Performance analysis of hybrid solar desalination system using ETC and CPC

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Abstract

This paper present analytical and experimental analysis of hybrid solar desalination system using evacuated tube collector (ETC) and compound parabolic concentrator (CPC) to obtain the maximum amount of soft water for drinking and industrial purposes. In this paper, thermal performance of hybrid system with varying heights between ETC and CPC and flow rates are investigated with single effect boiling method. Water is used as working fluid for experimentation and tested for different climatic conditions of Pune city (located in western region in the Maharashtra state, India). The experimental set-up of thermosiphon solar water system mainly consists of ETC and CPC, condenser, inlet water tank, outlet collection jar etc. The CPC (reflector) is used to improve thermal performance of solar desalination system. Further, thermal performance of said solar desalination system has been improved with aluminium foil as CPC (reflector) material. From obtained results, it is concluded that for the climatic conditions of selected location, solar (ETC + CPC) hybrid desalination system could produce 1.5–2 l of fresh water per day and purity is validated as per ISO 12500-2012.

Keywords Evacuated tube solar collector · Compound parabolic concentrator · Condenser · Solar desalination · Distilled water

List of symbols

Q_{abs}	Heat absorbed in kJ	C_{op}	Operating cost
Q_{cond}	Conduction heat loss in kJ	C_{fix}	Fixed charges cost
Q_{conv}	Convention heat loss in kJ	i	Interest per year
Q_{ref}	Reflection heat loss in kJ	M_{dis}	Mass of distilled water
Q_{loss}	Heat loss in kJ	A_c	Area of collector in m ²
Q_u	Useful heat in kJ	I_g	Intensity of solar radiation in W/m ²
H	Total height of CPC in mm	D	Diameter of evacuated tube in mm
a	Circumference of the absorber in mm	L	Length of evacuated tube in mm
d	Diameter of the CPC in mm	N	Number of evacuated tubes
Di	Inner diameter of evacuated tube in mm	C_R	Concentration ratio
B	Internal surface between tubes in mm	f	Focal length in mm
n	Reflective index	F_r	Heat loss factor
η_{opt}	Optical efficiency in %	A	Normal absorption factor
B	Collector tilt angle in degree	Do	Outer diameter of evacuated tube in mm
ETC	Evacuated tube collector	A_{abs}	Absorber area in m ²
MSF	Multi stage flash	T	Normal projection factor
RO	Reverse osmosis	θ	Air solar heater absorber groove angle
		θ_c	Acceptance half angle

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<i>CPC</i>	Compound parabolic concentrator
<i>MED</i>	Multi effect distillation
<i>C_t</i>	Total cost
<i>C_{main}</i>	Maintenance cost
<i>a</i>	Amortization factor
<i>n</i>	Number of life years
<i>C_{prod}</i>	Cost of production

1 Introduction

Now a day's demand of renewable energy is very high as non-renewable energy sources continuously depleting day by day. This research is an attempt to use solar energy for the desalination system. Earlier researchers have studied solar desalination system with reverse osmosis, membrane distillation, multi effect distillation, multi effect boiling, multi stage flash, electro dialysis etc. This paper mainly focuses on single effect boiling method with hybrid (ETC + CPC) desalination system. Now a days evacuated tube solar collector and compound parabolic concentrator are widely used for heating of fluids with the help of solar energy. Evacuated glass tube is made up of borosilicate glass with outer surface of inner tube coated with selective coating (Al-Ni) for the maximum amount of solar energy absorption and minimum heat loss. Though the solar rays enters to outer evacuated glass tube, heat is generated inside the inner tube with help of selective black coating (Al-Ni). Compound parabolic concentrator is made of aluminium sheet to increase the overall heating performance of solar desalination system. Earlier researcher had developed different mathematical models based on mass and energy conservation. This paper reports the analytical and experimental performance evaluation of developed hybrid mathematical model for desalination system.

Many researchers worked on the investigations of the solar desalination system Kumar et al. [1] studied the thermal performance of one end evacuated tube to produce hot air and observed that the reflector of solar air collector offers higher outlet temperature of air as 97.4 °C, whereas Al-Tabbakh et al. [2] performed experimental analysis of evacuated tube solar water collector with serpentine flow through pipe to find out the applicability to produce high temperature water or steam. Hunashikatti et al. [3] developed desalination unit using solar still coupled with evacuated tubes for domestic application. Experimental studies of single slope, single still solar still integrated with evacuated tube in natural mode in climatic conditions of Bangalore Karnataka, India. Yadav et al. [4] experimentally investigated thermal performance of one end evacuated tube solar air collector at different flow rates with focus on air heating with the help of evacuated tube collector, whereas Dabra et al. [5] experimentally investigated the effect of

