Performance Comparison of CPC based solar installations at different locations in India and analysis of variation pattern

Anagha Pathak1*, Anand Bhosle1, Pravin Baste1, Niranjan Kurhe1, Nitin Suryawanshi1 Asmita Marathe2, Sandesh Jadkar3)

1School of Energy Studies, Savitribai Phule Pune University, Ganeshkhind, Pune-411007, India.
2 Department of Technology, Savitribai Phule Pune University, Ganeshkhind, Pune-411007, India
3 Department of Physics, Savitribai Phule Pune University, Ganeshkhind, Pune-411007, India
*Corresponding Author
Email address: drpathakam@gmail.com

Abstract
Currently the industrial heat demand is met by using expensive fossil fuels. Exclusive use of solar energy is not feasible due to the fluctuating pattern of solar radiation intensity. Solar hybridization with the existing heating system can be an appropriate solution to meet the process heat requirement of many industries. Concentrator Solar Thermal (CST) technologies can generate the medium temperature heat required for industrial processes. The present study was undertaken with an objective of comparing and analyzing the designed performance of the solar fields using the Compound Parabolic Concentrator (CPC) technology against the actual measured performance values for boiler feed water preheating application at two different locations in India. The optical efficiency of the CPC collector, 64.8%, obtained when tested as per part 5 of IS 16648:2017 was used for designing the solar fields as per the daily heat requirement. The performance of the installations at both the locations was monitored for a period of five months. The observed variation in the performance of each installation than the designed performance was compared and analyzed for the causes. The average variation in designed and measured performance was in the range of 9.0% to 9.8% for location 1 and 2 respectively, attributing to heat rejection from the collector attachments and fluid transfer lines, dust effect on the absorber and reflector of CPC, instrument’s uncertainty, other losses due to shadow effect, vacuum loss from the tubes, dislocation of tubes, heat removal and usage pattern etc. The reasons of the losses from both the fields were of the similar nature, which should be taken into account to design a solar thermal system to achieve predicted performance near to the designed performance. Preheating of boiler feed water is one of the potential applications of solar CPC technology.

Keywords: Solar fluid heating, solar thermal concentrators, Compound Parabolic Concentrator, Industrial process heat, Performance analysis
# Nomenclature

| Symbol | Description | Units |
|--------|-------------|-------|
| $A_p$ | Aperture Area | sq.mt |
| $a_1$ | Heat loss coefficient – First order | (W/m²K) |
| $a_2$ | Heat loss coefficient- Second order | (W/m²K) |
| $C$ | Concentration Ratio | |
| $C_p$ | Heat Capacity per unit mass | (kJ/kg°C) |
| CPC | Compound Parabolic Concentrator | |
| $I_b$ | Beam or Normal Radiation | (W/m²) |
| $I_d$ | Diffused Radiation | (W/m²) |
| $I_g$ | Global or Total Radiation | (W/m²) |
| $K_{zl}$ | Incident Angle Modifier along longitudinal axis | |
| $K_{zt}$ | Incident Angle Modifier along transverse axis | |
| $\dot{m}$ | Mass Flow per unit time | (kg/sec) |
| $n$ | Average Number of Reflections | |
| $n_{me}$ | Total Number of times measurements carried out | |
| $p$ | Gap loss coefficient | |
| $T_a$ | Ambient or atmospheric Temperature | °C |
| $T_{in}$ | Inlet Temperature of working fluid | °C |
| $T_{out}$ | Outlet Temperature of working fluid | °C |
| $T_{me}$ | Mean Temperature of working fluid | °C |
| $k$ | Coverage Factor at particular confidence level | |

| Symbol | Description | Units |
|--------|-------------|-------|
| $\mu_A$ | Uncertainty - Type A | |
| $\mu_B$ | Uncertainty – Type A | |
| $\mu_C$ | Combined or Total Uncertainty | |
| $\mu_E$ | Extended Uncertainty | |
| $\mu_{fm}$ | Flow meter uncertainty | |
| $\mu_{tp}$ | Thermal performance test uncertainty | |
| $\mu_{pg}$ | Pyranometer uncertainty | |
| $\mu_{at}$ | Ambient temperature sensor uncertainty | |
| $\mu_{in}$ | Uncertainty for fluid inlet temperature sensor | |
| $\mu_{out}$ | Uncertainty for fluid outlet temperature sensor | |
| $\alpha$ | Absorptivity index | |
| $\rho$ | Reflectivity index | |
| $\tau_c$ | Transmittivity index | |
| $\tau_d$ | Transmittance with Dust accumulation | |
| $\sigma$ | Standard Deviation (S.D) | |
| $\theta$ | (Acceptance Angle/2) (°) | |
| $\phi$ | Outer Diameter (OD) | |
| $\eta$ | Instantaneous Efficiency | |
| $\eta_o$ | Optical or theoretical maximum Efficiency | |
1. Introduction

