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Cost effective design of compound parabolic collector for steam generation

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Abstract

In this paper we present a working model of Compound Parabolic Collector (CPC) system for the application of process steam generation. It is easy for fabrication, operation and has a lower cost compared to other available concentrating solar collector systems with further possibility of lowering the cost. An experimental demonstration unit having an aperture area of nearly 30 m^2 was set up and tested for steam generation. The performance analysis of the system shows potential of improving thermal efficiency up to 71%. By virtue of its geometry, the proposed CPC system requires much lesser mirror area compared to conventional CPC design and require single tilt adjustment per day for a daily 6 h operation.

Keywords: Solar energy; Compound Parabolic Collector (CPC); Solar thermal system; Solar steam generation

1. Introduction

Though electricity is the highest quality of energy and should be given priority, energy consumption in the form of direct heat also forms a major mode of energy consumption. It is the most widely known form of energy. It is used in various applications, from cooking and space heating to an extremely wide range of industrial applications. While at domestic levels it is used at lower temperatures, industrial use requires much higher temperatures. Storage and transfer is an important consideration in the usage of heat. Steam has been widely used over the years as a medium of heat transfer mainly due to the advantage of its high latent heat content. It is interesting to note that steam is just another form of water, an entity most familiar to the mankind next to air (to be specific, oxygen). In industry, steam is used as an economical and easy mode of heating for various applications like – (1) Unit Operations in Chemical Industry, (2) Textile industry, (3) Polymer and paint industry, etc.

For a developed country like US, industrial sector consumes about 40% of country's commercial energy. Of the total energy used by industry, a major portion, (approximately 45–65%) is used for direct thermal applications in the preparation and treatment of goods, as listed above, and is known as Industrial Process Heat (IPH). The thermal energy for IPH, in general is below the temperature of 300 °C. the percentage of IPH demand utilized in the temperature range of 92–204 °C is 37.2% of the total IPH. The largest share of the total IPH demand is currently met by steam (Thomas, 1995).

1.1. A case of developing country like India

Considering India's energy consumption pattern, industrial share is at 27.1% (Earth Trends, 2003). India's primary energy demand in 2005 was 537 Mtoe (Million

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Nomenclature

A	aperture area of system, m^2
C_p	heat capacity of water, $J\ kg^{-1}\ K^{-1}$
dT	temperature rise for water in time 't', K
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
m	steam mass flow rate, $kg\ h^{-1}$
m_w	mass (water + equivalent of piping etc.), kg
$Qc1$	rate of heat loss by convection, W
$Qc2$	rate of heat loss by convection, W
$Qrad$	rate of heat loss by radiation, W
S	beam solar insolation, $W\ m^{-2}$
t	time, s

Greek symbols

θ	angle, °
η	efficiency, %
ε	emissivity
λ	latent heat of vaporization of water, $kCal\ kg^{-1}$
σ	Stefan–Boltzmann constant, $W\ m^{-2}\ K^{-4}$

Subscripts

A	aperture
g	glass tube
w	water

Abbreviations

CPC	Compound Parabolic Collector
IMD	Indian Meteorological Department
IPH	Industrial Process Heat
Mtoe	Million tonnes of oil equivalent
OD	outer diameter

tonnes of oil equivalent) and with the annual growth rate of 3.2%, it was predicted to be 590 Mtoe in the year 2008 by International Energy Agency (IEA, 2007). With the share of IPH in industrial energy consumption as indicated above, approximate steam requirement (below 200 °C) in India can be calculated as to be of the order of 70,000 Tons/h. Looking at the available solar energy technologies PTC seems to be the most suitable for this application (Thomas, 1995). Based on the report of Sargent and Lundy (2003) for PTC technology (Capital cost estimation – Rs.15.13 Crore/MW in 2020) and the work by Eck and Zarza (2006), the cost of PTC technology for steam generation works out to be Rs.12,500/m^2 aperture area and the cost of most widely employed Scheffler dish technology (especially for cooking applications in India) is in the range of 18,000 Rs/m^2. Thus, for India, there is a need for developing a moderate temperature ($\leqslant$200 °C) and a low cost solar energy based technology for the annual energy requirements at levels of about 32.7 Mtoe.

