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Ray Tracing and Simulation of Parabolic Dish Collectorusing Soltrace for Vehicle Applications

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Abstract. Concentrated solar power has the potential to produce large-scale renewable energy sources. Concentrated solar energy is produced using mirrors, reflective materials, or lenses on conical surfaces such as a parabolic dishes, parabolic troughs, towers, Fresnel reflector systems, and dish sterling collectors. The concentrated light source was converted into heat energy, which drove the heat engine into an electrical power generator. To gain more heat energy, the solar rays must be trapped and concentrated on their conical focus points. To increase the net overall efficiency of the system, it is vital to know the optical performances of the subsystem formed by the solar receiver and the parabolic concentrator. In this study, a beam of incident solar rays was traced on a parabolic dish collector, and a simulation is performed for concentrator behaviour using the ray-tracing code SolTrace developed by the NREL laboratory. For an incident radiation of 1000 W/m^2 (considering 10000 photon rays), their optical performance and solar heat flux were simulated. The results show that the number of elements in SolTrace varies depending on the CFD mesh density, the number of rays utilised in the Monte Carlo technique and their impact on generating a resolution-independent solution. Investigating the ray tracing of the disc concentrator, the propulsive energy for viable applications can be analysed.

Keywords: solar thermal electricity, parabolic dish, ray-tracing simulation, thermal model, Monte Carlo.

1 Introduction

A solar reflector is a typical structure that collects or projects incident solar energy mostly in the visible and nearer visible light spectrum. It takes the circular paraboloid profile, which is formed when a parabolic curve rotates around an axis. The parabolic reflector converts the incident solar beam wavelength into a converging position towards

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the focal point. A plane wave transmitting as a collimated high-density beam down the axis is reflected by a spherical wave formed by a point source positioned at the focal point. Simpler spherical reflectors receive energy from afar and focus it, but parabolic reflectors correct for spherical aberration [1]. Cooking, steam generation, and a number of other uses can all benefit from the high-temperature heat provided by parabolic reflectors. Their specialties are a flexible surface curvature and a non-moving focal area. In many parts of the world, particularly in India, they are becoming increasingly popular. Solar energy is a clean energy source that does not emit any greenhouse gases or other pollutants into the Earth's atmosphere. This can't be drained in a time frame appropriate to the human race, so it's sustainable [2].

In most of India's arid as well as semi-arid regions, solar irradiance is enormous. As a result, her potential for solar collector implementation for steam generation is a promising, marketable venture. Nevertheless, much research on this trend is still lacking. This research aimed to employ suitable equipment in the design and analysis of a solar thermal steam generation module for electric energy production in the local community. Dish concentrators convert solar radiant energy in the shortwave with a wavelength of 0.29 μm to 2.5 μm into long-wave radiation and capture it as heat. Using the receiver, the concentrated heat transforms the fluid into steam. The steam has the potential to drive the low-powered turbine. In solar power plants, the high-generated steam is produced using high-heat-transferring thermic fluids. The high-superheated steam rotates the turbines to produce marketable power via transmission lines. A parabolic reflector is a structure that projects a point-oriented image on the solar surface. It forms a parabolic structure when the three dimensions are equal [3]. Solar Genix has successfully developed collector modules that can generate 176 kw of peak energy for dual-purpose factory roofs and solar heating [4].

The El Nasr project in Cairo includes a solar CSP that utilises 1,900 m^2 of land for a parabolic module setup to generate steam for plant-manufactured pharmaceuticals. Nevada Solar-One, which is in the Nevada desert and is set up on 250 acres of empty land to produce 134 MW annually, is an example of a worldwide parabolic trough system with viable standard operating systems. In the Mojave Desert of the United States, a larger solar-based plant produces 354 MW annually [5]. Torresol and Arcosol designed a 50 MW parabolic trough-based plant in Seville, Cadiz, Spain. Andasol 1, 2, and 3 in the province of Granada are other Spanish plants that use this technology [3]. Many studies address the design and installation of a parabolic dish solar water heater for residential hot water applications (approx. 100°C). The heater is estimated to provide 40 litres of hot water a day for a four-person family, considering that each person consumes 10 litres a day. The solar water heater's configuration mandates that it continuously monitor the sun for maximum efficiency, and an automatic ECU circuit was conceived and built for this purpose. According to the test results, the solar water heater's overall performance was excellent. Thermal efficiency of 52 percent to 56 percent was reached, which is better than the 50 percent specified value [1]. The use of a linear actuator to monitor the sun eliminates the need for a human operator to control the system on a continuous basis, lowering operating costs.

