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Research Article

Development and Economical Analysis of Innovative Parabolic Trough Collector Integrated Solar Still

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Abstract

Experimental setup of the integrated parabolic trough collector (PTC) with solar still was developed. PTC was designed considering the solar geometry and the physical laws of parabolic shape and the concentrators. Test were conducted at the location with latitude 19.9975^{O}N and longitude 73.7898^{O}E. Theoretical analysis was done using ray tracing and engineering equation solver (EES) software while designing the system. PTC system was developed with dimensions of 1.5 m length, 1 m width and a concentration ratio (CR) of 21.22. Theoretical thermal efficiency was predicted as 48.1% whereas experimental average thermal efficiency is observed as 42.76%. The observed temperature difference between the vapor and the glass cover is about 17 °C and between ambient air and vapor is about 24.4 °C. Maximum water temperature in the conventional solar still was 64.6 °C where as for the PTC coupled solar still was 74.4 °C. PTC coupled solar still is having averagely 37% higher production rate. This has definitely added an advantage because of higher energy absorption rate compare with the conventional solar still. PTC coupled solar still system has nearly 35% more heat absorption. Total embodied energy of the system is around 896.875 kWh. Total capital cost of the system is Rs. 41300/-. Total annual output of pure water is around 3 L/Day. Estimated energy payback period is around 2.29 years and the total carbon credit earned is Rs. 2165.38 per year.

Keywords: *Solar energy; solar still; parabolic trough collector, embodied energy.*

1. Introduction

Three fuels coal, biomass and oil meet India's 80% of total energy demand. In India coal is the primary fuel for the electricity generation. With increase in vehicles and transportation requirements oil consumption and its import has significant impact on the economy of the India. Even the availability of the various resources of energy in India still many of the Indians not switched towards the modern fuel and relying on the conventional resources for needs like cooking [1].

Total solar radiation that reaches the Earth's surface is a dispersed because of water vapors and other gases. This radiation because of the photons is directly converted in to the electricity using photovoltaic devices, or, in to the heat energy using various concentrators. In case of the solar concentrators the solar radiation is used to heat the fluid known as heat transfer fluid (HTF). This fluid is then used for driving the thermodynamic cycle. Flat plate solar collectors and the photovoltaic cells uses both direct as well as diffuse solar radiation. However, in concentrating solar collectors scattered sunlight cannot be concentrated, CSP uses only direct sunlight and not the diffused. In concentrating solar plants, mirrors provided on the collector surface concentrates the sun light as a point focus or line focus that's create a sufficiently high temperature level with relatively smaller heat loss. Various technologies are developed and demonstrated in CSP technologies. Based on the methods of concentration it is divided in two groups viz point focus and line focus. Trough like mirrors are used in line focus technology. This mirror concentrates the solar radiation on receiver tube that uses single axis tracking system. Parabolic Trough Collectors (PTC) and Linear Fresnel Reflector Systems (LFRS) are the examples of concentrating solar power.

PTC and LFRS designs can concentrate the solar radiation about 30 − 80 times and heats up the HTF up to the temperature of 400 ^{O}C. Generally the receiver tube is mounted at the focus point and made of steel or cooper and the tube is coated with a heat resistant black paint. Technological and financial risks involved are very low in parabolic trough technology as it is now a matured technology. Various parts of the parabolic trough collector are parabola shaped trough, mirrors, receiver tube with glasscover and support structure. Collector with parabolic shaped mirrors focuses the sunlight towards absorber tube [2].

India facing fresh water crises and it also varies with the location and time of the year as well as on varying scale and intensity. Need of India's fresh water is changing due to continuous rise in population and the change of life style. Due to extensive use of water in all sectors like domestic, agricultural and industry ground water table availability is deeper and deeper. Same time the spreading pollution reducing the ground water quality. Millions of people of India do not have the adequate quality of the safe water during the summer season. Pollutants like arsenic, fluoride and ingress of the salt affected millions of people of India. In many parts of India still the girls and women have to walk a long distance and spend many hours to collect the fresh water for their daily needs. Gujrat, Maharashtra and Rajasthan are the major areas where such scenes are observed by the authors. In spite of the good rain fall in the state of Maharashtra shortage of fresh water is observed and large quantity of ground water is the saline water [3-6].

R.K. Khanna et al. [7] reported his findings about the water quality from the village Chui located in the state of Rajasthan. He observed that in this village nearly all the family members need to search the fresh water, collect it and store the same. He also reported that the test of water was carried at the Ajmer and it is observed that water quality was very poor and not suitable for human health. He majorly founds that the people are expecting the suitable purification device (desalination of water) that can be easily operated by them and the group of people can offer the cost. Conventional desalination technology uses the conventional energy and needs a maintenance with skilled operators. Use of solar energy for distillation is a very good solution for the need of fresh water. Solar technology is simple and clean [8]. India is located in the tropical zone and receives the plenty of sunshine with average solar radiation in the range of 4 to 7 kW/h.m^2. Studies so far are focused on increasing the solar still output which depends on various factors. Sathyamurthy et al. [9] reported various methods to increase the yield of solar still. Methods that improves the solar still performance and productivity includes the use of flat plate collectors with evacuated tube, heat pipes, and use of parabolic trough collector.

Initial double slope desalination system was developed by IIT Delhi during 1984 and is represented in Figure 1. Developed system has multi-wick stills with an area of 1m^2 each and 85 L/day capacity [10].

Garg and Mann [11] and Tiwari and Madhuri [12] reported experimental analysis on solar passive still. They observed the year round performance and concluded that Glass covers with small angle gives higher output optimum angle was reported as 10^{O} and for low and high altitude locations single slope solar stills are recommended. It was reported that fixed height and width of the solar still with change in length output does not changes.

If the temperature difference between stored basin water and the glass-condensing surface is high solar still can have a higher production rate. Thus, it becomes important to increase the basin water temperature or to decrease the condensing glass surface temperature. Condensing surface is the surface of glass cover of the solar still. The evaporated water from the absorber tube of the PTC condenses on this surface. This surface temperature can be reduce by the water flowing over the surface.

Tiwari and Bapeshwara Rao [13] reported the study on single slope solar still as shown in Figure 2. During the experimentation they maintained the constant flow velocity of water over the glass surface. S.A. Lawrance et al. [14, 15] conducted the similar study and observed the significant yield of solar still with the large heat capacity of mass of water in the basin.

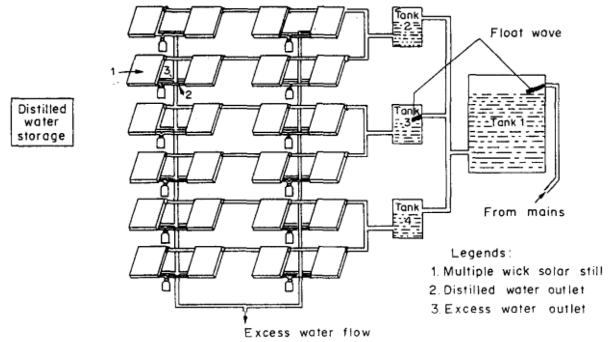

Figure 1. Multi wick distillation plant [10].

