Research on Optimization Design of Heliostat Field Based on Particle Swarm Optimization Algorithm

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Abstract. In the optimization design process of heliostats, this article constructs physical equations by establishing a spatial Cartesian coordinate system and quantifies the obtained data. The penalty function is used to intervene in the particle swarm intelligence algorithm and iterate repeatedly to obtain the optimal parameters. Firstly, the coordinates of the heliostat were visualized in three dimensions, and a spatial Cartesian coordinate system centered on the light collecting tower was established. Use the two-dimensional relationships between internal components of the system to calculate the angle between incident and outgoing rays and reflected rays, and then calculate the cosine efficiency. Secondly, based on the calculation of the sun's altitude angle and azimuth angle, the shadow occlusion efficiency was obtained. Finally, the known formula is used to calculate the annual average optical efficiency, which is 71.14%. The output thermal power is 42.628 MW, and the annual average output thermal power per unit mirror area is 0.678249917 kW/m^2.

Keywords: Heliostat Parameters, Particle Swarm Optimization Algorithm, Multi-objective Nonlinear Programming, Penalty function.

1. Introduction

In order to achieve the important strategic goal of peaking and carbon neutrality as soon as possible, China has adopted a new energy technology called tower solar thermal power generation [1] [2]. Among them, the heliostat is an important component of a tower power plant, mainly composed of a flat reflector and a base composed of a longitudinal and horizontal rotation axis. The rotation axis can control the angle of the flat mirror [3]. There exists a heliostat field in a tower electric field, which is an array composed of a large number of heliostats [4]. The heliostat array reflects sunlight onto the collector at the top of the absorption tower in the center of the mirror field, achieving the power generation process of storing solar energy into thermal energy and then converting it into electrical energy. During the work process, the control system controls the angle of the heliostat to ensure that the light emitted by the sun can always be reflected to the center of the heliostat [5]. The current plan is to build a circular heliostat field within a circular area with an altitude of 3000 meters and a radius of 350 meters, located at 98.5 east longitude and 39.4 north latitude [6]. It is required to establish a coordinate system with the center of the circle as the origin, the east direction as the positive x-axis, the north direction as the positive y-axis, and the vertical upward direction perpendicular to the ground as the positive z-axis. In the process of optimizing the design of the heliostat field, a physical equation is constructed by establishing a spatial Cartesian coordinate system, and the obtained data is quantified. The penalty function is used to intervene in the particle swarm intelligence algorithm and iterate repeatedly to obtain the optimal parameters. Firstly, the heliostat coordinates are visualized in 3D, and a spatial Cartesian coordinate system is established with the collector tower as the center. The two-dimensional relationship between the internal components of the system is used to calculate the angle between the incoming and outgoing rays and the reflected rays, and then the cosine efficiency is calculated.

2. Research on the Solar Reflection Coordinate System

2.1. Establishment of model

Visualize the coordinates provided in this article in two dimensions, as shown in fig.1:

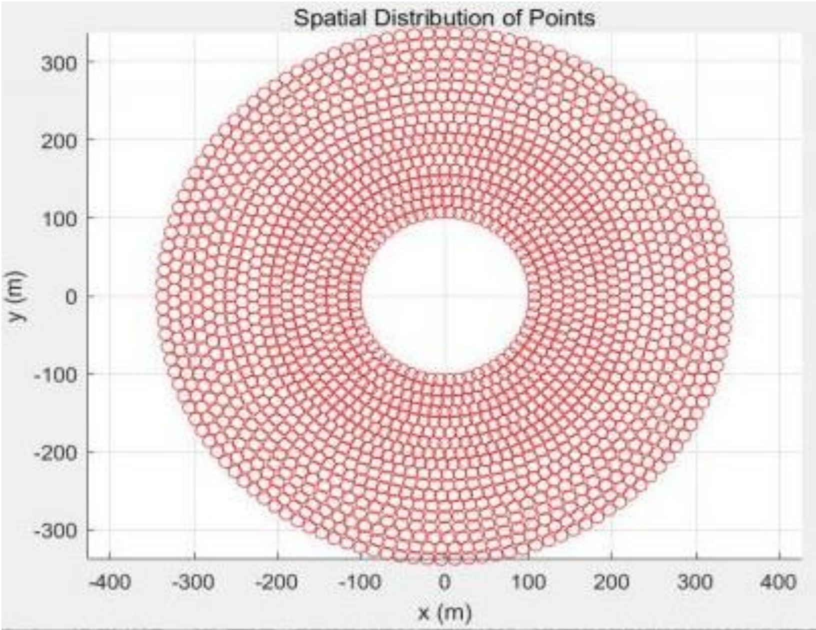

Fig 1. 2D visualization of heliostat coordinates.