In this context, relatively stationary non-evacuated CPC solar collectors could be of great interest for thermal energy supply of industrial processes heat if they were cost effective compared to parabolic trough and flat plate collectors. Tripanagnostopoulos et al. (1999) fabricated an asymmetric CPC collector with two separate absorbers in order to absorb and trap maximum solar radiation. At the same time they made the system cost effective compared to flat plate collector using low cost material, but with lower concentration and working fluid temperature less than 100 °C. Azhari and Khonkar (1996) tried to improve the efficiency of the CPC system using modified absorber. They modified absorber by introducing two cavities in the appropriate location for radiation trapping. Buttinger et al. (2010) designed a CPC collector which encloses the collector and absorber in an evacuated enclosure, thus increasing system performance but at higher cost. CPC designs with evacuated tube absorber (similar to one presented by Jiang et al. (2012) for PV/Thermal hybrid collector) also offer a good option for applications in the temperature range up to 200 °C. The complexities involved and associated costs in manufacturing evacuated absorber and additionally, making provisions for maintaining the vacuum with special means would be an important factor to be considered while commercialization. The research area which needed greater investigation was the nature of the reflector to generate concentration. The standard parabolic reflectors have very small acceptance angle. A Compound Parabolic Collector (CPC) has comparatively a larger acceptance angle. But CPC suffers from limitations because of multiple reflections and unwieldy size. In this work, modified CPC reflector curves were designed, fabricated and tested to overcome these limitations. The main objective of the present work was to develop various experimental models of the CPCs for steam generation in moderately low temperature range. It is to be noted here that, to understand the working of CPC systems, various models of CPC (including conventional, truncated CPC) were designed, fabricated and tested for water heating/steam generation. It was the system described below which gave the encouraging results for steam generation with reduced total system costs.

1.2. Basics of compound parabolic collectors

CPC are non-imaging concentrators and their potential as collectors of solar energy was pointed out by Winston and Hinterberger (1975). The basic shape of CPC is shown schematically in Fig. 1A and its theory and working principles can be found in the literature (Rabl, 1980). As seen from the figure, CPC is made of two halves of parabola with closely located focal points and their axes inclined to each other, such that rays incident within the angle between the two axes (acceptance angle of the CPC) are reflected with single or multiple reflections towards the region between the two focal points and get concentrated

