Research On the Design of Fixed-Sun Mirror Field Based on Particle Swarm Optimisation Algorithm

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Abstract. Solar energy, as one of the energy types mainly utilized in renewable energy, is the utilization of thermal radiation energy in the light rays irradiated to the earth by the sun. Photovoltaic power generation is a more widely used form of solar energy utilization, in order to maximize the use of solar energy, limited to the tower photovoltaic plant footprint, you can change the distribution of heliostat mirrors, so that the mirror field presents a better distribution. This paper aims to improve the efficiency of the mirror field as a whole on the use of solar energy, by analyzing the geometric relationship between the sun position and absorption tower and all the heliostat mirrors, calculate the average annual optical efficiency of the heliostat mirror field, the average annual output thermal power, and the average annual output thermal power per unit of the mirror surface area, the use of the shadow masking model the model to get the calculation of the thermal power of the parameters needed. Then, the potential geometrical dimensions and mounting height combinations of the heliostat were formulated, and an optimization scheme for the annual average thermal power based on the particle swarm optimization algorithm was constructed. The PSO particles are initialized with the heliostat to obtain the optimal solution for the heliostat installation. Finally, the annual average thermal power optimization scheme based on particle swarm optimization algorithm is constructed, and the optimal solutions for the installation of heliostat and the location of the absorber tower are obtained by iteratively eliminating the poor-quality solutions.

Keywords: Particle Swarm Optimisation Algorithm, PSO Algorithm, Shadow Occlusion Model.

1. Introduction

The construction of a new power system mainly based on new energy is an important measure for China to realize the goal of "carbon peak" and "carbon neutral". Tower solar photovoltaic power generation is a new type of low-carbon and environmentally friendly clean energy technology. The heliostat is the basic component of tower solar thermal power plant to collect solar energy, and the construction cost of heliostat field in tower solar thermal power plant accounts for 30%~50% of the total investment of the whole power plant, so how to arrange the heliostat field with high efficiency and low cost has become a hot topic of research nowadays as the energy input unit of the whole system, the concentrating efficiency of the mirror field directly affects the power generation of the whole system, so the specification size of the mirror field, the absorber tower and the position of the mirrors in the mirror field are particularly important [1].

In this paper, for the problem of improving the efficiency of the mirror field to utilize the solar energy, a shadow shading model and a model based on particle swarm optimization algorithm are constructed to determine the parameters of the heliostat mirrors. By analyzing the geometrical relationship between the sun position and the absorber tower and all the heliostats, the annual average optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area of the heliostat field are calculated, and at the same time, the shading model is constructed, which can be used to obtain all the parameters required for the calculation of thermal power. In the analysis of the shading relationship of heliostat mirrors, the shading parameters of the heliostat field are obtained by applying geometric and vectorial methods to determine whether the heliostat mirrors are shaded by other mirrors. After obtaining the parameters necessary for calculating the average thermal power output per unit area of the mirror, we input them into the computational model to obtain the final results. Under the condition that all the heliostats have the same size and installation height, the heliostat field is designed to achieve the rated annual average thermal power output of 60 MW and the annual average thermal power output per mirror area is as large as possible. Based on the geographic location of the target heliostat field and industry design experience, we formulated potential combinations of geometry and mounting height of heliostats and constructed a particle swarm optimization algorithm based annual average thermal power optimization scheme. The PSO particles are initialized using heliostats, and the position of each particle represents a possible solution. The optimal solution for the heliostat installation is obtained by iteratively eliminating the poor-quality solutions.

2. Shadow masking model

2.1. Model Building

Fig. 1 shows the mathematical model of the light rays from the heliostat field. The reflection of solar rays through the heliostat to the collector is actually an analysis of the positional relationship between the sun's altitude angle, declination angle, solar time angle and solar azimuth angle and all the heliostats, and the energy reflected from the mirrors is calculated according to the calculation formula and the shadow shading loss. Therefore, the heliostat and the absorber tower can be simplified into a one-dimensional space related only to height and distance [2].

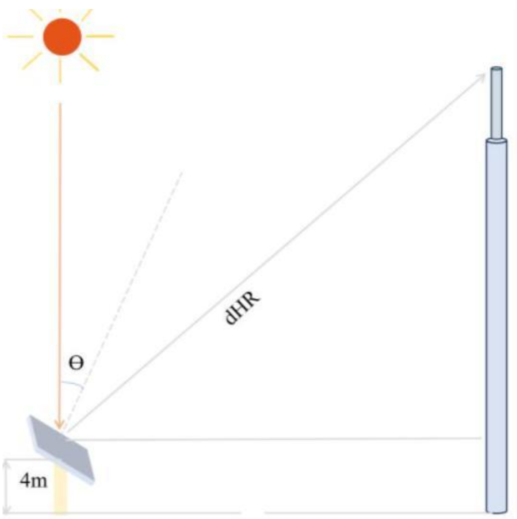

Fig. 1 Mathematical modelling of light in a heliostat field

The solar position was calculated using the geographic location (longitude 98.5◦ East, latitude 39.4◦North) and five time points on the 21st day of each month at 9:00, 10:30, 12:00, 13:30, and 15:00, and the supplied equations for solar declination δ, solar time angle ω, and solar altitude angle α_s. The solar energy received per unit of time, i.e., normal direct radiant irradiance (DNI), is calculated using altitude taking into account shadow shading efficiency, cosine efficiency, atmospheric transmittance, collector cutoff efficiency, and specular reflectance [3].