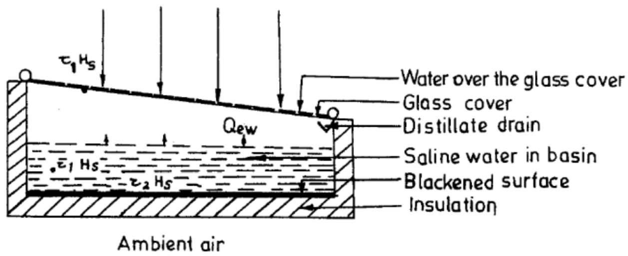

Figure 2. Solar still with water flow on glass [13].

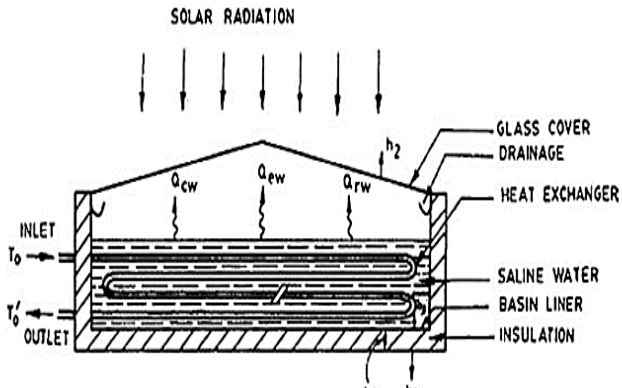

Figure 3. Solar still with internal heat exchanger [16].

Ashok Kumar and G.N. Tiwari [16] studied the use of heat exchanger in the solar still basin (Figure 3). They have developed the double slope solar still and conducted the experiment with heat exchanger installed into the basin. In this heat exchanger hot water exchanges heat energy with cold water in the basin. This way they increased the basin cold water temperature. They observed that the evaporation rate was increased with increase in the temperature of the hot water.

Materials like black rubber, aluminum sheets and gravels stores the heat energy. In addition to absorb solar radiation use of such a material in the basin increases the heat capacity. P. Valsaraj [17] reported an experimental findings using the gravels inside the solar basin. They used aluminum sheet as a floating absorber as shown in Figure 4. It was observed that compared with conventional solar still the rate of evaporation was higher. M. Sakthivel and S.

Shanmugasundaram [18] reported the similar studies using the black granite gravels and reported rise of 20% of yield.

Conventional type of solar stills have following limitations

- Since the absorbing surface is horizontal it intercepts the less solar radiation.
- Due to higher water storage capacity distilled output is also small since it has larger water heat capacities.

One solution to above limitations is decreasing the mass of water and exposing the small quantity of water to large solar radiation. This is possible by using a water wick. Blackened wet jute clothes are used for this purpose. This way water present in the jute can be heated to higher temperature and evaporation will be faster. In this case a series of jute threads separated by the polythene sheets are formed along the inclined plane whose one end is inserted in a saline water tank. Suction of water is then achieved by capillary action. Sodha et al. [19] reported the experimental study using the wick type of solar still. They observed that the cost of such a sill is lower than the conventional for the same area. It was also observed that yield of the distilled water is higher and the thermal efficiency is 4% more than the conventional still. G.N. Tiwari et al. [20] also conducted the similar experiments with multiple solar stills and observed 20% more yield than the conventional still. Dhiman and Tiwari [21] conducted the experimental study with the use of wet wick and water flowing on the glass surface. They observed that the yield was increased by 10%.

Gupta et al. [22] reported the experimental study on the double basin solar still as shown in Figure 5. During the experimentation they used the waste hot water in the lower basin during the off sunshine hours. They observed that the still yield increases as the waste hot water temperature increases. Similar studies was also reported by the Ashok Kumar [23].

S.N. Rai et al. [25] has reported his experimental study with use of single basin using jute cloth inside the basin and coupled with single flat plate collector. He also added the black dye of a small quantity to water in order increase the absorptivity and improve the rate of evaporation. The Y.P. Yadav [26] he reported 30-35% more yield compare to conventional solar still reported similar experiment with use flat plate collector.

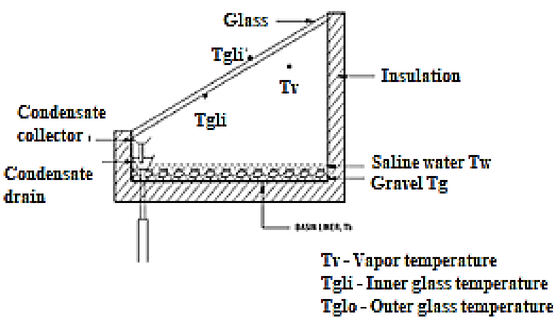

Figure 4. Solar still with internal heat exchanger [18].

Sanjeev Kumar, G.N. Tiwari [27] during their experimental studies using flat plate collector concluded that productivity of the solar still will be maximum when collector inclination is 20^{O} and inclination of the glass cover is 15^{O}. H.N. Singh, G.N. Tiwari [28] reported that when the condensing glass cover inclination is equal to latitude of the location yield from the solar still will be higher.

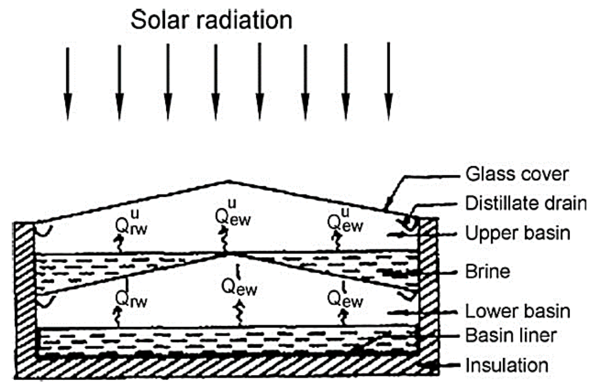

Figure 5. Double slope double basin solar still [23].

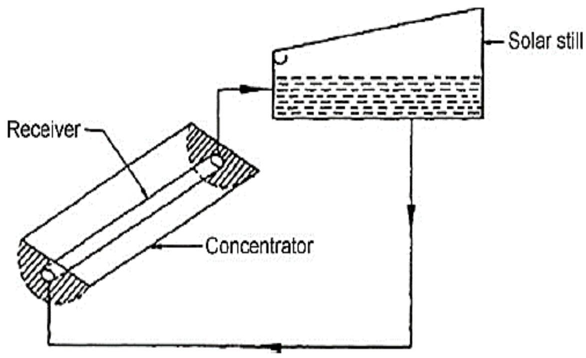

Figure 6. Solar still coupled with parabolic trough collector [29].

S.K. Singh et al. [29] reported the experimental study with the use of solar parabolic trough collector as shown in the Figure 6. They reported the 35% rise in the yield of the solar still with single basin.

Literature review findings are as summarized below

- Glass covers with small angle give higher output.
- It is better to face the solar still in east-west directions at high altitude locations.
- For low and high altitude locations single slope solar stills are recommended.
- Dyes are helpful to increase the absorptivity that leads to more evaporation.
- Decreasing the depth of water in the solar still increases the evaporation rate.
- Productivity of the solar still increases with increase in initial temperature of water.
- For the fixed height and width of the solar still with change in length output does not changes.
- Solar still can have a higher production rate if the temperature difference stored basin water and the condensing glass surface is high. Thus it become important to increase the basin water temperature or to decrease the condensing glass surface temperature.
- Use of internal heat exchanger increase evaporation rate.
- Performance of solar still will be improved by increasing the temperature of water in the basin. This is possible by making an active solar still coupled with solar PTC.