tilt angle on the performance of evacuated tube solar air collector. Tilt angle indicated that no positive effect on the thermo-syphon phenomenon inside the evacuated tubes. Reddy et al. [6] analysed the performance of evacuated multi stage solar water desalination system and seen that the multi stage evacuated solar desalination system is a viable option to meet the need of rural and urban communities. Yadav and Bajpai [7] developed evacuated tube solar collector for heating of air and observed that temperature difference of upper head and lower head, both of surface of pipes on the respective ends was lower in down flow. Ahmed et al. [8] had improved the productivity and efficiency of simple solar still with main focus on characterisation of multistage evacuated solar distillation, whereas, Shafii et al. [9] developed modified solar desalination system using evacuated tube collector and observed that theoretical model evaluated the system efficiency in quasi-static steady conditions. Arunkumar et al. [10] studied the effect of water and air flow on concentric tubular solar water desalting system and reported an innovative design of tubular solar still with a rectangular basin for water desalination system. Kedar et al. [11, 12] mainly worked on thermal analysis and experimental investigation on solar desalination system using evacuated tube collector.

Wisut et al. [13] investigated thermal performance of heat pipe with compound parabolic concentrator by ISO 9806-1 in which it is observed that the monthly average energy of the compound parabolic concentrator produced throughout the year is equal to 286.16 K or equal to 34.33.87 kWh/year. Borah et al. [14] developed a compound parabolic concentrator to increase the solar intensity for effective temperature with increase in solar radiation trapping time at constant temperature level by 1.5 h in comparison with to fixed compound parabolic concentrator. Saettone [15] describes a desalination system using parabolic through concentrator with the focus on PTC as a distiller device aligned on east–west orientation and using solar tracking system. Jiang et al. [16] presented characterization of novel mid-temperature CPC solar thermal collectors with testing method for two novel medium temperature solar thermal collectors with oil as the heat transfer fluid in the system. Umair et al. [17] developed compound parabolic concentrator with maximum effective temperature for solar driven system. Stefanovic et al. [18] described mathematical model and numerical simulation of CPC-2V concentrating solar collector. Kedar et al. [19] mainly presented the design and analysis of solar desalination system using compound parabolic concentrator.

Mohammad et al. [20] developed hybrid solar wind water desalination system and obtained that the yield can be 3–4 times more than conventional solar distillers. Their system mainly based on single basin solar still and a wind

water heater operating simultaneously, whereas Kedar et al. [21] studied the theoretical approach for hybrid solar desalination system using evacuated tube collector and compound parabolic concentrator. Poblete et al. [22] investigated the factors influencing the efficiency of the solar still combined with solar collector with the conclusion that the drying performance of the solar still can be increased using adequate operational controls in dewatering of brine. Sotehi et al. [23] studied hybrid PV/T water solar collector for non-zero energy building and fresh water production, whereas Kabeel et al. [24] studied the performance and productivity analysis of the modified solar power driven hybrid desalination system experimentally.

Kabeel et al. [25] reviewed the water desalination system using humidification and dehumidification techniques with main focus on thermal modelling of various types of humidification and dehumidification (HDH) distillation system, whereas Kabeel et al. [26, 34] mainly described a hybrid solar desalination system of air humidification and dehumidification with different configuration and water flashing evaporation. Kalogirou [27] studied the seawater desalination using renewable energy sources for desalination. Patel et al. [28] performed critical review with computational fluid dynamics (CFD) analysis of evacuated tube collector. Ali et al. [29] provided a comprehensive review of all the indirect solar desalination technologies along with plant specific technical details whereas Kabeel et al. [30] mainly described a review of water production for irrigation and drinking needs in remote arid communities using closed-system greenhouse and performed a critical review of development strategies and solar thermal energy utilization for water desalination system in remote region [31]. Sampatkumar et al. [32] performed the in-depth review of active solar distillation and observed that thermal modelling is done for various types of active single slope solar distillation system, whereas Elshamy et al. [33] worked on comparative study based on thermal, exergetic and economic analyses of a tubular solar still with semi-circular corrugated absorber.

Sapre and Auti [35] worked on design and manufacturing of absorber for solar desalination system in which absorber was designed as a thin wall pressure vessel manufactured by rolling, pressing and welding process. Siddiqui et al. [36] studied performance improvement of solar desalination system by using solar air heater and observed that the daily productivity and gained output ratio increased significantly, whereas Rajput et al. [37] mainly studied the utility of solar radiation at destination Pune and estimated the monthly averages of a sunshine hour and monthly variation of entire solar radiation. Kazemian et al. [38] presented experimental investigation of reverse osmosis with the help design of experiments method. The study mainly focuses on comprehensive techno-economic evaluation

