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Design and Performance of a Parabolic trough System for Process Heat Application

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***Abstract:** The worldwide energy demand is rapidly increasing, increasing in turn the necessity of power generation. The generated power is used to fulfill domestic and industrial needs. Industries use electricity for medium scale heating applications, which is the worst use of electricity. Concentrated solar power can prove itself a superior alternative of electrical heating load, being the only technology which produces high quality heat. In this paper, a systematic design approach of a parabolic trough based solar field for a defined thermal load is presented. The performance simulation of the field has been done for a small scale, medium temperature industrial drying process of 290 kW$_{th}$ at 120^{o}C, located in Bhopal using System Advisor Model (SAM), was found to be 23% efficient. The results can be used as a roadmap for designers for the feasibility analysis of local industrial application*

***Keywords:** SAM, parabolic trough, industrial process heat, performance analysis and design.*

I. INTRODUCTION

Climate change and global warming are the key current issues and well addressed on almost every field of science and technology. Researchers are working to develop various techniques to prevent, minimize and sequestrate the greenhouse gasses. Since, the starting of year 2020 the corona pandemic gives an extra thrust to researchers to devise new technologies to replace the use of fossil fuels, seen as a prime demand for the existence of human kind [1]. Solar energy is the most trusted and abundant source, which can perfectly replace the use of fossil fuel for power generation [2, 3]. Also various application require thermal energy like water heating, drying, steam generation, space heating, etc. can be served well with the help of solar energy using concentrated solar power technology [4]. Commercial and domestic use of thermal energy holds the 50% share of world's energy consumption [5]. Out of which industrial use of thermal energy reports 65% that too in medium temperature application i.e. 100^{o}C to 400^{o}C [6, 7]. Parabolic troughs are well suited for heat generation in low-medium temperature range. Among all concentrated CSP technologies PTC is most mature, simple to fabricate and economical. PTC are linear concentrators, they concentrates the incoming solar beam radiations on the focal line of the trough [8]. A basic parabolic trough comprises of a reflecting surface, receiver and heat transfer fluid [4]. Reflecting surface is basically a concentrator which reflects and concentrates the incident beam radiations; this is to increase the energy density of radiation as the energy density is of quite low. After getting concentrated the radiations fall upon an evacuated tube which acts as receiver or heat collecting element, here the heat gets absorbed in heat transfer fluid. Later heat transfer fluid is pumped to the location where heat is required [9]. In current scenario focus has been shifted to the small distributed roof mounted systems rather than a huge concentrated station [10, 11, 12]. Hence there is a great scope of development and utility of small sized parabolic trough heat generation systems which can be installed on roof of a process industry to serve its medium temperature heat requirements [13]. In contrast to large sized parabolic troughs having width in the range of 6-9 meters, medium temperature troughs require smaller troughs with 1-3 meters of width [14].

This work aims to design a parabolic trough based solar field for a defined thermal load. The performance simulation of the field has to be done for a small scale drying process located in Bhopal using System Advisor Model (SAM). The results can be used as a roadmap for designers for the feasibility analysis of local industrial application.

II. DESIGN OF PTC BASED PROCESS HEATING SYSTEM

The process of designing a parabolic trough solar field is divided into steps as represented through a flow diagram given in Fig. 1. The explanation is given subsequently for the important steps.

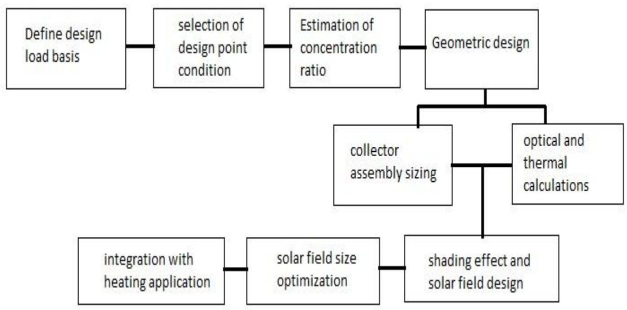

Fig.1. Design steps for PTC solar field

A. Design Load Basis

The system is intended for a industrial drying and baking process, where the temperature of 120^{o}C is required at a high heat flow rate like food, chemical and paper industries, . Hence, to deliver the heat at a high flow rate, the operating temperature of heat transfer fluid is set at 120^{o}C. The system is designed to deliver 290 kWt heat to the heat exchangers for drying.

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B. Selecting Design Point Condition

As no specific consensus over the criteria of selection of design point condition has been reached so far [15]. In the given case DNI is the only criteria which greatly affect the system output and is dependent on the geographical location. DNI for Bhopal, India lies in the range of 0 to 890 W/m^2. Minimum DNI required to run the system is 320 W/m^2, hence, the weighted average above the minimum required DNI is 450 W/m^2 [15].

