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Effect of water and air flow on concentric tubular solar water desalting system

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HIGHLIGHTS

- We optimized the augmentation of condense by enhanced desalination methodology.
- We measured ambient together with solar radiation intensity.
- The effect of cooling air and water flowing over the cover was studied.

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ABSTRACT

This work reports an innovative design of tubular solar still with a rectangular basin for water desalination with flowing water and air over the cover. The daily distillate output of the system is increased by lowering the temperature of water flowing over it (top cover cooling arrangement). The fresh water production performance of this new still is observed in Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore (11° North, 77° East), India. The water production rate with no cooling flow was 2050 ml/day (410 ml/trough). However, with cooling air flow, production increased to 3050 ml/day, and with cooling water flow, it further increased to 5000 ml/day. Despite the increased cost of the water cooling system, the increased output resulted in the cost of distilled water being cut in roughly half. Diurnal variations of a few important parameters are observed during field experiments such as water temperature, cover temperature, air temperature, ambient temperature and distillate output.

1. Introduction

Fresh water is a finite resource seriously impacted by pollution. Desalination based on renewable energy such as solar energy, presents a sustainable and a zero-polluting alternative to fossil fuel-based desalination, which aggravates environmental pollution problems. It is cheap, allows energy diversification, available for predictable periods of time, and helps avoid dependence on external energy supplies [1]. Solar still desalination uses a sustainable and pollution-free source to produce high-quality water. The main limitation of solar stills is their low productivity compared to conventional desalination processes. The operating efficiency is low due to main two limitations: (i) the rejection to the atmosphere of the latent heat of condensation and (ii) the difficulty of raising evaporation temperature and decrease condensation temperature as heating, evaporation and condensation take place in one container [2]. Solar stills may be economically viable if small water quantities are required and the cost of pipe work required to supply an arid area with water is high [3]. They represent the best technical solution to supply remote villages or settlements with fresh water without depending on high technology and expertise [4], particularly where sunshine is abundant. In their simplest design, they comprise transparently-roofed black-painted basins containing the water to be desalted. Water in the basin gets heated, evaporates, and the vapor condenses as it hits the roof and trickles down reaching a channel which transmits the flow into a collection container. The stills can have various forms, shapes, and cover materials and their operation requires little maintenance besides regularly flushing the basin to remove accumulated salts.

Chen et al. [5] studied on a membrane distillation desalination system. Tsilingiris [6] observed errors in temperature measurement and implications on performance. A thermal comparison of the performance of the compound parabolic concentric (CPC) with modified and non-modified absorber was designed and tested by Khonkar and Sayigh [7]. A modification has been undertaken in

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Nomenclature

C	specific heat capacity of water (4190 J/kg K)
T	temperature (°C)
Greek letters	
α	absorptivity
ρ	reflectance
τ	transmittance
ε	emissivity
Subscripts	
b	basin
g	glass
w	water

the absorber design by introducing two cavities in the most appropriate location. The experiment was done under a real condition of the sun. A new heat and mass transfer tubular solar still have been studied by Ahsan and Fukuhara [8]. The authors found that the heat and mass transfer coefficients can be expressed as functions of the temperature difference between the saline water and the cover. Ahsan et al. experimentally studied the evaporation, condensation and production of a tubular solar still. They found that the relative humidity of the humid air is definitely not saturated and the hourly evaporation, condensation and production fluxes are proportional to the humid air temperature and relative humidity [9,10]. Numerous research activities have been performed on CPCs, such as cost-effective asymmetric CPCs [11], non-modified absorbers [12], solar powered adsorption refrigerator with CPC collection system [13], non-imaging solar collector [14], non-tracking solar concentrators [15], non-evacuated solar collectors [16], and tilting collectors [17]. Singh et al. [18] studied the design parameters for concentrator assisted solar distillation system. The analytical expressions for the water and glass cover temperatures, the rate of heat flux due to evaporation; the rate of distillate output and the instantaneous thermal efficiency are derived in terms of the system design and climatic parameters. Analytical results show that the efficiency of the system with a concentrator is higher than that with a collector. Chaochi et al. [19] designed and built a small solar desalination unit equipped with a parabolic concentrator. The results show that, the maximum efficiency corresponds to the maximum solar lightning obtained towards 14:00 h. At that hour, the boiler was nearly in a horizontal position, which maximizes the offered heat transfer surface. The experimental and theoretical study concluded with an average relative error of 42% for the distillate flow rate. Mohamad and El-Minshawy [20] deals with the status of solar energy as clean and renewable energy applications in desalination. The daily efficiency of the still is about 29%. A study was made on the effect of a cooling tower on a solar desalination system by Marmouch et al. [21]. Water flowing over the condensing cover [22–44] has been done by many authors working in the field of desalination. A complicated system is, however, generally costly and may require regular monitoring [45].

