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Design of helichostat field based on shadow projection method and discretization principle

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Abstract: *The optical efficiency of the heliostat is investigated by discretization principle, light tracing method and frame conversion, and the best parameters were found by genetic algorithm and simulated annealing algorithm. First, the annual average optical efficiency of the heliostatic field is calculated, considering factors such as shadow occlusion efficiency, cosine efficiency, atmospheric transmission and collector truncation efficiency. The shadow occlusion efficiency includes the shadow loss of the absorption tower, the shadow loss of the rear helioscope and the reflection loss of the rear helioscope. The annual average shadow occlusion efficiency of 0.99 is calculated by the shadow projection method and the discretization principle. The cosine efficiency is equal to the cosine value of the incident light, and the calculated annual average cosine efficiency is 0.76. The truncation efficiency of the collector was calculated by ray tracing to yielding an average annual cutoff efficiency of 0.92. After the comprehensive calculation, the annual average optical efficiency is 0.61. Then, the annual average output thermal power of the heliostat field and the annual average output thermal power per unit mirror area are calculated, and the annual average output thermal power is 37370.00224 kW / m². The annual average output thermal power per unit mirror area can be simply calculated from the annual average output thermal power, which is 0.593871414 kW / m². These computational results provide an important reference for the performance of the heliostat field and help to optimize parameters and improve energy efficiency.*

Keywords: *Design of heliostatic field; discretization; light tracing method; genetic algorithm and simulated annealing algorithm*

1. Introduction

In recent years, the global problem of traditional energy shortage and environmental deterioration has attracted more and more attention. In order to cope with this challenge, many countries have put forward the goal of sustainable energy development. China has also made significant progress in this area, especially by proposing "carbon neutral" and "carbon peak" targets, aiming to actively address climate change, reducing greenhouse gas emissions and improving environmental quality. In achieving these goals, tower solar heating technology is increasingly considered as an important and great potential measure [1].

Tower solar heating power generation system is a power generation technology based on solar energy, which includes heliostat, collector and absorption tower components. Among them, the absorber is a key component. It is used to concentrate and absorb solar radiation, converting it into heat energy, which is then used to generate electricity. In order to maximize the power generation efficiency of the tower solar heating power generation system, various parameters need to be considered, including the position coordinate of the absorption tower, the size of heliostats, the installation height, the number of heliostats and the position of heliostats. Optimization of these parameters is crucial to ensure that the system can fully absorb solar energy and convert it into electricity[2].

Optimizing these parameters can help improve the energy efficiency of the system, reduce the cost of power generation, and reduce dependence on conventional fossil fuels, leading to better achieve carbon neutrality and carbon peak targets. In addition, tower solar heating technology can also help reduce carbon dioxide emissions in the atmosphere, help improve the environment and mitigate the impact of climate change.

In short, tower solar heating power generation technology is a renewable energy technology of great

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strategic significance, which can provide strong support for China and other countries to achieve their two-carbon goals. By continuously optimizing the parameters, we can make better use of solar energy resources, promote the development of green energy, protect the ecological environment, and contribute to sustainable development.

1.2 Restatement of the problem

Assuming the location of the absorption tower, the size of the heliostat, the annual average optical efficiency of the helioscope are of the same dimensions of 6m * 6m and 4m, and the average annual output thermal power respectively).

2. The basic funamental of BP neural network

2.1 Analysis of the problems

The data of the relevant heliostat field comes from the open source website. In the case of the absorption tower, the annual average optical efficiency, annual average output thermal power of the position of the field, the installation height of the heliostat, and the position of all the centers are determined.

The calculated optical efficiencies include shadow occlusion efficiency, cosine efficiency, atmospheric transmission, and collector truncation efficiency.

The cosine efficiency of the heliostatic field is equal to the cosine of the solar incidence angle, using the cosine of the product of the direction vector and the direction vector of the reflected light. Atmospheric transmission uses PyPyagorean theorem to find the distance of the mirror center of the helioscope to the center of the collector, and then directly using the given atmospheric transmission formula.

The truncation efficiency of the collector adopts ray tracing method to calculate the position coordinates of multiple rays on the collector after the reflection of the heliostat, and add the position coordinates to solve the truncation efficiency of the collector. Establish a light cone coordinate system as shown in the figure, write the light direction vector, and then use the coordinate system conversion principle to turn the light direction vector into the vector under the ground coordinate system. Combining the light equation with the plane equation of another collector, you can judge whether the light can fall on the collector.