C. Concentration ratio

It is the ratio of collector aperture area to the receiver aperture area. For attaining a particular temperature of HTF, a specific concentration ratio of the parabolic trough is required. The optimum concentration ratio can be obtained from the optimum CR – temperature curves [16].

D. Geometric design

Rim angle is the angle between the line joining the center of trough - receiver and the line drawn between receiver and the edge of the trough. It is a key parameter for the designing of trough. Smaller rim angle represents a flat trough and larger rim angle represents the trough which employs larger surface for the same aperture area [17]. The rim angle should lie in the range of 70^o – 115^o [18].

The performance of the PTC system depends upon its optical and thermal efficiencies. Eq. (1) used to calculate the e radiation absorbed per unit area of un-shaded collector and is given as [19]:

$$S = I_b.\rho.\gamma.\tau.\alpha.K_{\gamma\tau\alpha} \quad (1)$$

Here, $K_{\gamma\tau\alpha}$ is an incidence angle modifier, α is absorptance, ρ is the reflectance of the collector, I_b is effective incident beam radiation, τ is transmittance and γ is intercept factor.

The thermal performance can be evaluated by useful energy gain per unit area (Eq. (2)) is given as [19]:

$$Q_u = A_a F_R\left(S - \frac{A_r U_L}{A_a}(T_i - T_a)\right) \quad (2)$$

Here, A_r is the area of the receiver, A_a is the un-shaded collector area, T_i and T_a are inlet and ambient temperature.

E. Orientation of the Field

The solar field can be oriented in two ways, E-W orientation and N-S orientation as shown in Fig. 2. In E-W orientation the system tracks the sun's altitude, resulting in high cosine and endloss. In another arrangement, trough is placed in N-S position and it tracks the sun in east to west direction. Here it can be seen that in the later arrangement sophisticated tracking is employed, in turn providing better efficiency [19].

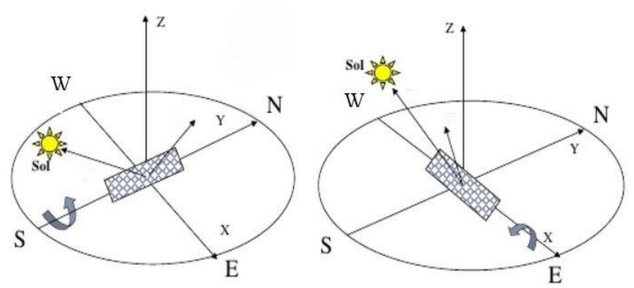

Fig.2. (a) N-S orientation, (b) E-W orientation [19]

F. Row Shading

Systems with tracking produces variable shadow length as the sun and the system moves throughout the day. Thus the shading of succeeding row is a major problem with such systems. To avoid the shading in potential generation hours, calculation has to be done to leave proper spacing between the rows to avoid shading. Fig. 3 presents the aperture planes of consecutive rows having separation p between them when seen from their axis of rotation. Height of the shadow cast (Eq. (3)) by one row on the other at any time can be written down as [20]:

$$H_s = [w - p\cos\beta]^+ \quad (3)$$

'+' show that only positive values of H_s will be taken into consideration.

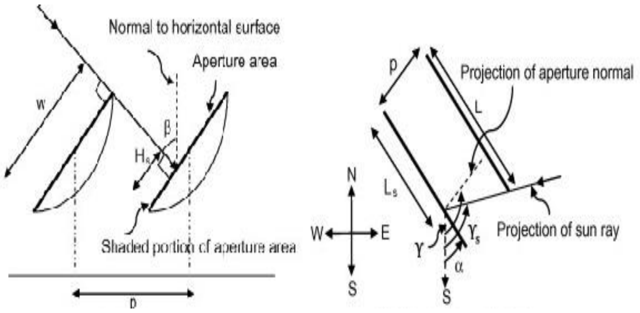

Fig.3. (a) Shaded height H_s, (b) Shaded length L_s [20]

Similarly, length of the shadow cast by one row on the other, shaded length is given by [20],

$$L_s = [L - |p\tan(\gamma - \gamma_s)|]^+ \quad (4)$$

III. PERFORMANCE SIMULATION OF A PTC BASED IPH SYSTEM

System Advisor Model (SAM) version 2020 has been used to study the thermal and optical performance of the parabolic trough heat generation system. SAM has extended capabilities by adding Industrial Process Heat (IPH) model. The IPH parabolic trough model is similar to CSP physical model with a change that, in the present case the simulation will take place till thermal energy generation from the solar field of parabolic trough concentrating collectors [21]. In the present study, physical model is used rather than empirical model because there is more flexibility in physical model [22].

