar pond

Fig. 4 shows the solar still integrated with a mini solar pond. The mini solar pond was made like a truncated conical shape with the top and bottom face area 0.63 and 0.07 m^2, respectively. The axial height of the solar pond was 0.3 m. The three zones were being maintained in the mini solar pond, namely lower convective zone (LCZ), non-convective zone (NCZ) and the upper convective zone (UCZ). The LCZ was maintained with uniform and high density of salt, which was closed to saturated brine. When the salinity of water increased, the specific heat of the water also increased and so the heat storage capacity, boiling point of water increased. To prevent the heat losses from the LCZ, the salinity must be increased with depth in the NCZ. The salt gradient decreased from the bottom to top which leads to no natural convection in this zone, it was also called as the non-convective zone. The salinity of the UCZ was very less and it was nearer to fresh water. The LCZ was acting as a thermal storage zone because of the solar radiation transmitted into this zone. The copper tube heat exchanger was placed in the LCZ to utilize the heat for preheating the inlet brine water. The brine water was circulated through the copper tube heat exchanger for every hour in batch mode. It was filled on the trays of the stepped basin to maintain the exact water level every hour.

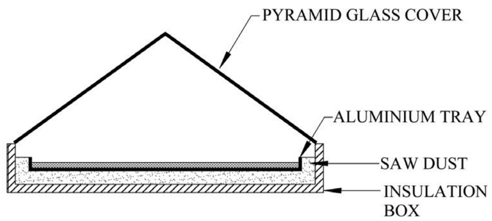

Fig. 2. Constructional details of the pyramid solar still.

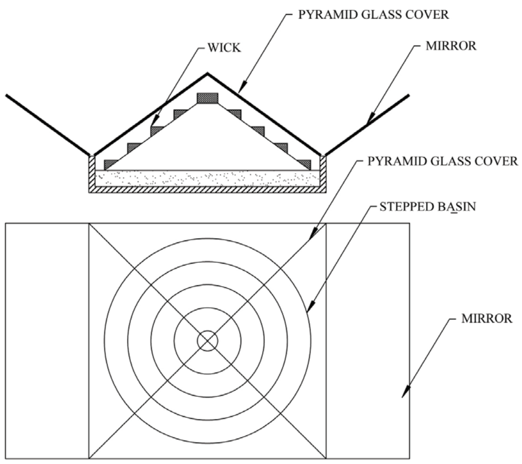

Fig. 3. Constructional details of the stepped basin pyramid solar still with mirrors.

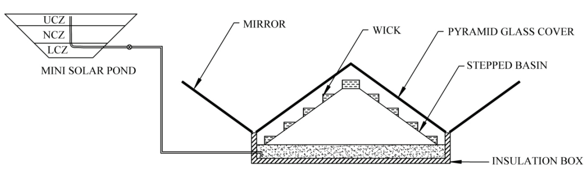

Fig. 4. Mini solar pond integrated with stepped basin pyramid solar still with mirrors.

3. Results and discussion

3.1. Pyramid solar still

Fig. 5 shows the hourly variation of solar radiation and ambient temperature for 3 d. Fig. 6 depicts the variation of

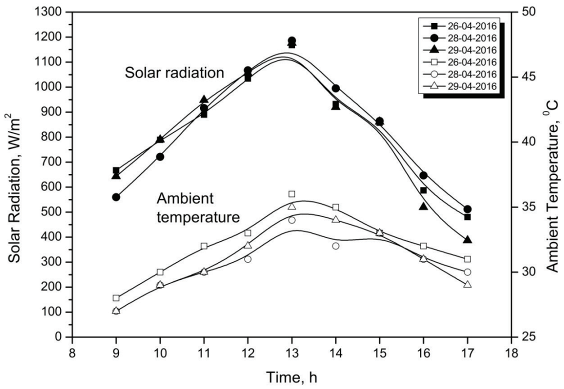

Fig. 5. Hourly variation of solar radiation and ambient temperature.