The annual average output thermal power and the annual average output thermal power per unit mirror area are calculated directly by using the output thermal power formula of the heliostat field given by the problem.

3. Results

3.1 The establishment of simulation model

The mirror field coordinate system is established with the center of the circular area as the origin, the east direction is the axis, the north direction is the axis, and the upward direction of the ground is the z axis. Using the position coordinates of each heliohoscope in the attachment to draw Figure 1:

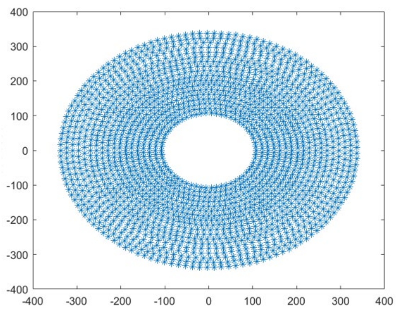

Figure 1: Location diagram of the heliostat in the heliostat field

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Solar altitude Angle and solar azimuth angle formula:

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

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

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

$$sin\delta = sin\frac{2\pi D}{365} sin\left(\frac{2\pi}{360}23.45\right) \tag{4}$$

According to the above four formulas, the solar height Angle and the solar azimuth Angle of each time point can be found by bringing each time point and days with matlab. The distribution of solar height angle at each point of the year is analyzed in Figure 1 and Figure 2, the sun height angle is between 12-52 and about 50; the sun azimuth is between 120 and 170 and the sun azimuth is at 12 and 165.754.

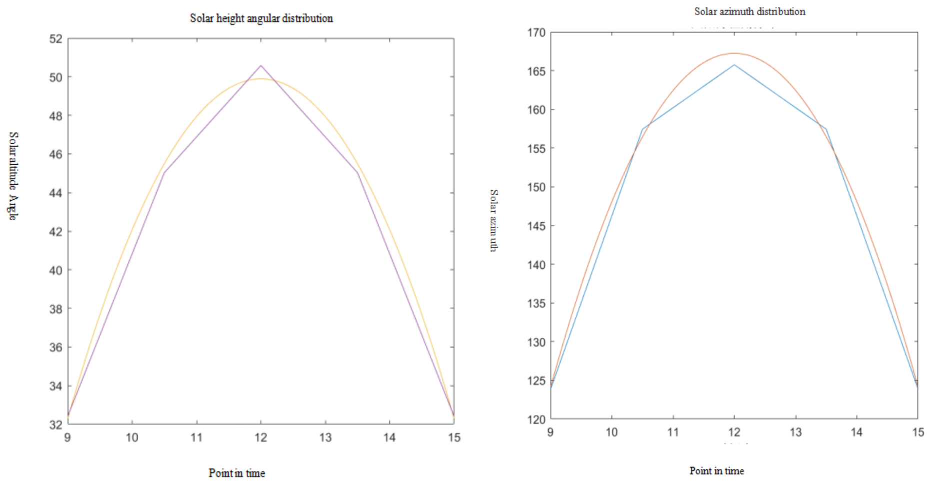

Figure 2: Solar altitude Angle at each time point (left) and solar azimuth Angle at each time point (right)

DNI calculation formula:

$$\mathrm{DNI} = \mathrm{G_0}\left[\mathrm{a} + \mathrm{b}\exp\left(-\frac{\mathrm{c}}{\sin\alpha_s}\right)\right] \tag{5}$$

$$\mathrm{a} = 0.4237 - 0.00821(6 - \mathrm{H})^2 \tag{6}$$

$$\mathrm{b} = 0.5055 + 0.00595(6.5 - \mathrm{H})^2 \tag{7}$$

$$\mathrm{c} = 0.2711 + 0.01858(2.5 - \mathrm{H})^2 \tag{8}$$

Among them, the solar constant is 1.366kW /, and the H altitude is 3000m. The calculated DNI value at each time point is shown in Figure 2 (right), and the maximum DNI value at 12 points is analyzed as shown in Figure 3, with a value of 1.01kW /.

