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Design development and performance evaluation of concentrating solar thermal desalination device for hot arid region of India

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ABSTRACT

A parabolic concentrating solar thermal desalination device was designed, developed, and fabricated. The surface area of the parabolic concentrator made of steel is 2.60 m and the projected area of the disc is 1.50 m. The performance evaluation of the device during the summer and winter months of the year 2019 in the hot arid climate of Jodhpur, India was carried out by measuring distillate output per day. The maximum productivity of 6.5 L/d within 9 h in a day was measured with the maximum average solar insolation of 745 W m^{-2} during May 2019 and 5.5 L/d in winter month December 2019. The maximum daily average efficiency of 34.2% in May and 32.3% in December was calculated with a maximum hourly output of 0.85 L/h. The distillate output of solar desalination device is to be mixed with the available saline water in appropriate proportion to make it drinkable. In fact, as much as 20 L/d of a potable water (150–180 ppm TDS – total dissolved solids) can be made available in a day from raw water containing 300 ppm TDS by a solar desalination device. The economic evaluation of the parabolic concentrating solar thermal desalination device revealed that high value of internal rate of return (74.6%) and low value of the payback period (1.45 y) make the unit very cost-efficient. The economic attributes of the system revealed its economic viability. Therefore, this solar desalination device can be successfully used for desalination of saline water in rural arid areas for meeting requirement of potable water as per WHO guidelines for drinking water quality.

Keywords: Parabolic concentrator; Solar desalination device; Daily efficiency; Productivity; Cost analysis

1. Introduction

Energy and water are two basic requirements for human civilization. The demand for energy and water could double or even triple, as the global population rises and developing countries expand their economies by the end of 21st century. Today the world is challenged to provide sufficient pure water resources for human needs. A recent reports show that the groundwater levels and rainfall are in decline [1]. The man has been still dependent on rivers, lakes, and underground water reservoirs for freshwater requirements in domestic life, agriculture, and industry. However, the use of water from such sources is not always potable or desirable on account of the presence of a large amount of salts and harmful organisms. The impact of many diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. As far as drinking water is concerned, it is scarcely available in the western arid region of India and people depend on rainwater collected from the rooftop, which is too little to meet their drinking water demand. The impact of water borne infectious diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. Generally, in summer season, villagers travel many miles in search of freshwater. It is observed that at least one or two family members are always busy in bringing fresh water from

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distant sources. The worst conditions are generated if the resources of water are not available and villagers are forced to take highly saline underground water containing nitrate and fluorides or contaminated with pathogenic microbes pond water [2]. Fortunately, India is blessed with abundant solar radiation. During winter from November to February most of the Indian stations receive 4.0–6.3 kWh/m^2/d of solar irradiance, while in summer season this value ranges from 5.0 to 7.4 kWh/m^2/d. The arid and semi-arid parts of the country receive much more radiation as compared to the rest of the country with 6.0 kWh/m^2/d mean annual daily solar radiation having 8.9 average sunshine hours a day at Jodhpur [3]. The conventional desalination technologies like multi-stage flash, multiple effect, vapor compression, ion exchange, reverse osmosis, electrodialysis are expensive for the production of a small amount of freshwater. Also, the use of conventional energy sources has a negative impact on the environment. Solar distillation provides partial support to human needs for freshwater with free energy, simple technology, and clean environment. Therefore, solar distillation seems to be a good substitute for conventional methods. The main advantages of the solar still distillation unit are that it is a relatively cheap method for water distillation as it depends on solar energy which is also clean and sustainable. In addition, solar stills have a simplistic design, low installation costs, and are simple to maintain. Additionally, there are no movable parts, which reduce maintenances needs. Moreover, the solar still can be transported to any place easily, which helps some applications such as, military barracks, remote, and poor areas [4,5]. Solar distillation has been in practice for a long time. Solar distillation is carried out in solar still. Historical review of desalination of water was reported by Nebbia and Menozzi [6]. The utilization of a sustainable and simple desalinating method such as solar stills is made to produce freshwater from brackish water by directly utilizing sunshine to meet the freshwater needs in remote arid areas without depending on high tech and skills [7]. Utilizing higher capacity, thermal desalinating technologies for low population areas face many restrictions such as lack of proper resources to operate these systems [8]. The basin-type solar still is in the most advanced stage of development. Several researchers have investigated the effect of climatic, operational, and design parameters on the performance of such still [9]. Researchers have done different types of analysis on basin – type solar still [10–13]. Elshamy and El-Said [14] tested the performance of two different shapes of tabular solar still, flat plate (TSS-FP) and semi-circular corrugated surface (TSS-SC). The TSS water production rate by using semi-circular corrugated surface was about 4.3 L/m^2 with enhancement by 26.47% rather than using a flat absorber with thermal and exergy efficiencies about 25.9% and 23.7%, respectively. Kabeel et al. [15] presented the performance of a solar still with composite black gravel PCM and paraffin wax. The productivity, energy efficiency, and exergy efficiency by utilizing PCM were about 3.27 L/m^2, 48.22%, and 3.08% with enhancement about 37.56%, 38%, and 37%, respectively, higher than SS-paraffin wax. Mohamed et al. [16] carried out experiments on the influence of heat and mass transfer enhancement on the solar still thermodynamic performance by using porous absorber. The results indicated that the exergy efficiency of the solar still with the 1, 1.5, and 2 cm fine stone particle size was enhanced by about 65%, 104.4%, and 123%, respectively, compared to solar still without stones. Mohamed et al. [17] tested experimentally and carried out thermo-economic investigation of a solar distillation system by inclusion of a natural fine stone (black basalt) as a porous sensible absorber. The yield of solar still for 1, 1.5, and 2 cm stone size was about 0.901, 1.005, and 1.075 L/m^2 with enhancement of about 19.81%, 27.86%, and 33.37% as compared to conventional solar still and the highest daily thermal efficiency of a solar still was about 22.6% at 2 cm stone size with enhancement of about 32.07%. El-Said et al. [18] investigated practically the performance of a tubular solar still using vibrated wire mesh screen and conventional still. The modified still water yield was 4.2 L/m^2 with augmentation by 34% rather than a conventional still. Thermal and exergy efficiencies are augmented by 31.36% and 40.08%, respectively. El-Said and Abdelaziz [19] experimentally investigated that the influence of utilizing high-frequency ultrasound waves atomizer still improved the efficiency and productivity in comparison to conventional solar still and found C-SS and HFU-SS daily productivity were about 3.58 and 4.41 L/m^2, respectively. The average thermal efficiency of the HFU-SS atomizer was augmented by about 28.75%–55.75% compared to C-SS. Salem et al. [20] experimentally examined the influence of integrating a floating sponge layer on the performance of a double slope single basin type solar distillation unit (SSDU) and found that the maximum freshwater production and the thermal efficiency of the SSDU was recorded as 4.9 L/m^2 day and 37%, respectively, with using a floating sponge of density of 16 kg/m^3, with corresponding variation percentages of +58.1% and +55.3%, respectively, when compared with the conventional unit (3.1 L/m^2 d freshwater productivity and 23.8% thermal efficiency).

