Research on Optimization Design Based on Heliostat Field

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Abstract. This study aims to deeply explore the mathematical modeling and performance optimization of solar heliostat fields, in order to improve their energy output efficiency. The solar heliostat field is an innovative solar heating system that focuses solar radiation on the absorption tower through a reflector, thereby generating high-temperature heat energy. This article mainly discusses the performance analysis and parameter optimization of the heliostat field to achieve optimal performance while meeting the rated power requirements. A simulated solar model was established using a three-dimensional Cartesian coordinate system, taking into account the effects of solar altitude angle and direct normal irradiance (DNI). The model in this paper comprehensively considers the effects of shadow occlusion loss, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance on the mirror field. The specific values of each parameter were calculated using model algorithms such as the HFLCAL model, To provide a basis for accurate performance analysis and solve the problem of parameter optimization, this article defines an objective function aimed at improving the energy utilization efficiency of the heliostat field by adjusting the parameters of the reflector, in order to achieve optimal performance. The above parameters are determined by establishing a genetic algorithm to define constants and initial parameters, and initializing the overall layout of the heliostat field to calculate the optical efficiency of the heliostat. In each iteration, the optimal heliostat field layout can be recorded. The final optimal solution includes parameters such as the position coordinates of the absorption tower, heliostat size, installation height, number of heliostats, and heliostat position.

Keywords: heliostat field, solar model, objective function, genetic algorithm, constraints.

1. Introduction

Carbon peaking "and" carbon neutrality "are key strategies for addressing excessive carbon dioxide emissions[1].With the rapid development of world industry and agriculture, global warming is accelerating, and carbon dioxide emissions are increasing day by day. Therefore, in order to achieve carbon emission control, it is first necessary to build a new type of power system with new energy as the main body. The function of the heliostat field in a tower solar thermal power station is to reflect and converge real-time solar radiation energy onto a heat absorber, in order to achieve the purpose of collecting solar radiation energy. It consists of a group of heliostats arranged in a certain way. Each heliostat can track the sun through biaxial rotation and reflect sunlight onto a heat absorber, which converts light energy into thermal energy and transmits it to a power generation device through a heat transfer medium for power generation[2]. The heliostat field is the core equipment of solar thermal power generation. The heliostat field reflects and gathers sunlight through a large number of heliostats, heating the working fluid and generating electricity. This article is a power generation problem for optimizing the design of a heliostat field, and the layout and parameter design of the heliostat are crucial for efficiency. In this issue, we have a pre designed heliostat field that includes components such as an absorber, collector, and heliostat.

2. Sun position

Ideally, the heliostat base is considered to be installed perpendicular to the horizontal plane, with the mirror surface pitching and rotating around the center point, with the two axes perpendicular. Firstly, it is necessary to use the mirror field coordinate system [3], where the center of the circular area is the origin, the east direction is the positive x-axis, the north direction is the positive y-axis, and the upward direction perpendicular to the ground is the positive z-axis. The solar altitude angle and solar azimuth angle are described using these two parameters, respectively, as shown in Figure 1.