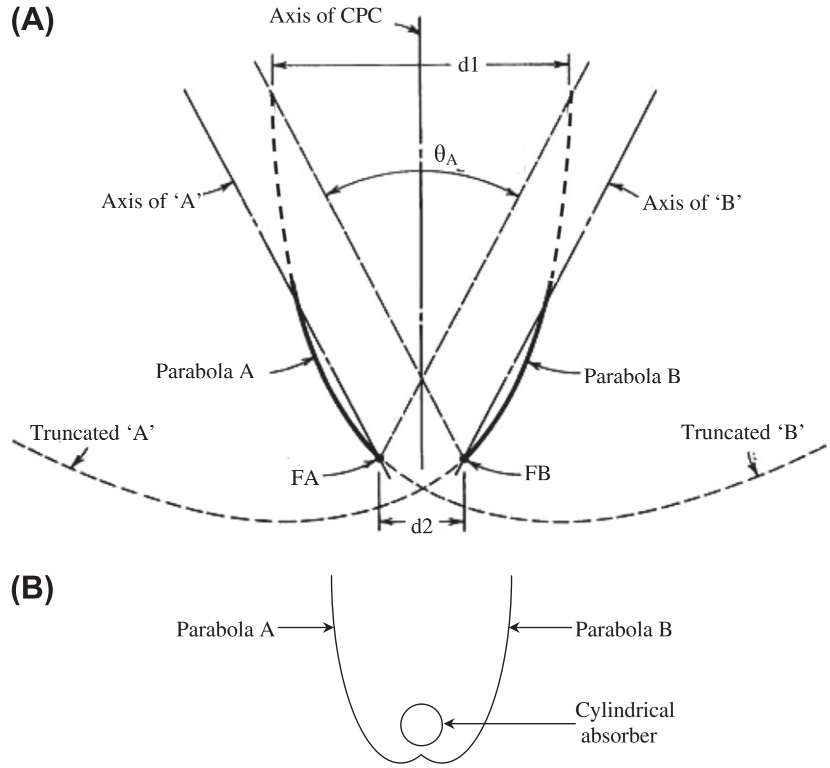

Fig. 1. (A) The geometry of conventional compound parabolic concentrator (CPC). d1: Aperture of CPC. θ_A: Acceptance angle of CPC. FA: Focus of Parabola A. FB: Focus of Parabola B. d2: Receiver opening. (B) Schematic of CPC with cylindrical absorber.

in that region. Thus, CPCs can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector. As the upper part of a CPC (dotted line as indicated in Fig. 1A) contribute little due to a steep angle of incidence to the radiation reaching the absorber, they are usually truncated thus forming a shorter version of the CPC (Rabl, 1976). In addition to the flat absorber (receiver) design discussed above, CPCs with other absorber geometries can also be designed. One such design is a cylindrical absorber as shown in Fig. 1B. Cylindrical shape has the advantage of utilizing full surface for energy absorption unlike flat absorber where the back side has to be insulated properly to prevent/minimize heat loss.

A CPC concentrator is mostly orientated with its long axis along the east–west direction and for a location in northern hemisphere; its aperture is tilted towards south for most of the time of the year, such that the sun rays are incident on CPC aperture within the acceptance angle. The tilt of the CPC may have to be adjusted periodically when the incident solar radiation moves outside the acceptance angle of the CPC.

The ideal concentration ratio of a CPC is related to the acceptance angle by

$$\mathrm{CR} = \frac{1}{\sin(\frac{1}{2}\theta_A)} \tag{1}$$

where θ_A is the acceptance angle of the CPC. The actual concentration ratio is usually lower than the ideal one. Rabl (1980) gives tilt requirements of CPCs with different acceptance angles along with daily collection time.

1.3. Modified design of CPC

The design of CPC (as shown in Fig. 1) has two disadvantages: (i) its height increases rapidly with aperture, making the structure unwieldy to handle and (ii) a sizable percentage of radiation incident within the acceptance angle suffers multiple reflections before reaching the receiver, resulting into a drop in its optical efficiency.

A modified version of CPC was designed, overcoming disadvantages of conventional CPC. Here, like conventional design, the axes of the two half parabolas were inclined to each other, defining the angle of acceptance and their foci were separated by a small distance; but, unlike conventional design, the two foci were very close to the plane of the aperture. To overcome disadvantages of conventional CPC, segments of two parabolic curves (forming CPC) above the focal point were removed and those below focal point were selected. As shown in Fig. 2, the receiver pipe is located near the aperture, and its size was selected such that all rays incident through the angle of acceptance are captured by it after reflection.

The incident rays change from one extreme (Ray 1, Ray 2) to other (Ray1′, Ray 2’) during the non-tracking period for CPC. In the first extreme position (Ray1), they are par-