The process of integration of the PTC considers the use of solar energy for heating of water in the receiver and this hot water is then supplied to the solar still for desalination. However, this results in to the major heat losses that includes heat loss through receiver, solar still and transmission pipe. These losses can be avoided by integrating the PTC receiver and solar still as a single device. Hence, main aim of this study was to develop integrated solar PTC solar still. The receiver of the PTC is designed to vaporize the water and the cover of the receiver was used to condense the steam. Thus it acts as a coupled solar PTC still.

2. Thermal Modeling

2.1 Introduction

System thermal modeling was conducted using the various aspects of the solar energy and its utilization. Following section discusses the details of the same.

2.1.1 Extraterrestrial Solar Radiation

Radiation following on the earth outside surface is known as extraterrestrial solar radiation. NASA has recommended the value of 1353 W/m^2 for a mean distance of 1.496 X 10^{11} m. The orbit of the earth around the sun is elliptical and hence the distance of the sun from the earth has a variation of about 1.7% and hence extraterrestrial solar radiation varies by the inverse square law according to the "Eq. (1)" [30-34, 35].

$$I_o=I_{sc}\left(\frac{D_m}{D_{es}}\right) \tag{1}$$

Where,
D_{es}= Distance between the sun and earth
I_{sc} = Solar constant 1353 *W/m^2*

"Eq. (2)" is used to calculate the value of I_O

$$I_o=I_{sc}\left[1+0.034\ \mathrm{Cos}\left(\frac{360\times d_n}{365.25}\right)\right] \tag{2}$$

Where d_n is day number.

2.1.2 Terrestrial Solar Radiation

The radiation from the sun outside the earth's atmosphere is around 1353 W/m^2. However, as it reached the earth surface its value reduces due to the effects of absorption and reflection due to the clouds, dust particles and various gas molecules. The radiation reaching on the earth surface has two different components known as beam radiation (I_b) and diffuse radiation (I_d). Beam radiation is the radiation that reaches the earth surface without scatter and the diffuse radiation is the radiation that has scattered significantly [32]. Sum of I_b and I_d is known as the global radiation (I_G). For solar concentrating collector only beam radiation is important and diffuse radiation is not considered.

2.1.3 Geometry of Parabola

PTC consist of a collector of a parabolic shape and has the cylindrical receiver at its focal distance as shown in the Figure 7. Parabolic reflector reflects all the incoming solar radiation towards the focal distance at which the cylindrical receiver tube is mounted. This reflection forms a line at the base of the receiver tube hence PTC is a line focus concentrator. The main dimensions of the parabolic collector are length (L) and the width (W) that forms the aperture area ($A_a = W\ X\ L$). The distance between center of the parabola and outer rim is the rim radius. Rim angle (θ_r) is the angle between reflected beam radiation by outer rim and the line joining of parabola centre and the focal point.

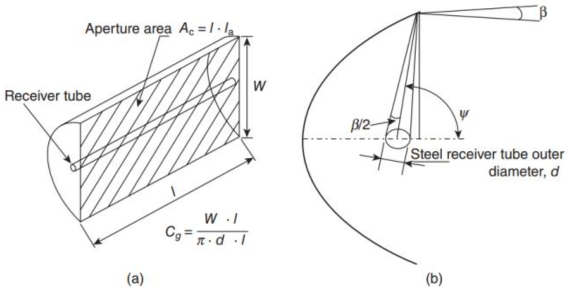

Figure 7. Geometry of the Parabola [45].

Focal length (f) of the parabola is given by the "Eq. (3)" [32, 33, 34, 35] where *W* is the width of parabola

$$W=4\ f\ \tan\left(\frac{\theta_r}{2}\right) \tag{3}$$

The geometric concentration ratio is given by the "Eq. (4)".

$$C=\frac{\text{Effective aperture area}}{\text{Receiver tube area}}=\frac{WD_{ro}L}{\pi D_{ro}L} \tag{4}$$

Concentration ratio in terms of rim angle is given by the "Eq. (5)".

$$C=\frac{\mathrm{Sin}\ (\theta_r)}{\pi\ \mathrm{Sin}(\theta_a)} \tag{5}$$

Where,
θ_r is the rim angle
θ_a is the acceptance angle Receiver tube diameter is given by the "Eq. (6)".

$$D_r=2r\mathrm{Sin}(\theta_a)=\frac{W\mathrm{Sin}(0.267)}{\mathrm{Sin}\ (\theta_r)} \tag{6}$$

2.1.4 Optical Efficiency of the PTC

The ratio of fraction of solar radiation absorb by the receiver tube to fraction of solar energy collected is known as optical efficiency and is given by the "Eq. (7)" [34, 35].

$$\eta_o=\frac{S}{I_b} \tag{7}$$

The actual amount of the solar radiation absorb by the receiver tube is given by the "Eq. (8)".

$$S=I_b\left(\boldsymbol{\rho_a\tau_g\alpha_r\gamma_i}\right)K_{\theta i}X_{END} \tag{8}$$

Where,
I_b = Beam radiation (W/m^2)
ρ_a= Absorptivity of receiver material
τ_g= Trasmissivity of the glass material
γ = Intercept factor (Generally taken as 0.9 due to imperfections of reflector surface
$K_{\theta i}$= Incidence angle modifier

Incidence angle modifier takes care of the errors due to manufacturing defects of the collector, error due to the displacement of the receiver from focus, tracking error etc.

This incidence angle modifier factor is calculated by the "Eq. (9)" [36, 37].

$$K(\theta_i)=\cos(\theta_i)+0.000884(\theta_i)-0.00005369(\theta_i)^2 \qquad (9)$$

Towards the end of the PTC receive tube small portion does no receives the reflected beam as shown in the Figure 8. This loss is not much significant in the long PTC system however for the short length PTC these losses must have to be considered and are given by the "Eq. (10)" [37].

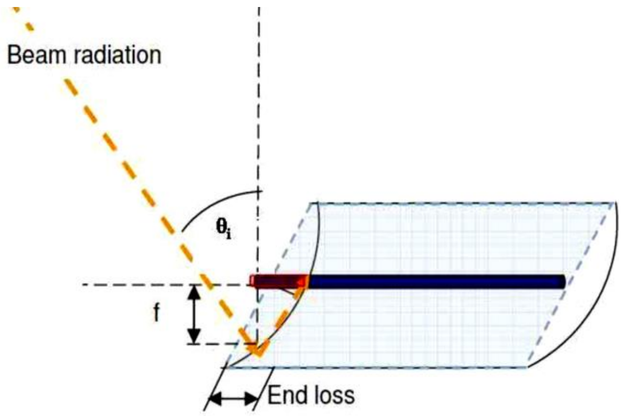

Figure 8. End loss for PTC system.

$$X_{END}=1-\frac{f}{L}\tan(\theta_i) \qquad (10)$$

2.1.5 Heat Transfer Analysis of the PTC System

HTF flows through the receiver tube of the PTC system. HTF may be water or any thermal fluid. Thermal efficiency is then defined as ratio of heat energy absorb by the HTF to the energy incident collector of the system [38].