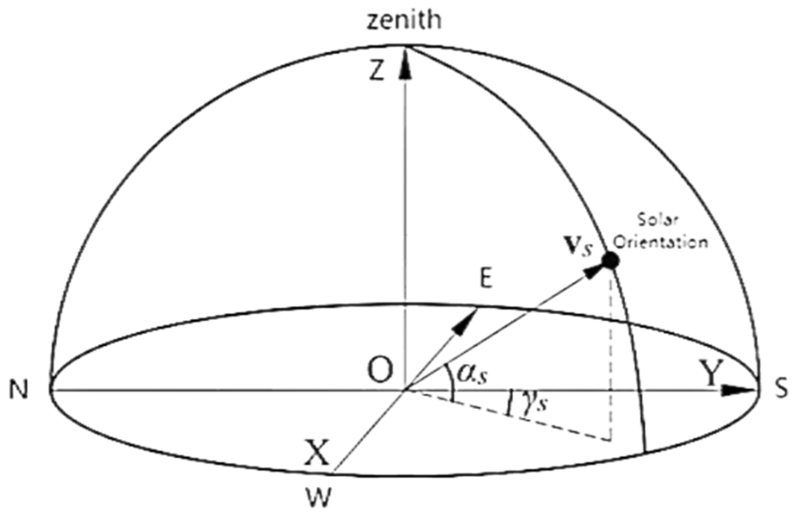

Figure 1. Calculation of Sun Position

Calculate the altitude α_s and azimuth angles γ_s of the sun at 39.4°N and 3000m above sea level at each time (5 times on the 21st of each month).

$$\sin \alpha_s = \cos \delta \cos \varphi \cos \omega + \sin \delta \sin \varphi \tag{1}$$

Wherein α_s、δ、φ、ω representing the solar altitude angle, solar declination angle, local latitude, and solar hour angle, respectively,

$$\cos \gamma_s = \frac{\sin \delta - \sin \alpha_s \sin \varphi}{\cos \gamma_s \cos \varphi} \tag{2}$$

Wherein γ_s represents the sun's azimuth angle,

$$\omega = \frac{\pi}{12}(\mathrm{ST} - 12) \tag{3}$$

Wherein ST represents local time, π represents pi.

2.1. Calculating Optical Efficiency

Determine the position of the absorption tower: the absorption tower is located at the center of the heliostat field[4], Calculate the optical efficiency of each heliostat: For each heliostat, calculate its shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance. Then multiply them together to obtain the total optical efficiency η.

2.1.1 Calculate shadow occlusion loss.

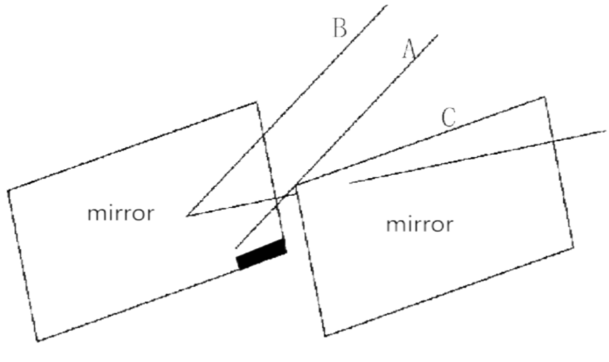

Figure 2. Mirror coordinate system

From Figure 2, it can be seen that A and B respectively represent the incident light of the sun, while C represents the light reflected by B through the heliostat. As can be seen from the ray path in the figure, A's incident light happened to be blocked by the left mirror during the process of incident on the right mirror, causing the right mirror to produce shadows from the left mirror[5-7].When the reflected light C generated by the right mirror reaches the heat absorber, B light is blocked by the right mirror, and the left mirror blocks the light. Therefore, calculate whether any point on the left mirror will fall into the area of the right mirror in the opposite direction of the incident or reflected light, and calculate its mirror coordinates on the right mirror. In the coordinate system of the left mirror, a point in the left mirror$P_1 = (x_1, y_1)$ find the coordinates of the passing light falling into the right mirror$P_2 = (x_2, y_2)$.The process of calculating the shadow blocking loss is to determine whether it is within the mirror surface based on the known information.Assuming the transformation relationship unit matrix from mirror coordinate system A to ground coordinate system B is:

$$T = \begin{bmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{bmatrix} \tag{4}$$

(l_x, m_x, n_x),$(l_y, m_y n_y)$,$(l_z, m_z, n_z)$are the vector representation of the three axes of the mirror coordinate system in the ground coordinate system b. The following will take the rotation mechanism of a traditional heliostat as an example, and its coordinate conversion relationship is as follows:

$$T = \begin{bmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{bmatrix} = \begin{bmatrix} -\sin E_H & -\sin A_H \cos E_H & \cos A_H \cos E_H \\ \cos E_H & -\sin A_H \sin E_H & \cos A_H \sin E_H \\ 0 & \cos A_H & \sin A_H \end{bmatrix} \tag{5}$$