A solar concentrator known as a parabolic dish collector transforms solar radiation into thermal energy. Commercially, parabolic dish concentrators are used in the majority of areas. A parabolic reflector and a receiver make up the system. A concentrator's specifications are defined by its aperture, diameter, rim angle, and focal length. The temperature of a surface increases as solar radiation strikes it. aluminum foil is used as a reflector to bring the rays together into a single focal point. aluminiumhaving high reflectivity in the order of 88% is inexpensive, light in weight. In 2012 [6] an Australian national university fabricated a 500 square meter dish for mass production of thermal energy being converted into electric power by the steam generator. Prof. Mohammed used a two-axis tracking system. EI Ouederni et al,[7] developed a parabolic solar concentrator experiment using the measurements of solar flux and temperature distribution of the receiver. A new concept of designing and fabricating a large parabolic dish having the dish mirror was formed from several optimum shaped thin flat metal plates with highly reflective surfaces. The main aim of present research is to design, fabricate and analyze the solar Dish concentrator for locomotive vehicle applications.

2 Raytracing Technique

Ray tracing is a popular technique for creating realistic images. An image synthesis algorithm must emulate the physical mechanism involved in taking a direct photograph of a real scene in order to produce a realistic image [8]. Ray tracing simulates the behavior of individual light rays to achieve this. Ray tracing was first created as a method for presenting shaded solids using simple illumination models. Under the name "point by point shading," Appel proposed the technique, which was successfully implemented and deployed by the Mathematical Applications Group [6]. Whitted's lighting model, which demonstrated how ray tracing could replicate shadows, reflection, and refraction, sparked Ray Tracing's present appeal in picture synthesis. Penumbrae, motion blur, gloss, translucency, and depth of field are all realistic effects that may be created with simple expansions of basic ray tracing.

Many evaluations of various strategies for ray tracing parametric contours acceleration are described [9]. Some of them are completely new to ray tracing, while others are enhancements on techniques that have been around for a long. To begin, parametric surfaces are subjected to a uniform spatial subdivision scheme. We provide a new technique for identifying ray-surface intersections that is both space and time economical. [10]. It combines numerical and subdivision methodologies, allowing for the use of ray-coherence and a significant reduction in the average time for ray-surface intersection. The use of coherence is made easier with the introduction of non-scan line sampling orders of the image plane. Finally, a method is provided for more efficiently handling reflected, refracted, and shadow rays [11]. The results of timing studies that show how effective these strategies are in different contexts are provided. The tool SOLFAST is given in this communication. [12]. It's a simulation tool that uses the Monte-Carlo approach and accelerated Ray-Tracing analysis to analyze the energy flux in concentrated solar farms.

3 Design Parameters of Parabolic Dish

The solar concentrating collectors are designed using the various parameters. By optimizing these design parameters, the collector can trap maximum energy. The incident solar irradiation is converted into useful energy efficiently [13].

3.1 Aperture Area (A_a)

The solar radiation is collected through the aperture area of a receiver. It doesn't have to be the receiver's overall size. The area occupied by the system after installation is not the same. The aperture area of a solar collector is about equal to the area of the absorber. This allows the aperture area to absorb nearly all of the sunlight that falls on it.

3.2 Acceptance Angle

The acceptance angle is defined as the range of angles at which a light source can be pointed while convergent at the receiver. A concentration with a low acceptance angle must follow the sun year-round, whereas a concentration with a high acceptance angle only needs to be adjusted annually.

3.3 Absorber Area (A_{abs})

The total area of the dish concentrator that absorbs incident solar energy is known as the absorber area. It is also the region from which utilizable energy can be derived. The absorber area design is based on the defined value of the locus of the parabola curve.