2.1.5.1 Overall Heat Loss Coefficient (U_L)

Heat loss from absorber tube is because of conduction, convection and radiation. All these losses are combined together to represent them single coefficient known as overall heat transfer coefficient. Considering the convection inside the glass tube then U_L value is evaluated by "Eq. (11)".

$$U_L=\left[\frac{A_r}{A_g\left(h_{c,\ g\text{-}amb}+h_{r,\ g\text{-}amb}\right)}+\frac{1}{h_{r,r\text{-}g}}\right] \qquad (11)$$

Where,
A_r = Receiver area
A_g = Receiver glass area
$h_{c,\ g\text{-}amb}$= Convective heat transfer coefficient between glass and ambient due to flow of wind around glass cover

$$h_{c,\ g\text{-}amb}=\frac{N_U k_a}{D_g} \qquad (12)$$

N_U is the Nusselt number of the air and is given by

$$N_U=0.4\times0.54\times R_e^{0.53} \quad \text{for } 0.1<R_e<1000 \qquad (13)$$

$$N_U=0.3\times R_e^{0.6} \quad \text{for } 1000<R_e<50000 \qquad (14)$$

$h_{r,\ g\text{-}amb}$ = Radiation heat transfer coefficient between glass and ambient

$$h_{r,\ g\text{-}amb}=\varepsilon_g\delta\left(T_g+T_{amb}\right)\left(T_g^2+T_{amb}^2\right) \qquad (15)$$

$h_{r,r\text{-}g}$ =Radiation heat transfer coefficient between receiver tube and the glass tube

$$h_{r,r\text{-}g}=\frac{\delta\left(T_r+T_g\right)\left(T_r^2+T_g^2\right)}{\frac{1}{\varepsilon_r}+\frac{A_r}{A_g}\left(\frac{1}{\varepsilon_g}-1\right)} \qquad (16)$$

Where
T_r = Temperature of the receiver tube
T_g = Temperature of the glass tube
ε_r = Emissivity of receiver tube material
ε_g = Emissivity of glass tube material
δ = Stephan Boltzmans constant = 5.67 x 10^{-8} W/m^2 K^4

2.1.5.2 Heat Transfer to HTF

Evaluation of the heat energy transfer to HTF depends on the type of flow inside the receiver tube and it is the function of Reynolds number. For flow through the tube Reynolds number is given by the "Eq. (17)".

$$R_e=\frac{4\dot{m}}{\pi D_r \mu_f} \qquad (17)$$

If R_e <2200 then Nu = 3.7 and If R_e > 2200 then

$$N_U=\frac{(f_f/8)R_{ef}P_{rf}}{1.07+12.7\sqrt{\left(\frac{f_f}{8}\right)}\,[P_{rf}^{\frac{2}{3}}-1}} \qquad (18)$$

Where friction factor f_f is given by,

$$f=(0.79\ln(R_{ef}-1.64))^{-2} \qquad (19)$$

Heat transfer coefficient, h_f is then evaluated by the equation

$$h_f=\frac{N_{Uf}k_f}{D_r} \qquad (20)$$

2.1.5.3 Heat Transfer Coefficient

Overall heat transfer coefficient was evaluated using "Eq. 21)".

$$U_O=\left[\frac{1}{U_L}+\frac{D_{ro}}{h_f D_{ri}}+\frac{D_{rO}\ln\left(\frac{D_{rO}}{D_{ri}}\right)}{2k_{rt}}\right]^{-1} \qquad (21)$$

Where k_{rt} is the thermal conductivity of absorber tube material.

Collector heat removal factor for the evaluation of the thermal efficiency is calculated by the "Eq. (22)".

$$F'=\frac{U_O}{U_L} \qquad (22)$$

Thus the "Eq. (21)"is now represented as following,

$$F'=\frac{1/U_L}{\frac{1}{U_L}+\frac{D_{ro}}{h_f D_{ri}}+\frac{D_{rO}\ln\left(\frac{D_{rO}}{D_{ri}}\right)}{2k_{rt}}} \qquad (23)$$

Collector heat removal factor is the ratio of the actual heat energy collected to the heat energy collected if receiver tube would is at the constant temperature and is given by the "Eq. (24)" [39].

$$F_R = \frac{\dot{m}_f c_p}{A_r U_L}\left[1 - \exp\left(-\frac{A_r U_L F'}{\dot{m}_f c_p}\right)\right] \tag{24}$$

The collector flow factor is given by the "Eq. (25)".

$$F'' = \frac{F_R}{F'} \tag{25}$$

2.1.5.4 Thermal Efficiency of the Parabolic Trough Collector System

Thermal efficiency is the ratio of the useful energy gain by the receiver to the total solar insolation falling the aperture area.

$$\eta_{thermal} = \frac{Q_u}{A_a I_b} \tag{26}$$

The useful energy gain can be estimated as,

$$Q_u = A_a F_R \left[S - \frac{U_L(T_{fi} - T_{amb})}{C}\right] \tag{27}$$

Combining the "Eqs. (26) and (27)",

$$\eta_{thermal} = F_R \left[\eta_O - \frac{U_L(T_{fi} - T_{amb})}{I_b C}\right] \tag{28}$$

2.1.6 Modeling Results

- Number of models were studied and found that many key parameters like, incidence angle, PTC receiver end loss, factor for cleanliness, shadow effect and day number in a year are not considered simultaneously for the analysis.
- Hence, an effort was made to develop the thermal model using EES programming language to consider these factors in one dimensional analysis of PTC receiver.
- Outcome of such model analysis will be used for development of experimental setup.

All above equations were solved simultaneously using EES for obtaining the mathematical model with following assumption

- One dimensional heat transfer analysis.
- ambient temperature is monthly average of the selected site.
- External HTC (convection coefficient is constant).
- Radiative properties of the surface are constant.
- Heat loss (Q_{loss}) was estimated assuming the grey body radiative heat exchange from the receiver tube.

The Engineering equation solver (EES) program was developed for performance estimation. Figure 9 represents the simulation results for optical efficiency and thermal efficiency of the collector evaluated for the year round thermal performance. Clean factor is assumed as 0.9 and row shading factor was 1. Maximum optical efficiency was observed as 77.19%, which, agrees with the experimental reported value of 77% by Dudley, V. E., and Workhoven [39] who reported the experimental study on parabolic trough collector with similar setup and the glass mirror with the same range of the irradiance.

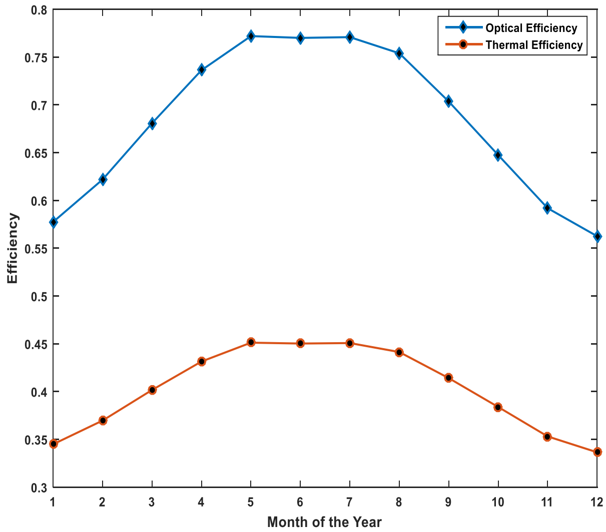

Figure 9. Optical and Thermal efficiency of the PTC System (Theoretical Modeling).