Apart from this, other types of stills are also proposed with modeling and analysis [21,22]. All these stills work at temperatures well below 100°C for conversion process. For achieving conversion at higher temperature (>100°C), thermal devices like flat-plate collectors and concentrators were used. Such system is called “active” system as given in the literature [23]. The low efficiency of all solar desalination devices is mainly due to heat loss because of the large area of the collector. However, it is not the case of parabolic trough concentrators because they have less area where heat could be lost. For this reason, these devices can reach high temperatures and are also used to generate electricity [24], additionally with a lower cost than other solar collectors [25]. Concentrator powered solar distillation systems play a significant role in producing desalted water. Presently, many researchers are involved in these activities to accumulate high-quality de-salted water through concentrator-assisted systems. The effect of water flow on parabolic concentrator with heat exchanger solar still has been analyzed with maximum productivity of 3.56 L/m^2/d [26]. Chaouchi et al. [27] designed and built a small solar desalination unit equipped with a parabolic concentrator. The experimental and theoretical study concluded with an average relative error of 42% for the distillate flow rate. Gorjian et al. [28] designed and fabricated a point focus parabolic concentrator solar still and found maximum productivity of 5.12 L within 7 h/d. Elashmawy [29] tested the performance of parabolic concentrator solar tracking system integrated with a tubular solar still system which was able to increase TSS daily yield by 676% and cost per liter (CPL) is reduced by 45.5%. Many authors have performed the distillation process with concentrator-assisted techniques with and without PCM [28,30–34]. Total cost of ownership (TCO) method is used to carry out the economic analysis in the present work. The TCO is the sum of the fixed investment costs, the production costs, the internal rate of return (IRR) on investment, the operating costs, and the energy costs [35,36].

Solar desalination units made of building materials overcome the problems of corrosion but salt scaling and algae problems still exist. All metallic solar stills whether multistep basin or single basin are prone to corrosion, salt scaling, and algae problem and have less life [9]. To overcome these problems a concentrator based distillation device was developed at ICAR-Central Arid Zone Research Institute, Jodhpur, India. However, economic analysis has not been carried out in earlier reports. In the present paper, experimental and economic analyses of a distillation unit equipped with a parabolic solar concentrator have been carried out in order to study the real-time possibilities for its use in desalination.

2. Materials and methods

2.1. Design parameters of parabolic concentrating solar thermal desalination device

The design of parabolic dish is affected by many parameters that include, material of the reflector concentrators, diameter of the parabolic dish concentrator, size of the aperture area of concentrator, focal length of the parabolic dish, sizing of the aperture area of receiver, geometric, and area concentration ratio in addition to solar radiation parameter and thermal properties of the receiver. The steps for designing parabolic solar dish is as follows: (i) calculate the surface area of parabolic dish concentrator, (ii) calculate the focal length of the parabolic dish, (iii) calculate the aperture area of receiver, and (iv) calculate the concentration ratio of the parabolic dish.

2.1.1. Surface area of concentrator

The surface area of dish concentrator (m^2) is defined as the total surface area of the solar concentrator upon which solar energy is incident [34]. The size of the solar concentrator will affect the amount of solar thermal energy delivered to the receiver. The surface area of the parabolic solar dish concentrator was calculated by Eq. (1).

$$A_{\text{con.}} = \frac{\pi}{4} D_{\text{con.}}^2 \tag{1}$$

The surface area of parabolic concentrator made of steel is 2.60 m and the height of disc at center is 28 cm.