3.4 Concentration Ratio

It's the ratio of the light aperture area of the collector reduced by the receiver/absorber area of the collector. Because it is difficult to manufacture precise conventional lenses with very short focal lengths and the concentration ratio is related to the ratio of the lens's diameter to its focal length, the concentration ratio that can be attained by a single lens is limited.

$$c = \frac{A_a}{A_{abs}} \tag{1}$$

3.5 Optical Efficiency

Optical efficiency is defined as the ratio of energy absorbed by the absorber to energy incident on the concentrator aperture. reflection and transmission losses, tracking accuracy, shading, receiver-cover transmittance, absorber absorptance, and sun beam incidence effects are all aspects to consider. The optical efficiency is given as:

$$\eta_o = \frac{P_{abs}}{A_a I_D} \tag{2}$$

Most solar concentrators have an optical efficiency of 0.6 to 0.7 [6]. The optical efficiency can be increased by selecting a high-reflectivity material surface, removing the dirt periodically, and using nanomaterial coatings for dirt-free disposal.

3.6 Thermal Efficiency

Thermal efficiency is defined as the ratio of useful energy delivered to the energy incident at the concentrator aperture. The conical receiver design is used to achieve improved thermal efficiency. For varied designs and operating conditions, it has been established that the average collector efficiency of solar dish collectors is in the range of 45 percent to 62 percent.

$$\eta_{th} = \frac{\rho V c_{pf} (T_2 - T_1)}{A_a I_b} \tag{3}$$

The incident solar radiation is based on two types of radiation: beam direct and diffuse radiation. On the other hand, the majority of focusing collectors can only utilise beam radiation. Most solar concentrators have a thermal efficiency of 0.4 to 0.6. Effective heat utilisation and conversion of solar energy increase thermal efficiency.

The initial procedure of designing the solar dish concentrator is to evaluate the above mentioned parameters for the specific location. In this present study, the geographical location was taken as Chennai, TamilNadu, India (13°4′57″N 80°16′30″E). The average solar irradiation at mentioned location is 800 W/m^2. Table 1 enlist the calculated design parameters of the Solar Dish collector system. Using these data, the Dish concentrator is fabricated for further Ray Tracing and performance analyses.

Table 1. Solar Dish Concentrator Specifications.

Parameters	Design values
Focal length of the Dish (F)	2500 mm
Diameter of the Dish (D)	5000 mm
F/D ratio	0.5
Depth of the Dish (d)	625 mm
Concentration Ratio (C)	204.08
Aperature area (Aa)	10 m^2
Absorbing area (Aabs)	0.049 m^2
Acceptance Angle (ϕ)	4.01
Optimum Rim Angle (ψrim)	85.99°
Geo location and position	Chennai, TamilNadu, India (13°4′57″N 80°16′30″E).
Average solar irradiation	800 W/m^2

4 Procedure For Determining F/D Ratio and Other Specifications

Firstly, thedish reflector was created with the help of the Parabola Calculator 2.0 version. This tool traces the reflector geometry by providing the values of the focal length, depth, and segment dimensions.

4.1 Focal length (F)

The focal length is the distance between the vertex and the focus as measured along the axis of symmetry.

4.2 Depth (d)

The depth of the concentrator dish is the distance between the vertex and the diameter of the dish coincide.

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$$Depth(d) = \frac{D^2}{16F} \tag{4}$$

4.3 Acceptance Angle (ϕ)

The maximum angle at which incoming sunlight can be captured by a solar concentrator is called the acceptance angle. Its value is determined by the optic's concentration and the refractive index of the medium in which the receiver is immersed.

$$\phi = \sin^{-1}\sqrt{\frac{1}{c}} \tag{5}$$

4.4 Optimum Rim Angle (ψ_{rim})

The rim angle is a variable that determines the imaging and non-imaging diameters of flux radiation. Larger imaging and non-imaging diameters result from an acute rim angle.

$$\psi_{rim} = 90 - \phi \tag{6}$$

Secondly, the dish reflector was modelled using the locus points created by the parabola calculator. It traces the geometry with the parabola dimensional parameters such as diameter, depth, F-D ratio, focal length, segments, and linear diameter, as shown in **Fig. 1**.