Since the results are deviated only with 0.2% model has a good validity with the published results. Model was then tested with solar trace software for validating the dimensions of the PTC. Figure 10 represents the output of the ray-tracing and it was observed that 90% of the solar radiation following on the aperture software are concentrated at the base of receiver tube with the selected dimensions of the PTC.

3. Experimental Setup

Experimental setup was installed at the institute at the location with details as Latitude 19.9975 ^{O}N and longitude 73.7898 ^{O}E. Single slope solar still was developed and is coupled with PTC system. The solar still contains a saline water at its basin (dark black color as represented in Figure 11) which is the receiver of the parabolic trough as illustrated in Figure 11.

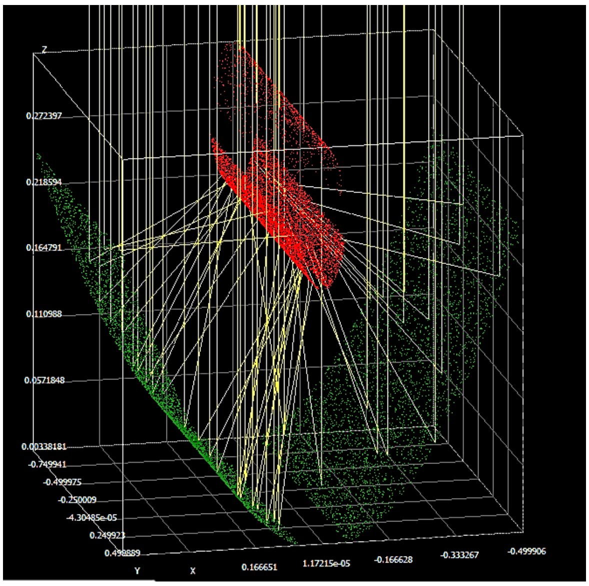

Figure 10. Validation of the system design using ray tracing.

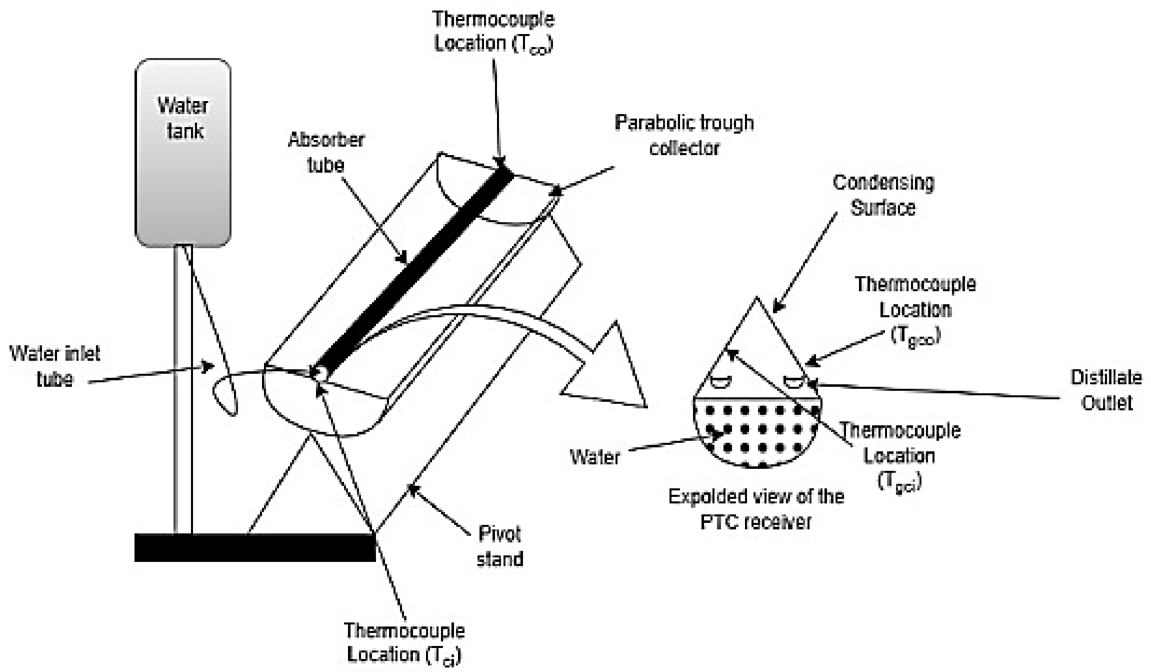

Figure 12. Schematic of the test setup.

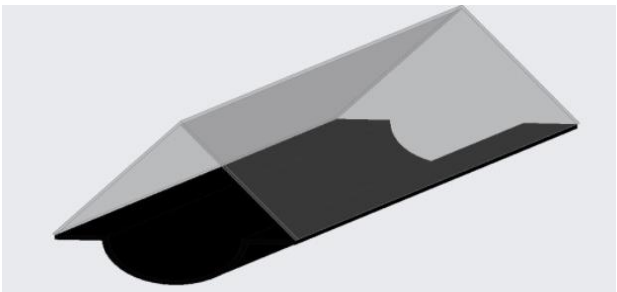

Figure 11. Inbuilt PTC receiver-solar still.

Acrylic sheets attached (light brown color in the Figure 11) forms the condensing surface. The basin is made of MS material half pipe of 1.5 mm thickness and receiver is divided in three parts throughout the length containing the porous material. For increasing the basin absorptivity receiver tube is painted with black paint (both at inside and outside). The receiver tube is fitted with an acrylic sheet covers as represented by the outline diagram Figure 11. These acrylic sheets forms the condensing surface and condensate is collected with the half cut PVC pipe provided at the bases of condensing surface. Figure 12 represents the photograph of the experimental setup with the innovative receiver tube.

Acrylic sheet is a transparent material of 4 mm thickness and two sheets were fixed with the receiver tube and angle between them is 45° with the horizontal which is the sum of the locations latitude angle and declination angle. This arrangement ensures the fall of radiations at an angle of approximately 90^{O} and ensures maximum absorption of energy by receiver. During experimentation, system was oriented in south-north direction of the city as the maximum sun radiation falls in this direction. Silicon material was used at the joints to prevent any leakage. Distillate channels are made from the PVC pipe and are attached with the condensing surface of the still to collect the condensed freshwater. PTC system was inclined at an angle equal to latitude of the location.

Cylindrical parabolic collector was developed and the glass strips were attached on the collector sheet this concentrates solar beam radiation on the absorber tube. Concentrator was made from the MS sheet of 0.3 mm thickness with width of 1 m and length equal to 1.5 m and aperture area of 1.5 m^2 having concentration ratio 22.6. PTC receiver tube is made of half MS pipe of 102 mm diameter. Table 1 represents the dimensions of the system.

Table 1. Test model specifications.