of RO based process for changing energy consumption. Zheng et al. [39] studied on group of multi-effect tubular solar desalination devices and indicated that the devices exhibit excellent application prospects. Khalil et al. [40] presented solar water desalination using an air bubble column humidifier with the observation that the air bubble column achieves higher performance than the conventional humidifier. Ahmed et al. [41] had improved the productivity and efficiency of simple solar still with main focus on characterisation of multistage evacuated solar distillation. Wu et al. [42] studied heat and mass transfer in air bubbling enhanced vacuum membrane distillation and observed significant influence of temperature polarization coefficient (TPC) and concentration polarisation coefficient (CPC) due to flow patterns. Auti et al. [43–45] design parabolic concentrator for solar desalination system with absorber and produced 20 l drinking water within 6 h, whereas Liu [46] studied the thermal and economic analysis of desalination system using low-temperature multi-effect desalination system. Ahsan et al. [47] described detailed comparison of six numerical models for estimation of water production from solar still and seen that present evaporation and condensation model are the most reliable tool for predicting the daily production of the tubular still. Whereas, Palanisami et al. [48] studied experimentally the desalination of real seawater using direct membrane distillation process. Moungar et al. [49] describes double slope still with fins immersed in a basin for Algeria climatic condition and observed that the productivity of the proposed system about 15–27% higher than that of simple single slope still. Whereas Bhambare et al. [50] presented an overview of desalination status and fresh water demand, fuel requirements, solar energy availability, thermal desalination technologies and solar thermal technologies of Oman. Abdullahi et al. [51] described the optical and thermal performance of double receiver compound parabolic concentrator to highlights the potential of two tubular receivers or single elliptical one aligned horizontally in one concentrator, whereas Kabeel et al. [52, 53] studied technological aspects in low—capacity solar thermal desalination units and developed economic analysis of a small scale hybrid air HDH-SSF (humidification and dehumidification water flashing evaporation) desalination plant.

From literature review as well discussion with expert working in same domain it observed that, most of the studies performed by earlier researcher are based on RO, MSF, MEB, humidification and dehumidification etc. Their primary focus was to predict thermal performance of evacuated tube, compound parabolic concentrator, and wind turbine for solar desalination system. Again it is observed that the numerical studies for solar and wind hybrid system is performed for desalination. However due to inherent limitations of experimental measurements and

maximum availability of drinkable soft water through (ETC + CPC) hybrid system is necessary. Along with this whole study is planning to perform for different climatic and environmental conditions of Pune city. Thus main objective this study is to develop mathematical model in hybrid system (ETC + CPC) for desalination system.

This paper presents a new hybrid solar desalination system of evacuated tube collector and compound parabolic concentrator. An evacuated tube solar water heater is integrated with compound parabolic concentrator to evaluate the continuity production of distillate water. Thermal performance of the developed hybrid solar desalination system is studied. All experimentation is performed for the climatic and environmental conditions of the Pune city. This paper reports an attempt to develop mathematical model to estimate the heat absorbed by ETC and CPC, total exposed area of collector, heat loss to surrounding by solar collector and net heat gain.

2 Thermal model of hybrid system

Thermal model is developed for solar desalination system under atmospheric conditions of Pune city. For solar desalination system hard water is used as working fluid which is easily available in the nature. For hard water hardness lies in the range of 270–400 mg/l. Through the entire developed system all possible parameters are controlled with specified limits as per IS standard 10500:2012 drinking water specification. The developed mathematical model (refer Fig. 1) depends upon on the energy conservation. In particular mathematical modelling serves the purpose for collector runs significantly. Following assumptions are made for propose mathematical model of hybrid energy system.

- Evacuated tube collector and compound parabolic concentrator is undergoing to steady state.
- Solar diffused radiation on the actual system is neglected.
- Heat flow through back insulation is less.

- Heat flow through ETC glass tube and CPC is one dimensional.
- There is no shading on ETC and CPC.
- There is no heat loss for the entire system.

The flow of evacuated tube collector is completely closed in addition to copper tubes inserted inside the tubes. The main purpose of the copper tubes, copper has high thermal conductivity 380 w/mK, with latent heat of evaporation 4796 J/g and latent heat of fusion 205 J/g and maximum heat storing capacity. On one side hard water comes into the tubes and another side steam passing through to the condenser. Their use as a first wall material has been proposed in designs where high thermal loads are expected on the first wall or where a shell of high electrical-conductivity material is required. Copper alloys have also been considered for the electrically-conducting material. The following equations are considered for mathematical modelling in evacuated tube collector and compound parabolic concentrator (Fig. 2).