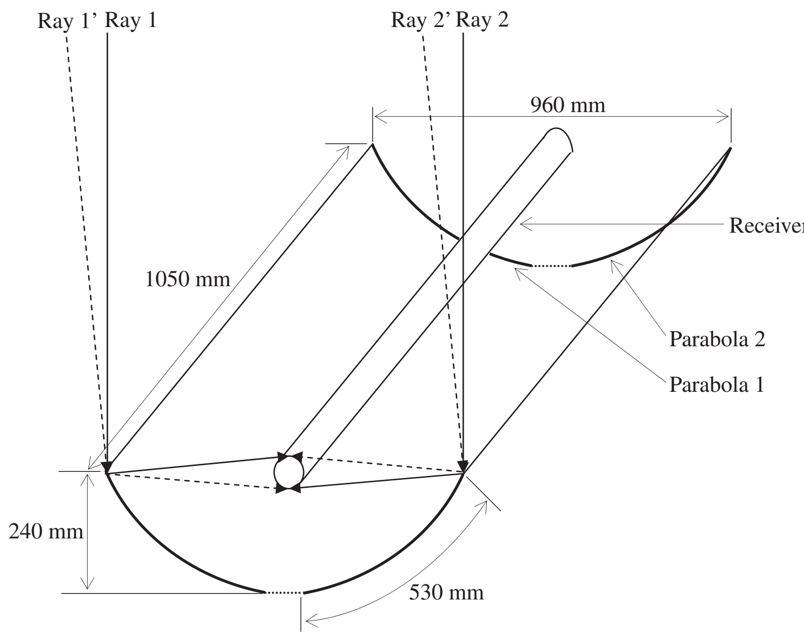

Fig. 2. Schematics of single unit of new CPC system.

allel to axis of one of the parabola and hence are reflected to the focus of respective parabola on the receiver pipe (in this case, top of receiver pipe: Fig. 2). At this time, the reflected rays from other arm of CPC are focused on the bottom of the receiver pipe (Ray 2). It is to be noted that, due to the intersection of the reflected rays with receiver pipe wall, on their way to the focus, the reflected rays are actually distributed on the receiver surface. The position of the reflected rays with respect to the receiver pipe is exactly reversed when the incident rays come from other extreme (Ray 1′ and Ray 2′).

Further, when the rays are shifting from one extreme position (Ray1 and Ray2) to the other extreme position (Ray1′ and Ray2′), they are not getting focused on either of the focal points. The dimensions of the assembly however are such that, under this condition, the rays reflected from the end points of the two halves of the compound parabolic collector strike the receiver pipe at some intermediate points. From the 'Edge Ray Principle' it follows therefore, that all the rays reflected from the intermediate points of the reflector also strike the receiver, during the transition from one extreme of the acceptance angle to the other.

Thus, a CPC with acceptance angle of 6°, requiring tilt adjustments once a day for a daily operation of 6 h, was designed aiming at steam temperature up to 150 °C.

2. Experimental set up and procedure

As explained above, the CPC system was designed in such a way that the focus was at the level of the aperture as shown schematically in Fig. 2. It had an aperture area of 0.96 m^2 per unit and system parameters are listed in Table 1. The curve length was 53 cm (on one side) requiring 10% extra mirror area over aperture. This is much less compared to conventional CPC designs. The acceptance angle of the CPC was 6° for which tilt adjustment is required every day. Decreasing the acceptance angle resulted in an increase in the concentration ratio with increased aperture requiring reduced receiver pipe size. The receiver pipe size was 1.5″ (outer diameter of 48.3 mm) with concentration ratio (CR) of 6.3 (upper limit, as per Eq. (1), CR = 19). The length of each unit was kept at 1 m so as to conveniently fix the mirror strips. The exact length of the CPC fame was 1050 mm to allow fixing from both ends giving clear length of 1 m. To reduce the end losses, it is necessary to connect as many units in series as possible. The CPC frames were fabricated from MS with semicircular ring at the bottom such that absorber remains fixed and the CPC unit can rotate around it. In order to reduce the cost by minimizing the material requirement, the CPC units were supported from the receiver pipe itself with intermediate support for the pipe. With the requirement of the perfectly straight receiver pipe, maximum of 3 units of above design could be supported from the pipe. Thus, the final configuration was three CPC units attached in series to form a single larger unit with supports for pipe after every 3 m length. 30 units were arranged in two rows as shown in photograph (Fig. 3). The total land area used was approximately 60 m^2 (20 m × 3 m). This arrangement ensured maximum effective utilization of the piping (minimum pipe length requirement) and reduced the auxiliary length of pipe that requires to be insulated. The piping at two ends, around the tank and pump was insulated by glass wool with aluminum cladding. All the CPC units were fixed on the receiver pipe with 3 layers of asbestos cloth (total thickness ~ 20 mm) between them to prevent the conductive heat loss. Each CPC unit was fabricated using angles

Table 1
CPC-design parameters.