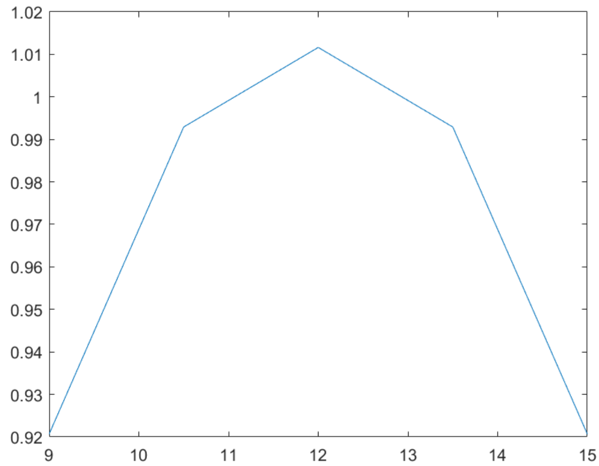

Figure 3: Mean DNI at each time point

3.1.1 Optical efficiency of the heliostat, [3]

Formula for calculating the optical efficiency:

$$\eta = \eta_{sb}\eta_{cos}\eta_{at}\eta_{trunc}\eta_{ref} \tag{9}$$

Among them, it is the optical efficiency, shadow occlusion efficiency, cosine efficiency, atmospheric transmission rate, truncation efficiency, and mirror reflectivity (desirable constant 0.92).

1) Shadow occlusion efficiency(η_{sb})

Shadow occlusion efficiency formula:

$$\eta_{sb} = 1 - Shadow\ occlusion\ loss \tag{10}$$

The shadow occlusion loss includes two parts:①Effect of the shadow of the absorption tower on the heliostat field ②Effect of the shadow of the heliostat on the heliostat.

Step 1: Consider the effect of the shadow of the absorption tower on the heliostat field

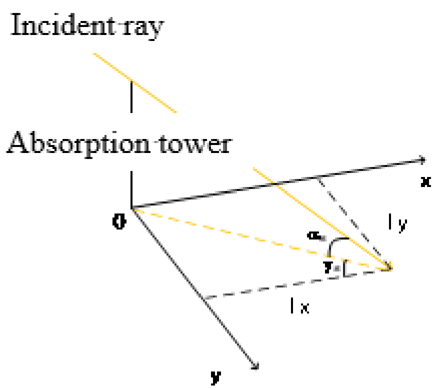

Figure 4: Shadow-projection diagram of the absorption tower

Take the center of the absorption tower as the origin. The x-axis points due east. The y-axis points to the due-north direction, and a two-dimensional coordinate system is established in Figure 4, lx for the projection length of the absorption tower shadow on the x-axis, ly for the projection length of the absorption tower shadow on the y-axis, H_0 for the absorption tower height:

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$$lx = \frac{H_0}{\tan\alpha_s} cos\gamma_s \tag{11}$$

$$ly = \frac{H_0}{\tan\alpha_s} sin\gamma_s \tag{12}$$

The critical coordinate is obtained from the projection length of the shadow of the absorption tower on the x-axis and y-axis, and then the position coordinate of each heliostat in the attachment is used to determine whether the position of the heliostat is in the shadow of the absorption tower. If the position of a heliostat is in the shadow, then the point is no longer considered in step2. The number of heliostats of each time point was obtained by matlab:

Table 1: Number of heliostats shaded by the absorption tower shadow at each time point

Month	9:00	10:30	12:00	13:30	15:00
January	174	41	19	41	174
February	55	3	0	3	55
March	10	0	0	0	10
April	0	0	0	0	0
May	0	0	0	0	0
June	0	0	0	0	0
July	0	0	0	0	0
August	0	0	0	0	0
September	10	0	0	0	10
October	65	5	0	5	65
November	191	48	22	48	191
December	272	71	37	71	272

The results of Table 1 showed the least number of heliostats blocked by the shadow of the absorption tower at 12 o'clock in the day, and the least number of heliostats blocked by the shadow of the absorption tower in December of the year.