Compound parabolic concentrators (CPCs) consist of curved segments of reflectors with two parabolas. They have been called

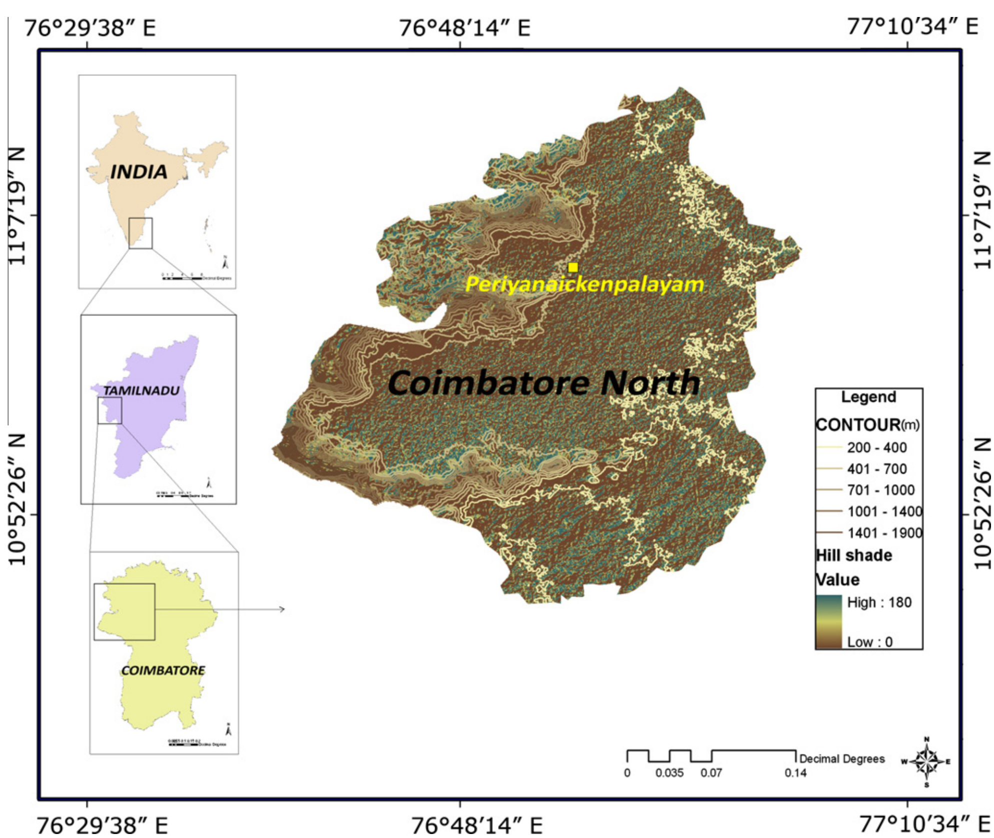

Fig. 1. The map showing hill shade and contour pattern of the study area.