Parameter	Value
Mounting	E–W
Acceptance angle	6°
Aperture area	28.8 m^2 (30 units; 0.96 m^2 per unit)
Concentration ratio	6.3
Absorber	1.5″ pipe with matt black paint with 2 glass tube covers
Reflecting Surface	Glass mirror strips (15 mm × 1000 mm × 2 mm thickness)
Curve length	1.06 m
Mirror area	32 m^2

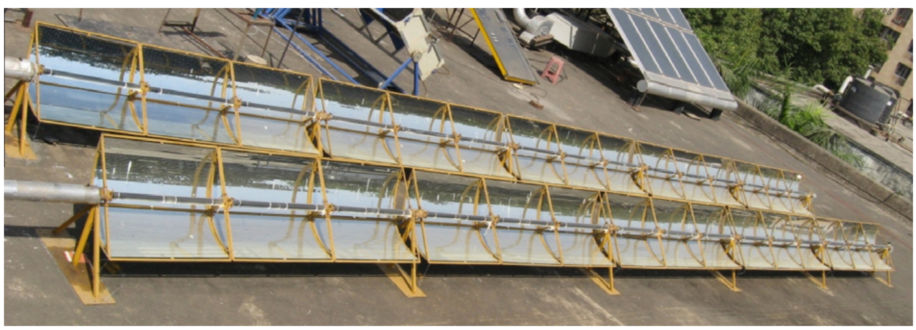

Fig. 3. Photograph of installed CPC system.

to form the main frame to give mechanical strength. The CPC curve was formed by metal strips of appropriate cross section for rigidity. The curved reflector surface was obtained by using mirror strips of 15 mm width and 1050 mm length. The strips were first fixed on the metal frame using double sided adhesive tape and then from the top with a dummy CPC curve strip. The depth of each unit was 240 mm with the receiver pipe located at aperture level (Fig. 2). Two glass tubes (60 mm and 70 mm OD and of nearly 2 mm thickness, separated by a Teflon ring of thickness 3 mm) were fixed on the receiver pipe to prevent the convective losses which were found to be substantial after few initial trials with bare receiver pipe. Water temperature measurements were done at inlet, outlet of system and in the tank. Solar intensity was measured with pyranometer supplied by M/s Weathertec, Pune, India (calibrated by IMD). Following is the typical procedure followed during the experiments.

The centrifugal pump was started and the water circulated through the receiver pipe of the CPC system. After noting initial temperatures, all the units were tracked manually and fixed in their position. The temperatures and the solar intensity were recorded at regular time intervals during the experiment. After the steam generation was started, the generated hot water–steam mixture was fed back to the tank, which also acted as the separator for the steam. The steam was taken out from the connection provided at the top and its flow rate was measured by condensing directly in cold water. To ensure complete condensation, sufficient quantity of fresh cold water was taken for each measurement. Thermal efficiency of the system was calculated as per Eqs. (2) and (3).

For sensible heat gain period (water temperature rise):

$$\eta = \frac{m_w C_p dT}{SAt} \times 100 \tag{2}$$

and for latent heat gain period (steam generation):

$$\eta = \frac{m\lambda}{0.86SA} \times 100 \tag{3}$$

where 'm_w' is the amount of water heated through temperature rise of 'dT' in time 't'. 'S' is the solar beam radiation falling on aperture area 'A' and 'm' is the rate of steam generation.

3. Results and discussion

Following is the discussion of the results obtained with the new CPC system and the analysis for estimation of heat losses and the possible measures to improve the system performance.