To calculate the value of $P_2 = (x_2, y_2)$, First, remove a point from the left mirror P_1 convert to coordinates in the ground coordinate system and represent asP_1';Then, in the ground coordinate system P_1' convert to the right mirror coordinate system, Expressed as P_1'';Convert the incident or reflected light into the coordinate system of the right mirror; In the coordinate system of the right mirror, determine a straight line between two points and calculate the intersection point between the light and the right mirror;Consider whether P_2 is inside the mirror.

Next, we will calculate in steps according to the above process:

$P_1(x_1, y_1, 0)$ convert to P_1'

$$P_1' = \begin{bmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{bmatrix} \times P_1 + O_{left} = \begin{pmatrix} x'_1 \\ y'_1 \\ z'_1 \end{pmatrix} \tag{6}$$

$P_1'(x_1', y_1', z_1')$ convert to P_1''

$$P_1'' = \begin{bmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{bmatrix}^T \times (P_1'' - O_{right}) = \begin{pmatrix} x''_1 \\ y''_1 \\ z''_1 \end{pmatrix} \tag{7}$$

O_{left}、O_{right} represent the coordinate values of the origin of the left and right mirror coordinate systems in the ground coordinate system, respectively[8], expressed As $(x_{left}, y_{left}, z_{left})$ 、 $(x_{right}, y_{right}, z_{right})$.Determine whether$P_2$ falls within the mirror range,in the efficiency of shadow blocking in the mirror field, there is mutual influence between the heliostats to produce shadows and light blocking, as well as the influence of the absorption tower on the mirror field, as shown in Figures 3, 4, and 5. However, the absorption tower only has a shadow effect on the heliostat field and no light blocking effect. After determining the mirror field area caused by tower shadow, it is necessary to calculate the tower shadow of the heliostat in that area[9].