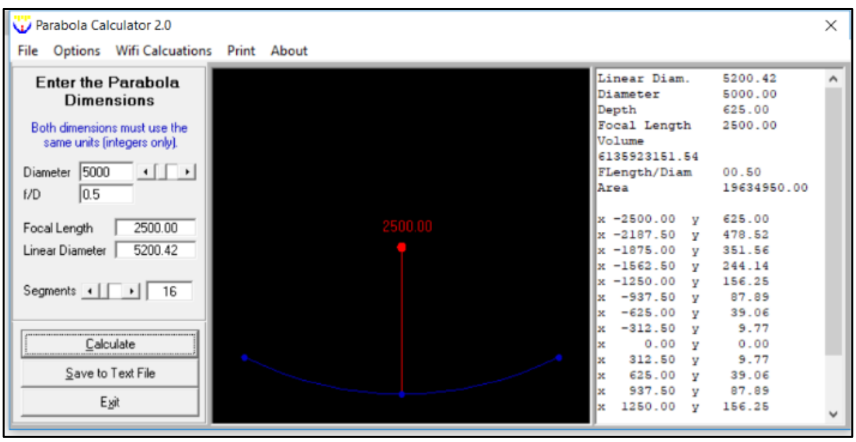

Fig. 1. Tracing of reflector geometry using parabolic calculator v2.0.

5 Ray Tracing Using Soltrace

SolTrace is a software programme created by the National Renewable Energy Laboratory (NREL) for modelling and analysing concentrating solar power optical systems. Although the code was developed for solar applications, it can be used to simulate and analyse a wide range of optical systems. SolTrace is capable of simulating parabolic trough concentrators, as well as dishes, towers, and other unusual geometries (linear power towers, solar furnaces, etc.). It represents optical geometries as a succession of stages made up of optical elements with a wide range of qualities such as shape, contour, and optical quality.

- SolTrace software consists of basic commands such as File, Run, Optics, Stage, and Help.
- The File command consists of open, save, recent, and save as. Then run commands like tracing and editing trace options. Optics Command deals with transmissivity, reflectivity, and errors.
- A stage command is used to describe system geometry.

A SolTrace project file contains a complete set of inputs that define a model or analysis. This includes information about the sun's shape and position, a set of surface optical interaction properties, and all the elements for each stage in the system. The data is stored in a plain text-formatted file with the "*.stinput" extension. The results of a ray trace are not stored in this file, nor are externally defined surface types such as those described by VSHOT data. As a result, the *.stinput files are generally quite small. When we open the Soltrace Software, we click the Sun Shape Command, and it deals with sun direction, sun shape parameters, and sun shape profile.

5.1 Preprocessor

5.1.1 Defining the sun position

The sun shape varies with sky condition, location, and time. Sun shape is determined by two probabilistic distributions. The methods are either Gaussian or pillbox. Gaussian distribution of the sun is the half angle of the distribution. Pillbox is a flat distribution that is basically halfangle distance. Sun direction is determined by a global and local coordinate

- Global Coordinate (defines sun’s origin point)
- Latitude, day, hour (Alternate method to find sun’s origin by calculating day of year and local solar time)

The design values listed in Table 1 is used for defining the sun position.

5.1.2 Defining optical parameter

The optical parameter is used to define reflectivity, refraction, transmissivity, slope error, and specularity error. Based on optical stages, the values are defined. Parabolic dish has different optical properties and receiver also has different optical properties.

Optical properties are defined on the second input page. Each Soltrace project may have numerous optical property sets defined. Use the Add and Remove buttons under Optics to add new sets of optical properties or simply click on the Optical Properties icon to bring up an additional dialog. The name of the property can be added in the add dialog or changed in the set name input box. Every optical property type has a set of parameters for the front and back of the surface, which may be accessed using the Editing selection choices. The z-axis vector defines the front and back sides of element surfaces. The front side of a surface faces the positive z-axis, whereas the back side faces away from it. The front and rear of most surfaces are rather straightforward, but some, such as the cylinder, can be perplexing. Optical properties can be saved by Exporting and then used in other projects via the Import button. The default file extension is *.opt.