The quantity of heat absorbed by evacuated tube collector,

$$Q_{abs} = A_c \times I_g \times \eta_{opt} \quad (1)$$

Total area exposed to collector,

$$A_c = \pi \times D \times L \times N \quad (2)$$

Heat loss to surrounding by solar collector,

$$Q_{loss} = Q_{Cond} + Q_{Conv} + Q_{ref} \quad (3)$$

Net Heat gain by collector,

$$Q_u = Q_{abs} - Q_{loss} \quad (4)$$

Heat absorbed by ETC and CPC

$$\begin{aligned} &= (Q_{abs} + Q_u) \\ &= (A_c \times I_g \times \eta_{opt}) + (A_c \times F_r \times (S - U_L(T_i - T_a))) \\ &= (A_c \times I_g \times \eta_{opt}) + (A_c \times F_r \times (S - U_L(T_i - T_a))) \\ &= A_c \times ((I_g \times \eta_{opt}) + (F_r \times (S - U_L(T_i - T_a)))) \end{aligned} \quad (5)$$

Fig. 1 Thermal model of evacuated tube collector with Cu tubes

Fig. 2 Compound parabolic concentrator model

Total area exposed to collector ETC and CPC,
 $A_{abc} = \pi \times D \times L \times N$

Heat loss due to surrounding solar collector = (Q_{loss})

$$= (Q_{cond} + Q_{conv} + Q_{ref}) \quad (6)$$

Net heat gain by the collector,

Q_u = Heat absorbed by collector – Heat loss by collector

Considering the flow in evacuated tube collector and compound parabolic concentrator is completely enclosed. The energy balance equation can be applied to determine the variation in mean temperature of working fluid. Hence heat gain by the working fluid represented as,

Heat gain by the working fluid

$$= c_f \times (\delta T_f / \delta t) + u \times (\delta T_f / \delta x) + C_R \times (\delta T_f / \delta x) + u \times (\delta T_f / \delta x) \quad (7)$$

Compound parabolic concentrator is a radiation concentrator of the fixed concentrator having moderate temperature in the range of 100–300 °C with solar radiation reflector. The main purpose of compound parabolic concentrator (Fig. 2) is to utilize solar heat and reverse back to evacuated tube collector bottom side for maximum amount of soft water formation within less time. The above equations are used in compound parabolic concentrator.

Concentration ratio depending on the medium between reflector area and acceptance half angle is given as, $C_{R2-Dimension} = (n / \sin \theta_c) \approx$ total height of compound parabolic concentrator (H), focal length (f), acceptance half angle (θ_c), circumference of the absorber (a), diameter of CPC (d)

$$H = (a/2) \times (0.5 + (1/\pi \sin \theta_c) + (1/(\sin \theta_c \times \tan \theta_c))) \quad (8)$$

The parabolic arc can be represented by,

$$BC = (d/2) \times [(\beta + \theta_c + \pi/2) - \cos(\beta - \theta_c)] / (1 + \sin((\beta - \theta_c))) \quad (9)$$

Using these equations, selected parameters such as intensity of solar radiation, mass flow rate, absorber area, density and specific heat of fluid and temperature are considered for modelling. Using Buckingham's π theorem π_1, π_2, π_3 equations are generated with the help of regression analysis to generate the equation in the form of mass flow rate of water for solar desalination.

Quantity of soft water is mainly depends on intensity of solar radiation, flow rate of water, heat transfer rate in water to steam and steam to water.

$$m = \{1.802 \times 10^{-6} \times (\rho \times k) \times (Q^{0.605} \times I_g^{0.21} \times D^{0.22}) \times (y \times \theta)^{0.185}\} / (\Sigma A_{abs}^{0.2025}) \quad (10)$$

Hence, rewriting Eq. (10) in the form of 'Q' i.e. quantity of soft water for desalination system as,

$$Q = m \times (\Sigma A_{abs}^{0.2025}) / (1.802 \times 10^{-6} \times (\rho \times k) \times (I_g^{0.21} \times D^{0.22}) \times (y \times \theta)^{0.185})^{(1/0.605)} \quad (11)$$

From Eq. (11) it is seen that output parameter 'Q' mainly depends upon intensity of solar radiation, density of fluid, quantity of heat absorbed, absorber area of the evacuated tube and compound parabolic concentrator.

3 Materials and method

3.1 Experimental setup

The experimental set-up of the this study is located in the premises of MKSS's Cummins College of Engineering for Women, Karvenagar Pune, Maharashtra (INDIA) [74.15° (74°9' East), latitude 18.6° (18°36' North)]. The experiments

Table 1 Evacuated tube collector configuration

ETC related parameter	Symbol	Dimension
ID of tube	D_i	47 mm
OD of tube	D_o	65 mm
Internal surface between tubes	B	116 mm
Length of the tube	L	1500 mm
Glass thickness	t	1.6 mm
Absorber area	A_{abs}	1.6 m ²
Normal projection factor	T	0.92
Normal absorption factor	A	0.86
Heat loss coefficient	U_L	2w/m ² °C
Heat loss factor	F_r	0.95
Refractive index	n	1.474

are carried out during the period of March 2018 to May 2018. The experimental set up mainly consist of evacuated tube collector, compound parabolic concentrator, condenser, hard water tank, Cu tubes inside ETC and soft water collecting flask.