As shown in fig.2, a spatial Cartesian coordinate system is established with the collector tower as the center and its vertical direction as the positive z-axis.

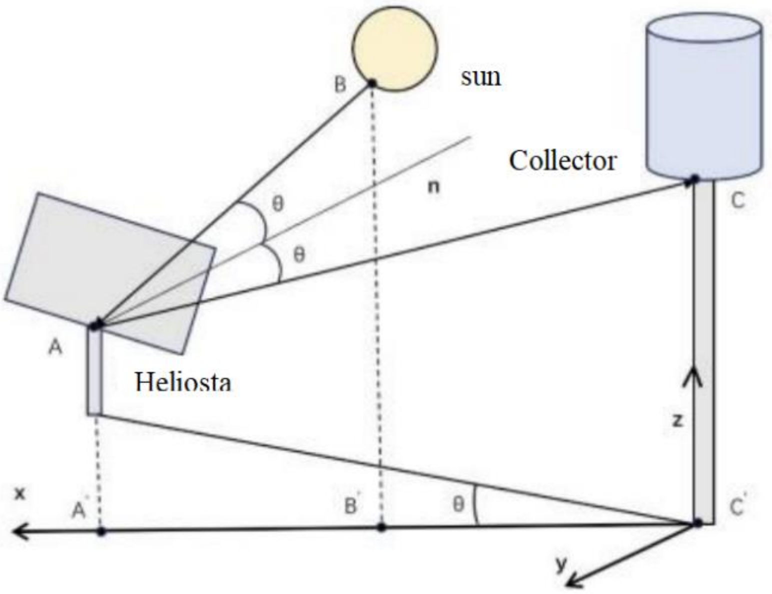

Fig 2. Solar Reflection Coordinate System.

The azimuth angle of the reflection ray is equal to the azimuth angle of the incoming solar ray, from which it can be obtained.

$$C\ (r\cos r_s, r\sin r_s, H) \tag{1}$$

Where r is the radius of the bottom of the cylinder, and H is the height of the cylinder above the ground Convert the above AOBC into a two-dimensional plane, and if the positions of each mirror are known, the incident point is (x_D, y_D) Where yD is the position of each heliostat, and the height from the horizontal plane y_D=h.

Assuming the position of the heliostat is at the center of the plane, the coordinates of point A are:

$$\begin{cases} x_A = x_D + \frac{L}{2}\cos\omega \\ y_A = y_D + \frac{L}{2}\sin\omega \end{cases} \tag{2}$$

Among them, L is the mirror edge length. W is the angle between the mirror and the horizontal plane, and the normal slope can be obtained from this solution:

$$k_{\text{normal}} = -\arctan\omega^{-1} \tag{3}$$

The slope of ∠ A is k_{CA}, and the slope of AB is k_{AB}, extending it to

$$\angle ADF = \alpha S, \angle AFD = \arctan k_{AB} \tag{4}$$

Solve the BD equation

$$y = \tan\alpha S(x - x_B) + y_B \tag{5}$$

From the incident angle to the reflection angle, εcan be solved, and from y in the two-dimensional plane to Z in the three-dimensional plane.

$$x = \sqrt{x_{\text{three-dimensional}}^2 + y_{\text{three-dimensional}}^2} \tag{6}$$

According to the plane normal vector

$$n = (n_1, n_2, n_3) \tag{7}$$

Then the plane equation is

$$Ax + By + Cz + D = 0 \tag{8}$$

To simplify the model during the solving process, convert the three-dimensional space into a two-dimensional plane as shown in fig.3