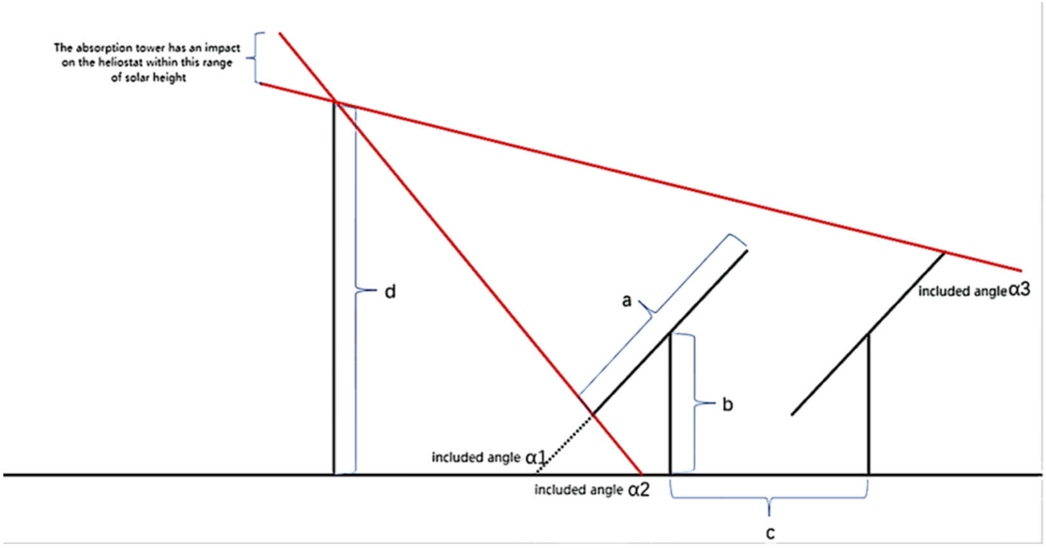

Figure 3. Impact of absorption tower

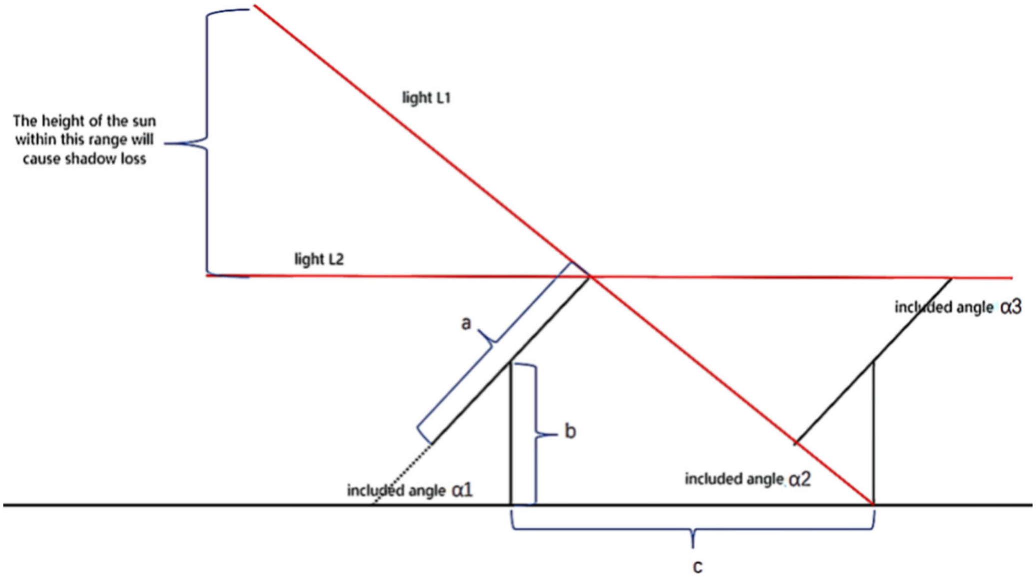

Figure 4. Shadow loss

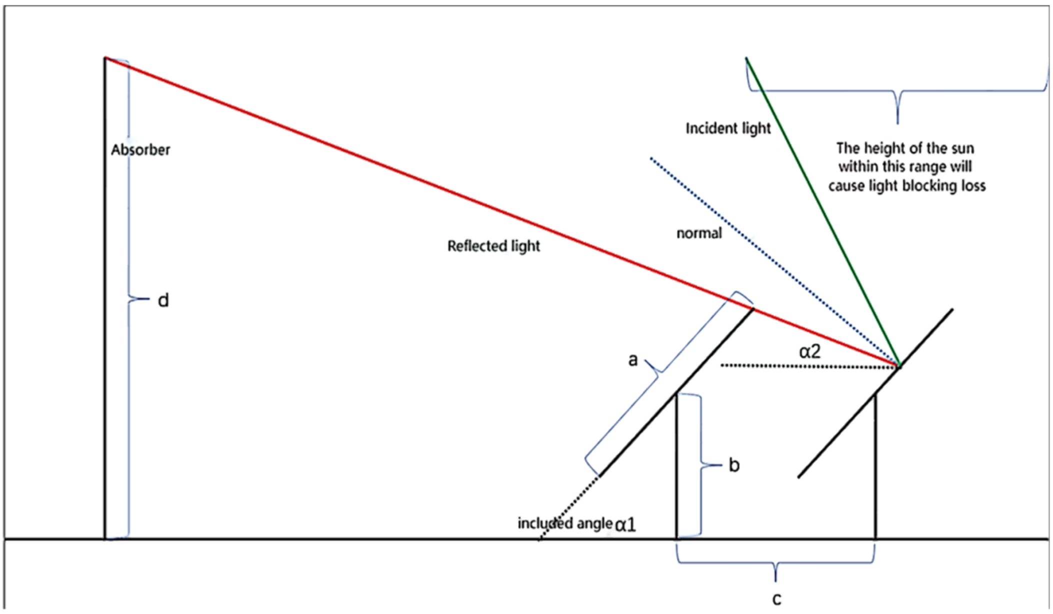

Figure 5. Occlusion loss

2.1.2 Calculation of cosine efficiency

The smaller the incident angle of the sun, the larger the effective area reflected on the heliostat, and the higher the cosine efficiency. The lower the inverse cosine efficiency. According to the previous calculations in this article, the solar altitude angle and solar direction angle are:

The direction vector of the incident light from the sun

$$\vec{S} = (\cos\alpha_s, \sin\gamma_s, \cos\alpha_s, \cos\gamma_s, \sin\alpha_s) \tag{8}$$

(2) The direction vector of the reflected light from the sun

$$\vec{R} = \left(\frac{-x_i}{\sqrt[2]{(x_i^2+y_i^2+(z_0-z_i)^2)}}, \frac{-y_i}{\sqrt[2]{(x_i^2+y_i^2+(z_0-z_i)^2)}}, \frac{z_0-z_i}{\sqrt[2]{(x_i^2+y_i^2+(z_0-z_i)^2)}} \right) \tag{9}$$

$$\cos 2\theta_i = \frac{-x_i \cos\alpha_s \sin\gamma_s - y_i \cos\alpha_s \cos\gamma_s + (z_0-z_i)\sin\alpha_s}{\sqrt[2]{(x_i^2+y_i^2+(z_0-z_i)^2)}} \tag{10}$$

Calculate the value of the solar incidence angle θ to obtain the cosine efficiency

$$\eta_{cos} = \cos\theta_i \tag{11}$$

2.1.3 Calculation of optical efficiency

(1) Atmospheric transmittance

$$\eta_{at} = 0.99321 - 0.0001176 d_{hr} + 1.97 \times 10^{-8} \times d_{hr}^2 (d_{hr} \leq 1000) \tag{12}$$

Where d_{hr} represents the distance from the center of the mirror surface to the center of the collector (unit: m).

(2)Collector truncation efficiency