One evacuated tube is selected and compound parabolic concentrator is designed and fabricated to evaluate the performance of solar desalination system. Pilot experiments are performed to evaluate the performance of designed solar desalination system which help to improve and modify the developed experimental setup. The photographs of solar

desalination system are shown in Figs. 4, 5. Table 1 shows the specifications of evacuated tube (Fig. 3). In case of evacuated tube collector, the evacuated tube with length of 1500 mm, outer diameter (OD) 65 mm and inner diameter (ID) 47 mm respectively is selected. The evacuated tube (Fig. 3) made of borosilicate glass tube. The whole tube inner surface was coated with black paint from inside to increase the absorptivity. In the tube vacuum was created to heat the fluid. Inside the evacuated tube two copper tubes are added to heat the water with higher rate. At one side of the copper tube hard water flows with moderate velocity, while at the other side heated water in the form of steam flows. Plastics pipes are connected to drain the fresh water distillate. To get the fresh water (distillate) the formed steam passes through surface condenser and other pipe is connected to basin i.e. bottom of the surface condenser to drain the brine to waste.

On the bottom side of the evacuated tube, compound parabolic concentrator was mounted to enhance the heat transfer rate or steam formation rate to get maximum amount of soft water at the outlet. Compound parabolic concentrator mainly consists of collector and frame supporting the evacuated tube (Fig. 4). The overall hybrid system (ETC + CPC) is proposed for solar desalination system as shown in Fig. 5. The Table 1 shows that entire specifications of evacuated tube collector.

Fig. 3 Evacuated tube

Fig. 4 Compound Parabolic Concentrator at inclined stage

Fig. 5 Hybrid (ETC+CPC) system

3.2 Experimental procedure

Different experiments are performed on hybrid desalination system in outdoor environment and climatic conditions of Pune city located in western region in the state of Maharashtra. The entire set was fixed due to south during experimentation. The different parameters as ambient temperature of water (input), temperature of evacuated

tube glass cover, water vapour, intensity of solar radiation, wind speed were measured for half time interval. The temperatures at different points are measured with the help of thermocouples. Wind speed is measured by wind anemometer. Intensity of solar radiation is measured with by solar power meter. For the entire day inlet mass flow rate of water is constant. It is measured with the help of water meter. For the entire different days in the month of

March 2018 to May 2018, different experiments are connected with variable flow of water and variable distance in between ETC and CPC. The generated fresh water (distillate) is collected in the graded Jar to quantify the amount of fresh water. The steps of experimental procedure are as follows: (1) Fill the hard water tank up to it reaches the operating levels. (2) Adjust the test case parameters (temperature, flow rate) (3) Keep ready all instruments for measurements of various parameters (such as intensity of solar radiation, wind velocity, thermometer, flow rate etc.) (4) Open the non-return valve through which hard water flows into copper tubes in evacuated tube collector. (5) Set and adjust open and close timing of valve according to water flow rates. (6) The valve is then adjusted to another point of copper tubes through which steam passes through the condenser. (7) Adjust the steam stop valve for smooth flow of steam to condenser. (8) Then collect saline/soft water in jar. (9) Repeat steps 3–8 for different flow rates and different distances between ETC and CPC.

To evaluate the performance of hybrid solar desalination system parameters such as variation of water flow, variation of the distance between ETC and CPC with keeping inclination angle of solar radiation constant for the Pune city are studied. The half hourly variation input and output for hybrid solar desalination system were observed and data collected for thermal performance of hybrid solar desalination system. Different experiments are carried out as per the environmental and climatic condition of Pune city.

After entire experimentation of hybrid solar desalination system using evacuated tube collector and compound parabolic concentrator, different samples are prepared in inlet hard water and outlet distilled (fresh) water is tested using WHO guidelines and Indian standard drinking water specification (IS 10500:2012) for the Pune city region villages (such as Dapodi (bhophkhel), Hadapsar, Kothrud, Cummins COEW Karvenagar Pune, Ravet, Katraj, Nigdi). For the entire Pune city region obtained results shows that outlet water from the developed hybrid desalination system is suitable for drinking and industrial applications and useful to reduce the contaminants of inlet water samples. This entire system is successful for reducing total dissolved solids, hardness and alkalinity present in the inlet water sample. This distillate obtained from the system contains

chemical contaminants within the limit of drinking water standard.

3.3 Chemical analysis of water samples

After entire experimentation of hybrid solar desalination system using evacuated tube collector and compound parabolic concentrator, different samples are prepared in inlet hard water and outlet distilled (fresh) water is tested using WHO guidelines and Indian standard drinking water specification (IS 10500:2012) for the Pune city region villages (such as Dapodi (bhophkhel), Hadapsar, Kothrud, Cummins COEW Karvenagar Pune, Ravet, Katraj, Nigdi). For the entire Pune city region obtained results shows that outlet water from the developed hybrid desalination system is suitable for drinking and industrial applications and useful to reduce the contaminants of inlet water samples. This entire system is successful for reducing total dissolved solids, hardness and alkalinity present in the inlet water sample. This distillate obtained from the system contains chemical contaminants within the limit of drinking water standard.