Sr. No	Description	Design values
01	Collector length (L)	1.5 m
02	Collector width (W)	1 m
03	Concentration ratio (CR)	22.6
04	Receiver Outer Diameter (r_o)	25.4 mm (1”)
05	Receiver Inner Diameter (r_i)	21.4 mm
06	Rim Angle (Φ)	90^{O}
07	Receiver length (L_r)	0.9 m
08	PTC Diameter (D)	1 m
09	Focal length (f)	0.250 m
10	PTC linear Diameter	1.114733 m
11	F/W ratio (f/W)	0.25

4. Results Discussion and Economical Analysis

4.1 Thermal Performance

The experimental measurements were carried out from morning at 8:00 am to evening till 5:00 pm during April 2023. Parameters like wind velocity (V), ambient temperature (T_a), inside and outside glass cover temperature (T_{gi}), (T_{go}), and temperature of water (T_w) etc. were recorded. Water temperature was measure at the center receiver tube using K-type thermocouples and temperature indicator with an accuracy of 0.1 ^{O}C. The intensity of solar radiation (I) was evaluated by using developed ANN model and the HTC make solar pyranometer. Wind velocity was measured with hot wire anemometer of HTC make with a range of 0.1 to 25 m/s. Calibrated flask was used for the measurement of the condensate.

Figure 14 shows the variation of the water temperature for conventional and PTC Coupled Solar Still and Figure 13 indicates the variation in solar radiation it was observed that solar intensity increases with time till 1 PM and after this time solar intensity decreases with increasing time. Maximum solar radiation intensity was observed at 12:45 PM. Water temperature changes with the variation in solar intensity and after 12:45 PM the temperatures decrease as shown in Figure 15. Maximum temperature difference between the vapor and the glass cover was around 17 °C and the maximum temperature difference between the receiver tube vapor and ambient air is around 24.4 °C.

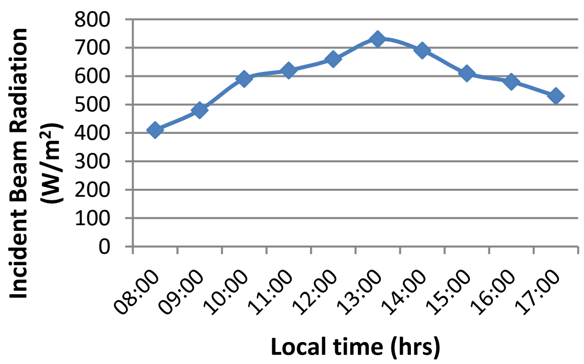

Figure 13 Incident Beam Radiation falling on the collector surface area.

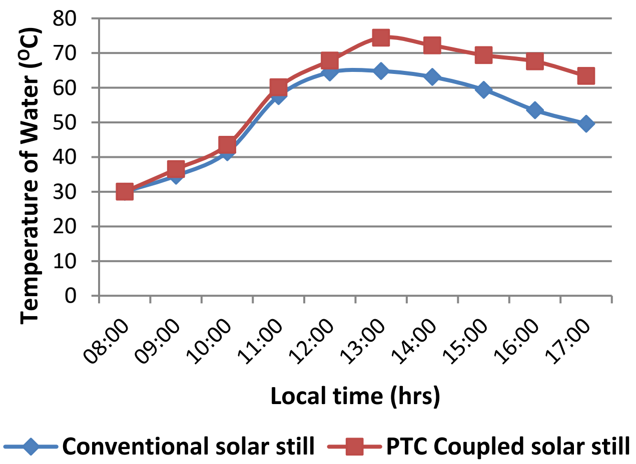

Figure 14. Comparative analysis of Conventional and PTC Coupled Solar Still.

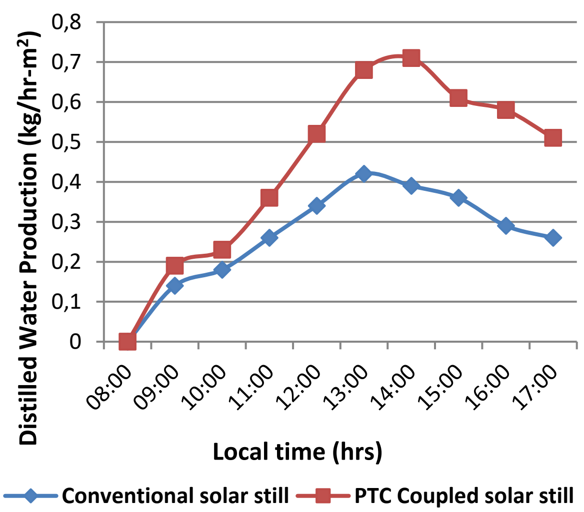

Figure 15. Comparative study of the distilled water production rate.

Figure 14 indicates that water temperature for PTC coupled solar still is more than conventional solar still this confirms the faster evaporation of the water due to the PTC use. It was observed that the temperature difference between the outer and inner acrylic sheet is around 1 °C and the maximum water temperature in case of conventional solar still is 64.6 °C and for the PTC coupled solar still is 74.4 °C.

Figure 15 shows the comparative analysis of the conventional and PTC coupled solar still for the production rate of the distilled water. It was observed that the PTC coupled solar still is having averagely 37% higher production rate. This has definitely added an advantage because of higher energy absorption rate compare with the conventional solar still.

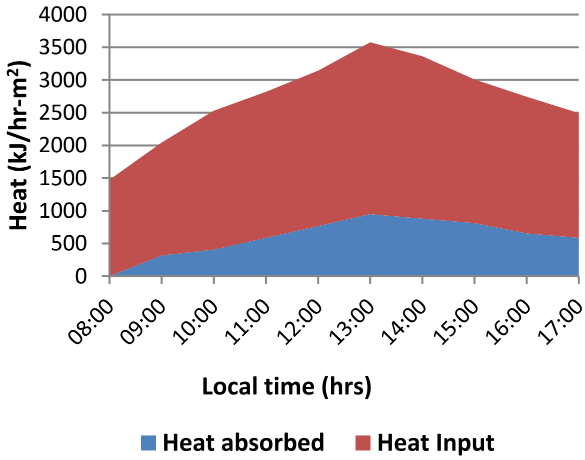

Figure 16. Heat input and absorbed for conventional solar still.

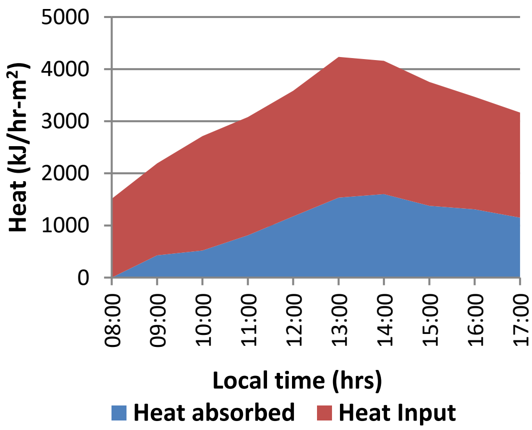

Figure 17. Heat input and absorbed for PTC coupled solar still.

Figure 16 and 17 shows the rate of heat energy absorbed by these two different systems. Section 4.2 discusses in detailed economic analysis of the system. Blue shaded area represents the heat absorbed by the conventional and PTC coupled solar still system. It was observed that the PTC coupled still system is having nearly 35% more heat absorption. Hence it would be better to propose the direct steam generation and condensation system for further studies.

Figure 18 represents the thermal efficiency performance of conventional and PTC coupled systems under this study. Since the heat absorbed across the total absorbing surface is higher in PTC coupled system the thermal efficiency is higher by 35% in terms of production rate of the distilled water.