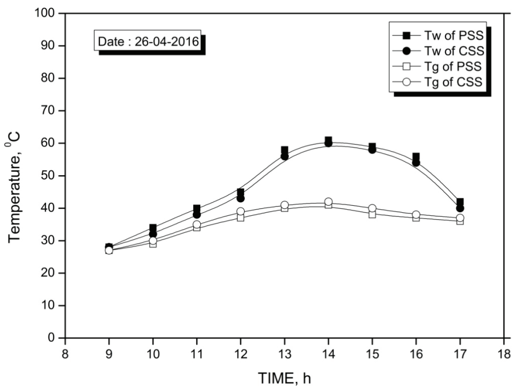

Fig. 6. Hourly variation of water temperature, glass temperature of conventional and pyramid solar still.

water temperature, glass temperature of the conventional and PSS with respect to time. The water and glass temperature increases gradually up to 13.00 h and then decreases. The glass temperature of PSS was lower than the CSS at all time. The PSS had a large glass surface area exposed to the flowing wind. The heat loss from the pyramid glass cover was faster than the conventional still glass cover. Fig. 7 indicates that the productivity of the solar still increased gradually from morning with respect to the solar radiation. Solar radiation is the driving force for distillation. The glass temperature of PSS was lower when compared with the CSS. So the temperature difference between the basin water and glass was increased in PSS which leads to higher evaporation rate. It reached its peak at the 13.00 h. In the PSS, the condensation area had increased. The minimum water thickness of 2 cm was maintained in the basin. The pyramid shaped glass cover gave the advantages such that incident of direct solar radiation without shadow effect and penetration of diffused solar radiation from all directions was felt inside solar still. Also, the condensation area is high. The daily productivity of the PSS and CSS was 3,780 and 3,010 mL/m^2, respectively.

3.2. Stepped basin pyramid solar still with mirrors

Fig. 8 illustrates the water, glass temperatures of the conventional and pyramid shaped solar still. It can be noted that the temperature of all the components reached its maximum temperature in the mid of the day due to the higher intensity of solar radiation. Fig. 9 shows that the yield of the solar still increased gradually from morning to the noon and decreased gradually from noon to the evening. It can be noted that the yield of the stepped basin pyramid solar still with mirrors was higher than the CSS. The usage of the cotton wicks in the basin increased the water surface area due to its capillary action. The external mirrors reflected more solar radiation, therefore, the basin water temperature increased faster than that of the still without reflecting mirrors. The stepped form of basin reduced the distance between the evaporating surface and condensing surface; therefore, the stepped pyramid still produced more output as compared with the basic CSS. Fig. 9 shows that the productivity of the pyramid still with a stepped wick basin (4,130 mL/m^2) was more than that of the basic PSS (3,040 mL/m^2).

3.3. Mini solar pond integrated with stepped pyramid solar still and mirrors

Fig. 10 represents the hourly variation of water, glass temperatures of the conventional and pyramid shaped solar still. Table 1 shows the distribution of distilled output of the stepped PSS. It can be observed that the glass temperature

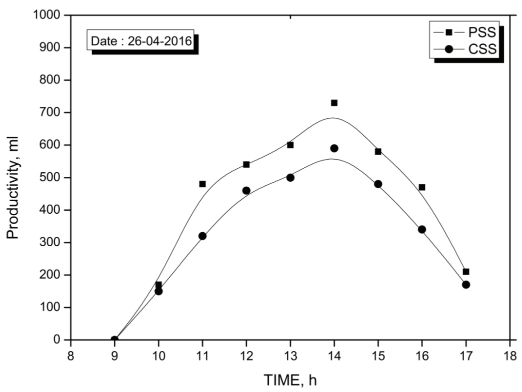

Fig. 7. Productivity of conventional and pyramid solar still.

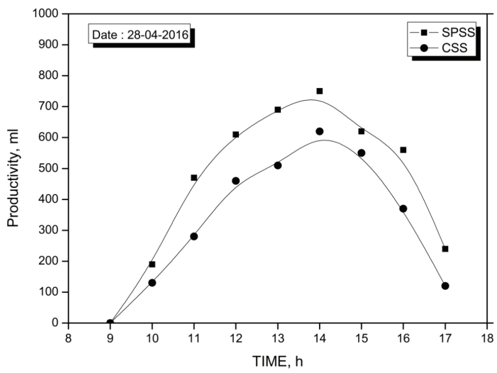

Fig. 9. Productivity of conventional and stepped basin pyramid solar still with mirrors with respect to time.