3.4 Experimental error analysis

There were some uncertainties associated with experimental measurements system. Solar power meter, anemometer, water flow meter, thermocouple, infrared thermometer instruments used for measurement. Uncertainties measurements have been carried out. Calculations shows that the total uncertainty in estimation of daily performance efficiency and number of soft water in litres was approximately $\pm 2\%$ to $\pm 4\%$ respectively (Table 2).

3.5 Model validation

The hybrid solar desalination system model is validated by comparing theoretical with corresponding experimental results. The different graph shows that theoretical and experimental data; It is observed that there was an acceptable agreement between theoretical results and experimental results. The deviation between experimental and theoretical results is very minimum i.e. 3–4%. These

Table 2 Instruments specifications

Sr. No.	Parameter	Instrument	Type/Model	Range
1	Temperature	Infrared thermometer	IRL-380	– 50 to 380 °C
2	Wind velocity	Anemometer	KM-910	0–45 m/s
3	Intensity of solar radiation	Pyronometer (Solar power meter)	KM-SPM-530	0–2000 W/m ²
4	Flow rate of water	Water flow meter	STD	0.01–100 lpm

Fig. 6 Variation of solar radiation and wind velocity through a day for Pune city

deviations may be due to the ambient conditions considered for half hourly theoretical reading.

4 Results and discussion

4.1 Effect of intensity of solar radiation and wind speed on solar desalination system

The numbers of test are performed on the various combinations in hybrid solar desalination system using ETC and CPC. Figure 6 shows the variation of the effect of intensity of solar radiation and wind velocity on the solar desalination system. From Fig. 6 it is seen that as the intensity of solar radiation increases, it produces maximum amount of distilled water. As compared to morning time, during afternoon maximum distilled water is collected, which result in increase in the water productivity. In hybrid solar desalination system, the effect of wind speed was considered. The wind speed was measured with the help of anemometer. It is also notice that the wind velocity has

no significant effect on performance of the hybrid solar desalination system. The Fig. 6 shows that in the morning and afternoon wind flows at the average speed of 4–6 m/sec for the climatic conditions of Pune city region.

4.2 Effect of ambient temperature on the performance of solar desalination system

The ambient temperature of Pune city region varies from 23 to 35 °C. Figure 7 indicates that the ambient temperature varies from morning time to evening time. There is increase in ambient temperature during afternoon as compared to from morning. Maximum temperature difference is observed in the entire session for heating of water, which indicates that it will be higher rate of absorption (heat). Due to this, the ambient temperature in summer season varies in the range 25–40 °C. Figure 7 shows the variation of fresh water with respect to time. During morning very less amount of fresh water is collected and then it increases during afternoon time. The rate of evaporation

Fig. 7 Variation of solar radiation and ambient temperature through a day

Fig. 8 Variation of solar radiation and collector outlet temperature through a day

equal to the rate of formation of soft water. During the entire experimentation amount of soft water formation from morning to evening per day is approximately 1.7 l. It is notice that the behaviour of the distillation depend on the intensity of solar radiation and wind speed. Due to higher rate of evaporation, the formation of water droplets observed to be higher in afternoon session of the solar desalination system. Figure 7 mainly present the variation of solar radiation with ambient temperature throughout a day in Pune city. From the Fig. 8 it is clearly observed that from 11:00 AM to 13:00 PM intensity of solar radiation gradually increases in the range of 800–900 W/m² with collector outlet temperature 70–85 °C. For the Pune city region ambient temperature of air varies in the range of 30–34 °C. Due to increase in intensity of solar radiation as well as ambient temperature the satisfactory results are observed to get the maximum amount of soft water which is useful for drinking as well as industrial applications.

Figure 8 shows that entire variation of solar radiation and collector outlet temperature throughout the day.

From Fig. 8 it is seen that collector water outlet temperature continuously increased from morning to afternoon. The maximum collector outlet temperature recorded as 85 °C along with solar intensity of radiation 930 W/m². Figure 9 shows that variation of collector outlet temperature with soft water collected entire throughout the day. From the Fig. 9 it is observed that collector outlet temperature increases with increasing rate of soft water collection. For the entire day soft water collected 1.7 l from single hybrid (ETC + CPC) configuration.