For simulating a PTC assisted IPH process, a case of drying process, with temperature requirement of 120^{o}C at the mass flow rate of 1.1 kg/s. The location was taken as Bhopal (India), due to its resource potential. The simulation inputs are given in Table .1,

Table.1. Design parameters of simulation

Categories	Values
City	Bhopal, India
Time zone	GMT + 5.5
Latitude	23.25 N
Longitude	77.45 E
Global Horizontal Radiation	5.47 kWh/m^2/day
Direct Normal radiation	4.69 kWh/m^2/day
Diffuse horizontal Radiation	2.25 kWh/m^2/day

Deploy angle	10 degree
Tracking power/ SCA	125 W
Pipe length	50 m
HTF maximum Temp	220°C
Collector Model	LUZ LS-2
Length of assembly	49 m
Optical error	0.99
Mirror reflectance	0.935
Receiver type	Schott PTR80
Absorber Outer diameter	0.08 m
Design point DNI	850 W/m^2
Target solar multiple	1
Target Receiver thermal power	290 kW_{th}
Loop outlet HTF temperature	120° C
Number of loops	1
Loop aperture	482.9 m^2
Stow angle	170 degree

HTF pump efficiency	0.85
Total tracking power	500W
HTF minimum temperature	10°C
Freeze protection temperature	50°C
Aperture width	5 m
Tracking error	0.99
Geometry effects	0.96
Dirt effect	0.97
Absorber Inner diameter	0.076 m
Envelop outer diameter	0.12 m

A. Solar Potential Assessment

India subcontinent lies into a medium DNI receiving zone (4 kWh/m^2/day to 6.62 kWh/m^2/day), which makes it feasible to employ highly performing PTC systems for industrial applications. The simulation is carried out for a whole year with the TMY data provided by NREL. The DNI distribution for each month is shown in Fig. 4.

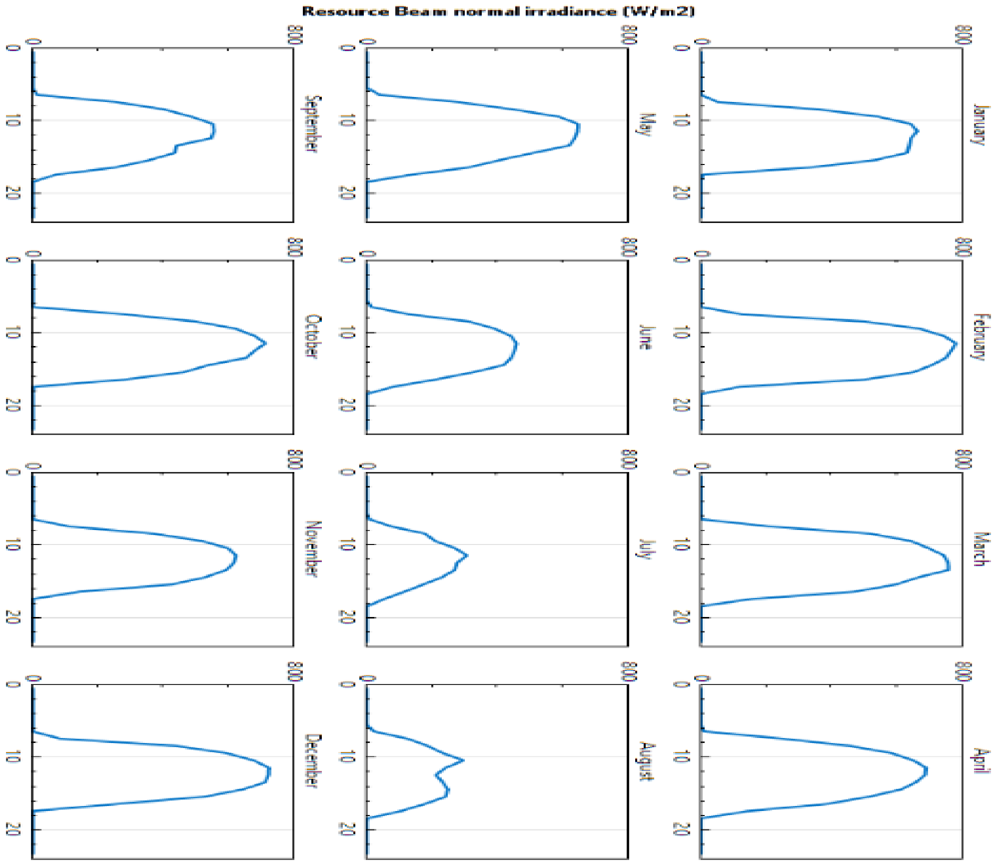

Fig.4. Monthly DNI for Bhopal, India

B. System Performance

The annual average incident thermal power for sunrise to sunset was found to be 544 kWt, and the yearly distribution is shown in Fig .5.