2.1.2. Focal length of the parabolic dish

The solar parabolic mirrors of the concentrator are used to focus solar radiation to the receiver, which in turns reflect and focus the radiations on the focal point. Thakkar et al. [37] defined the focal length (f) as the distance from the vertex to the focus. The focal length of the focal point from the dish concentrator was calculated by Eq. (2).

$$\text{Focal length} = \frac{1}{4 \cdot a}; \text{ where } a = \frac{\text{Depth}}{\text{Radius}^2} \tag{2}$$

The focal length of the disc is 72 cm and it is covered with highly reflective silver colored foil of high surface quality and good specular reflectance.

2.1.3. Aperture area of receiver

The receiver is used to collect the maximum amount of reflected solar radiation from dish concentrator for working as a heat source to a fluid. The receiver aperture area was calculated by Eq. (3) [34]:

$$A_{\text{rec.}} = \frac{\pi}{4} D_{\text{rec.}}^2 \tag{3}$$

The absorber, mounted at the focal point, was made of steel alloy which has a receiving surface of 1.50 m.

2.1.4. Geometric concentration ratio or area concentration ratio

The geometric or area concentration ratio (C) is the ratio of the concentrator aperture area to the receiver aperture area [34]. It is important to build solar dish with a concentration ratio greater than 10. The concentration ratio vary from unity to power of 10,000 and may reach values up to 46,000 as mentioned by [34]. The geometric or area concentration ratio (C) was calculated by Eq. (4):

$$C = \frac{A_{\text{con.}}}{A_{\text{rec.}}} \tag{4}$$

The concentration ratio of this parabolic concentrator is calculated about 38.

2.2. Experimental setup

A parabolic concentrating solar thermal desalination device was designed and fabricated during the year 2019. The experimental device comprises a solar parabolic concentrator (SK-14 type) unit with a dish diameter 2.60 m and a performance of up to 700 W. The net power of the concentrator is approximately 600 W in good sunshine hours and the average stagnation temperature at the bottom of the vessel of absorber surface is around 350°C, which is sufficient for boiling of water and steam generation. The number of reflector sheets varies from 24 to 36 in different designs manufactured by different manufacturers. Polished, anodized hardened aluminum sheets are used as reflectors [27]. The system has been designed and fabricated in such a way that it could enable the combined production of distilled as well as hot water. The parabolic concentrating solar desalination device consists of a parabolic dish concentrator, evaporating vessel, condensing unit with glass tube, stand, and distillate jar. The parabolic dish concentrator uses a parabolic mirror that focuses incoming solar radiation on a receiver mounted above the dish at its focal point. The diameter of parabolic concentrator made of steel is 2.60 m and the height of disc at center is 28 cm (Fig. 1). The inner surface of the dish is covered by an aluminum foil to make it work as a reflector. The receiver is fixed in an advanced place to the focal point to confirm receiving all dish reflected rays. The receiver is fabricated from steel of 25 cm diameter and 20 cm depth. The receiver shadow on the collector's face can decrease the amount of solar radiation reflected, so the receiver's insulation thickness is limited. The container has two openings, one in the bottom of water interring the container from the brackish water container, and the other from the top for hot water exit to the distiller. The parabolic dish tilt angle was chosen as 30° from the horizontal facing the south, depending on conclusions of reference [38]. However, the focusing system works effectively on direct solar irradiation, which required taking into consideration another loss. The main part of diffused radiation that is about 20% of the solar beam cannot be focused. For this reason, flat collectors are used for low-temperature applications (diffuse radiation is not lost). The setting procedure employed in this study limited the lost diffuse radiation. The focal length of the disc is 72 cm and it is covered with highly reflective silver colored foil of high surface quality and good spectral reflectance and projected area of disc is 1.50 m (Fig. 2). A silver colored foil of high reflectivity is used because of light weight, ease of covering the dish, and low cost compared to aluminum foil or glass. The absorber, mounted at the focal point, was made of steel alloy which has a receiving surface of 1.50 m and a geometric concentration of 100. The concentration ratio of this parabolic concentrator is calculated as 38. This pot is completely insulated except the part lit by the solar rays reflected by the parabolic surface. The sun tracking mechanism for this solar distiller has two axes according to previous researches and it is a manual system [36,39]. The saline water is kept inside the pot. Glass tube condenser fixed in a wooden box was used in this work. The brackish water is supplied to the glass tube condenser from the concentrating unit where it is condensed. The flow of brackish water is not continuous and steady, and the formed vapor can stop it. This point was taken into consideration, and an aperture in the brackish water storage tank for ventilation was left opened. Distilled water was gathered in a jar and measured every operating hour.

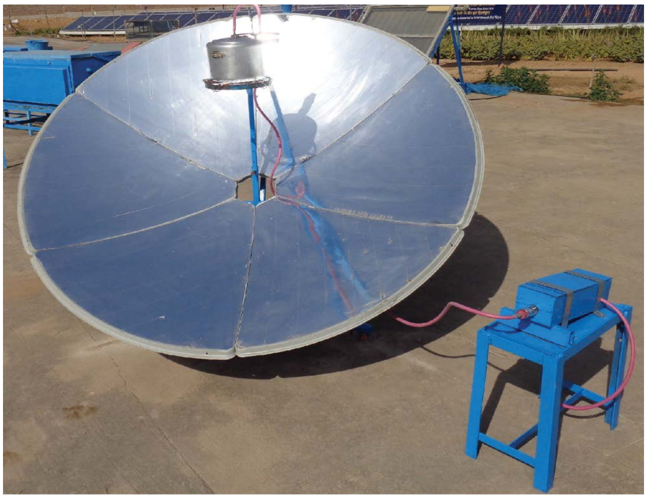

Fig. 2. Parabolic concentrating solar thermal desalination device.

