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Effect of parabolic solar energy collectors for water distillation

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ABSTRACT

This research article briefly summarizes the augmentation of condensate output using concentrators. This study compares a single-slope solar still, a compound conical concentrator (CCC) solar still, and a compound parabolic concentrator–tubular solar still (CPC–TSS). The effect of miniaturization of the absorber (increase in the concentration factor) and some modifications in the solar still assembly show a remarkable increase in output. The measured daily yield rate per square meter of absorber area of the single slope solar still, CCC solar still, and CPC–TSS is 2,100, 18,000, and 6,100 ml, respectively. It was found that the CCC solar still provides the maximum yield.

Keywords: Compound conical concentrator; Compound parabolic concentrator; Desalination; Solar still

1. Introduction

Solar energy can be used either for seawater desalination by producing thermal energy required to drive phase change processes or by generating the electricity required to drive membrane processes. Solar desalination systems are classified into two categories, i.e. direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in the solar collector, whereas, in indirect collection systems, two subsystems are employed. Conventional desalination systems are similar to solar systems because the same type of equipment is applied. The prime difference is that in the former, either a conventional boiler is used to provide the required heat or mains electricity is used to provide the required electric power, whereas in the latter, solar energy is applied [1]. Many papers have addressed solar stills of various

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configurations, including [2–8]. More specific studies include a hemispherical solar still [9,10], pyramid solar still [11,12], double-basin solar still [13–17], triple-basin solar still [18], multiple basin solar still [19,20], inverted absorber solar still [21–24], tubular solar still [25–30], plastic solar still [31], weir-type cascade solar still [32,33], inverted absorber solar still [34–37], and PV-powered desalination [38]. Several modifications with the use of phase change material, integrating solar water heater and nanofluids are also identified [39–50]. Arunkumar et al. [51,52] experimentally investigated the effect of heat removal from a tubular solar still. Results show that the yield of fresh water increased with water as cooling medium.

Passive solar stills can be implemented at the small scale in rural areas [53]. In this work, three designs of solar still systems were designed, constructed, and tested with same climatic conditions. Two different concentrator desalination systems were employed, i.e. compound conical concentrator (CCC) and compound parabolic concentrator. Additionally, these two results are compared with the single slope solar still.

2. Material and methods

2.1. Single slope solar still

The water storage basin of the still was designed with dimensions 0.50 m × 0.50 m. The bottom and sides of the still were coated with black paint for good absorption of solar radiation. An inlet pipe of ½ inch was used for pouring water into the still. The outer box for the still is made up of wood of thickness 4 mm with the length of 0.70 m and breadth of 0.70 m, respectively. The bottom of the outer box was filled with sawdust to the height of the 0.11 m. The side wall was insulated with glass wool of 0.05 m. These insulation layers reduce the conduction heat loss through the base and sides of the solar still. The top cover of the still is made up of a glass of thickness 4 mm. The top cover is placed on the grooves that are provided on all sides for levelling. A 11˚ slope is maintained for the top glass cover. The water collection segment was placed at the desired position for collecting the evaporated water, and it is of dimensions 0.66 m × 0.038 m × 0.015 m. The schematic and pictorial view of the solar still is shown in Figs. 1 and 2. Table 1 shows the technical details of the singleslope solar still.

2.2. CCC-coupled single-slope solar still

The CCC solar still consists of a spherical section collector and a hemispherical absorber. The hemispherical part was separately designed and attached to the basin bottom part of still. This entire hemispherical absorber volume acts as water storage for the still. The absorber is made up of copper of thickness 4 mm. The diameter of the hemispherical base is 0.22 m. The inner and outer surfaces were painted black, and a ¼ inch inlet pipe served as a water inlet. The top surface of the still is made up by a cover of area 0.25 m (0.25 m. The top cover is composed of transparent glass 2 mm thick. The top cover was placed over the grooves with uniform resting slope of 11˚. A water collection segment was also provided at the appropriate place. The segment has a length of 0.27 m and a width of 0.025 m. This entire setup was mounted at the focal point of the concentrator (aperture area 0.6385 m^2) below. A schematic view and photograph of the concentrator system of the CCC solar still are shown in Figs. 3 and 4. The specifications of the still are listed in Table 2.