3.1. Steam generation efficiency

As noted before, initial trials were carried out without the glass tubes on the receiver pipes. During these trials, it was found that substantial time was taken for initial rise of temperature to boiling point and also, the steam generation rate was much lower. For instance, on a clear day (January 24) trial was started at 10 a.m. and steam generation was found to be started at 12:30 p.m. requiring 2 h and 30 min for raising the water temperature to its boiling point. Also, the rate of steam obtained was very low at 3–3.5 kg/h. This indicated high convective heat losses from the receiver pipes and the need for preventing/reducing this convective heat loss. Hence the set up was dismantled and the receiver pipe was covered with two borosilicate glass tubes (having 60 and 70 mm OD, 2 mm thickness and 3 mm clearance). The results for steam generation on a typical day (April 12) are shown in Fig. 4. It shows the variation of the rate of steam generation with time along with solar intensity. The initial time of heating of water to boiling point was found to reduce by more than 25% to 1 h 50 min. The steam generation rate was found to steeply increase with an increase in the irradiation intensity and then falls after the maxima obtained around noon-time.

The steam generation started after 1 h 50 min of irradiation with an initial rate of 7 kg/h. The maximum steam flow rate obtained was around 10 kg/h. The efficiency for the initial time up to steam generation was calculated considering the sensible heat gain by the water and the set up (thermal inertia). After the steam generation, the efficiency calculation considered the rate of steam generation and the heat of vaporization (latent heat = 540 kCal/kg at 100 °C). It can be observed from Fig. 4 that the solar intensity was maximum at 12:30 pm. The average intensity over the period of the experiment was found to be 700 W/m^2.

The temperature of outlet water was always slightly higher than that at the inlet. The time average thermal efficiency (over a period of 6 h) of the system was found to be 25%. The average steam generation rate was 8 kg/h. Fig. 5 shows the comparison of thermal efficiencies for the new CPC system without and with glass tube cover on receiver pipe (Case 1 and Case 2). We can see that the thermal efficiency is always higher for Case 2 indicating the reduction in heat losses except at a time of 11:30 a.m. This observation is due to the fact that, in Case 2, the steam generation was observed at this time which may have flooded the system, resulting into lower heat absorption rate by the receiver pipe due to the lower heat transfer coefficient of the vapor film. The overall increase in thermal efficiency due to covering of receiver pipe with glass tubes was found to be 7.4% in absolute terms (46.8% relative rise). Thus, the use of double glass tubes as cover for receiver pipe resulted in reduction in convective losses and improved the system performance by slightly less than 50%. Therefore, the system was further studied for the quantification of thermal losses occurring at various stages of energy transfer and the possibility of improvements was examined. It was found that apart from material properties such as-mirror reflectivity, optical transmissivity of the glass-tube and receiver coating absorptivity, the factors contributing to the reduction in the heat collected are: (a) use of mirror strips (instead of continuous curved mirror), (b) radiative and convective losses from receiver and other hot surfaces and (c) loss of concentrated radiation at receiver due to end supports (100 mm length is used for support per *m* length of receiver pipe) which are quantified in the next session.

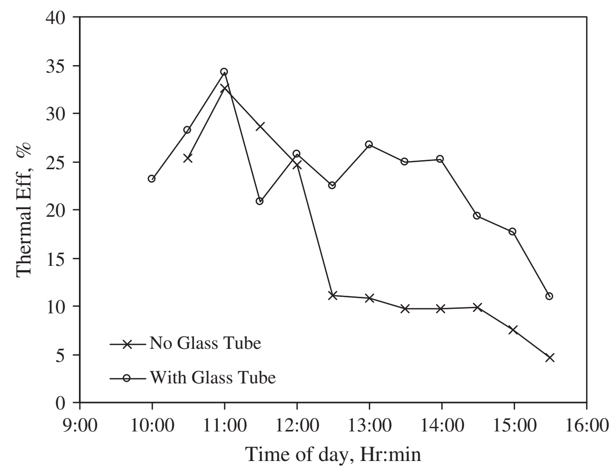

Fig. 5. Comparison of thermal efficiencies for CPC system. 'no glass tube' and 'with glass tube' on receiver pipe.