1.1 Concentrating Solar Thermal (CST) Technologies

Hot water or steam can be generated at various temperature and pressure ranges using the Concentrating Solar Thermal (CST) Technologies. The concentration ratio of the CST technologies decides the temperature and pressure ranges. The CST collector can concentrate solar radiation many times using mirrors or lenses, achieving the temperatures in the range of 100 to 450°C or even more. These devices need tracking for focusing the sun rays on a receiver all the time. Solar energy is received in direct and diffused form and CST works on the direct normal radiation. However, the Compound Parabolic Concentrator (CPC) is the only non-imaging concentrator, which uses global radiation, i.e. both direct and diffuse radiation. The CST systems can be used for medium and high temperature requirement for different applications in industries, commercial establishments and organizations. Anagha Pathak, 2017 [1] in their article have given a range of concentrating solar thermal technologies available which can be used based on the required temperature of the process. Figure 1 shows various solar thermal technologies and their temperature ranges.

![Figure 1 Temperature ranges of various solar thermal concentrator technologies](image)

From Solar Thermal technologies which are currently available, Compound Parabolic Concentrator Technology is the simplest technology. The technology highlights of compound parabolic collector include it’s modular and easy to install design. Ground mounting and installation on flat or inclined roof is possible with CPC collectors. CPC is well spread technology compared to other available CST technologies, due to better thermal and optical performance for temperature needs below 100°C. Due to the non-tracking, stationary design, CPC collectors are low maintenance with less tracking inaccuracies. cost of stationary collectors is much lesser than the tracking collectors per unit heat gain. Another important aspect of CPC collector is that unlike CST technologies, it uses global radiations falling on collector plane from surrounding [2]. CPC generates good amount of heat even at low radiation level. Therefore, CPC has gained popularity over other CST collectors for the application of Industrial Process Heat. CPC collector was tested for the performance evaluation at the Regional Test Centre, Pune as per the part 5 of IS 16648[3] as well as on the field installations.
CPC collectors can easily be integrated with existing heating sources in the industries like textile, food, dairy, chemical, pulp and paper industry to cater the needs like sterilization, pasteurization, dyeing, bleaching, drying, cooking, Pre-heating boiler feed water etc. [4], [5].

The present study was undertaken in two leading FMCG (Fast Moving Consumer Goods) companies in India one at Pune location and the other at Bangalore location, with an objective of analyzing the performance variation of solar CPC based installations when measured at actual with respect to designed performance. Both the CPC fields were used for preheating of boiler feed water. The CPC collector was tested at Regional Test Centre, Pune at S. P. Pune University as per the part 5 of IS 16648:2017 and the efficiency values obtained as per the performance equation were used for designing the solar field [6]. The reasons for performance variation were analyzed and studied. This study will help in designing more accurate performance predictions of solar thermal energy-based installations.

2. Compound Parabolic Concentrator (CPC) technology
RABL, 1985 [7] in his book on ‘Active Solar Collectors and their Applications’, has defined CPC as a solar collector designed in such a way, where two parabolas meet each other at a particular position. CPC is a high aperture area, non-imaging solar thermal collector. The concentration ratio that can be achieved in the non-tracking mode is up to 10. The concentration ratio of solar concentrators is the ratio of aperture area of reflector to the aperture area of receiver. The concentration ratio depends on the tracking system and geometry of both the reflector and receiver. Higher concentration ratio helps to achieve higher temperatures.

2.1 Basic concept of CPC
The non-imaging concentrators or CPC collectors are capable of reflecting the incident radiation to the receiver aperture area over incidence angles range within broader limits. Sarbu and Sebarchievici, 2017 [8] has stated that the acceptance angles of the CPC are defined by these limits. Figure 2 shows the geometry of the CPC.