4.3 Effect of water flow rate with varying distance between ETC & CPC

Figures 10, 11 and 12 shows the variation of water flow rates with varying distance between (ETC + CPC) on the performance of soft water collected from hybrid desalination system. From Fig. 10 it is observed that for (ETC + CPC) distance 10 cm, water flow rate was 0.03 lps. From the Fig. 11 it is observed that for (ETC + CPC) distance 20 cm,

Fig. 9 Variation of collector outlet temperature with soft water collected through a day

Fig. 10 Effect of water flow with distance between ETC & CPC = 30 cm and water flow rate = 0.03 lps

Fig. 11 Effect of water flow with distance between ETC & CPC = 20 cm and water flow rate = 0.02 lps

Fig. 12 Variation of water flow with distance between ETC & CPC = 10 cm and water flow rate = 0.01 lps

water flow rate was 0.02 lps and from the Fig. 12 it is observed that for (ETC + CPC) distance 10 cm water flow rate was 0.01 lps. From Figs. 10, 11 and 12 is seen that soft water collected 1.5, 1.7, 2.1 l for (ETC + CPC) distances as 30, 20, 10 cm. Figures 10, 11, and 12 shows that effect of variable flow rate of water. In the present study tests are performed for 8–10 h (from 7:00 AM to 18:00 PM). Less amount of flow of water flow rate (i.e. 1 lpm) resulting

maximum amount of soft water collected in entire day. Figure 12 shows that the variation of soft water collected for the 0.03, 0.02, 0.01 lps flow rate of water. If the flow rate of water increases, results in production of less amount of soft water. Various tests are conducted with varying the flow rate of water. It is observed that in the afternoon time from 13:00 PM to 15:00 PM maximum amount of soft water is generated for the same position of system. Hence there

is direct correlation of flow rate with the output distilled water for hybrid solar desalination system.

The Figs. 10, 11 and 12 shows the effect of varying distance in between (ETC + CPC). A distance of 10 cm was maintained in between ETC and CPC. In this case concentration ratio is very high result in high heat transfer between evacuated tube and compound parabolic concentrator. Hence due to higher concentration ratio maximum amount of soft water is generated in hybrid solar desalination system. On next day the distance in between ETC and CPC was increased to 20 cm and 30 cm etc. It is observed that as the distance increases, evacuated tube collector heating time is more to get minimum amount of soft water per day from morning to time. This represents the daily distillate amount of soft water per day.

Hence as the distance in between ETC and CPC increases result in less quantity of soft water due to maximum heating time required to heat evacuated tube. Also it is observed that radiation and conduction loss may be more in the solar desalination system. To avoid the losses, it is recommended to keep optimum distance (ETC + CPC) to get the best performance of solar desalination system.

4.4 Effect of pH, TDS, hardness, calcium on hard and soft water

From Fig. 13 it is observed that in various regions of Pune city such as Dapodi (bhophkel), COEW Karvenagar, Ravet, Hadapsar, Katraj, Nigdi, Kothrud the pH values of soft water and hard water are as 7.24, 7.23, 7.46, 7.1, 7.23, 7.67, 7.67 etc. and 7.9, 7.35, 7.98, 7.82, 7.67, 7.9, 7, 9 etc. (State region of pH Variation). Figure 14 shows the TDS range various from 600 to 1400 mg/l for the Pune city and soft water range observed below 200 mg/l. Figure 15 shows the effect of hardness for the various region of Pune city. It is observed that maximum hard water observed in Katraj region as compared to bhophkel and Ravet region. Maximum TDS in hard water observed in Hadapsar region as compared to Nigdi region. Figure 15 shows hardness of hard and soft water of various regions in Pune city. The average range varies from 300 to 600 mg/l for hard water in the Pune city and soft water range observed below 100 mg/l. Figure 15 shows the effect of hardness for the various region of Pune city. It is observed that maximum hard water observed in Katraj region as compared to bhophkel and Ravet region. Maximum hardness in hard water observed in Hadapsar region as compared to Nigdi region. Figure 16 shows calcium of hard and soft

Fig. 13 Effect of pH on Hard and Soft water samples for different region of Pune city

Fig. 14 Effect of total dissolved solids (TDS) on hard and soft water samples for different region of pune city

Fig. 15 Effect of hardness on hard and soft water samples for different region of pune city

Fig. 16 Effect of Calcium on hard and soft water samples for different region of pune city

water of various regions in Pune city. The average range varies from 60 to 120 mg/l for hard water in the Pune city and soft water range observed below 15 mg/l. Figure 15 shows the effect of hardness for the various region of Pune city. Similarly it is observed that maximum hard water observed in Katraj region as compared to bhokhel and Ravet region. Maximum hardness in hard water observed in Hadapsar region as compared to Nigdi region. For the region of Pune city (the entire area covered) the various parameters are tested in Hydrotech Laboratory at Pune. For all the samples as per laboratory report indicate that the entire new hybrid solar desalination system (ETC + CPC) model is useful for drinking and industrial applications. Again it is observed that water quality lies acceptable limit according to IS standard and WHO guidelines.