$$\eta_{trunc} = \frac{Collectors\ receive\ energy}{Specular\ reflection\ energy - Shadow\ occlusion\ loses\ energy} \tag{13}$$

(3)Optical efficiency of heliostats

$$\eta = \eta_{sb}\eta_{cos}\eta_{at}\eta_{trunc}\eta_{ref} \tag{14}$$

Where η_{sb} represents shadow occlusion efficiency, Its value is 1-shadow occlusion loss;η_{ref}represents the specular reflectance, which can be taken as a constant.

Calculate the annual average optical efficiency: Calculate the optical efficiency for each moment and calculate the average based on the weight of sunlight time at each moment.

2.2. Calculation of Annual Average Thermal Power Output

Calculate the output thermal power of each heliostat using the solar radiation data (normal direct radiation irradiance DNI) and optical efficiency at each time, then average it based on the weight of the sunlight time at each time, and finally multiply it by the number of heliostats to obtain the annual average output thermal power.

Normal direct radiation irradiance DNI(unit: : kW/m2) refers to the solar radiation energy received per unit area and per unit time on a plane perpendicular to the sun's rays on Earth. It can be approximately calculated according to the following formula

$$\mathrm{DNI} = \mathrm{G_0}\left[\mathrm{a} + \mathrm{bexp}\left(-\frac{\mathrm{c}}{\sin\sigma_s}\right)\right] \tag{15}$$

$$\mathrm{a} = 0.4237 - 0.0082(6 - H)^2 \tag{16}$$

$$\mathrm{b} = 0.5055 + 0.00595(6.5 - \mathrm{H})^2 \tag{17}$$

$$\mathrm{c} = 0.2711 + 0.01858(2.5 - \mathrm{H})^2 \tag{18}$$

whereinG_0 Is the solar constant, Its value is taken as 1.366 kW/m^2, H is altitude (unit: km).