![Figure 2: The Geometry of Compound Parabolic Concentrator](image)

Figure 2 shows the parabola, axis and focus of one side of the parabola although both sides of CPC are parabolas. The surface of the parabola is parallel with the axis of CPC. The acceptance half angle $\theta_a$ is the angle that the axis of CPC makes with the connecting line of focus of one parabola with the opposite edge of the aperture. In case of a perfect reflector, the radiation which enters the aperture at angles within $\pm\theta_a$ reflects to the receiver.
CPC specifications include width, height, acceptance angle and concentration ratio. For the CPC to be ideal, 
\[ C = \frac{1}{\sin \theta_c} \]  
(1)  
Where, \( C \) is Concentration ratio 
\( \theta_c \) is half of acceptance angle.

The CPC collector consists of an absorber tube which is selectively coated and enclosed in a co-axial glass covering to reduce the thermal losses by convection. The vacuum is maintained in empty space between the tube and its outer glass covering. The glass tube is placed at the focal plane of two parabolic reflectors that are designed as troughs structure. The axes of the two parabolas are inclined at the acceptance angle to reflect the radiations on to the receiver tubes which carries working fluid.

The construction of the CPC tubes used for the field installations is shown in fig. 3. The tube has geometric concentration ratio equal to 2.43. The dimensions of Reflector placed below each CPC tube are shown in fig. 3. The reciever is all glass evacuated tube type with U-Tube inside for working fluid circulation. The external surface of the absorber tube is selectively coated by aluminium nitrate. The outer cover is made of low impurity, high transmittance, borosilicate glass. The evacuated tubes used for the CPC collectors are available commercially at reasonable costs. Anodised aluminium having reflectivity more than 80% has been used as a reflector material (Kurhe et al., 2020)

![Figure 3: Construction and Dimensions of CPC used in the present study in the field installations](image)

Technical specifications of the CPC collector which are used in the presented study are shown in Table 1.

| Sr.No. | Parameter                        | Specification          |
|--------|----------------------------------|------------------------|
| 1.     | OD of absorber Tube              | 36mm                   |
| 2.     | OD of Outsideglass Tube          | 47 mm                  |
| 3.     | Material of Absorber Coating     | Al-N                   |
| 4.     | Material of U-Tube               | Copper                 |
| 5.     | Reflector width for single tube  | 114 mm                 |
| 6.     | Reflector height for single tube | 27.5mm                 |
| 7.     | Reflector length                 | 1500 mm                |
| 8.     | Total Number of tubes in one collector assembly | 18 |
| 9.     | Collector Aperature Area         | 3.0 m²                 |
3. Industrial Process

3.1 Boiler feed water preheating

Boiler feed water preheating is an important part of boiler operations. The feed pump adds the water into the steam drum where it gets converted into the steam to be used for further process. Many industries use different fossil fuel-based boilers for steam generation which makes steam generation costlier. The makeup water temperature needs to be raised from ambient temperature of 25 to 30 °C to higher temperatures as per boiler requirement. Preheating of feed water increases the steam generation rate and quantity as less energy is lost in increasing the temperature of feed-water from ambient to evaporation conditions. Bhaskaran, 2016 [9] in his analysis on effect of feed water temperature on boiler efficiency has shown that there is an increase in the boiler efficiency with rise in feed water temperature. A typical scheme for boiler feed water preheating is shown in figure 4(a).

3.2 Solar integration with boiler feed water preheating:

The solar collector’s heat generation depends on the input solar radiations which vary widely from morning to evening and from winter to summer depending on the seasonal variations in sun’s position. However, industrial process needs a stable source of heat energy and variation is not acceptable. The challenge of ensuring consistent supply of heat to the plant while using all the solar energy available on collector area can be addressed by integration of solar thermal technology with existing heating source which can be fossil fuel, electricity or biomass. Such integration scheme utilizes maximum solar energy potential. Supporting conventional fuel is used to fill the required gap from the solar energy-based system, as per requirements. Preheating of boiler feed water is potential application of the above-mentioned integration scheme to meet the heat and temperature demand.

3.3 System description

The present study compares the performance of two CPC based solar fluid heating systems out of which the first system has been installed at a Fast-Moving Consumer Goods (FMCG) company near Pune, India, here referred as location 1. The second system has been installed at FMCG in Bangalore, India, here referred as location 2. Based on site study and feasibility check, detailed system design was worked out at both the sites. The application and scheme of both the installations was same.