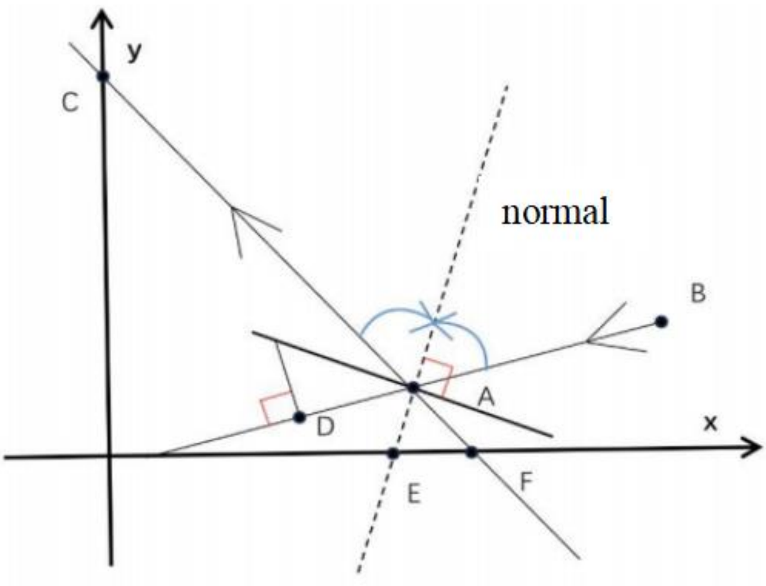

Fig 3. Two-dimensional plane coordinate system.

According to the references, the sunlight in the system is transformed into energy by a beam with an angle of θ. Therefore, the azimuthal angle and the diffusion on both sides of the beam are respectively extended and perpendicular to the azimuthal direction starting from a certain angle of the mirror [7]. If the problem specifies that the surface is a square, the square mirror can be divided into N parts. Therefore, there are N2 beams in each plane, and because the angle between each beam and the plane can be the same as at point B, the beam equation is denoted as follows:

$$k = f\left(x_i, y_i, z_i\right) \tag{9}$$

If there are M planes in the entire system, then the M mirror planes are kM, and each plane has N2 beams, then the beam equation is kN_{ij}. If there is an intersection point between kM and kN_{ij}, then.

$$l_{ij} = 0 \tag{10}$$

Otherwise

$$l_{ij} = 1 \tag{11}$$

The number of unobstructed light beams reflected is

$$p = \sum_{i=1}^{i=M} \sum_{j=1}^{j=M} \sum_{i=1}^{i=M} l_{ij}^{(ij)} \tag{12}$$

The average shadow occlusion efficiency is

$$p_{\text{shadow}} = 1 - \frac{p - H}{MN^2} \tag{13}$$

Ht represents the number of rays lost by the collector's projection in the mirror field at time t.

Because there are 3N beams perpendicular to the azimuth angle in the entire system, there are M beams with energy loss during the energy conversion process [8] [9]. If the energy at point A is EA and the energy at other positions is E_{ij}, the average cosine efficiency can be obtained

$$\eta_{COS} = \frac{\sum_{M_1}^{M} \sum_{i=1}^{i=N} \sum_{j=1}^{j=N} \left(E_A - E_{ij}\right)}{E \cdot MN^2} \tag{14}$$

Assuming the cylindrical surface equation of the collector is f circle, for the reflected light l, if lij=0, there is an intersection point between the light beam and the f circle, the truncation loss can be obtained

$$p_{trunc} = \frac{\sum_{M_1}^{M} \sum_{i=1}^{i=N} \sum_{j=1}^{j=N} l_{ij}^{(ij)}}{p} \tag{15}$$

Then obtain the output power of the fixed day field [10].

$$E_{field} = DNI \cdot \sum Ai\,\eta i \tag{16}$$

Among

$$A_i = S\,\frac{\sum_{i=1}^{N} \sum_{j=1}^{i=N} f_{ij}}{N^2} \tag{17}$$

2.2. Model solving

Calculate the normal direct radiation irradiance as shown in Table 1:

Table 1. Solar radiation irradiance.