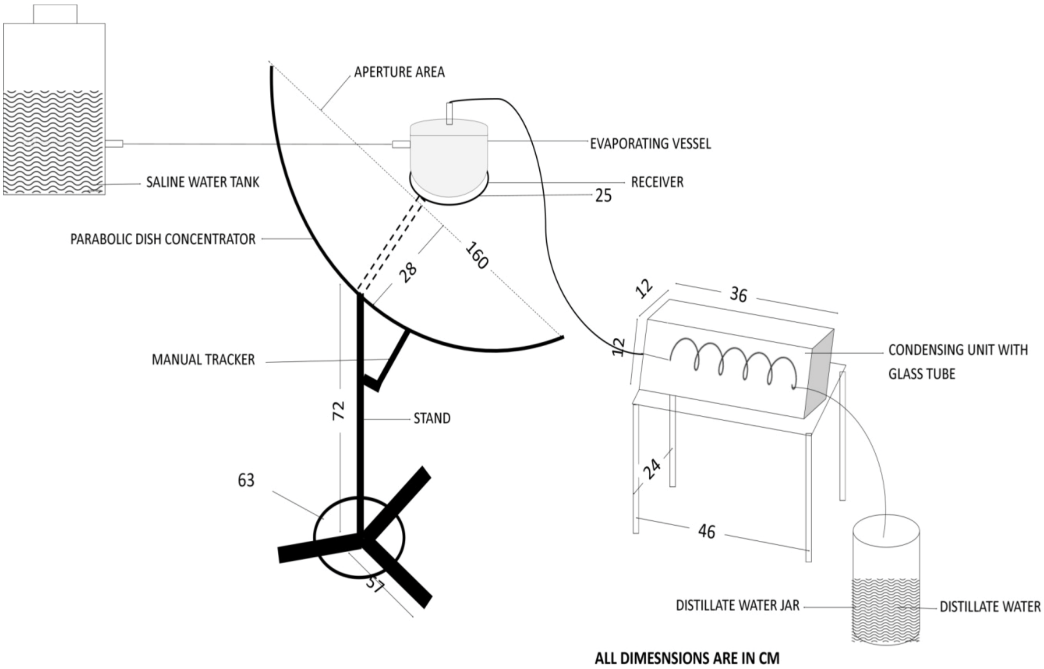

Fig. 1. Schematic diagram of parabolic concentrating solar thermal desalination device.

2.3. Experimental procedure

To predict the performance of parabolic solar concentrator based distillation unit on-field experiments were conducted at the campus of the Central Arid Zone Research Institute, Jodhpur, India, (26°18′N and 73°04′E) for carrying out the performance in winter and summer months during 2019. The still is made to face the south direction and the saline water is poured inside the vessel in the early morning. The absorber is fixed at the focus of the concentrator with the help of the iron stand. The variations of water temperatures of both units as well as the productivity are recorded with time during the entire experiment. The solarimeter Testo 454 was used in the experiments of the solar distillation unit, with a measurement range of 0–1,400 Wm^{-2} with an accuracy of ±0.1 Wm^{-2} and 0.25% error. Temperature was measured using *K* type thermocouples (Chromel–Alumel) with 0.2 mm diameter and accuracy of ±2% were connected to a Testo 935 digital temperature indicator. The range of temperature extends from –40°C to 900°C with an accuracy of ±0.1°C and error is 0.25%. Ambient air temperature was measured using a mercury thermometer (PT 100) (accuracy ±0.55°C, range: 0°C–400°C, and error: 0.25%) placed in an ambient chamber and the distillate output are measured by a measuring cylinder having a least count of 10 mL (accuracy: ±2.0 mL, range: 0–500 mL, and error: 2%).

The performance evaluation of the parabolic solar concentrator based distillation unit has been carried out by measuring distilled water obtained per day and average output of the system. The distillation efficiency and system efficiency were computed by using the following formulae:

$$\eta_{\text{distillation}}(\%) = \frac{m_e \times L \times 100}{I_{\text{bav.}} \times A_p \times \text{hr} \times 3{,}600} \tag{5}$$

$$\eta_{\text{system}}(\%) = \frac{\left[m_{\text{water}} \times C_{\text{pw}}\left(T_f - T_i\right) + m_e \times L\right] \times 100}{I_{\text{bav.}} \times A_p \times \text{hr} \times 3{,}600} \tag{6}$$

where A_p is the aperature area (m²); C_{pw} is the specific heat (J/kg/°C); I_b is the beam radiation (W/m²); L is the latent heat of distiller water (J/kg); m_e is the mass of distilled water obtained (L); m_{water} is the mass of water remaining in evaporative vessel (L); T_i is the initial temperature of evaporative vessel (°C); T_f is the final temperature of evaporative vessel (°C); $\text{h}_{\text{distillation}}$ is the distillation efficiency (%); η_{system} is the system efficiency (%).

2.4. Experimental uncertainty analysis

Experimental uncertainty (error) always exists as a result of the measuring method, observation (reading) process, environmental conditions, and calibration and error of measuring instruments. The error in experimental readings and instruments can be represented as:

$$Z = Z_{\text{best}} + \Delta e \tag{7}$$

where Z_{best} is the best estimated reading of physical quantity, and Δe is an absolute error that occurs during the experiment. The uncertainty in the experimental study is described below.