Fig 4(a) shows already existing sytem and Fig 4(b) shows upgraded system with solar CPC field. In earlier system, condensate collected from the application was being collected in feed water tank at 85°C. Also, the make-up water was being added in the same tank. The water from the feed water tank was sent to the boiler via an economizer. In the previous system, water at the room temperature was added to the feed water tank hence due to the sensible heat load the water temperature in the feed water tank was decreasing. Later on, the makeup water was heated up to 85°C and then supplied to the feed water tank to decrease the sensible heat load. Fig.5 shows the actual image of CPC based solar installation at location 1. Considerations for design of solar system for boiler feed water preheating application are shown in Table 2.
Table 2: Considerations for design of solar system for boiler feed water preheating application.

| Parameter                  | System 1 (Pune Location) | System 2 (Bangalore Location) |
|----------------------------|----------------------------|--------------------------------|
| Latitude of installation   | 18.52°                     | 12.97°                         |
| Aperture area per Collector | 3 m²                       | 3 m²                           |
| Number of collectors per array | 130                       | 200                            |
| Design Temp.               | 85°C                       | 85°C                           |
| Operation hours            | 6 Hours                    | 4-6 Hours                      |
| Heat demand per day        | 817 kWh - Th/day (7,03,000 kcal/day) | 1360 kWh/ day (1,170,000 kcal/day) |
| Capacity                   | 3000 Liters/hour           | 3000 Liters/hour               |

Figure 4: a: Existing steam generation system b. Upgraded system with the CPC-based solar field

Figure 5: CPC field installation for industrial process heat application at location 1
3.4 System Design

The CPC collectors as per the specifications mentioned in Table 1 were used for the field installation. The collector was tested as per part 5 of IS 16648 2017, in the Regional Test Facility, Pune for testing Concentrated Solar Thermal Technologies at Savitribai Phule Pune University, Pune. The test results obtained are used for designing CPC field at both the locations.

The basic equation for computation of performance of the CPC is,
\[
\eta = \eta_o \times \cos \theta \times K_{\theta L} \times K_{\theta T} - a_1 \left( \frac{T_m-T_a}{I_g} \right) - a_2 \times I_g \left( \frac{T_m-T_a}{I_g} \right)^2
\]  
(2)

Where, \( \eta_o \) represents the optical efficiency, \( \theta \) is the angle of incident between beam radiation and normal to the collector plane, \( K_{\theta L} \) and \( K_{\theta T} \) are modifiers for incident angle along the longitudinal and transverse axis respectively, \( T_m \) is mean of outlet and inlet temperature (°C), \( a_1, a_2 \) are first (W/m²K) and second (W/m²K²) order heat loss coefficients respectively.

The equation (2) can be rewritten as
\[
A_P = Q / (I_g \times \eta_o \times \cos \theta \times K_{\theta T} \times K_{\theta L} - a_1 \times (T_m - T_a) - a_2 \times (T_m - T_a)^2)
\]  
(3)

Instantaneous efficiency can be calculated using equation (4)
\[
\eta = \left( \frac{\dot{m} \times C_p \times (T_{out} - T_{in})}{I_g \times A_P} \right)
\]  
(4)

The instantaneous efficiency is obtained from graph as a function of \( \left( \frac{T_m - T_a}{I_g} \right) \) as shown in Fig. 6. The data is plotted using least square method of curve fitting. Data was collected for various water inlet temperatures at uniformly spaced interval. \( a_1 \) and \( a_2 \) are calculated by multiple regression method. The optical efficiency \( \eta_o \) is obtained by keeping the water mass flow rate in such a way that \( T_m \) is near to \( T_a \). The \( \eta_o \) obtained is checked with the efficiency got from Y- intercept of graph as shown in fig. 6.

The testing standard IS standard 16648- part 5, 2017 was referred for all the equations mentioned above.

The performance equation shown in Equation 5 for the tested CPC collector was obtained from the testing results of the CPC collector tested in National Test Facility at Savitribai Phule Pune University as per the standard IS 16648 (Part 5):2017 [6]
\[
\eta = 0.6481 \times \cos \theta \times K_{\theta L} \times K_{\theta T} - 1.12 \left[ \frac{T_m-T_a}{I_g} \right] - 0.01 \left[ \frac{(T_m-T_a)^2}{I_g} \right]
\]  
(5)
Figure 6: Performance of the solar CPC collector tested as per standard test conditions

4. Uncertainty calculations

Errors in the instruments can cause changes in experimental results. The uncertainty of each sensor or instrument used during experiment was calculated using following steps as mentioned in JCGM 100, 2008 guidelines [10].