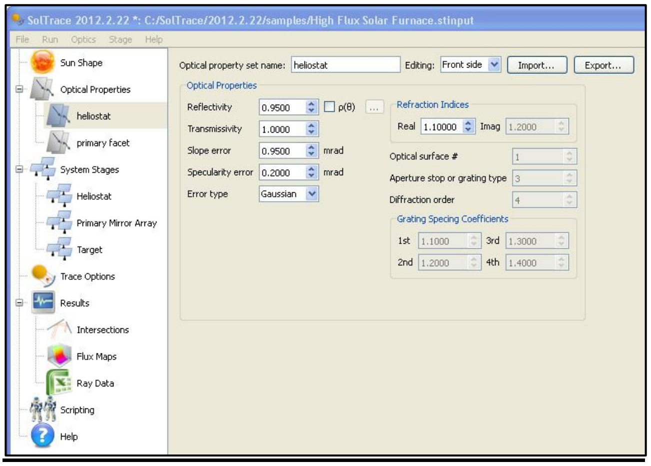

Fig. 2. Optical Properties of the reflector system.

For the Optical Properties Command, for both the Dish and Receiver, the dimensions should be given in two optical property stages.

- For dish inputs (describing the reflectivity of the dish), For receiver inputs (describing the transmissivity of the dish),
- For dish input, we have given 88% reflectivity, and for receiver input, we have given 0% transmissivity.

5.1.3 Defining System Geometry

In the system stage, it is used to form a parabolic dish shape. Given an origin, point to set a parabolic trough, and then to set aim points. Choose an aperture shape of circular, and then choose a parabolic surface. Similar steps are to be followed for the receiver, except for the surface chosen for the cylinder. After the sun has been defined, the system's optical geometry is specified. On a selected system stage, the system geometry is defined.

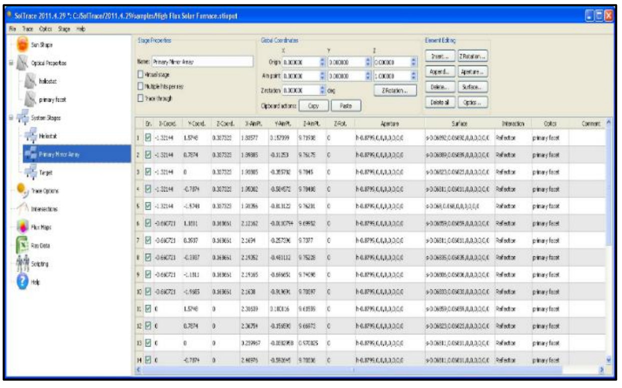

Fig. 3. System Stages of the Dish collector system.

System Stages deals with sun x, y, z points, and aim points/coordinates and for specifying dish and receiver, two stages should be opened.

- Dish (describing the dimensions of the parabolic dish)

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- Receiver (to select the surface element, describing the focal length in aim point, and mention the receiver dimensions).

5.2 Processor

5.2.1 Trace options

Once the sun shape, optical, and geometry are defined, now proceed with the ray tracing option. Several iterations of rays are received at the focal point. The accuracy of the result is increased by increasing the number of rays. Trace options: this command is used to describe the parameters required for the number of rays and to start a new ray trace.

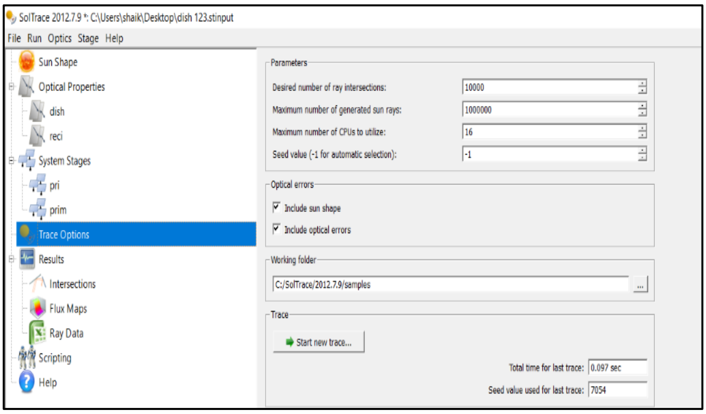

Fig. 4. GraphicalTrace Options for simulation of the system.