2.4.1. Internal uncertainty

An estimation of uncertainty is performed for the experimental observations of various parameters. The sample calculations of experimental uncertainty in each set of observations of individual parameters are conducted by Nakra and Choudhary [40], Tiwari et al. [41], and Agrawal and Rana [42]. The mathematical expression of the percentage of uncertainty is presented as:

$$\text{Percentage uncertainty} = \frac{U_i}{B} \times 100 \tag{8}$$

where

$$U_i = \sqrt{\frac{\sigma_1^2 + \sigma_2^2 + \ldots\ldots\sigma_s^2}{S^2}} \tag{9}$$

$$\sigma = \sqrt{\frac{\sum X - \bar{X}}{S_0}} \tag{10}$$

where U_i is the internal uncertainty; B is the average of total number of observations; σ is the standard deviation of one set of observations; S is the total number of observations; $X - \bar{X}$ is the deviation of observations from mean; S_0 is the number of observations in one set.

The sample calculations of experimental uncertainties for distillate outputs for the months of May 2019 (summer) and December 2019 (winter) was worked out by using Eqs. (8)–(10), and found that the uncertainty percentage of the distillate output during summer (May 2019) is 3.33% and during winter (December 2019), the corresponding value is 3.42%, respectively.

3. Results and discussion

Table 1 shows the hourly experimental observations of average air temperature, water temperature, and solar intensity for a typical day in the month of May and December 2019 for the period of 9 h in day times, that is, 9:00–17:00 h in the parabolic solar concentrator based distillation unit. The average maximum water temperature (brackish water) in the case of May and December month are 92.0°C and 83.2°C and the ambient temperature are 37.7°C and 29.1°C, respectively (Table 1). The time gap between the maximum solar intensity value and maximum ambient air temperature increases because of the high thermal inertia of atmospheric air. It is evident that the effect of solar intensity at dawn is less; it gradually increases up to a maximum range, and then decreases until sunset. The average solar insolation was varied in the range of 375 to 980 W/m² in the month of May and 210 to 720 W/m² in the month of December as shown in Table 1.

Figs. 3 and 4 show the instantaneous distillate yield of the parabolic solar concentrator based distillation unit in the summer (May 2019) and winter (December 2019) month.

Table 1
Performance of parabolic solar concentrator distillation unit in summer and winter

Time (h)	Insolation (W/m^2)		Inside water temperature (°C)		Ambient temperature (°C)	
	May	December	May	December	May	December
9:00	542	310	60.0	50.0	30.4	24.2
10:00	711	415	85.0	75.0	33.5	26.0
11:00	871	550	95.0	85.0	35.9	29.7
12:00	945	625	96.0	90.0	38.0	31.7
13:00	980	720	100.0	92.0	39.9	32.3
14:00	935	650	100.0	95.0	41.5	31.8
15:00	779	450	99.0	92.0	41.0	29.7
16:00	580	310	98.0	90.0	40.6	28.9
17:00	375	210	95.0	80.0	38.5	27.4

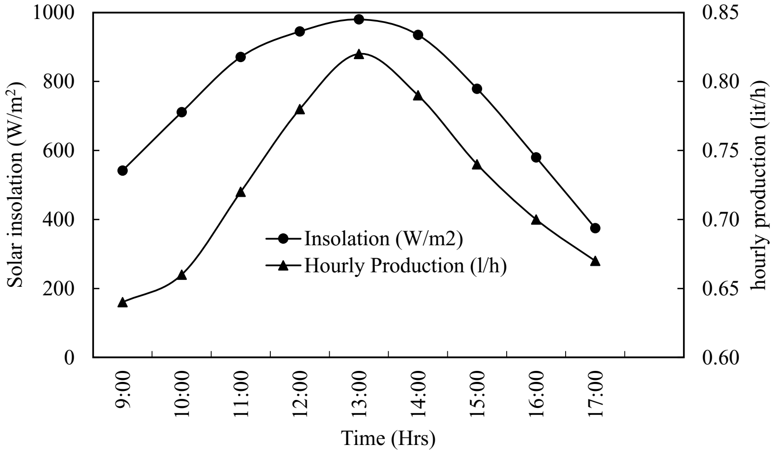

Fig. 3. Variation of distillate yield for parabolic concentrating solar thermal desalination device during May 2019.

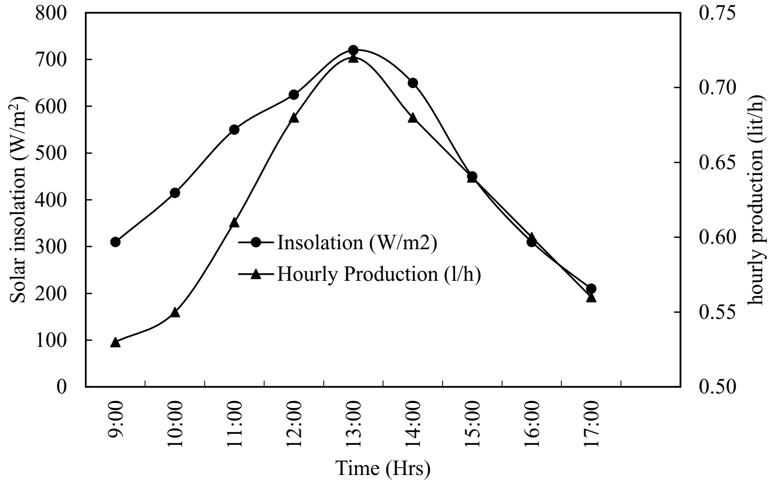

Fig. 4. Variation of distillate yield for parabolic concentrating solar thermal desalination device during December 2019.