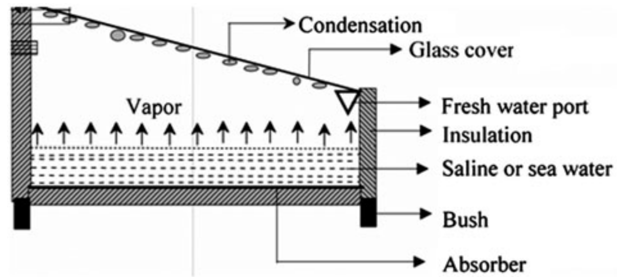

Fig. 1. Schematic view of single-slope solar still.

2.3. Compound parabolic concentrator-tubular solar still

In general, CPCs are used for steam generation and water heating processes, since they can produce higher temperatures than flat plate collectors. In this work, the tubular section was transformed into a water storage basin. A 2-m-long concentric tubular solar still was designed and fabricated as illustrated in Fig. 5. The specifications of CPC–TSS are shown in Table 3. The inner and outer circular tubes are positioned with a 5 mm gap for the flowing water and air to cool the outer surface of the inner tube. A rectangular trough of dimension 2 m × 0.025 m was designed and coated with black paint using a spray technique. The surface was free of dust, dirt, rust, and moisture before spraying. The water level in the trough decreased due to fast evaporation from the basin, so a dry spot appeared in the basin. This was avoided in successive trials by continuous flowing of the water in the still with the help of a graduated tube. This tube maintains a constant level of water in the basin independent of evaporation rate. This continuous supply

Fig. 2. Pictorial view of single-slope solar still.

Table 1
Single slope solar still technical details

Parameters	Values
Horizontal dimensions	0.50 m × 0.50 m
Height	0.40 m
Angle of inclination	11°
Absorptivity of the cover (α_c)	0.05
Emissivity of the cover (ε_c)	0.85
Transmittivity of the cover (τ_c)	0.9
Number of glass layers	1
Thickness of the glass	4 mm

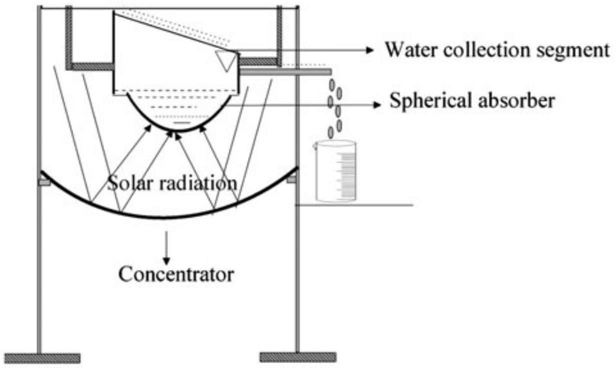

Fig. 3. Schematic view of hemispherical absorber.

of water is provided by a water storage tank, which is kept near the tubular still. The outlet of the storage tank is connected to the inlet of the tubular still. A stopwatch was used to record the time to allow the flow rate of water to the still from the graduated tubes to be calculated. Before the commencement of the experiment, a thorough cleaning of each tube was performed. After pouring the saline water into the trough, the entire arrangement was sealed with a rubber cork to prevent air leakage. A glass measuring jar was used to collect the distillation yield.

2.4. Temperature measurement

Multi-channel K-type thermocouples were used to measure all the basin water temperatures, internal air temperatures, and inner and outer cover temperatures. A pyranometer was used to measure global radiation. Wind velocity was measured using a digital-type anemometer. Graduated measuring jars were used to collect and measure the condensate from stills. The reliability and error analysis of the various

Fig. 4. CCC solar still.

Table 2
CCC solar still technical details

Parameters	Values
Horizontal diameter	0.22 m
Height of absorber and cover assembly	0.35 m
Angle of inclination	11˚
Absorptivity of the cover (α_c)	0.05
Emissivity of the cover (ε_c)	0.85
Transmittivity of the cover (τ_c)	0.9
Number of glass layers	1
Thickness of the glass	2 mm

instruments are presented in Table 4. Experiments were conducted in January 2014 at the terrace of the solar energy laboratory, Department of Physics, Dr. N.G.P Institute of Technology, Coimbatore (11.01˚ N 76.96˚ E), Tamil Nadu, a metropolitan city in southern India. Readings were recorded every 30 min.