Uncertainty: Type A

\[ u_A = \frac{\sigma}{\sqrt{n}} \]  \hspace{1cm} (6)

Uncertainty: Type B

\[ u_B = \sqrt{(\sigma_1^2) + (\sigma_2^2) + \cdots + (\sigma_n^2)} \]  \hspace{1cm} (7)

\( \sigma_1, \sigma_2 \) etc are computed from standard methods of Type B uncertainty, calibration certificates and data sheets.

Combined uncertainty:

\[ u_C = \sqrt{(u_A)^2 + (u_B)^2} \]  \hspace{1cm} (8)

Expanded uncertainty:

\[ u_E = K \times u_C \]  \hspace{1cm} (9)

Uncertainty is calculated for each sensor and instrument, by using equations (6) to (9). The confidence level for the above calculations was considered as 95 % and coverage factor \((k)\) was considered to be 1.96.

Uncertainty for complete thermal performance analysis is calculated by taking root of square of each individual expanded uncertainty of each sensor and instrument from equation (10).
\[ u_{TP} = \sqrt{(u_{t})^2 + (u_{o})^2 + (u_{pg})^2 + (u_{pb})^2 + (u_{f})^2 + (u_{a})^2 + (u_{mt})^2} \]  

The instruments details used for parameter monitoring and uncertainty measurement are shown in table 3 and table 4 for location 1 and for location 2 respectively.

**Table 3**: Instruments details with uncertainty calculations for Location 1 (Pune)

| Instrument Name          | Accuracy and Range                  | Least count (L.C.) | Combined or Total Uncertainty (\(U_C\)) (%) | Expanded Uncertainty (\(U_E\)) (%) |
|--------------------------|-------------------------------------|--------------------|---------------------------------------------|-----------------------------------|
| Pyrheliometer \((I_b)\)  | Response 2.6 sec 0-1500 W/m²/Time   | 0.1 W/m²           | 0.13                                        | 0.25                              |
| Pyranometer \((I_g)\)    | Response 2.6 sec 0-1500 W/m²/Time   | 0.1 W/m²           | 0.08                                        | 0.15                              |
| Mass Flow meter          | Accuracy +/- 1%, 0-2500 Kg/hr        | 1Kg/hr             | 0.05                                        | 0.1                               |
| Ambient Temperature sensor \((T_a)\) | Accuracy +/- 0.5°C, -50 to 50 °C | 0.1                | 0.4                                         | 0.78                              |
| Temperature Transmitter \((T_{in})\) | Accuracy +/- 1%, 0-200 °C      | 0.1                | 0.49                                        | 0.95                              |
| Temperature Transmitter \((T_{out})\) | Accuracy +/- 1%, 0-200 °C  | 0.1                | 0.48                                        | 0.94                              |
| Measuring Tape           | Accuracy +/- 1%, 0-3m 1mm           |                    | 0.015                                       | 0.031                             |

Uncertainty of thermal performance test \((U_{TP})\): 1.67% @ 95% Confidence Level

**Table 4**: Instruments details with uncertainty calculations for Location 2 (Banglore)

| Instrument Name          | Accuracy and Range                  | Least count (L.C.) | Combined or Total Uncertainty (\(U_C\)) (%) | Expanded Uncertainty (\(U_E\)) (%) |
|--------------------------|-------------------------------------|--------------------|---------------------------------------------|-----------------------------------|
| Pyrheliometer \((I_b)\)  | Response 2.6 sec 0-1500 W/m²/Time   | 0.1 W/m²           | 0.31                                        | 0.61                              |
| Pyranometer \((I_g)\)    | Response 2.6 sec 0-1500 W/m²/Time   | 0.1 W/m²           | 0.57                                        | 1.14                              |
| Mass Flow meter          | Accuracy +/- 1%, 0-2500 Kg/hr        | 1Kg/hr             | 0.17                                        | 0.35                              |
| Ambient Temperature sensor \((T_a)\) | Accuracy +/- 0.5°C, -50 to 50 °C | 0.1                | 0.025                                       | 0.049                             |
| Temperature Transmitter \((T_{in})\) | Accuracy +/- 1%, 0-200 °C      | 0.1                | 0.26                                        | 0.51                              |
| Temperature Transmitter \((T_{out})\) | Accuracy +/- 1%, 0-200 °C  | 0.1                | 0.14                                        | 0.28                              |
| Measuring Tape           | +/- 1%, 0-3m 1mm                    |                    | 0.015                                       | 0.031                             |

Uncertainty of thermal performance test \((U_{TP})\): 1.49% @ 95% Confidence Level
5. Solar field performance at Location 1 and Location 2

Performance of the solar field based on CPC technology was monitored and analyzed for process heat application.