The distillate yield was measured with a measuring jar at 60 min intervals from 9:00 am to 17:00 pm. It was observed that steam generation was started after half an hour in each experiment, resulting in production rate of zero at 8:00 am. As the water temperature in the absorber increases, the thermal capacity of the water decreases, causing an increase in the evaporation rate, hence reaching the maximum hourly production rates of at 13.00 h and decreases thereafter as shown in Figs. 3 and 4. This evolution is closely linked to solar lightening, which is responsible for this production and therefore has a similar rate. This deviation can be explained by the fact that in the morning, only a small part of absorbing surface is covered with water because of the strong tilt in addition to the geometry imperfection and the sun's manual follow-up. In the summer month of May 2019, the total cumulative amount of daily productivity was 6.5 L/d, while the productivity in the winter month of December 2019 was 5.50 L/d. The wall temperature of the absorber is increased due to higher values of solar insolation (more than 750 W/m^2) which is the major effective parameter on the productivity [28]. Therefore, steam generation rate and consequently the production rate increase. As the parabolic dish provides concentrated heat flux for the salt water in the absorber, this parameter appears as a driving force for evaporation rate and productivity. In this case, it is expected that the developed point-focus solar still produces acceptable amount of fresh water in high solar intensity weather conditions even in cold and windy hours [28].

The daily efficiency obtained for all of the five experiments days in summer (May 2019) and winter (December 2019) month is shown in Fig. 5. By using Eqs. (5) and (6), the maximum average daily efficiency of the parabolic concentrating solar thermal desalination device was 34.2% in month of May and 32.3% in month of December 2019. It can be observed that the daily efficiency of the December month is less than that of the May month in all experimental days. The efficiency presents an increase in the beginning; then it has a decrease thereafter. The deviations of efficiency can be explained by the fact that in the beginning, only one part of the absorbing surface is covered with salt water, the manual sun pointing, and the existence of imperfections in the concentrator surface. In the other case, the maximum efficiency corresponds to the maximum solar lightning obtained toward 13:00. At this hour, the boiler is nearly in a horizontal position, which maximizes the offered heat transfer surface [36].

Comparing the different types of solar stills, especially those employed as parabolic concentrators, with nearly equal experimental periods shows that the present study has a fairly good performance. The P_d = 4.46 kg/m^2 d was reported by Arunkumar et al. [1] for the hemispherical solar still, during 9 h/d, P_d = 2.65 L/m^2 during 7 h/d [36], and the P_d = 2.34 kg/m^2 d was reported by Chaouchi et al. [27] for the parabolic dish solar still with the same operating hours. Whereas, the still configuration studied by Omara and Eltawil [30] has a productivity of 6.7 kg/m^2 d and the maximum daily efficiency of 68%. The point focus parabolic concentrator solar still found maximum productivity of 5.12 L within 7 h/d [28]. In order to perform a comprehensive comparison, considering all of the effective parameters as the weather conditions and geographical location is mandatory. The present device is superior to metallic and basin type building material made devices as it overcomes the problem of algae, salt accumulation, and corrosion [9,13]. It was found far better as compared to conventional RO plant. However, in hot arid area of India this parabolic concentrating solar thermal desalination device was evaluated for the first time and has tremendous potential for further work with PCM, etc.

A comparison between conventional RO plant and parabolic concentrating solar thermal desalination device was also done using highly saline and the performance of such units was found to be better than that of conventional RO plant. Electrical conductivity (EC) of raw saline water having salt varying from 4.15 to 10.50 m mhos that was reduced to 0.94 to 2.56 m mhos in commercial RO plant while it varied from 0.10 to 0.48 m mhos in solar desalination devices, respectively (Table 2).

4. Economic analysis of parabolic solar concentrator based distillation unit

The economic analysis of the present parabolic solar concentrator based distillation unit was carried out by computing the life cycle cost (LCC) and life cycle benefit (LCB) of the device. In addition, five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (*A*), IRR, and payback period (PBP) were also determined for judging the economic viability of the technology.

4.1. Life cycle cost

LCC of the parabolic solar concentrator based distillation unit is the sum of all the costs associated with a solar desalination energy system over its lifetime in terms of money

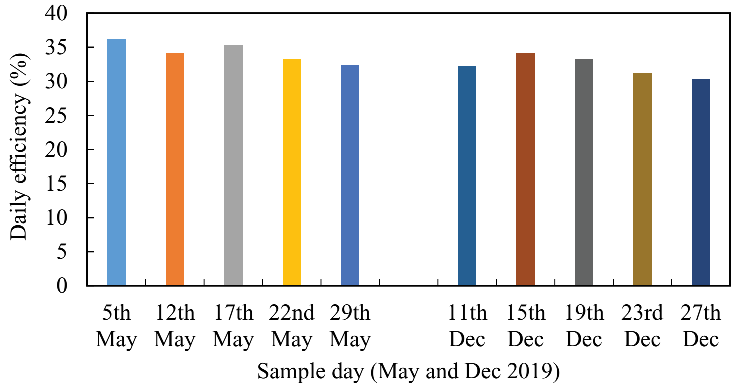

Fig. 5. Daily efficiency of the parabolic concentrating solar thermal desalination device obtained for five experiment days in May and Dec 2019.