3. Economic analysis

The overall cost of the experimental setup is given in Tables 5–7. The overall fabrication cost of the CCC is 59 USD, CPC–TSS is 279 USD, and the single-slope

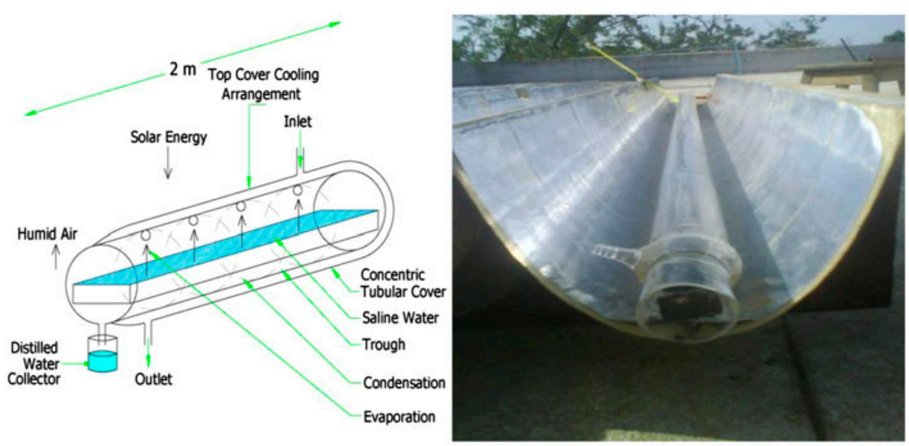

Fig. 5. Schematic and pictorial representation of CPC–TSS.

Table 3
Technical details of the CPC–TSS

Parameters	Values
Tubular cover	
Length	2 m
Absorptivity of the cover (α_c)	0.05
Reflectivity of the cover (ρ_c)	0.05
Emissivity of the cover (ε_c)	0.85
Transmissivity of the cover (τ_c)	0.9
Outer diameter	0.05 m
Inner diameter	0.045 m
Thickness of the tube	2.5 mm
Gap between the two glass layers	5 mm
Weight	7 kg
Material	Borosilicate
CPC details	
Aperature area of the CPC	2.04 m^2
Reflectivity of the envelope (ρ_e)	0.03
Emissivity of the envelope (ε_e)	0.85
Transmissivity of the envelope (τ_e)	0.92
Base material	Teak wood
Reflector foil	Aluminium polyester foil
Half acceptance angle	23.5°
Concentration ratio	2.5
Absorber	
Thermal conductivity of absorber $K_{absorber}$ (K_r)	385 W/m K
Absorptivity (α_r)	0.90
Length, breadth, and height	2 m × 0.02 m × 0.02 m
Thickness of the absorber	3 mm

Table 4
Accuracies and error for various measuring instruments

Instruments	Accuracy	Range	% Error
Pyranometer	±30 W/m^2	0–1750 W/m^2	3
Digital thermometer	±1℃	0–100℃	0.3
Thermocouple	±1℃	0–100℃	0.4
Measuring jar	±10 ml	0–1,000 ml	10

solar still is 55 USD. The overall cost of the water produced by this project = cost of still/total water output in liters. Eighty percent equivalent sunny days was assumed (because some output is produced even when it is cloudy), and a discounted life years of 10 were estimated (15 years life and 6% discount rate). The daily output was 3.5, 1.5, and 0.5 L for the CCC, CPC–TSS, and single-slope solar still, respectively. This corresponds to a water cost of 0.0058, 0.0635, and 0.0380 USD/L for the CCC, CPC–TSS and single slope, respectively.

Table 5
Cost estimation for the components of CPC–TSS

Component	Cost ($)
Compound parabolic concentrator (2 m × 1 m)	125.05
Borosilicate glass tubes (5 pieces × 2 m)	116.11
Rectangular basin (5 numbers × 2 m)	13.40
Black paint and primers	8.93
Water tank	15.18
Total cost ($)	278.67

4. Results and discussion

The variation in solar radiation and ambient temperature is shown in Fig. 6. The variation in ambient temperature is in the range of 24.7–36.2℃ and solar radiation received during the study is in the range of 362–1,038 W/m^2. The freshwater productivity of the still is proportional to daily solar radiation.