4.5 Variation of soft water and collector outlet temperature with time

Many researchers worked on solar desalination system using evacuated tube collector as well as compound parabolic concentrator. Hunashikatti et al. [3] developed

desalination unit using solar still coupled with evacuated tubes for domestic application. From experimental studies of single slope, single basin solar still integrated with ten evacuated tube (in natural mode in climatic conditions of Bangalore Karnataka, India) it is observed that the maximum distillate yield obtained for the basin of area 0.51 m^2 was 5.534 kg of water depth 0.02 m for the time period of 7.00 PM–19.00 PM. During this experimentation they mainly focus on intensity of solar radiation and coupled system with water depth 0.02 m, 0.04 m, 0.06 m and obtained less amount of soft water, whereas the proposed hybrid single ETC and CPC system produces 1.7 l of soft water for the time period of 7.00 AM–18.00 PM. Similarly Reddy et al. [6] conducted performance analysis of an evacuated multi-stage solar water desalination system utilizing latent heat recovery with optimum number of stages as 4, gap between the stages and supplied mass flow rate as 100 mm for the system and obtained $55 \text{ kg/m}^2/\text{day}$ respectively throughout the year. Al-Nimr et al. [20] developed desalination unit using hybrid solar wind water desalination system and seen experimentally that the time variation of the glass and water temperature was

Fig. 17 Variation soft water

estimated to be 0.5296 kg/day (in natural mode in climatic conditions of Irbid, Jordan) with the maximum distillate yield 0.5296 l/day less amount of soft water.

Figure 17 shows the comparative study of soft water obtained analytically and experimentally. Soft water obtained by analytically and experimentally also show a much closed match. From this study, it is concluded that the approach presented in this paper will be helpful to practitioners and industries working in the same area. Figure 18 shows the comparative study of collector outlet temperature obtained analytically and experimentally. Collector outlet temperature obtained analytically and experimentally shows very less (i.e. 2–4%) variation.

4.6 Heat balance deviation between hard and soft water

In the month of April 2019 various trials/tests were conducted. The entire test was done during Morning 7:00 AM

to 18.00 PM. The Fig. 19 shows the temperature difference in between cold water and hot water obtained by performing different tests. In Pune city, the cold water temperature generally observed in the range 20–30 °C and hot water temperature observed in the range 100–121 °C. Figure 20 shows the percentage deviation in the hot and cold water per day for 15 days obtained by performing different tests.

4.7 Economic analysis of hybrid solar desalination system

The economic analysis of the present work is carried out for life cost analysis. The total cost of the present work mainly includes (fixed cost, production cost, running cost) as shown in Table 3. These costs are based on real purchasing price. All the cost are adopted at 2019 year in US dollars.

We know,

Fig. 18 Variation of collector outlet temperature

Fig. 19 Temperature difference in hot and cold water with trials **Fig. 20** Percentage difference in hot and cold water with trials **Table 3** Economic Analysis of hybrid solar desalination system

Sr. No.	Quantity of the system	Cost (US Dollar as per July2019)
01	One single ETC tube	5.83
02	One single CPC for ETC	17.50
03	Stand for the entire setup	7.29
04	Cu tubes for insides ETC tube	14.58
05	Hard/soft water tank	11.67
06	Condenser for desalination system	20.42
07	Entire plumbing/pipe line work	14.58
08	Valves and labor cost	21.88
	Total cost	113.75

$$C_t = C_{op} + C_{main} + C_{flx}$$

$$C_{flx} = a_X C_c$$

where a is the amortization factor and presented as; $a = i / (1 + i)^n / (1 + i)^n - 1$

Considering i = interest per year which is assumed as (15%) in Pune. n is the no. of life years which is to be assumed as = 15 years in this analysis. The product water cost can determine as,

$$C_{prod} = (C_t) / (n \times M_{dis} \times N)$$

where N is the number of the days in a year and assumed to be 350 in this analysis. The operating and maintenance costs are 20% are the fixed charges cost.

5 Conclusions

The objective of this work is to study the performance of Hybrid (ETC + CPC) solar desalination system. It is achieved by developing mathematical model for proposed hybrid (ETC + CPC) desalination system and extensive experimentation work. Experimental results indicate that hybrid system gives faster response to solar radiation with high operating temperature of soft water. The proposed hybrid

system produces 1.7–2 l of soft water during entire day (from 7:30 AM to 18.00 PM). Soft water obtained by analytically and experimentally also show a much closed match. From this study, it is concluded that the collector outlet temperature obtained analytically and experimentally shows also very less variation (up to 2–4%), hence developed analytical model can be successfully used. The hybrid solar desalination technology could be a cost effective technology for future in various domestic and industrial applications. Hence, it can be conclude that, hybrid (ETC + CPC) solar desalination system could be a promising alternative for desalination to convert hard water to soft (fresh) water for drinking/industrial purposes.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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