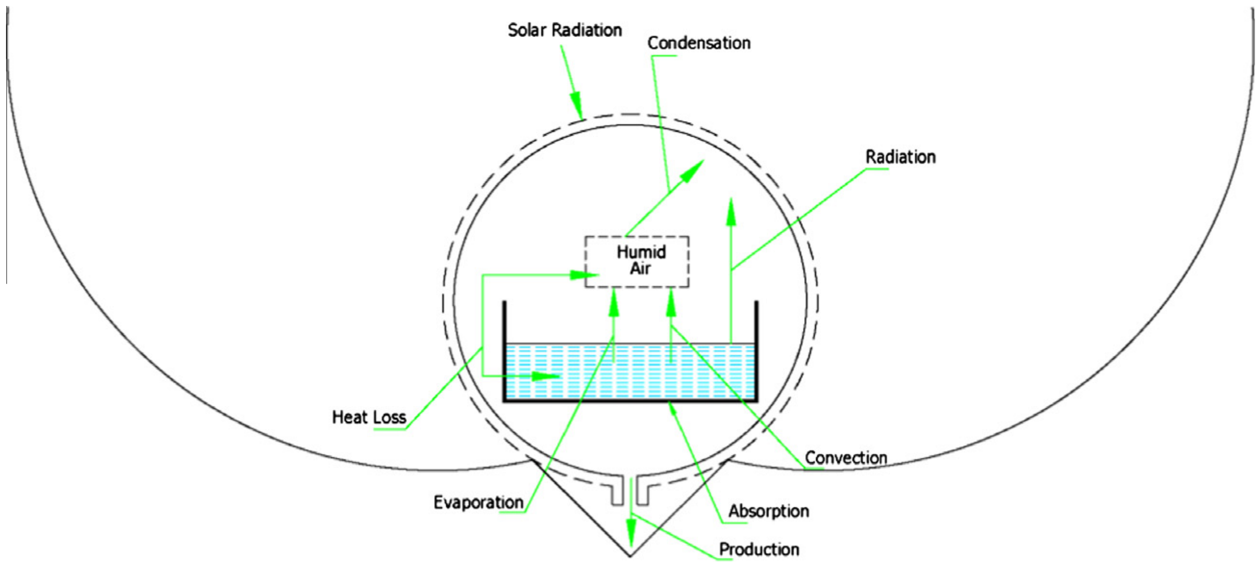

Fig. 2. Reflector shape for tubular absorber.

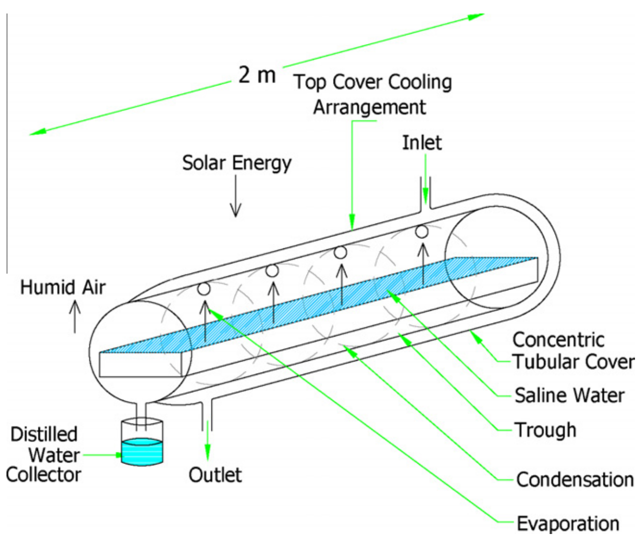

Fig. 3. Schematic view of experimental setup.

Fig. 4. Pictorial view close-up of tubular solar still.

'ideal light collectors' as they concentrate light at the thermodynamic limit. In general, CPCs are used for steam generation and water heating processes, since they are able to produce higher temperatures than flat plate collectors. But in this study an attempt is made to use this concentrator for solar desalination. The tubular absorber assembly of the CPC is converted as solar still basin and distilled output is collected directly from this assembly. In this case, beam radiation received by CPC trough is reflected to the blackened metal tube placed at its focal line. This work is only the beginning and the results are only a starting point to improve the desalination unit in order to extrapolate to a larger scale. This solar distillation system shows great potential in terms of higher distillation yield per unit area as compared to other available designs. The fresh water obtained from the built-in solar distillation system can be blended with available brackish water in order to improve its quality for the usage of irrigation in protected cultivation. These analyses suggest that the method is able to produce a low cost distillation unit for acquiring high purity distilled water. This paper presents an experimental analysis of a compound parabolic concentrator concentric tubular solar still (CPC-CTSS). The productivity and efficiency of a CPC-CTSS are analyzed. It is expected that the concentrating assembly with air and water cooling would improve the overall potable water yield on the tubular solar still.

2. Pure water production principle

The evaporated water is condensed at the inner surface of the top cover by releasing its latent heat. The condensed water, under gravity, trickles down and is finally collected through a drainage provided at the lower periphery. The temperature of the top cover is an important parameter for condensation. Wind affects the temperature of the top cover, but it is not controllable. Here, the idea is cooling the top cover in a controlled way with water and air on the outer surface of the inner tube at a constant flow rate. The driving force of the solar distillation technique is the difference between temperature of water in the basin and the cover ($T_w - T_g$). The