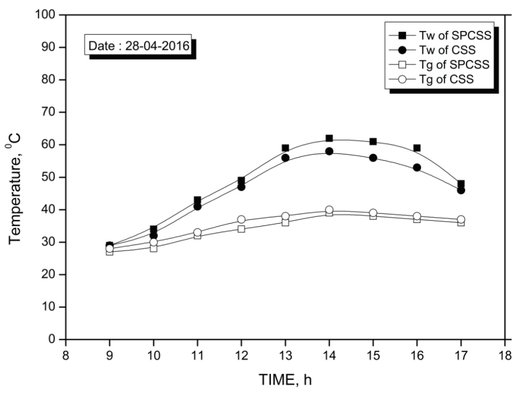

Fig. 8. Hourly variation of water temperature, glass temperature of conventional and stepped basin pyramid solar still with mirrors.

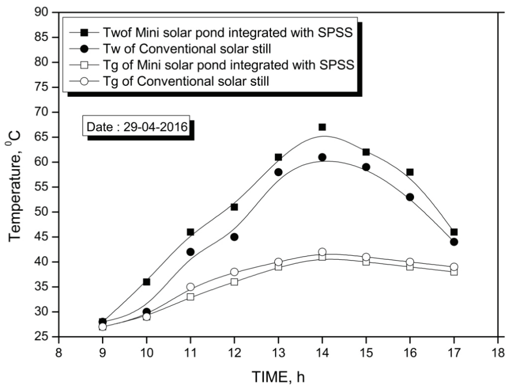

Fig. 10. Hourly variation of water temperature, glass temperature of conventional and mini solar pond integrated with stepped basin pyramid solar still having mirrors.

Table 1
Distribution of distilled water productivity

Time (hr)	9	10	11	12	13	14	15	16	17
Solar intensity (W/m^2)	643	790	948	1,056	1,177	920	861	520	387
Ambient temperature (°C)	27	29	30	32	35	34	33	31	29
Conventional solar still									
Water temperature (°C)	28	36	46	51	61	67	62	58	46
Glass temperature (°C)	27	29	33	36	39	41	40	39	38
Difference between water and glass temperature (°C)	1	7	13	15	22	26	22	19	8
Hourly productivity (mL)	0	230	560	690	820	940	740	660	280
Percentage (%)	0	7.77	18.92	23.31	27.7	31.76	25	22.3	9.46
Cumulative Productivity (mL)	0	230	790	1,480	2,300	3,240	3,980	4,640	4,920
Cumulative %	0	4.67	16.06	30.08	46.75	65.85	80.89	94.31	100
Mini solar pond integrated with stepped pyramid solar still and mirrors									
Water temperature (°C)	28	30	42	45	58	61	59	53	44
Glass temperature (°C)	27	29	35	38	40	42	41	40	39
Difference between water and glass temperature (°C)	1	1	7	7	18	19	18	13	5
Hourly productivity (mL)	0	140	330	410	480	610	520	370	100
Percentage (%)	0	4.73	11.15	13.85	16.22	20.61	17.57	12.5	3.38
Cumulative productivity (mL)	0	140	470	880	1,360	1,970	2,490	2,860	2,960
Cumulative %	0	4.73	15.88	29.73	45.95	66.55	84.12	96.62	100

was lower than the basin water temperature in the evening due to the ambient conditions, therefore, the temperature difference between the basin water and glass increased, which enhanced the rate of evaporation. Fig. 11 represents that the hourly outcome of the solar still which increased gradually from morning to the noon and decreased gradually from noon to the evening. It can be observed that the time required for evaporation was very low in the stepped PSS integrated with the mini solar pond. This is because the integration of mini solar pond preheated the inlet brine water and so it got evaporated faster than the CSS. The mini solar pond was acting as the sensible heat storage medium. The graph denoted that the introduction of a mini solar pond had increased the productivity of the solar still. The productivity of the PSS integrated with a mini solar pond (4,920 mL/m^2) was higher than the PSS without a mini solar pond (2,960 mL/m^2). A comparison between this research work and previous research works is given in Table 2.