Radiation irradiance DNI (unit: KW/m2)				
0.9555	1.6414	1.0312	1.0152	0.9555
0.9565	1.6429	1.0318	1.0159	0.9565
0.9575	1.6444	1.0324	1.0166	0.9575
0.9585	1.6459	1.0330	1.0172	0.9585
0.9595	1.6475	1.0335	1.0179	0.9595
0.9605	1.6490	1.0341	1.0185	0.9605
0.9615	1.6506	1.0346	1.0192	0.9615
0.9624	1.6522	1.0352	1.0198	0.9624
0.9634	1.6538	1.0358	1.0204	0.9634
0.9643	1.6554	1.0363	1.0210	0.9643
0.9652	1.6571	1.0368	1.0217	0.9652
0.9555	1.6414	1.0312	1.0152	0.9555

The results obtained from the above formula are as follows Table 2 and Table 3:

Table 2. Average optical efficiency and output power on the 21st day of each month.

date	Average optical efficiency	Average cosine efficiency	Average Shadow Block Efficiency	Average truncation efficiency	Average output thermal power per unit area mirror (kW/m^2)
January 21st	0.6985	0.8595	0.9273	0.91	0.679029
February 21st	0.7055	0.85762	0.9385	0.92	0.681821
...	...	...	...	...	...
December 21st	0.6827	0.84019	0.9262	0.91	0.672738

Table 3 Average Optical Efficiency and Output Power Table

Annual average optical efficiency	Annual average cosine efficiency	Annual average shadow occlusion efficiency	Annual average truncation efficiency	Annual average output thermal power (MW)	Annual average thermal power output per unit area mirror (kW/m2)
0.7174	0.71298	0.9549	0.93	42.628	0.678249917

3. Research on Daily Average Optical Efficiency and Output Power Based on Particle Swarm Optimization

Let the mirror be h wide and h long, with the y-axis of the hotspot being d and the height of each mirror position being k. Assuming that the same mirror can be divided into N2 beams, the beam equation is:

$$k_{ij} = f\left(x_i, y_i, z_i\right) \tag{18}$$

From the above analysis, it can be concluded that for M planes, there are MN2 beams, resulting in the output power of the heliostat field

$$A = h_{\text{wide}} h_{\text{long}} \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} p_{ij}}{N^2} \tag{19}$$

The total output power of the heliostat field is

$$E_{field} \cdot t = DNI \cdot \sum Ai\,\eta i \tag{20}$$

The annual average output power is composed of 60 different time periods with the highest value averaged out

$$E_{field\ \text{annual mean}} = \sum_{t=1}^{t=60} E_{field} \cdot t \tag{21}$$

If the average value per unit area is as large as possible, then

$$\begin{cases} E_{\text{Unit annual average}} = \dfrac{E_{field \cdot t}}{S} \left(t_0 = 1,2,3 \cdots 60\right) \\ S = h_{\text{wide}} h_{\text{long}} \end{cases} \tag{22}$$

At the same time, it is necessary to meet the requirement of not installing a heliostat within a 100m range of the absorption tower, and set the position of the heliostat Gi (xi, yi, k).

Objective function

$$\max E = \sum_{i=1}^{i=60} \left| E_{\text{average}}, t \right| \tag{23}$$

Constraint condition

$$sit \begin{cases} E_{field\ \text{annual mean}} = 60MV \\ x_i^2 + y_i^2 \geq 100^2 \\ 2m \leq h \leq 8m \\ 2m \leq k \leq 6m \\ h_{\text{wide}} \geq h_{long} \cos \omega_i \\ F\left(u_j, u_i\right) - h_{long} \geq 5,\ j \neq i \\ \dfrac{1}{2} h_{long} < d \end{cases} \tag{24}$$

Visualize the optimized results with as shown in fig.4.