Table 6
Cost estimation for the solar single slope solar still

Component	Cost ($)
Iron sheet	24.10
Plywood	12.85
Glass	2.41
Black paint and primers	8.93
Labor charge	16.06
Total cost ($)	55.42

Table 7
Cost estimation for the CCC solar still

Component	Cost ($)
Iron sheet	8.03
Concentrator	32.13
Glass	1.61
Black paint and primers	8.93
Labor charge	15.05
Stand	5.62
Total cost ($)	59.44

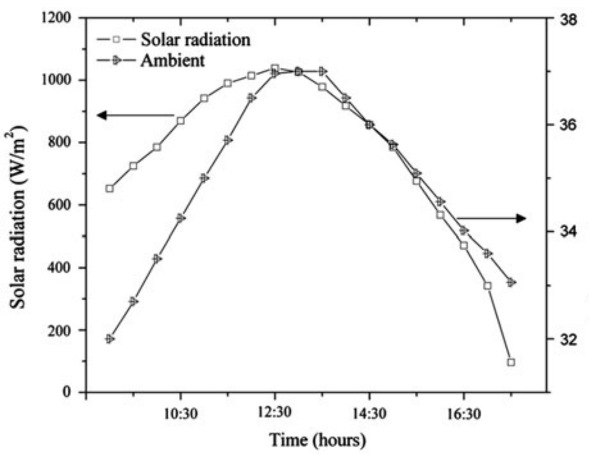

Fig. 6. Variation of solar radiation and ambient temperature with respect to time.

Fig. 7 illustrates the variation of water temperature, internal air temperature, and outer cover temperature with respect to time for the single-slope solar still. The maximum water temperature was observed as 56˚C; the maximum internal air temperature was 53˚C, and the maximum outer cover temperature at 42˚C. Fig. 8 shows the variation of water temperature, internal air temperature, and outer cover temperature with respect to time for the CCC solar still. The maximum water temperature was observed as 90˚C, the maximum internal air temperature was 80˚C, and the maximum outer cover temperature was 55˚C. Fig. 9 describes the variation of water temperature, internal air temperature, and outer cover temperature with respect to time for the CPC–TSS. The maximum water temperature was observed as 95˚C, the maximum internal air temperature was 80˚C, and the maximum outer cover temperature was 54˚C. The saline water temperature has an important influence on the distillate yield. From the temperature measurement, the water temperature was increased considerably by the concentrators. The CCC solar still produced a maximum

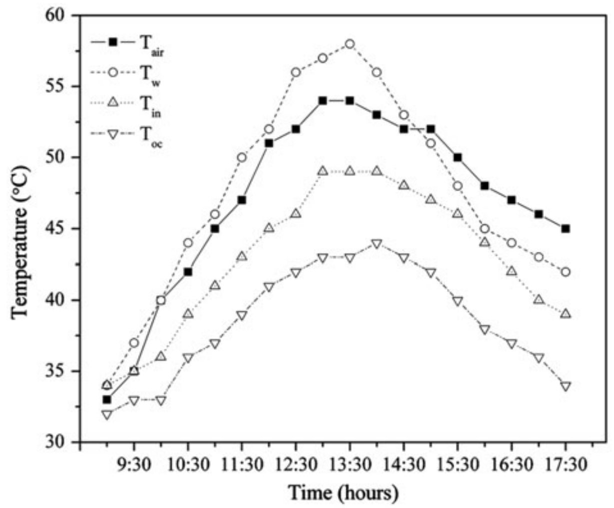

Fig. 7. Variation of temperature with respect to time for the single-slope solar still.