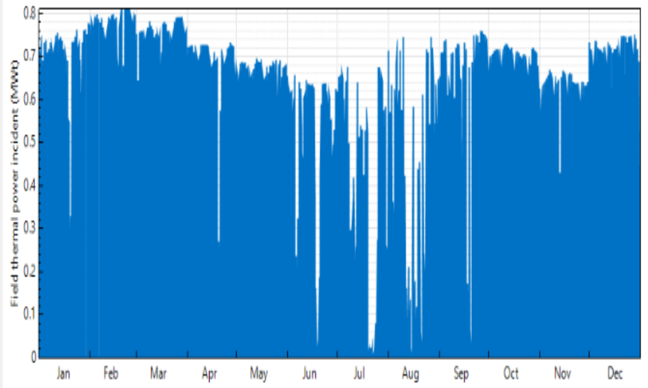

Fig.5. Field incident thermal power (MWt)..

The cosine loss incurred due to the non-alignment of trough because of single axis tracking and the heat absorbed in the HTF of receiver is shown in Fig. 6 for comparison,

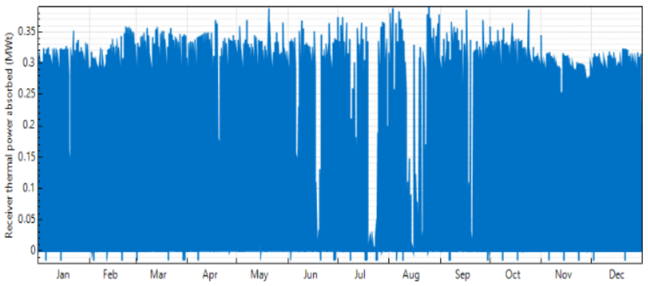

Fig.6. Receiver absorbed thermal power (MWt).

The annual net energy generation was 800,979 KWh-t, while the annual gross energy generation was 805,531 kWh-t. Generation dips has been noticed between June to August period, and are due to the monsoon season, which provides lower generation, hence system has to be over powered or a substitutive arrangement has to be employed of that certain period for economic reasons. As can be seen in Fig.4, October, November and December are the months of low resource, but the generation in these months do not shows the impact because of the quality of resource. The quality of radiation (DNI) for whole year is shown in Fig.7,

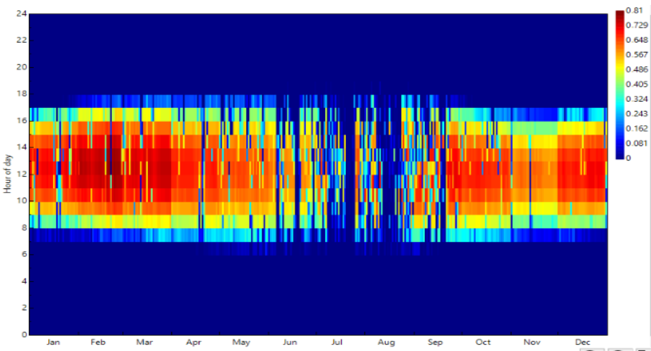

Fig.6. Field thermal power incident (MWt).

Annual thermal power for freeze protection is a redundant portion of energy consumed in this simulation which was found to be 4551kWt. The PTC based IPH system shows 95% net conversion with the system efficiency to be 23%.

IV. CONCLUSIONS

The design and performance analysis of a parabolic trough based heat generation plant for industrial process of drying has been done. The temperature requirement of 120°C at a mass flow rate of 1.1 kg/s was achieved. The location for analysis was taken as Bhopal because of its above average annual DNI (4 kWh/m^2/day to 6.62 kWh/m^2/day). It was found that the system performs at 23% efficiency. The following are the observations,

1. The performance simulation was carried out for Bhopal region.
2. The DNI was observed to be 4.69 kWh/m^2/day.
3. A single loop system array is beneficial to reduce system complexity.
4. IAM and optical efficiency was found to be 1.00018 and 0.871124.
5. Cosine losses were found to be less prominent from March till September.
6. Receiver thermal losses are minimum for the month of May, due to the higher ambient temperature.
7. The designed plant works well for all the year, except for the month of November and December.

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ABBREVIATIONS

CSP	Concentrated Solar Power
PTC	Parabolic Trough Collector
HTF	Heat Transfer Fluid
HCE	Heat Collecting Element
SAM	System Advisor Model
DNI	Direct Normal Incidence
MP	Madhya Pradesh
CR	Concentration Ratio
E-W	East West Orientation
N-S	North South Orientation
IPH	Industrial Process Heat
GMT	Greenwich Mean Time
SCA	Solar Collector Assembly
TMY	Typical Meteorological Year
NREL	National Renewable Energy Laboratory

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