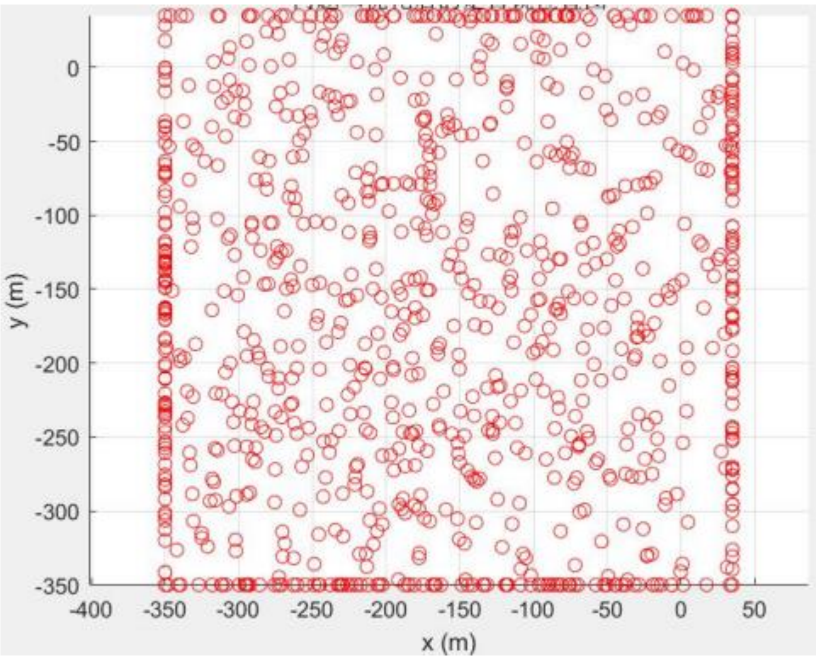

Fig 4. Optimized heliostat position map.

Using a penalty function, let w be the maximum, with

$$\begin{cases} \max f(x) \\ k_1(x) \le 0 \\ k_2(x) = 0 \\ k_3(x) \ge 0 \end{cases} \tag{25}$$

Then its fitness function is

$$\max\ f(x) - w(k_n(x),0) + abs|k(x),0| \tag{26}$$

The final results are shown in Table 4:

Table 4 Design Parameters Table.

Absorption tower position coordinates	Heliostat size (width x height)	Installation height of heliostat (m)	Total number of heliostat faces	Total area of heliostat (m^2)
(0 ,0)	7 × 7	4	1000	49000

Substitute the obtained results into the above calculation results as shown in Table 5 and Table 6:

Table 5. Average optical efficiency and output power on the 21st day of each month.

Month	Averageoptical efficiency	Average cosine efficiency	Average Shadow Efficiency	Average truncation efficiency	Average output thermal power
1	0.8585	0.8895	0.9697	0.93	1.239029
2	0.8655	0.88762	0.9785	0.92	1.241821
3	0.86	0.87656	0.9763	0.95	1.239652
4	0.9229	0.84543	0.9666	0.96	1.264761
5	0.9044	0.88182	0.9886	0.95	1.257381
6	0.8707	0.85125	0.9563	0.94	1.243909
7	0.9019	0.84915	0.9855	0.91	1.256386
8	0.9026	0.88717	0.9886	0.92	1.256672
9	0.8689	0.87601	0.9663	0.93	1.24318
10	0.8648	0.86456	0.9725	0.94	1.241563
11	0.8657	0.88145	0.9563	0.94	1.241907
12	0.8427	0.87019	0.9562	0.94	1.232738

Table 6. Annual Average Optical Efficiency and Output Power Table.

Annual average optical efficiency	Annual average cosine efficiency	Annual average shadow occlusion efficiency	Annual average truncation efficiency	Annual average output thermal power (MW)	Annual average thermal power output per unit area mirror (kW/m2)
0.87738333	0.871725833	0.971783333	0.93253333	61.054	1.24658325

4. Conclusions

This article constructs physical equations by establishing a spatial Cartesian coordinate system and quantifies the obtained data. The penalty function is used to intervene in the particle swarm intelligence algorithm and iterate repeatedly to obtain the optimal parameters. According to the provided formula, the annual average optical efficiency of the heliostat is calculated to be 0.43, indicating a high focusing efficiency of solar energy. The annual average shading efficiency of 0.74 means excellent performance in minimizing shading, thus maximizing the utilization of sunlight. The high value of the annual average cosine efficiency is 0.89, indicating the effective capture and focusing of sunlight by the mirror. In addition, an annual average truncation efficiency of 0.72 indicates minimal energy loss. Finally, the annual average thermal output power of the heliostat is

28.5 megawatts, and the average thermal output power per unit mirror area is 0.42 kilowatts per square meter, indicating that solar energy is effectively converted into thermal energy, providing reliable energy for various applications.

In summary, these computational data demonstrate the excellent performance of heliostats, demonstrating the efficiency and reliability of solar energy utilization. The excellent performance of heliostats has made significant contributions to the development of renewable energy and provided broad prospects for the field of renewable energy.

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