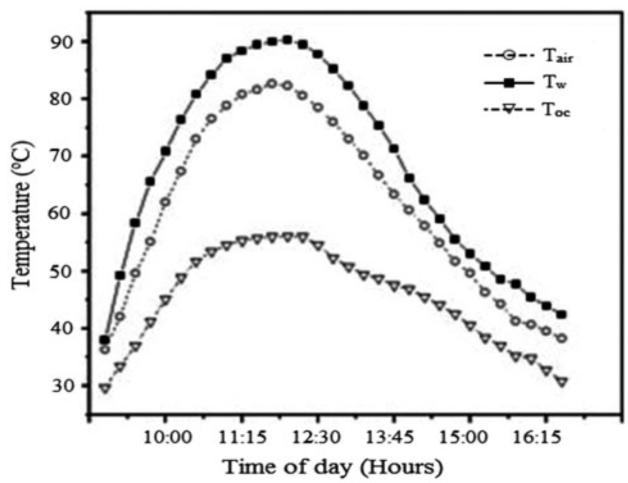

Fig. 8. Variation of temperature with respect to time for the compound concical concentrator solar still.

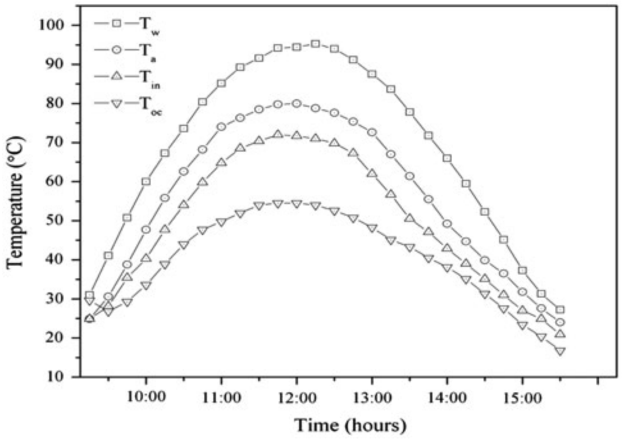

Fig. 9. Variation of temperature with respect to time for the CPC–TSS.

temperature of 34˚C higher than the singleslope solar still. This concentrator reduces the warm-up time. A. The small amount of volume in the CPC–TSS coupled with the high concentration factor reduces the warm-up time to a few minutes. The water flow was controlled at 10 ml/min using pressure head connected with the water tank This type of still produced a 5˚C higher maximum temperature than the CCC solar still. An increased temperature causes an increase in distilled yield. Fig. 10 shows the distillate yield with respect to three experimental designs. The measured daily yield rate of the single-slope solar still, CCC solar still, and CPC–TSS per square meter of absorber area is 2,100, 18,000, and 6,100 ml respectively. From the obtained results, the CCC solar still shows the maximum yield. The concentration factors of the single slope solar still, the CCC solar still, and the CPC–TSS are approximately 1, 10, and 2. Therefore, it is reasonable that the greatest productivity per square meter comes from the CCC solar still.

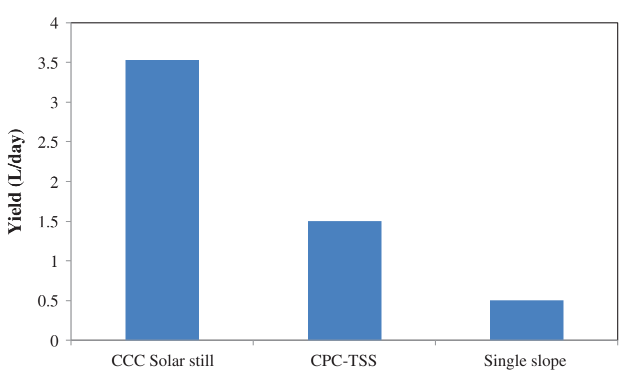

Fig. 10. Variation of yield with respect to different designs.

We further conclude that all of the solar stills produced high purity distilled water. Velmurugan et al. [39] tested the product water produced from a solar still in India. The results of the physical and chemical analyses indicated that the product water could be used for potable purposes.

5. Conclusions

Three different solar still designs were studied. The following conclusions are drawn from the study:

(1) The increased concentration factor of the CCC solar still and CPC–TSS produces higher saline water temperature.
(2) The concentrators produce higher productivity per square meter of absorber area.
(3) The CCC solar still exhibits the maximum distillate yield per square meter of the absorber.
(4) These ideas can be implemented in rural desert areas.

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