Table 2
Comparison of desalination unit with conventional RO

S. No.	Electrical conductivity (EC) of raw water (m mhos)	Electrical conductivity (EC) after desalination (m mhos)	
		Conventional RO	Desalination unit
1	4.15	0.94	0.10
2	8.20	1.85	0.35
3	10.50	2.56	0.48

value at the present instant of time and takes into account the time value of money [43]. The initial investment (P) in desalination unit is INR 14,000. The annual cost of operation and maintenance (O&M) including labor are taken as INR 8,000/y. The benefit was computed for desalination output at a rate of 6.0 L/d for 300 d/y priced at INR 10 a liter. The salvage value is taken as 10% of the initial investment.

4.1.1. Determination of LCC

Economics of parabolic solar concentrator based distillation unit was calculated through LCC analysis. Let P_i is initial investment (INR), E is operational and maintenance expenses including replacement costs for damaged components (INR), n is life of the desalination unit (year), E (SV) is salvage value of the solar desalination unit at the end of the life (INR). The procedure of LCC estimation as adopted by [36,44–46], the LCC is given as:

(i) LCC (Unit) = Initial cost of unit (P_i) + E (O&M costs including labor) – E (SV)

$$\text{LCC} = P_i + E\frac{X\left(1-X^n\right)}{1-X} - \text{SV}\left(1+i\right)^{-n} \tag{11}$$

$$\text{LCC} = 14{,}000 + 8{,}000\frac{X\left(1-X^n\right)}{1-X} - 1{,}400\left(1+i\right)^{-n}$$

$$\text{LCC} = 14{,}000 + 8{,}000\frac{X\left(1-X^{10}\right)}{1-X} - 1{,}400\left(1+0.1\right)^{-10}$$

$$\text{LCC} = 14{,}000 + 8{,}000\frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} - 1{,}400\left(1.1\right)^{-10}$$

$$\text{LCC} = 14{,}000 + 59{,}385 - 540$$

$$\text{LCC} = 72{,}845$$

where $X = \frac{1+e}{1+i} = \frac{1+0.04}{1+0.1}$

where e is the annual escalation in cost (in fraction); i is the interest or discount rate (in fraction); E is the annual expenditure.

4.1.2. Life cycle benefits

The valuse of R (annual benefit) is obtained by using the desalination output at a rate of 6.0 L/d for 300 d/y priced at INR 10 a liter. The ensuring annual benefit from parabolic solar concentrator based distillation unit was about INR 18,000.

The LCB can be given as:

$$\text{LCB} = R\frac{X\left(1-X^n\right)}{\left(1-X\right)} \tag{12}$$

$$\text{LCB} = 133{,}560$$

where R is the gross annual benefit (Rs.) and $X = \frac{1+e}{1+i}$.

4.2. Economic attributes

- BCR: The ratio of discounted benefits to the discounted values of all costs given as LCB/LCC.
- NPW: It is the sum of all discounted net benefits throughout the project given as LCB-LCC.
- The A of the project indicates the average net annual returns given as:

$$\text{(Annuity)} = \frac{\text{NPW}}{\sum_{t=1\text{ to }10}\left(\frac{1+e}{1+i}\right)^n} \tag{13}$$

- PBP: It is the length of time from the beginning of the project before the net benefits return the cost of capital investments (value n for LCB – LCC = 0).
- IRR: It is that rate of interest which makes LCBs and LCC equal (LCB – LCC = 0).

4.2.1. Determination of economic attributes

- BCR: The ratio of discounted benefits to the discounted values of all costs can be expressed as:

$$\text{Benefit cost ratio }\left(\text{BCR}\right) = \frac{\text{Life cycle benefits of parabolic solar concentrator based distillation unit}}{\text{Life cycle cost of parabolic solar concentrator based distillation unit}} \tag{14}$$

$$\text{BCR} = \frac{R\dfrac{X\left(1-X^n\right)}{\left(1-X\right)}}{P_i + E - E(\text{SV})} = \frac{\text{LCB}}{\text{LCC}} = \frac{1,33,560}{72,845} = 1.83 \tag{15}$$

- NPW = LCB – LCC = 60,715.
- The *A* of the project indicates the average net annual returns. This term can be given as:

$$A\left(\text{Annuity}\right) = \frac{\text{NPW}}{\sum_{t=1\text{ to }10}\left(\dfrac{1+e}{1+i}\right)^n} = \text{INR } 8,183 \tag{16}$$

- PBP can be determined as following: –LCC + LCB = 0

$$\text{PBP} = P_i + E\frac{X\left(1-X^n\right)}{1-X} - \text{SV}(1+i)^{-n} = R\frac{X\left(1-X^n\right)}{\left(1-X\right)} \tag{17}$$

$$\text{Or} = 14,000 + 8,000 \times \frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} - 1,400(1+0.1)^{-10}$$
$$= 18,000\frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} \tag{18}$$

$$\text{Or } 14,000 + 8,000 \times \frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} - 540$$
$$= 18,000\frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} \tag{19}$$

$$\text{Or } 13,560 = 10,000\frac{0.945\left(1-0.945^{10}\right)}{\left(1-0.945\right)} \tag{20}$$

$$\text{Or } \left(1-0.945^n\right) = \frac{13,560\ (0.055)}{10,000 \times 0.945} \tag{21}$$

$$\text{Or } 0.945^n = 1 - \frac{13,560\ (0.055)}{10,000\ \times\ 0.945} = 0.921 \tag{22}$$