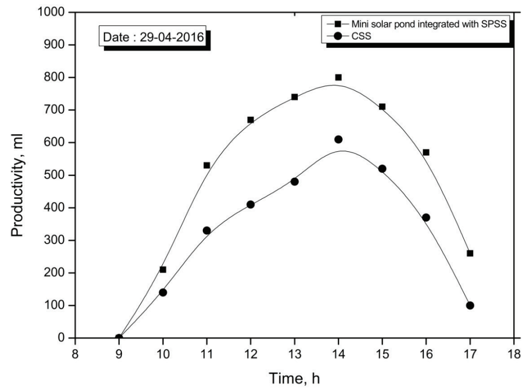

Fig. 11. Productivity of conventional and mini solar pond integrated with stepped basin pyramid solar still having mirrors with respect to time.

4. Error analysis

The thermocouples were used to measure the temperature of water at the input, output, basin and glass temperatures, which was connected to a digital multimeter. A pyranometer was used to measure the hourly solar radiation in the range from 0 to 5,000 W/m^2. Table 3 shows the measure of error analysis for various measuring instruments used in the experiments. This experimental setup was designed, installed and tested in Tirunelveli, India.

5. Economic analysis

The payback period of the stepped basin PSS integrated with mini solar pond depends on the fabrication cost, maintenance cost and cost of feed water. The investment cost of the different modifications in the PSS is given in Table 4.

Table 2
Comparison of this work with earlier research works

Sl. no.	Name of the authors	Modification done	Productivity (mL/m²/day)		Daily productivity rise (%)
			Modified solar still	Conventional solar still	
1	Abdullah [19]	Stepped basin solar still	4,350	3,350	30
2	Taamneh and Taamneh [21]	Pyramid solar still	2,990	2,485	25
3	Velmurugan and Srithar [9]	Mini solar pond integrated with solar still	3,700	2,820	27.6
4	This work	Pyramid solar still	3,780	3,010	25.6
5	This work	Stepped basin pyramid solar still with mirrors	4,130	3,040	35.9
6	This work	Mini solar pond integrated with stepped pyramid solar still and mirrors	4,920	2,960	66.2

Table 3
Accuracies and ranges of measuring instruments

Sl. no.	Instrument	Accuracy	Range	% Error
1	Anemometer	±0.1 m/s	0–15 m/s	10
2	Pyranometer	±1 W/m²	0–5,000 W/m²	0.25
3	Measuring beaker	±10 mL	0–1,000 mL	10
4	Thermocouple	±1°C	0–100°C	0.25

Table 4
Economic analysis of the fabricated solar still

Cost of different modifications of the solar still	Fabrication cost Rs.	Fabrication cost $	Productivity per day Litre	Payback period days
Conventional solar still	5,000	80	3	167
Pyramid solar still	5,500	88	3.78	145
Stepped basin pyramid solar still with mirrors	5,800	92.8	4.13	140
Stepped basin pyramid solar still with mirrors integrated with mini solar pond	6,700	107.2	4.92	136

The maintenance cost and the cost of feed water is negligible. The cost of distilled water is Rs. 10/L ($0.16).

Cost of water produced = daily productivity × cost of distilled water per litre.

Payback period = fabrication cost / cost of water produced.

6. Conclusion

The performances of the conventional solar still, PSS, stepped basin PSS and stepped basin PSS integrated with a mini solar pond were experimentally investigated. The effect of the pyramid shaped glass cover, stepped basin, preheating of inlet brine water using a mini solar pond on the productivity of the solar still was observed from the experimental results. The following conclusions may be drawn from the experimental results:

- The surface area of the pyramid shaped glass cover was higher in the PSS. Thus the productivity of the PSS was 25.5% higher than the conventional solar still.
- The gap between the water and glass was less in a stepped pyramid shaped basin and the mirror reflected more solar radiation on the stepped basin which enhanced the productivity 35.8% higher than the conventional solar still.
- The preheated brine water was supplied by the mini solar pond and mirrors increased the solar intensity rate. And so the stepped basin PSS having mirrors integrated with a mini solar pond which results in the increased productivity of 66.2%.

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