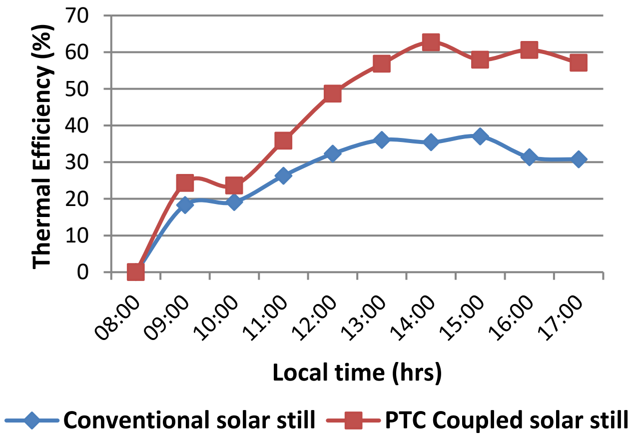

Figure 18. Comparative thermal efficiency of the systems based on distilled water production.

4.2 Economical and Energy Analysis

For any experimental setup economical and energy analysis is critical since it involves various cost including the charges for fuel, material, transportation and other.

4.2.1 Embodied Energy

Energy required for developing the system and its various parts is referred as embodied energy. This consists of the manufacturing of all parts of the PTC system as represented in Table 2.

Table 2. Embodied energy of the system.

Sr. No	Components	Material	Quantity (kg)	Embodied energy (MJ/kg)	Total (kWh)
1	Collector	MS	20	35	194.44
2	PTC stand	MS	20	35	194.44
3	Receiver tube	MS	2.5	35	24.31
4	Collector and Receiver	Glass	10	26.2	72.78
5	Inlet and exit pipe	Rubber	8	110	244.44
6	Water tank	Plastic	5	70	97.22
7	Tank insulation	Heat loan	1	14.6	4.06
8	Paint	Paint	1.5	98.1	40.88
9	Iron bush	MS	1	35	9.72
10	Receiver side flat plate	MS	1.5	35	14.58
Total Embodied Energy					**896.875**

4.2.2. Energy Payback Time

This is the required time to payback the entire systems embodied energy. Payback period is calculated by the "Eq. (29)" and annual output energy by "Eq. (30)" [40-44].

$$\text{Energy Payback Time} = \frac{\text{Embodied Energy (kWh)}}{\text{Annual Output Energy (kWh)}} \quad (29)$$

$$\text{Annual Output Energy } (E_{out}) = \frac{\text{Yearly distilate water (kg)} \times h_{fg}\text{(kJ/kg)}}{3600} \quad (30)$$

h_{fg} = Latent heat of vaporization

Note: 1 kWh=3600 kJ.

Thermal efficiency is evaluated using "Eq. (31)",

$$\eta_{\text{thermal system}} = \frac{Q_u}{I \times A_a} \quad (31)$$

Where
$Q_u = M_y \times L_w$ Daily useful energy (W)
A_a = Total aperture area in m^2
I = Total incident solar radiation (W/m^2)
M_y = Daily output of pure water (kg/sec)
L_w = Latent heat of vaporization (kJ/kg)

4.2.3 CO_2 Emission

CO_2 released by the electricity generation from the coal has an intensity of around 0.98 kg of CO_2 /kWh and it can be calculated by "Eq. (32)" [40-44].

$$CO_2 \text{ emission per year} = \frac{\text{Embodied Energy} \times 0.98}{\text{Life Time}} \quad (32)$$

The average transmission losses are considered as 40% the distribution losses are considered as 20% for the Indian system of transmission. To consider these losses CO_2 intensity value of 0.98 is increased to 1.58 and "Eq. (32)" was modified and given by "Eq. (33)" [40-41].

$$CO_2 \text{ emission per year} = \frac{\text{Embodied Energy} \times 1.58}{\text{Life Time}} \quad (33)$$

4.2.4 CO_2 Mitigation

CO_2 is a green gas and hence mitigation is a factor that evaluates the climate change potential and it is calculated by "Eq. (34)" [40-44].

$$CO_2 \text{ Mitigation per year} = E_{out} \times 1.58 \quad (34)$$

For the entire life span CO_2 mitigation is calculated by the "Eq. (35)" [40-41].

$$\text{Total CO2 mitigation over the lifespan} = ((E_{out} \times \text{Life Span}) - E_{in}) \times 1.58 \times 10^{-3} \quad (35)$$

4.2.5 Earned Carbon Credit

The carbon credit is evaluated by "Eq. (36)" [40-44].

$$\text{Earned carbon credit} = \text{Net } CO_2 \text{ mitigation over the life span} \times D \quad (36)$$

Where D = Carbon credit earned.

This value varies from \$2 to \$25/ton of CO_2 mitigation Presently \$1 = Rs. 82.49 INR (dated 17 March 2023).

4.2.6 Economic Analysis

It is important to conduct the economic investigation to understand the economic feasibility of the developed setup [40-41]. Table 3 represents the cost of fabrication of the experimental test setup.

4.2.6.1 Capital Cost (CC)

Total fabrication cost of the test setup of this innovative system and as shown in Table 3.

4.2.6.2 Lifetime of the System (LT)

This is the time period over which the system is expected to provide the output and represented in terms of years of service [40-41]. For this developed system life span is taken as 30 years.

4.2.6.3 System Salvage Value (SV)

The cost of the system after its lifetime (LT) represents the salvage value (SV). For this system SV is taken as 20% of CC and is evaluated by "Eqs. (37) and (38)" [40-41].

$$SV=0.2\times CC \tag{37}$$

"Eq. (33)" was used for the estimation of Annual salvage value (ASV).

$$ASV=SFF\ (\text{Sinking Fund Factor})\times SV \tag{38}$$

4.2.6.4 Sinking Fund Factor (SFF)

This indicates the amount that must be kept aside so that after the life time span one can developed the new system and it is calculated by "Eq. (39)" [40-41].

$$SFF=\frac{i}{(1+i)^{LT}-1} \tag{39}$$

Where

i = interest rate (%) and LT is the life time in years

Table 3 Capital Cost of the system.

Sr. No	Component	Material	Cost (INR)
1	Parabolic Collector Side Sheets	MS	2500
2	Parabola Shape	MS	2200
3	Receiver Tube	MS	800
4	Receiver Tube Still Acrylic Sheet Cover	Acrylic	2200
5	Collector glass	Glass	2400
6	Receiver tube valves	MS	600
7	Rubber tube	Rubber	500
8	Collector stand	MS	1900
9	Other missing	--	3000
Total Cost of Equipment			**16100**
Labor Cost @ 35% of equipment cost			**5635**
Machining Cost @ 25% of equipment cost			**4025**
Transportation and other @15% of equipment cost			**2415**
Total Cost of Equipment			**28175**

4.2.6.5 Capital Recovery Factor (CRF)

To obtain the constant annual amount over certain period at certain interest it is important to obtain the capital recovery factor and it is calculated by "Eq. (40)" [40-41].

$$CRF=\frac{i(1+i)^{LT}}{(1+i)^{LT}-1} \tag{40}$$

4.2.6.6 First Annual Cost

It is calculated by the "Eq. (41)" [40-41].

$$FAC=CC\times CRF \tag{41}$$

4.2.6.7 Annual Operational and Maintenance Cost (AOMC)

To maintain the system in terms of cleaning, mechanical maintenance, handling of the system, saline water and distillate collection it is important to obtain the annual operation and maintenance cost and is calculated by the "Eq. (42)" [40-41].

$$AOMC=0.15\times FAC \tag{42}$$

4.2.6.8 Total Annual Cost

Total annual cost is given by the "Eq. (43)".

$$TAC=FAC+AMC-ASV \tag{43}$$

4.2.6.9 Distillate Production Cost

The distilled water output is measured by the measuring flask in L. Output of the desalination water is calculated by the "Eq. (44)" [40-41].

$$CPL=\frac{TAC}{M_y} \tag{44}$$

4.2.6.10 Payback Period

Payback period is the time taken to recover the invested cost and is given by the equation (45) [40].

$$\text{Payback Period}=\frac{\text{Investment}}{\text{Net Earning}} \tag{45}$$

Table 4 represents the summary of the above economic analysis, Payback period and the carbon credit earned with the renewable energy utilization [40-41].