Step 2: Effect of the shadow of the heliostat on the heliostat

In the center of the heliogram O_1 as the origin, point due east on the x1 axis,the y1 axis points in the positive direction, the z1 axis points to the zenith, the following mirror coordinate system is established as shown in Figure 5:

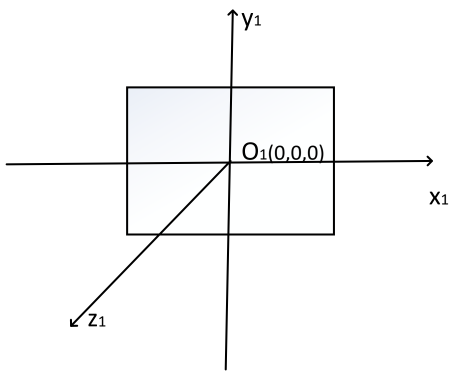

Figure 5: Mirror surface coordinate system diagram

Select two heliographs in the helioscope field. They are recorded as I and II。Choose a light, the light shoots at I the points formed on the mirror are indicated in the I mirror frame $Q_1(x_1, y_1, 0)$,then you need to determine whether the light is reflected and falls into the mirror. Using the discretization principle, divide the heliostat mirror into a grid of 20 * 20,that is, 20 * 20 discrete points, Q_1 Is at any of these discrete points. Suppose that the point formed by the light being reflected and falling into the mirror is below the mirror frame $Q_2(x_2, y_2, 0)$,then by transforming the coordinate system [4],convert all mirror coordinate systems to ground coordinate systems and the matrix of transformation units is:

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$$\mathrm{T} = \begin{pmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & l_z \end{pmatrix} \quad (13)$$

$\left(l_x, m_x, n_x\right)$、$\left(l_y, m_y, n_y\right)$, $\left(l_z, m_z, n_z\right)$ is the vector representation of the three axes under the mirror coordinate system in the ground coordinate system,rotate the coordinate axis around the x1 axis at a ,the rotation angle b around the z1 axis is:

$$\mathrm{T_z} = \begin{pmatrix} cos(b) & -sin(b) & 0 \\ sin(b) & cos(b) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (14)$$

$$\mathrm{T_x} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(a) & -sin(a) \\ 0 & sin(a) & cos(a) \end{pmatrix} \quad (15)$$

$$\mathrm{T} = \mathrm{T_z} * \mathrm{T_x} \quad (16)$$

Using formula (16) can calculate the matrix obtained after rotation. Through the transformation of the above matrix, we can turn the point coordinates on the mirror coordinate system to the point coordinates under the ground coordinate system, set the incident light direction vector in the ground coordinate system $\vec{S} = \left(s_1, s_2, s_3\right)$,any point in the mirror $Q_1\left(q_1, q_2, q_3\right)$,from $\vec{S}$ and Q_1 a straight line can be drawn.

Let the normal vector of the mirror in the ground coordinate system be $\overrightarrow{V_{f2}} = \left(u_1, u_2, u_3\right)$, the mirror center coordinate is $\mathrm{B}\left(t_1, t_2, t_3\right)$,then the plane equation of the mirror is:

$$u_1\left(x - t_1\right) + u_2\left(y - t_2\right) + u_3\left(z - t_3\right) = 0 \quad (17)$$

Combine the line and the aspect equation to get the intersection point, and then turn the coordinate system into the mirror coordinate, and judge whether the intersection point is in the heliostat mirror in the mirror coordinate system.

2) The cosine efficiency($\eta_{\cos}$)

The cosine efficiency is the cosine value of the incidence Angle of the sun. The smaller the incidence Angle of the sun, the larger the effective area reflected on the heliostat, and the higher the cosine efficiency is. Conversely, the larger the incidence angle of the sun, the smaller the effective area reflected on the heliostat is, and the lower the cosine efficiency becomes.[1]

As shown in the figure below, the xyz 3 D coordinate system was established,Where the x-axis points to the west direction, the y-axis points to the south direction, the z-axis points to the zenith, the OT is the receiving tower, the M point is the mirror center of the i th heliostat. Its coordinates are(x_i, y_i, z_i) , $\vec{S}$ Is the directional vector of the solar incident rays at point M, $\vec{R}$ Is the direction vector of the sun at point M(Figure 6).