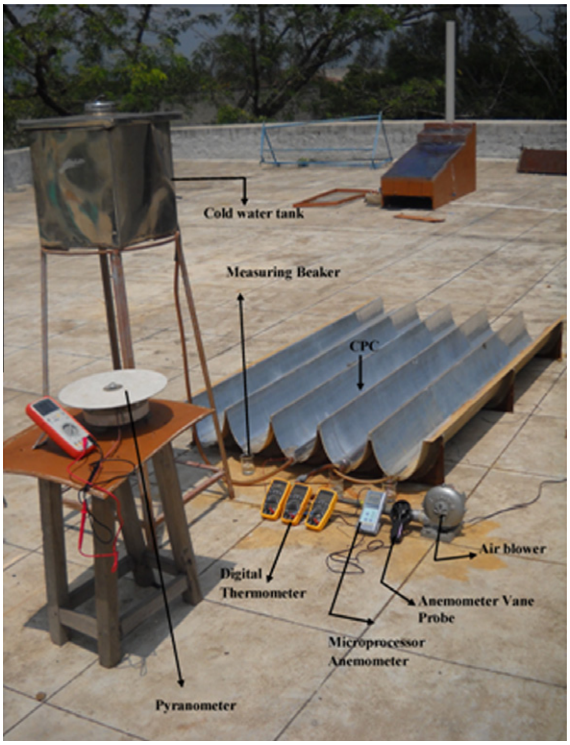

Fig. 5. Pictorial view of compound parabolic concentrator tubular solar still.

Table 1
Design parameters of the concentric tube.

Parameters	Values
Length	2 m
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

Table 2
Still technical and operation details.

S. no.	Climatic conditions	Parameter	Value
1	Clear sky	Solar radiation (W/m^2)	652–1159
		Ambient (°C)	26.2–34
		Humidity (%)	55–21
		Average wind velocity (m/s)	1
2	Design	Basin absorptivity (α_b)	0.90
		Emissivity (ε)	0.13
		Absorptivity of cover (α_g)	0.05
		Reflectance of cover	0.05
		Transmittance of cover (τ_c)	0.88
		Ground reflectance (ρ)	0.75
		Specific heat of water (C_w)	4190 J/kg K
		Length (m)	2
		Width (m)	0.102
		Radius of the receiver (m)	0.0158
		Radius of the envelope (m)	0.022
		Gap thickness (m)	0.005

existence of such temperature difference ensures the continuation of the distillation process.

Table 3
Accuracies and error for various measuring instruments.

Sl. no.	Instrument	Accuracy	Range	% Error
1	Pyranometer	±30 W/m^2	0–1750 W/m^2	3
2	Digital thermometer	±1 °C	0–100 °C	0.3
3	Thermocouple	±1 °C	0–100 °C	0.4
4	Anemometer	±0.2 m/s	0.4–30.0 m/s	2
5	Measuring jar	±10 ml	0–1000 ml	10

3. Materials and methods

ASTER GDEM 30 meter digital elevation data is used to derive the study area map in the ArcGIS platform (ArcGIS, version 9) as shown in Fig. 1. The contour lines show that the maximum elevation is in the North-West zone of the study site, while the minimum elevation is in the East zone.

A 2 m concentric tubular solar still is designed and fabricated as illustrated in Figs. 2–5. The specification of concentric tubular solar still is shown in Table 1, while the still's operational parameters are shown in Table 2. 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 × 0.03 m × 0.025 m is designed and coated with black paint using a spray technique. The surface is 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 of water is maintained by a water storage tank which is kept near to the CPC still. The outlet of the storage tank is connected to the inlet of the CPC still.

A stop watch was used to record the time and the flow rate of water to the still from the graduated tubes was calculated. Before the commencement of the experiment, a thorough cleaning of each circular tube was performed. After pouring the saline water into the trough, the entire arrangement was sealed properly with a rubber cork to prevent air leakage. The measuring jar made of glass was used to collect the distillation yield. The solar radiation intensity was recorded by a precision pyranometer with accuracy of ±30%. The following parameters were measured every 10 min: water temperature (T_w), interior humid air temperature (T_a), ambient temperature (T_{amb}), inner cover (T_{ig}), outer cover (T_{og}), total diffuse solar radiation (I), and the distillate yield. The experiment was first performed without circulation of cooling fluid. Then, experiments were conducted to study the performance improvements with air (at 4.5 m/s) and water (at 10 ml/min) as cooling fluids. An air blower was used to flow the air inside the tube at constant rate of 4.5 m/s. The waste water flow was controlled at 10 ml/min using pressure head connected with a saline water tank. Type K thermocouple (accuracy ±1 °C) was used to measure the input cold temperature and outlet hot temperature. The Microprocessor digital anemometer (AM 4201) with anemometer vane probe was used to measure the flow rate of air inside the concentric tubes. Minimum error occurred in any instrument is equal to the ratio between its least count and minimum value of the output measured. Accuracies and error percentage of various measuring instruments used in the experiment are shown in Table 3.