Format for data collection and recorded representative data for solar field performance testing for various parameters is shown in Table 5 and Table 6 for location 1 and location 2 respectively. Table 5 and table 6 show the hourly variation of weather and heat parameters. The representative data is collected on a normal day of operation at location 1(Pune) and location 2 (Bengaluru).

Table 5: Hourly variation of weather and heat parameters at location 1 (Pune)

| Time of the day | T_a (°C) | I_a (W/m²) | T_in (°C) | T_out (°C) | Heat output (kWh) |
|-----------------|----------|------------|-----------|------------|-------------------|
| 09.00           | 19.8     | 532        | 40.5      | 46.2       | 129.2             |
| 10:00           | 21.6     | 743        | 48.3      | 53.8       | 170.1             |
| 11:00           | 25.4     | 908        | 57.2      | 66.3       | 206.3             |
| 12:00           | 28.6     | 982        | 68.3      | 78.1       | 216.5             |
| 13:00           | 29.5     | 986        | 80.7      | 89.8       | 202.1             |
| 14:00           | 30.8     | 903        | 90.4      | 98.9       | 192.7             |
| 15:00           | 31.7     | 754        | 76.1      | 83.1       | 159.7             |
| 16:00           | 31.5     | 528        | 76.2      | 80.8       | 102.0             |
| 17:00           | 30.8     | 479        | 76.1      | 80.5       | 99.8              |

Average Hourly Heat output per day from 390 m² area of collectors at Location 1, Pune, is 164.3 kWh. Therefore, hourly heat output per m² comes out to be 0.42 kWh with a minimum of 0.25 kWh and Maximum 0.55 kWh per day per m² collector area.

Table 6: Hourly variation of weather and heat parameters location 2 (Bangalore)

| Time of the day | T_a (°C) | I_a (W/m²) | T_in (°C) | T_out (°C) | Heat output (kWh) |
|-----------------|----------|------------|-----------|------------|-------------------|
| 09.00           | 19.9     | 452        | 42.7      | 49.0       | 135.9             |
| 10:00           | 21.4     | 609        | 57.1      | 63.3       | 132.5             |
| 11:00           | 23.5     | 726        | 64.3      | 72.7       | 180.0             |
| 12:00           | 24.1     | 786        | 73.0      | 81.5       | 181.8             |
| 13:00           | 26.2     | 803        | 92.4      | 103.6      | 249.2             |
| 14:00           | 26.6     | 638        | 94.1      | 101.9      | 173.3             |
| 15:00           | 27.2     | 568        | 78.3      | 88.1       | 210.7             |
| 16:00           | 25.5     | 530        | 78.5      | 87.8       | 198.9             |
| 17:00           | 23.4     | 489        | 79.0      | 86.9       | 167.6             |

Average Hourly Heat output per day from 600 m² area of collectors at Location 2, Bangalore, is 181.1 kWh. Therefore, hourly heat output per m² comes out to be 0.30 kWh with a minimum of 0.22 kWh and Maximum 0.42 kWh per day per m² collector area.

The variation in performance is due to the difference in solar radiation availability at both the locations on a typical day. The average radiation at location 1 at Pune is 17.8 % more than at location 2 at Bangalore hence per square meter output is less at location 2 on a typical day of a month.

The or energy output from the solar field was calculated using below equation

\[ Q = \dot{m} \times C_p (T_{out} - T_{in}) \]  