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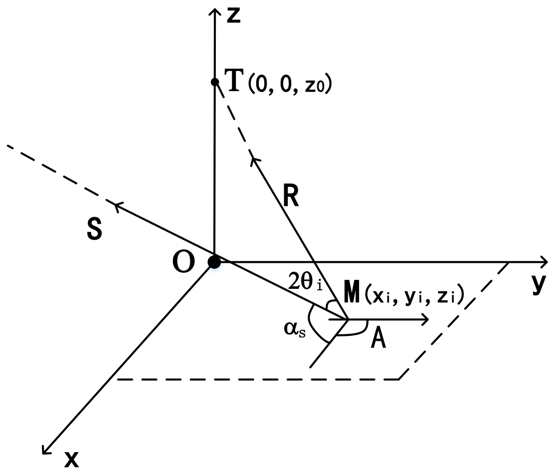

Figure 6:3 D coordinate map with the bottom end of the absorption tower as the origin

The heliostat cosine efficiency is expressed as[2]:

$$\eta_{\cos} = \cos\theta_{\mathrm{i}} = \cos\left[\arccos\left(\vec{S}*\vec{R}\right)/2\right] \tag{18}$$

Direction vector of the sun's incoming rays $\vec{S}$:

$$\vec{S} = \left(cos\alpha_s sinA, cos\alpha_s cosA, sin\alpha_s\right)$$

Among them, angle A is calculated as follows:

$$\sin\mathrm{A} = \frac{\cos\delta\sin\omega}{\cos\alpha_{\mathrm{s}}} \tag{19}$$

Direction vector of the sun reflects light $\vec{R}$:

$$\vec{R} = \left(\frac{-x_i}{\sqrt{x_i^2 + y_i^2 + \left(z_0 - z_1\right)^2}}, \frac{-y_i}{\sqrt{x_i^2 + y_i^2 + \left(z_0 - z_1\right)^2}}, \frac{z_0 - z_i}{\sqrt{x_i^2 + y_i^2 + \left(z_0 - z_1\right)^2}}\right) \tag{20}$$

$\cos2\theta_{\mathrm{i}} = \vec{S}*\vec{R}$, by substituting the above formula into the:

$$\cos2\theta_{\mathrm{i}} = \frac{-x_i cos\alpha_s sinA - y_i cos\alpha_s cosA + \left(z_0 - z_i\right) sin\alpha_s}{\sqrt{x_i^2 + y_i^2 + \left(z_0 - z_1\right)^2}} \tag{21}$$

At this point, the cosine efficiency of the heliostat can be calculated. The average cosine efficiency of each month is between 68% and 70%, obtaining the maximum cosine efficiency in June and the maximum cosine efficiency in December, and the fitting graph presents a quadratic function, which is in line with the actual situation (Figure 7).

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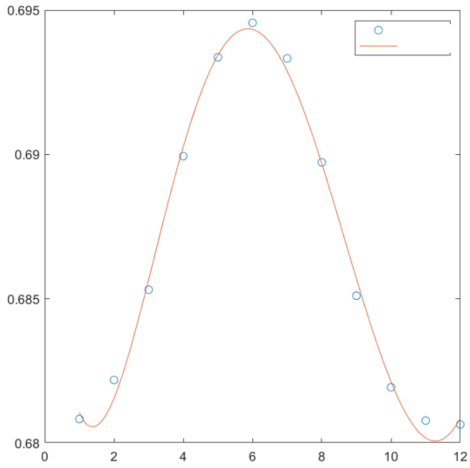

Figure 7: Plot of cosine efficiency for 12 months

3) Collector truncation efficiency(η_{trunc})

The position coordinates of multiple rays arriving on the collector after reflection by the heliostat are calculated, and the achieved position coordinates are accumulated to solve the truncation efficiency of the collector.

A light cone coordinate system is established as shown, the x axis is parallel to the ground plane, the y axis is perpendicular to the x axis and z axis, pointing to the center of the sun along the light direction in the light cone(Figure 8).