Or $n \log 0.945 = \log 0.921$

$$n = \frac{\log\left(0.921\right)}{\log\left(0.945\right)} \tag{23}$$

$n = 1.45$ y

Or PBP = 1.45 y

- Internal rate of return (IRR):

The values of NPW at varying discount rates are given in Table 2. From Table 2, it may be inferred that at 10% interest rate the NPW is INR 60,715, respectively. At 50% rate of interest the NPW is INR 8,447. However, the NPW is negative at 100% interest rate (i.e., NPW = INR –8,726). The IRR can determined using data presented in Table 3 and the following relationship:

$$\text{IRR} = \text{Lower discount rate} + \frac{\begin{array}{c}\text{Difference of discount rate} \times \\ \text{NPW at lower discount rate}\end{array}}{\begin{array}{c}(\text{NPW at lower discount rate} + \\ \text{NPW at higher discount rate})\end{array}} \tag{24}$$

$$\text{IRR} = 50 + \frac{50 \times 8,447}{8,447 + 8,726} = 74.6\% \tag{25}$$

The IRR which comes to 74.6% in the present case, which is very high for a project to be economically viable.

The values of five economic attributes, namely, BCR, NPW, *A*, IRR, and PBP was presented in Table 4.

5. Conclusion

This study was undertaken to design, fabricate, and evaluate a parabolic solar concentrator based distillation unit under weather conditions of hot arid region of India during 2019. The effect of various environmental and operational parameters on productivity of the still was discussed. The solar unit can be successfully used for desalination of saline water in rural areas for meeting requirement of potable water. The distillate output of solar unit can be mixed with the available saline water in appropriate proportion to make it drinkable. In fact as much as 20 L/d of potable water (150–180 ppm TDS – total dissolved solids) can be made available in a day from raw water containing 300 ppm TDS by improved solar still. Moreover, the use of this device would result in the reduction of the release of CO_2 to the environment. The solar desalination unit will overcome the problem of corrosion, salt scaling, and algae associated with metallic and basin type solar still made of construction materials. In addition, there is a wide scale adoption of distilled water

Table 3
Values of NPW for different rates of discount/interest (*i*)

Interest rate *i* (%)	NPW (INR)
10	60,715
50	8,447
100	–8,726

Table 4
Values of economic attributes

Sr. No.	Attributes economics	Values
1	BCR	1.83
2	NPW	60,715
3	*A*	8,183
4	IRR (%)	74.6
5	PBP (y)	1.45 years

in dispensaries, laboratories, batteries, etc. According to the previously introduced results and discussions, the following conclusions can be drawn:

- The most effective parameters on productivity are available solar insolation, as the most average daily production rate of 6.5 L/d with the maximum average solar insolation of 745 W m^{-2} during May 2019 and in winter month December 2019, the maximum productivity was 5.5 L/d with the maximum average solar insolation of 471 W m^{-2}.
- The average daily efficiency of the unit was calculated to be 34.2% in month of May and 32.3% in month of December 2019 with the maximum hourly productivity of 0.85 L/h.
- Comparing different types of solar stills, especially those employed as concentrators, with nearly equal experimental periods shows that the present unit has a fairly good performance as this hot arid region receives abundant solar radiation (6.0 kWh/m^2/d).
- The present study is a relatively good starting point for hot arid areas of India and further work is needed to carry out to further improve the efficiency of the still by using the phase change material (PCM) and to extrapolate it on an industrial scale. Therefore, the following recommendations are useful.
- The total weight of the concentrator and the absorber should be decreased. This reduction of weight not only reduces the energy consumption of the sun tracker, but also makes the system more transportable as well as cost effective.
- The quality of the absorber insulation should be improved (both in terms of the material and bracing).

Symbols

$A_{\text{con.}}$ — Interior surface area of solar dish concentrator, m^2
$A_{\text{rec.}}$ — Area of the receiver, m^2
$D_{\text{con.}}$ — Diameter of the solar dish concentrator, m
$D_{\text{rec.}}$ — Diameter of the solar dish receiver, m
C — Geometrical concentration ratio of the solar dish
h — Height of the dish, m
f — Focal length, m
A_p — Aperture of concentrator area, m^2
C_{pw} — Specific heat at a constant pressure for water = 4,200, kJ/kg K
I_b — Beam radiation, W/m^2
L — Latent heat of distiller water, J/kg
m_e — Mass of distilled water obtained, L
m_{water} — Mass of water remaining in evaporative vessel, L
T_i – Initial temperature of evaporative vessel, °C
T_f – Final temperature of evaporative vessel, °C
$\eta_{\text{distillation}}$ — Thermal efficiency of the solar concentrating system, %
η_{system} — System efficiency the solar concentrating system, %
LCC — Life cycle cost of the device, INR
LCB — Life cycle benefit of the device, INR
BCR — Benefit-cost ratio
NPW — Net present worth of the device, INR
A — Annuity
IRR — Internal rate of return, %
PBP — Payback period, y
P_i — Initial investment of the device, INR
E — Operational and maintenance expenses including replacement costs, INR
n — Life of the desalination unit, year
E (SV) — Salvage value of the solar desalination unit at the end of the life, INR
e — Annual escalation in cost (in fraction), INR
i — Interest or discount rate (in fraction), INR
E — Annual expenditure, INR
R — Gross annual benefit, INR

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