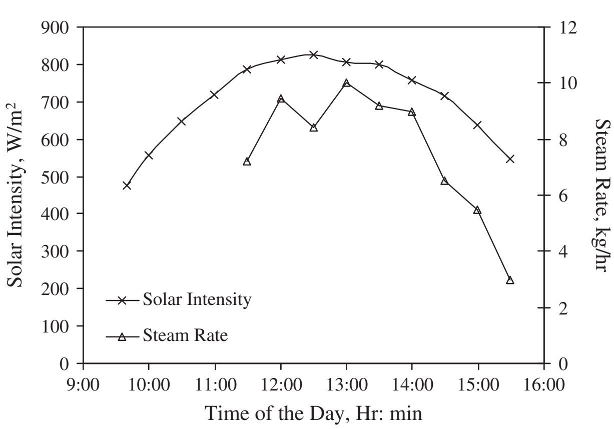

Fig. 4. Variation of solar intensity and steam generation rate.

3.2. Heat loss analysis and measures for improvement

The loss of energy at various stages is estimated as shown below and the possible measures to reduce it are also listed. Table 2 shows the estimated loss values (and available energy) at various steps for two cases-the present and that possible after improvements.

3.2.1. Radiation loss at mirror surface

Use of mirror strips to form the required curved shape gives rise to losses at each joint between adjacent strips. The entire area of the CPC is not covered by the mirrors and space of 1 strip (15 mm) is lost in the length of 530 mm; amounting to 2.8% of surface loss. In ideal case, the curved mirrors could be used and this loss can be eliminated completely.

Table 2
Losses and improvements in CPC system.

No	Step/Item	Present system		After improvements	
	Description	Loss (%)	Available (W/m^2)	Loss (%)	Available (W/m^2)
0	Available solar radiation	–	700.0	–	700.0
1	Mirror strip	02.8	680.4	0.0	700.0
2	Reflectivity	15.0	578.3	5.0	665.0
3	Manufacturing errors	05.0	549.4	1.0	658.4
4	Glass tube Transmitivity	15.4	465.0	5.0	625.4
5	Receiver absorption	20.0	372.0	8.0	575.4
6	Radiation loss	15.4	314.7	2.8	559.4
7	Convective loss	30.5	218.6	1.0	553.8
8	Other losses	20.0	174.9	5.0	526.1
	Available energy to water	25.0[a]	174.9	71.2[a]	498.4

[a] Energy available to water as percentage of incident solar radiation (700 W/m2).

3.2.2. Mirror reflectivity

The glass mirrors used (MODI GUARD) have the reflectivity of 85% (measured using pyranometer). Thus, 15% of the radiation is lost at this stage. The mirrors available for commercial solar reflectors (e.g. developed for PTC technology) have reflectivity in the range of 95% bringing down these losses to only 5%.

3.2.3. Manufacturing errors

The present CPC units were fabricated by a local skilled fabricator but without any automation. The CPC curve was prepared manually by hammering/bending. After matching the fabricated curve with the plotted one from *x–y* data, this fabrication error was found to be around 5%. It can be assumed that with automation these losses can be reduced to less than 1%.

3.2.4. Transmission through glass tubes

The borosilicate glass tube has a transmitivity of 92% for the sunlight. Since two glass tubes were used in series, the losses are 15.36%. With special type of glass for solar applications (low iron content) having transmitivity of 95%, these losses can also come down to 10% and with an evacuated single glass tube receivers, transmission losses can come down to less than 5%.

3.2.5. Losses at receiver

These come from the properties of the coating material and its combination with the receiver pipe material. The absorptivity of the paint used from the local market was only 80% thus loosing 20% of the incident energy in the form of reflection. Selective coatings have absorptivity in excess of 91%, which can reduce these losses to about 8%.