4. Experimental results

The water quality analysis is performed at the Tamil Nadu Agricultural University's, Soil Science and Agricultural Chemistry Department in Coimbatore, India. The results obtained are

Table 4
Tested water quality results.

Sample no.	TDS (mg/l)		pH		Conductivity (dS m^{-1})	
	Before desalination	After desalination	Before desalination	After desalination	Before desalination	After desalination
Sample A–B	320	40	7.60	7.32	1	0.10

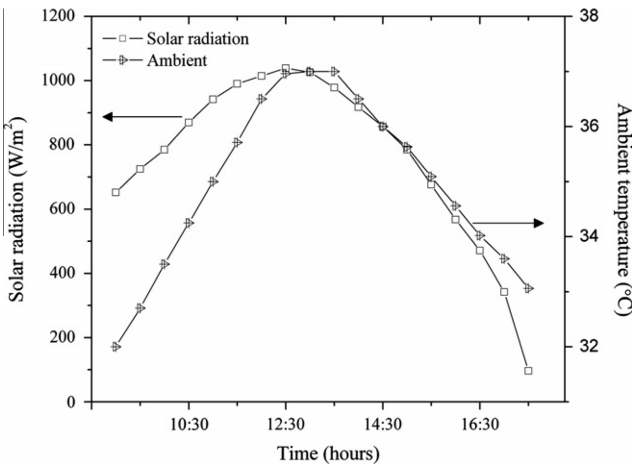

Fig. 6. Variation of solar radiation and ambient temperature with respect to time.

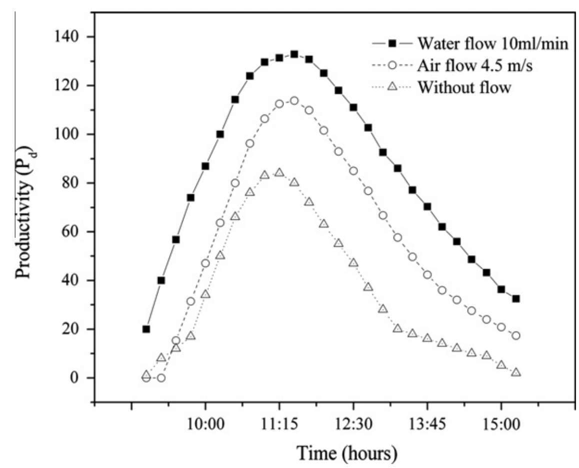

Fig. 8. Variation of yield with respect to time.

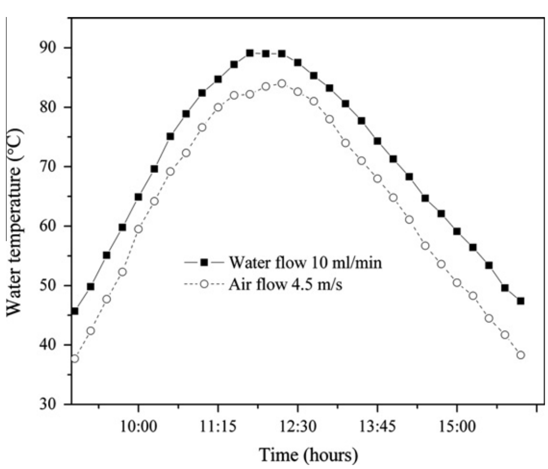

Fig. 7. Variation of water temperature with respect to time.

presented in Table 4. Two different water samples (A and B) are tested with their pH and electrical conductivity (in dS m^{-1}) measured before and after desalination. Before desalination, the level of electrical conductivity in the water of about 1 dS m^{-1} which is ~2% of ocean water, but not drinkable is obtained. However, after desalination it decreased to 0.10 dS m^{-1}, which is drinkable. The typical pH varies from one water sample to another as well as on the nature of the construction materials used in the water distribution system. It is usually in the range of 6.5–8. The solar radiation and ambient temperature for a typical day are shown in Fig. 6, while the variations of water temperature and daily productivity (P_d) (10 ml/min) with respect to local time are shown in Figs. 7 and 8 respectively.