(11)
Energy produced by the CPC field for the month of January for location 1 at Pune and location 2 at Bangalore is shown in Fig. 7 and Fig. 8 respectively. For location 1 and location 2, Fig. 9 and Fig. 10 show performance of the CPC field for five months of operation respectively. In this study, the collector’s mounting parameters were kept same during laboratory testing and field testing. The instantaneous parameters were measured for determining the performance at location 1 and location 2. The graph for performance of solar field shows, irradiation (kWh) measured for the period of 4 to 7 hours using a pyranometer. For calculating the heat output (kWh), temperature and flow rate of the operating fluid were measured on the days of operation. Equation no. 5 is used to calculate heat output (KWh) of CPC field for both the locations. The expected output of the system was determined by considering the various parameters like \( I_g, T_m, T_a \) i.e. \( [(T_m - T_a)/I_g] \). The \( [(T_m - T_a)/I_g] \) values varied between 0.02 to 0.13. Lower value of \( [(T_m - T_a)/I_g] \) specifies inlet water entering at temperature near to the ambient temperature at higher radiation level. Higher values of \( [(T_m - T_a)/I_g] \) specify the higher temperature of water at collector inlet at lower radiation level in the evening time. The same parameters were logged continuously for 5 months of the year for both the installations.

Comparative curves for estimated versus actual heat output of the designed and installed solar fluid heating system for location 1(Pune) and 2 (Bengaluru) is shown in Fig. 7 and Fig. 8 respectively. These figures also show the difference in predicted and actual solar insolation. The detailed analysis for the variation in estimated and actual output was conducted and discussed below.

**Figure 7:** Energy gain of the CPC field for the month of January at Location 1, Pune
CPC field performance is shown in Fig.9 and Fig.10 for five months period for location 1 and location 2 respectively.

Figure 8: Energy gain of the CPC field for the month of January at Location 2, Bangalore

Figure 9: Monthly Heat gain of the solar field for five months at location 1, Pune
The average variation in expected performance based on design and measured actual performance for five months period at location 1 is 9.8% and a maximum variation of 11.3% at location 1 whereas average variation at location 2 is 9.0% and a maximum variation of 14.7% is observed. The deviation from standard testing is considerable and the possible reasons behind that are listed below, based on the field observations.

1) Heat losses from the piping and attachments and manifold of the CPC collectors:
   During the laboratory testing, temperature sensors were mounted at the collector outlet whereas during actual field testing, temperature was measured at the water storage tank; The losses through piping and manifold are calculated to be 4.2% at location 1 and 3.9% at location 2, based on the insulation used. The losses will alter depending on the inlet temperature of the water, wind speed and ambient temperature of the location.

2) Dust accumulation on the reflector and receiver:
   Another factor which is responsible for the lower output than predicted is formation of dust layer on reflector and receiver surfaces. As per the manual and site dust conditions, the recommended cleaning frequency was one week for both the locations. However, it was observed that cleaning of the reflectors and collectors was carried out at the interval of one month at location 1 and 15 to 20 days at location 2. The transmittance of the glass and reflectivity of the reflector surface reduce due to coverage of dust or dirt on the absorber as well as on the reflector surface. The calculated heat loss due to soiling contributed to 1.95% at location 1 and 1.72% at location 2.

3) Instruments measurement uncertainties:
   The equation (12) is used to calculate this uncertainty, which was found to be 1.67% at location 1 and 1.49% at location 2.

4) Receiver tubes dislocation from the desired position:
   Ten numbers of tubes at location 1 and 56 numbers of tubes at location 2 were found dislocated from the original position. The loss of vacuum was found in 1 tube out of 20 tubes at location 1 and 2 tubes out of 20 tubes at location 2 when checked randomly. The loss of vacuum was result
of cracks to the tubes. The loss of vacuum was tested and verified by using spark leak detector. Further investigation is required to be carried out to know the heat loss from these tubes.

5) Shadow effect:
No shadow was observed on any of the collectors at location 1 whereas at location 2, six of the collectors were found to be covered by the mild shadow of the branches of surrounding trees.

6) Non-withdrawal of hot water:
The incomplete use of hot water from the tank led to high temperature heat loss. This non-uniformity was result of variation in the boiler load.

Thus, at location 1 at Pune, out of the total loss of 9.8%, average heat loss of 7.82 % can be elaborated based on generated field data and from other sources, and at location 2 at Bangalore, 7.11% of the losses out of 9.0% can be elaborated, while further investigation is needed to know the causes for remaining 1.98% out of 9.8% at location 1 and 1.89 % out of total average heat loss of 9.0%.

6. Conclusion
The performance evaluation results of the solar field designed using CPC technology proves that the CPC collector of the given specifications are suitable for preheating boiler feed water below 100 Deg C without phase change. The solar installation generated 1,27,373 kWh heat energy during five months of operation at location 1 from 390 m² collector area and 1,94,527 kWh at location 2 from 600 m² collector area.