5. Conclusions

Experimental analysis was conducted to analyze the performance of an inbuilt solar PTC Still. This study was conducted with an aim of improving the performance of conventional solar stills. Following conclusions are drawn.

- Conventional solar still has a low rate of evaporation. PTC has a good temperature rise because of line focus arrangement with high concentration ratio and hence useful for desalination of water.
- Evaporation increases with decrease in water depth in solar still and use of porous material.
- PTC has high concentration ratio and results in increase in temperature of water. Hence it is possible to develop an active solar still coupled with solar PTC or flat plate collector.
- Large PTC system assisted solar still are easily affordable by the group of village peoples.
- Maximum temperature difference between the vapor and the glass cover was around 17 °C and the maximum temperature difference between the receiver tube vapor and ambient air is around 24.4 °C.
- It was observed that the temperature difference between the outer and inner acrylic sheet is around 1 °C and the maximum water temperature in case of conventional solar still is 64.6 °C and for the PTC coupled solar still is 74.4 °C.
- PTC coupled solar still is having averagely 37% higher production rate. This is because of higher energy

absorption rate compare with the conventional solar still.

- PTC coupled still system has nearly 35% more heat absorption. Hence it would be better to propose the direct steam generation and condensation system for further studies.

Table 4 Summary of Economic analysis, Payback Period and Carbon Credit.

Sr. No	Cost	Value
1	Capital Cost (CC)	28175 INR
2	Life Time (LT)	30 Years
3	Salvage Value (SV)	5635 (INR)
4	Interest rate (i)	12 (%)
5	Sinking Fund Factor (SFF)	4.58×10^{-33}
6	Salvage Value (SV)	2.58×10^{-29}
7	Capital Recovery Factor (CRF)	12
8	First Annual Cost (FAC)	338100 (INR)
9	Annual Operation and Maintenance Cost	33810 (INR)
10	Annual Cost (TAC)	371910 (INR)
11	Annual output of pure water (My)	900 (L.)
12	Cost of Production (Cost of distillate)	1.132 (INR)
13	Net Sale Value	20 (INR)
14	Annual Earning	18000 (INR)
15	Payback period	1.565 (Years)
16	Embodied energy	896.87 (kWh)
17	Energy Output (Eout) Annual	564.25
18	Payback time of Energy	1.589 (Years)
19	Daily useful energy (Qu)	313.472 (W)
20	Total incident solar radiation (average of the year)	600 (W/m^2)
21	Area of the collector	1.5 (m^2)
22	Thermal efficiency	34.83 (%)
23	CO_2 Emission per year for equivalent electricity consumption	67.58
24	CO_2 Mitigation (Climate change potential)	26.25
25	Carbon credit earn	2165.38 (INR)

Nomenclature

A_a	Aperture area (m^2).
A_r	Receiver area (m^2).
A_g	Glass cover area (m^2).
A_{ir}	Inside cross sectional area of the absorber tube (m^2).
C	Concentration ratio.
C_p	Specific heat (kJ/kg.K).
D_{ci}	Inner diameter of a glass cover (m).
D_{co}	Outer diameter of a glass cover (m).
D_{ri}	Inner diameter of absorber (receiver) tube (m).
D_{ro}	Outer diameter of absorber (receiver) tube (m).
D_{es}	Distance between sun and earth.
d_n	Day number of the year.
E	Radiation energy.
f	Focal length (m).
F'	Collector efficiency factor.
F''	Collector flow factor.
F_R	Collector heat removal factor.
h_{fi}	Heat transfer coefficient for the HTF inside the tube (W/m^2.K).
h_w	Wind heat transfer coefficient (W/m^2.K).
I_b	Beam radiation (W/m^2).
I_b	Diffuse radiation (W/m^2).
I_G	Global radiation (W/m^2).
I_O	Extraterrestrial solar radiation (W/m^2).
I_{SC}	Solar constant (W/m^2).
k_c	Thermal conductivity of a glass cover (W/m.K).
L	Collector length (m).
Pr	Prandtl number.
Q_{abs}	Solar radiation absorb by the receiver tube (W).
Q_u	Net energy transfer to the HTF inside the receiver tube (W).
S	Solar radiation absorbed by receiver (W).
T_a	Ambient Temperature (^{O}C).
T_i	Receiver inner surface temperature (^{O}C).
T_{co}	Outer surface temperature of a glass cover (^{O}C).
T_{ci}	Inner surface temperature of a glass cover (^{O}C).
T_{fi}	HTF temperature at inlet of the receiver (^{O}C).
T_{fm}	Mean fluid temperature (^{O}C).
T_{sky}	Sky temperature (^{O}C).
U_L	Receiver overall heat transfer coefficient based on receiver outside surface area (W/m^2.K).
U_O	Receiver overall heat transfer coefficient based on receiver outside tube diameter (W/m^2.K).
W	Width of parabola (m).
Wa	Parabola's aperture width (m).
X_{end}	Performance factor that accounts for losses from ends of heat collector element.

Greek Letters

α	Altitude angle (^{O}).
α_r	Absorptance of receiver surface coating.
δ	Declanation angle (^{O}).
γ	Surface azimuth angle (^{O}).
γ_i	Intercept Factor.
σ	Stephan Boltzmann's Constant (5 x 10^{-8} W/m^2.K^4).
$\emptyset$	Latitude location of the solar field.
μ	Absolute viscosity of heat transfer fluid.
η_o	Optical efficiency.
η_t	Thermal collector efficiency.
θ_a	Acceptance angle.
θ_i	Angle of incidence.
θ_r	Rim angle.
θ_z	Zenith angle.
ρ_a	Clear mirror reflectivity.
ρ_f	Density of heat transfer fluid (kg/m^3).
τ_g	Transmittance of glass cover.
ω	Hour angle.
ε_{ci}	Emittance of glass cover inner surface.
ε_{co}	Emittance of glass cover outer surface.
ε_r	Emittance of receiver.

Abbreviations

ANI	Aperture normal irradiance (W/m^2).
ANN	Artificial Neural Network.
CSP	Concentrating Solar Power.
CFD	Computational Fluid Dynamics.
DNI	Direct Normal Irradiance (W/m^2).
EES	Engineering Equation Solver.
HTF	Heat Transfer Fluid.
hr	Hour.
IAM	Incidence Angle Modifier.
INR	Indian National Rupees.
PTC	Parabolic Trough Collector.
SC	Solar Collector.
LF	Linear Fresnel Reflector Systems.
L	Liter.

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