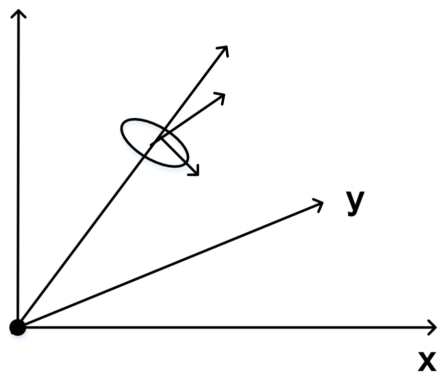

Figure 8: Light cone light coordinate system diagram

Let the angle of any light with the main light from the center of the sun be σ , the sandwich angle with the x-axis is τ ,then any line of light can be expressed as:

$$\overrightarrow{S_x} = \left(sin\sigma cos\tau, sin\sigma sin\tau, cos\sigma \right) \tag{22}$$

Use the coordinate frame transformation, Points on the mirror coordinate frame Q convert to the coordinate extreme under the ground coordinate system Q' ; Convert the light vector in the light cone coordinate system to the coordinates under the ground coordinate system;

Write out the light direction vector, and then use the coordinate system conversion principle to turn the light direction vector into the vector under the ground coordinate system. Combining the light equation with the plane equation of another collector, you can judge whether the light can fall on the collector.

4) Atmospheric transmissivity(η_{at})

Atmospheric projection rate formula:

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$$\eta_{at} = 0.99321 - 0.0001176 d_{HR} + 1.97*10^{-8}*d_{HR}^2 (d_{HR} \le 1\,000) \tag{23}$$

As shown in the Figure 9 and Figure 10 below, Let the midpoint coordinates in the mirror surface be given as follows D(x_1, y_1, z_1) ,the point coordinates in the collector are X(x_2, y_2, z_2) ,use the trigornogagorean theorem d_{HR} ,

$$d_{HR} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{24}$$

Solving with matlab yields an annual average atmospheric transmission rate of 0.9666.

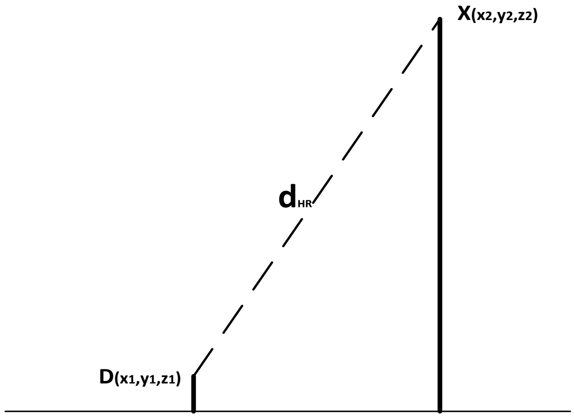

Figure 9: Distance between the midpoint of a certain mirror to the midpoint of the collector

5) Calculate the annual average optical efficiency

The results obtained from 3.1.1.1~3.1.1.4 can calculate the annual average optical efficiency of 0.61. At four times on December 21, the optical efficiency of the heliostat in the north is higher than that in the south, which is in line with the reality.

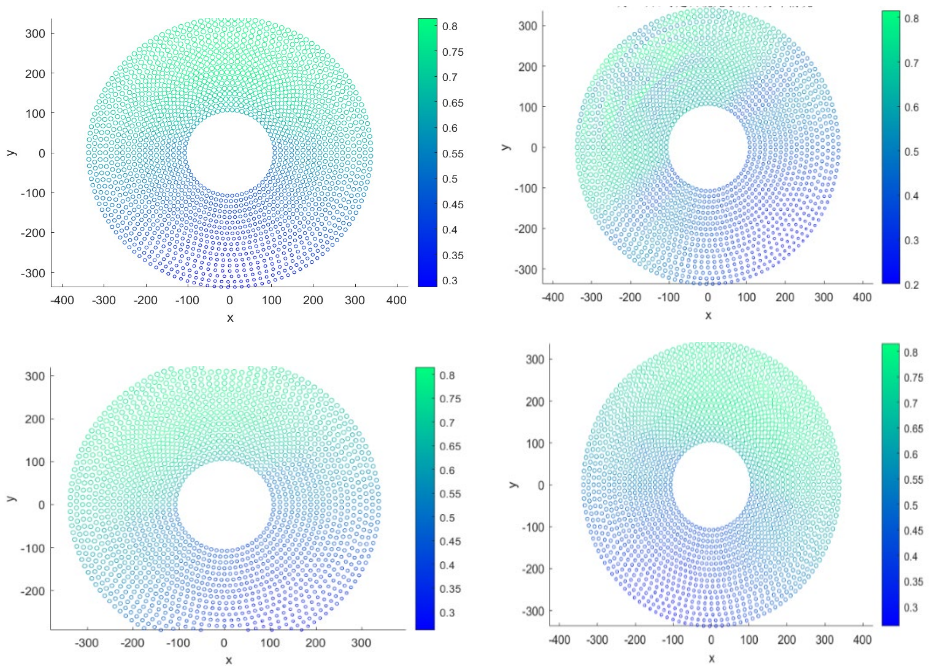

Figure 10: Optical efficiency distribution diagram at four moments on December 21