2.3. Calculate the annual average output thermal power per unit mirror area and monthly indicators

Divide the annual average thermal output power by the total area of the heliostat to obtain the annual average thermal output power per unit mirror area. The calculation of monthly indicators first initializes variables used to store the average value of each month, including average optical efficiency, cosine efficiency, shadow occlusion efficiency, truncation efficiency, output thermal power, and monthly hours; Then, the data for each month was calculated through nested loops. Loop traversal[10]Every month (1 to 12 months) and the position of each heliostat. For the combination of each month and location, the optical efficiency, cosine efficiency, shadow occlusion efficiency, truncation efficiency, and output thermal power were calculated for each hour, so that the cumulative value and number of hours per month can be obtained; Finally, the monthly average was calculated by dividing the cumulative value of each month by the number of hours per month. These monthly averages include optical efficiency, cosine efficiency, shadow occlusion efficiency, truncation efficiency, and output thermal power.

3. Research on heliostat layout based on genetic algorithm

This article defines constants and initial parameters: The code first defines some constants, including solar constant(G_0)、 pi(π) and the center coordinates of the heliostat field. Some initial parameters were also defined, including the initial guess values for mirror width, mirror height, tower height, and total number of mirrors. Randomly generate an initial set of heliostat field layouts, including the position coordinates of the absorption tower, heliostat size, installation height, number of heliostats, and heliostat position. Calculate the solar altitude angle and normal direct radiation irradiance (DNI): Calculate the solar altitude angle through mathematical formulas, which is the elevation angle of the sun in the sky. Next, the normal direct radiation irradiance (DNI) was calculated, which is the radiation intensity of solar radiation directly onto the mirror surface.

Defined a function calculate_optical_efficiency, used to calculate the optical efficiency of a heliostat.The optical efficiency comprehensively considers factors such as shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, truncation efficiency, and mirror reflectance to evaluate the performance of the mirror. objective function objective The opposite number used to calculate the annual average output thermal power per unit mirror area, in order to maximize this value through optimization. This function calculates the annual average output thermal power at each mirror position and different times in the heliostat field, and then accumulates it to obtain the annual average output thermal power per unit mirror area.

Define constraints[11]: constraint condition constraint Ensure that the annual average output thermal power is not less than the rated power(60e6 kW). This is an equation constraint that ensures that the heliostat field meets the given power requirements. Optimize:Using the minimize function, starting from the initial parameters, optimize the objective function to find the optimal mirror width, mirror height, tower height, and total number of mirrors, in order to maximize the annual average output thermal power per unit mirror area while meeting the requirements of rated power. Set the stopping conditions for genetic algorithms, usually by reaching a certain number of iterations or finding the optimal solution that meets the requirements. In each iteration, record the optimal heliostat field layout and related parameters, and after the optimization process, obtain the optimal solution. The optimal solution includes the position coordinates of the absorption tower, the size of the heliostat, the installation height, the number of heliostats, and the position of the heliostat.

The main optimization algorithm that can be used here is the heuristic algorithm as the solving algorithm, which arranges the heliostat field by changing the radial spacing of different regions of the heliostat field, in order to find the optimal layout of the heliostat field. For the radial spacing Δ r of heliostats in different regions, it is necessary to ensure that there is no mechanical collision between adjacent heliostats, i.e. the constraint condition Δ r is

$$\text{Ar} > \cos 30^{\circ} \quad \text{d} = 0.866\text{d} \tag{19}$$

(1) Define independent variables

Taking the position of the absorption tower (0,0) as the origin of the coordinate axis, the dimensions of the heliostat are: length a, width b, and $a < b$

installation height: h_1 Height of collector center: h_2

number: n

position: (x_n, y_n)