5. Results analysis and discussion

In this work, a novel compound parabolic concentrator tubular solar still was designed and experimentally tested under the outdoor climatic conditions. Climatic conditions can affect the still productivity. The variation of solar radiation and ambient temperature are shown in Fig. 6. The variation of ambient temperature is in the range of 24.7–36.2 °C and solar radiation received during the study is in the range of 362–1038 W/m^2. The fresh water productivity of the still is generally proportional to daily solar radiation. But the measured ambient temperature is lower than other temperatures [46].

The comparison of water temperature of Fig. 7 indicates a range of 37.7–84 °C for the effect of air flow and 45.7–89 °C for water flow through the inner tube. It is observed that the temperatures at all points have maximum values near noon.

Comparison between the hourly variation of fresh water productivity is illustrated in Fig. 8. Solar radiation is reflected by a compound parabolic concentrator and then absorbed by the rectangular absorber [47]. From the figure it is found that the maximum fresh water productivity occurs in the afternoon for the present solar desalination system. The production rate depends on water, glass and atmospheric temperatures, water–glass temperature difference and glass-atmospheric temperature difference [48,49]. This solar desalination system has less water storage than basin type solar desalination systems, so the present system has a low warm up time. Also, it operates at high temperatures because of the focusing of the compound parabolic concentrator. The total amount of daily productivity obtained without cooling was 2050 ml/day. With cooling air flow, productivity increased by 49% to 3050 ml/day. Finally, with cooling water flow, productivity increased another 64% to 5000 ml/day. This shows that the concentric tubular solar still with cold water flow has the highest productivity, 144% more than without cooling. The input and output heat extracted air, water temperatures are shown in Table 5. The temperature difference achieved due to the flow of water increases the daily productivity [50]. The heat transfer coefficient of water is higher than that of air. Therefore, even though the cooling water temperature is generally higher than the cooling air temperature, it is likely that the condensing surface is lower temperature in the case of water cooling. Also the specific heat capacity of water is

Table 5
Results of cooling fluid temperatures.

Time (h)	Water flow (10 ml/min)		Air flow (4.5 m/s)	
	In	Out	In	Out
9:00	36	54	23	37
9:30	36	56	25	42
10:00	37	58	26	48
10:30	37	60	28	55
11:00	37	62	30	58
11:30	37	64	32	60
12:00	37	66	34	61
12:30	37	68	35	62
13:00	37	61	35	63
13:30	35	57	36	65
14:00	36	65	34	65
14:30	36	62	31	61
15:00	35	59	27	55
15:30	34	56	25	45
16:00	34	53	23	40

Table 6
Cost estimation for the components of the solar still.

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

high at 4190 J/kg K. These would help to explain why the tubular solar still with top cover water cooling is superior to the air flow.

The cost estimation for various components of CPC-TSS is given in Table 6. The total cost of the fabricated CPC-TSS with the water cooling apparatus was approximately $279, i.e. $137/m^2$ (as the aperture area was 2.04 m^2). With an output of 2.5 kg/m^2 d, a life of 15 years, and an interest rate of 6%, this is approximately $0.015/kg water. If there is no water cooling arrangement, cost would be saved in the water tank ($15.18) and in the outer glass tube (half of the double tube cost, i.e. $58.06). Therefore, the total cost of the fabricated CPC-CTSS without the water cooling apparatus would be approximately $206.[1] With the same aperture area, lifetime, and interest rate, but an output of 1.5 kg/m^2 d, this is approximately $0.018/kg water. Therefore, even though the water cooling arrangement costs more, the greater water production results in overall lower cost of purified water (roughly half). Velmurugan et al. [51] 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 purpose. In general, the quality of the product water is good to use as drinking water.

6. Conclusion

In this paper, the design, implementation and performance evaluation of a novel compound parabolic concentrator-concentric tubular solar still (CPC-CTSS) under the climatic conditions of Coimbatore, India is presented. The effect of cooling air and water flowing over the condensation surface is studied and found that the productivity was increased. The yield was 3050 ml/day with air flow and 5000 ml/day with cold water flow and 2050 ml/day without air or water flow. With cooling air flow, productivity increased by 49% to 3050 ml/day. Finally, with cooling water flow, productivity increased another 64% compared with air flow. This shows that the concentric tubular solar still with cold water flow has the highest productivity, i.e. 144% more than the normal CPC-CTSS without air or water flow.

[1] Technically, this was not the configuration tested, but we are being conservative by subtracting the cost of the outer tube.

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