3.1.2 Average annual output thermal power of the heliostat field

Output thermal power of the heliostat field E_{field} :

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$$E_{field} = DNI\sum_{i}^{N} A_i \eta_i \tag{25}$$

Where, DNI is the normal direct radiation irradiance, A_i the first i heliostam lighting area, η_i Optical efficiency of the i-th helostat,lighting area of the heliostat in the first question A_i 6m*6m.

The average annual output thermal power of the helioscope field was calculated by matlab as37307.00224 $\mathrm{kW/m^2}$.

3.1.3 Average annual output thermal power per unit mirror area[5]

Output thermal power per unit mirror area E_{avg} :

$$E_{avg} = \frac{E_{field}}{N * S_N} \tag{26}$$

The average annual output thermal power of the helioscope field was calculated by matlab as0.593871414 $\mathrm{kW/m^2}$.

3.1.4 Solve the results

Specific results such as (Table 2):

Table 2: Various parameters of the heliostat field

Average annual optical efficiency	Average annual cosine efficiency	Annual average shadow occlusion efficiency	Average annual truncation efficiency	Average annual output thermal power	Mean annual output thermal power per unit area
0.610320649	0.759902216	0.990844114	0.919316304	37.30700224	0.593871414

4. Conclusions

By applying the discretization principle, ray tracking method and frame conversion, we successfully solve the optical efficiency of heliostatic field, and optimize the parameters of heliostatic field by using genetic algorithm and simulated annealing algorithm.

First, we calculate the average annual optical efficiency of the heliostat field, which is influenced by many factors, including shadow occlusion efficiency, cosine efficiency, atmospheric transmission, and collector truncation efficiency. The shadow occlusion efficiency includes the shadow loss caused by the absorption tower, the shadow loss caused by the shielding of the front heliostat, and the influence of the front heliostat on the heat absorber. Through the shadow projection method and the discretization principle, we conclude that the annual average shadow shading efficiency is up to 0.99. The cosine efficiency is obtained by calculating the cosine value of the incident light and the heliostat mirror normal, and the annual average cosine efficiency reaches 0.76. The truncation efficiency of the collector is calculated by the ray tracking method. We tracked the paths of multiple rays and calculated their position coordinates on the collector, and finally obtained the average annual cutoff efficiency of 0.92. Combining these efficiency values, we finally obtained an annual average optical efficiency of 0.61.

Next, we calculated the annual average output thermal power and annual average output thermal power per mirror area. The annual average output thermal power is obtained by multiplying the optical efficiency with the lighting area of the heliostat, while the annual average output thermal power per unit mirror area is a simple standardization treatment on the basis of the annual average output thermal power. The final calculation results show that the average annual output thermal power of the heliostat field is 37307.00224 kW per square meter, while the average annual output thermal power per mirror area is 0.593871414 kW per square meter. These results provide important reference data for us to deeply study and optimize the performance of heliostatic fields, which are expected to make important contributions in the field of renewable energy.

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References

[1] Liu Jianxing. Optical efficiency modeling and simulation and optimal layout of tower photothermal power station. Lanzhou Jiaotong University. 2022
[2] Xiao Yixing. Distribution optimization and cluster control of heliostat in tower solar thermal power plant. Changsha University of Science and Technology, 2020.
[3] Zhang Ping, optical efficiency of solar tower [J]. Technology and Market, 2021, 28 (6): 5-8.
[4] Du Yuhang et al., analysis of the impact of different focusing strategies of the helichoscope of tower photothermal power stations [J]. Journal of Power Engineering, 2020, 40 (5): 426-432.
[5] Zhao, Lei, Liu, et al. Design of multi-narrowband metamaterial perfect absorbers in near-infrared band based on resonators asymmetric method and modified resonators stacked method[J]. Optics Communications: A Journal Devoted to the Rapid Publication of Short Contributions in the Field of Optics and Interaction of Light with Matter, 2018.