3.2.6. Radiation from receiver

For the experimental stet up used in this study (receive pipe without selective coating), the radiation losses can be estimated as follows:

Pipe OD = 48.3 mm.
Length = 1 m.
Surface area = 0.1517 m^2 (per m^2 of aperture area).
Pipe temperature = 120 °C.
Inner glass tube temperature = 80 °C.

The steady state losses can be computed from the radiation losses from the metal pipe to inner glass tube which in turn is losing to outer glass tube and then to the surrounding.

$$Qrad = \sigma \varepsilon A(T^4 - T_g^4)$$

With radiation constant $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4, these losses comes to be 57.3 W for 1 m^2 aperture area. This amount is 15.4% of the incident solar energy at this stage or nearly 8.2% of the incident radiant energy of 700 W/m^2.

With selective commercial solar coatings like Solkote (Make: Solec, US), these losses can be reduced substantially (Absorptivity = 0.9137 and emissivity = 0.2244); hence, radiative = losses come down to 16 W/m^2 or to only 2.8% of the incident energy available at this stage.

3.2.7. Convective losses

The convective losses occur from all of the hot surfaces like piping, tank, pump and the glass tubes. These were estimated roughly as follows.

(a) Insulated surfaces

$$Qc1 = h \cdot A \cdot dT$$

The area is estimated from the length of the piping, pump, tank, etc. and comes to be nearly 10 m^2; the heat transfer coefficient, '*h*' is typically 10 W/m^2/K (McAdams, 1954), and the temperature difference (insulation at 45 °C and air) is of the order of 15 °C.

Thus the total loss comes out to be 1500 W for entire CPC system, or 52.1 W/m^2 for system aperture area of 28.8 m^2.

(b) Glass tube surface

The outer glass tubes were of 70 mm OD and 1 m length; each for 1 m^2 aperture area.

The glass surface temperature was 50 °C and with same value for '*h*',

The losses are

$$Qc2 = 44\ \text{W}$$

Thus, total convective losses are around 96.1 W/m^2 accounting for 30.5% of the incident energy available at this stage or 13.7% of the initial incident energy. Ideally, with evacuated tubes and proper insulation, these losses can be reduced substantially (of the order of 1%).

3.2.8. Other losses

For supporting of the CPC units on the absorber pipes, clamps of 100 mm length were provided. Two adjacent units shared one clamp totaling 16 clamps for one row of 15 units. Thus, though direct end losses were avoided combining three CPC units to form a group, concentrated radiation falling on these clamps was lost. This loss can be estimated to be 10.6% of the concentrated radiation. Another loss, not considered previously is the conductive loss through joints. These along with clamp losses are roughly estimated to be of the order of 20%.

Thus, it can be seen from Table 2 that, the final available energy to water is 175 W/m^2 which is 25% of incident 700 W/m^2. Also, as seen from table, the system performance can be improved to 71% with energy made available through these suggested improvements to 498 W/m^2.

Thus, with better materials (solar-special mirror and glass tubes, selective receiver coating) the losses related to basic properties can be minimized. Further, the scale up of the system with appropriate design modifications (increasing the aperture diameter and unit length) will also help in lowering the various heat losses discussed above. Thus with proper improvements, the proposed new design has the capability of harnessing solar energy with relatively high thermal efficiency.

4. Conclusions

From the study undertaken, it can be concluded that (i) modified CPC design is easy to fabricate and worked reasonably well for steam generation at atmospheric pressure (ii) the limitations of conventional CPC systems are quantitatively identified and were partially overcome in the new design which helped in reduction in overall system cost (iii) newly designed CPC models can substantially reduce the mirror area requirements per unit aperture area compared to conventional CPC systems (iv) heat loss analysis has been carried out and it was found that more refinements in the design and scale up would further enhance the system performance and will enable steam generation at temperatures at which significant fraction of process heat can be used.

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