(2) Optimization objectives

Average output thermal power per unit area mirror:

$$\max\left(\text{E}_{\text{fieldaverage}} = \frac{\text{E}_{\text{field}}}{\text{n}\times\text{a}\times\text{b}}\right) \tag{20}$$

Wherein E_{field} is the output thermal power of the heliostat field, with a value of:

$$E_{field} = DIN \cdot \sum_i^N A_i \eta_i \tag{21}$$

Where DIN is the normal direct radiation irradiance; N is the total number of heliostats (unit: face);A_i is the lighting area of the i-th heliostat(unit: m^2); η_i is the optical efficiency of the i-th mirror.

(3) Objective function

$$E_{fieldaverage} = (a, b, h_1, h_2, n) \tag{22}$$

E.B layout[12]: Heliostat feature length is D_M、azimuth spacing of the first ring heliostat in each region is $A_{zi,1}$,Orientation of each region is A_{zi} ,Number of heliostats in each environment is $N_{hel,i}$.The calculation is as follows:

$$D_M=\sqrt{W_s^2 + H_s^2} \tag{23}$$

$$\Delta A_{zi,1}=(1.791+0.6396\theta_L)\times W_s+\frac{0.02873}{\theta_L-0.04902} \tag{24}$$

$$N_{hel,i}=\frac{2\pi}{\Delta\alpha_{zi,1}} \tag{25}$$

The corresponding data can be obtained as shown in Tables 1 2, and 3.

Table 1. Monthly Data

Date	Average optical efficiency	Average cosine efficiency	Average shadow occlusion efficiency	Average truncation efficiency	Average output thermal power per unit area mirror(kW/㎡)
January 21st	0.394099	0.087118	0.1	1.111111	0.137333
February 21st	0.457630	0.119154	0.1	1.111111	0.218114
March 21st	0.516630	0.156739	0.1	1.111111	0.323903
April 21st	0.457630	0.119154	0.1	1.111111	0.218114
May 21st	0.394099	0.087118	0.1	1.111111	0.137333
June 21st	0.367246	0.075329	0.1	1.111111	0.110657
July 21st	0.390110	0.085305	0.1	1.111111	0.133114
August 21st	0.451752	0.115916	0.1	1.111111	0.209461
September 21st	0.513228	0.154113	0.1	1.111111	0.316381
October 21st	0.463487	0.122445	0.1	1.111111	0.227006
November 21st	0.398362	0.089079	0.1	1.111111	0.141943
December 21st	0.367604	0.075479	0.1	1.111111	0.110986

Table 2. Annual Data

Annual average optical efficiency	Annual average cosine efficiency	Annual average shadow occlusion efficiency	Annual average truncation efficiency	Annual average thermal power output(MW)	Annual average thermal power output per unit area of mirror surface(kW/㎡)
0.42934	0.106176	0.1	1.111111	0.182342	0.190362

Table 3. Optimal Parameters

Absorption tower position coordinates	Heliostat size (width * height)	Installation height of heliostat (m)	Total number of heliostat faces	Total area of heliostat(㎡)
	36.0	6.0	1745.0	

4. Conclusion

This article establishes a solar position model, calculates the solar position at any time, and conducts sensitivity analysis based on experimental results to identify which parameters or inputs have a significant impact on the performance and output results of the model, and which have a small impact on the model. This can be achieved by comparing performance indicators of different parameters or input values. For each selected parameter or input, a series of experiments are performed within its defined range of variation. This article presents the optimization results, including the optimal parameter combination and performance indicators. This article also calculates the annual average optical efficiency, cosine efficiency, shadow occlusion efficiency, truncation efficiency, and output thermal power, which comprehensively evaluate the performance of the heliostat field. The results of this study provide strong support for the design and optimization of solar heliostat fields, and are expected to promote the development of solar energy utilization technology, reduce dependence on traditional energy, and achieve sustainable energy supply, which is of great significance for solving energy problems.

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