The expected heat output on the basis of actual measured weather parameters differed by 9.8% average than the actual output from the solar installation at location 1. The maximum difference in the output values between expected and actual values was 11.3% at location 1. The average difference between the expected heat output and actual measured output at location 2 was 9.0 % and the highest variation was 14.7%. The actual energy gain at both the locations was found to be lower than the expected energy gain.

The main causes of the lower actual performance, are associated with the heat losses through the collector piping, connections and manifold which are 4.2% at location 1 and 3.9 % at location 2, dust accumulation or soiling of reflector and receiver tubes of CPC contributed to 2.1 % at location 1 and 1.72 % at location 2, uncertainties of instruments , 1.52 % at location 1 and 1.49 % at location 2 and other unaccounted losses due to displacement or dislocation of the receiver tubes from its desired position, vacuum loss through evacuated tubes of the CPC collectors, shadow effect on the solar field, heat utilization pattern of the process etc which is 1.98 % at location 1 and 1.89% at location 2. Detailed investigation is required to be carried out to know the percentage of the unaccounted losses.

The variation in the values of \([(T_m - T_a)/I_g \) for storage tank connected CPC, was found to be more when compared to the once through flow system i.e. without storage. However, the presented study confirms that solar CPC technology can be efficiently used for boiler feed water pre-heating or any other Industrial Process Heat application below the operating temperature of 100°C with tank storage system.
The performance results of the CPC collector tested under laboratory conditions and actual site conditions at location 1 and 2 proves that a factor of safety is required to be applied for the justifiable as well as unpredicted and unaccounted losses. The comparative study at both the locations shows that while designing the CPC based solar system, a factor of safety of around 15% should be applied considering various heat losses at field conditions as mentioned above.

Unpredictability of the available solar radiation and other climatic conditions is a major constraint in propagation of solar process heat application. The available solar energy can be used effectively for preheating of boiler feed water without any loss of gained heat, even at lower radiation. This comparative study shows that the CPC technology based solar installations can be accepted commercially by taking care of avoidable losses and using factor of safety during design for unpredictable and unavoidable parameters. The integration scheme of CPC based solar field with the existing fossil fuel-based heating system to meet the heat and temperature requirement is most suitable for Steam Boiler Feed Water preheating. To understand the actual field issues and performance of the solar thermal technologies, more such studies are recommended which are also necessary to build confidence among users and technology providers.

7. References

[1] Anagha Pathak (2017) ‘Application of Solar Thermal Energy for Medium Temperature Heating in Automobile Industry’, IRA-International Journal of Technology & Engineering (ISSN 2455-4480), 7(2 (S)), p. 19. doi: 10.21013/jte.icsesd201703.

[2] Bellos, E. et al. (2016) ‘Design, simulation and optimization of a compound parabolic collector’, Sustainable Energy Technologies and Assessments, 16(December 2017), pp. 53–63. doi: 10.1016/j.seta.2016.04.005.

[3] IS standard 16648- part 5 (2017) Concentrated Solar Thermal Energy, Energy Sources.

[4] ESTIF (European Solar Thermal Industry Federation), 2004. (2004) Solar Assisted Cooling, State of the Art, Key Issues for Renewable Heat in Europe.

[5] Kalogirou, S. (2003) ‘The potential of solar industrial process heat applications’, Applied Energy, 76(4), pp. 337–361. doi: 10.1016/S0306-2619(02)00176-9.

[6] Kurhe, N. et al. (2020) ‘Compound parabolic solar collector – Performance evaluation as per standard test method and actual field conditions for industrial process heat application in Indian context’, Energy for Sustainable Development, 57(August), pp. 98–108. doi: 10.1016/j.esd.2020.06.001.

[7] RABL (1985) Active Solar Collectors and their Applications.

[8] Sarbu, I. and Sebarchievici (2017) ‘Concentrating Collector’.

[9] Bhaskaran, H. A. (2016) ‘Influence of Flue Gas and Feed Water Temperatures on Boiler Efficiency – An Analysis’, International Journal of Innovative Research in Science, 5(1), pp. 94–109. doi: 10.15680/IJRSET.2015.0501012.

[10] JCGM 100 (2008) ‘Evaluation of measurement data — Guide to the expression of uncertainty in measurement’, International Organization for Standardization Geneva ISBN, 50(September), p. 134. Available at: http://www.bipm.org/en/publications/guides/gum.html.