6 Results

In Trace Options, there are two options

- Intersections
- Flux Maps

6.1 Intersections

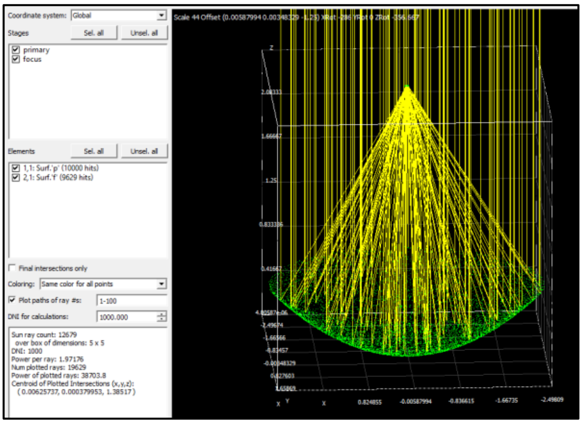

Fig. 5. Graphical solar ray simulation

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The system stage has two stages. primary, i.e., parabolic, and focus, i.e., rectangular plane. The rays are in yellow. The rays incident on the parabolic dish are then accurately focused at the receiver point. Around 100,000 rays were traced through the system. For tracing results, intersections provide a visualisation view of rays that have converged into a single-point reflector. It automatically plots a graph in 3D coordinates and provides the exact point of intersection.

6.2 Flux Maps

Provides a thermal image in which the levels of heat are generated and the amount of flux intensity being present as an image.
It is classified into two types

- Contour Plot
- Surface Plot

6.1.1 Contour plot

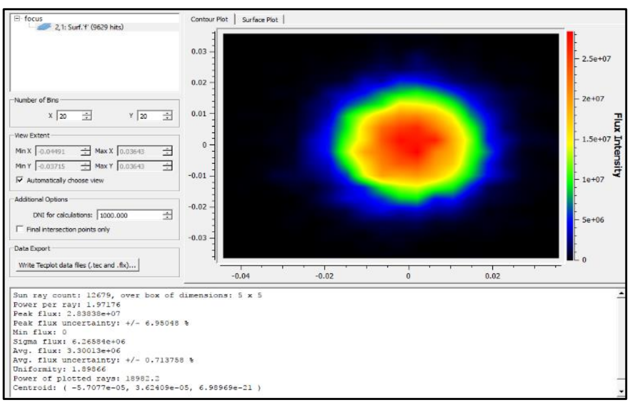

Fig. 6. Contour Plot of the simulation

The contour plot the dish concentrated system depicts the intensity of the solar radiation over the reflector system. The average and peak flux over the reflector was determined using this evaluation. The development and optimized material selection for the reflector system can be performed using this simulation.

6.1.2 Surface plot

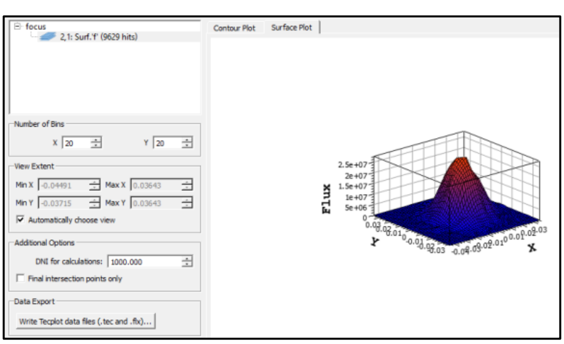

Fig. 7. Surface Plot

Fig. 7 illustrates the Surface plot that describes the peak flux variation over the reflector system in 3D view. Over the target plane, a graphic depicts the distribution of power per unit area. The peak flux, as well as other statistical data, is displayed below. During the development of the solar dish, SolTrace was widely used. The anticipated flux levels matched measurements taken at the HFSF once it was completed.

7 Conclusion

SolTrace is a ray tracing application that uses Monte Carlo simulations to model concentrating solar optical systems. It's one of a number of various programmes meant to simulate various sorts of concentrating solar optical systems, including commercial ray trace software for more general optical design. Soltrace's future development will focus on improving processing speed and data display, as well as adding surface contour choices, such as output from structural finite element analysis algorithms.

The 10 kW solar dish collector is modelled in this article according to the needed dimensions. For the most successful use of the dish concentrator, the optical parameters are determined. The ray-tracing simulations are examined using SolTrace to improve solar flux and other parameters. For thermal steam generation applications, an optimum solar flux distributed disc concentrator is installed. The research's future goals include employing high-reflective nanocoatings, thermal insulation, and energy-efficient power production systems to increase optical characteristics.

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