Solar altitude angle α_s

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

The solar azimuth angle γ_s is given by:

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

Where φ is the local dimension, as evidenced by north latitude; ω is the solar time angle:

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

Where ST is the local time, and the solar declination angle δ is given by the following (4):

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

Where D is the number of days counted from the equinox as day 0, e.g., if the equinox is March 21, then April 11 corresponds to $D = 11$. Normal direct radiation irradiance DNI (unit: kW/m^2) is the solar radiation energy received per unit area of the earth's plane perpendicular to the sun's rays and per unit time, which can be approximated by the following equation.

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

Where $a = 0.4237 - 0.00821(6 - H)^2$, $b = 0.5055 + 0.00595(6.5 - H)^2$, $c = 0.2711 + 0.01858(2.5 - H)^2$.

The output thermal power of the heliostat field E_{field} is:

$$E_{\text{field}} = DNI \cdot \sum_{i}^{N} A_i \eta_i \tag{6}$$

The optical efficiency η of a heliostat is defined as:

$$\begin{cases} \eta = \eta_{\text{sb}}\eta_{\cos}\eta_{\text{at}}\eta_{\text{trunc}}\eta_{\text{ref}} \\ \eta_{\text{at}} = 0.99321 - 0.0001176 d_{\text{HR}} + 1.97\times 10^{-8} \times d^2_{HR} \end{cases} \tag{7}$$

The specular reflectivity $\eta_{\text{ref}} = 0.92, d_{HR}$ indicates the distance from the center of the mirror to the center of the collector (unit: m).

2.2. Overall modeling algorithm flow

The overall algorithm flow is shown in Fig. 2.

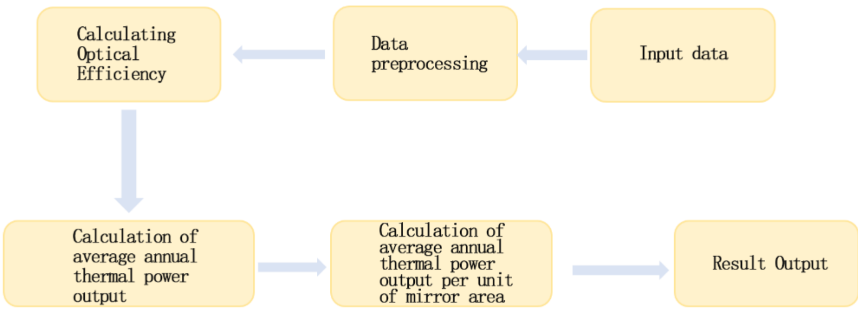

Fig. 2 Model Algorithm Flowchart

2.3. Modeling of Shadow Occlusion

To accurately assess the size of the shadows produced by each heliostat under solar irradiation and to determine whether these shadows overlap with collector towers and other shadows. Main idea:

1. Iterate over all the heliostats: each heliostat may produce shadows, so next time it is necessary to iterate over the entire data set for each heliostat.

2. determine the coordinates of the positions of the sidereal mirrors: express the exact position of each sidereal mirror on the ground in terms of x and y coordinates.

3. Calculate the distance: using the Pythagorean Theorem, calculate the straight-line distance from the center of the heliostat to the center of the collector tower based on the coordinates of the heliostat in the plane and the difference in heights of the collector towers.

$$dHR = \sqrt{x^2 + y^2 + (z_0 - z)^2} \tag{8}$$

4. Calculate shadow length and direction based on the position of the sun: use the sun's elevation angle α_s to calculate the length of the shadow. The length of the shadow is determined by the complementary angle of the sun to the horizon:

$$L = h \times \tan\left(\frac{\pi}{2} - \alpha_s\right) \tag{9}$$

Adjust the sun azimuth γ_s to get the shadow direction. The direction of the shadow is the azimuth of the sun plus 180◦, and after getting the opposite direction of the shadow direction, the modulo operation ensures that the value is between 0◦ and 360◦.

1. Calculate the coordinates of the end point of the shadow: Using the length and direction of the shadow, calculate where the shadow ends on the ground

$$shadow\_end\_y = y + L \times \sin(\gamma_{shadow}) \tag{10}$$

$$shadow\_end\_x = x + L \times \cos(\gamma_{shadow}) \tag{11}$$

2. Determine the overlap of the shadow with the collector tower: Using the coordinates of the shadow's endpoints and the width and height of the heliostat, determine if the shadow overlaps the collector tower. If there is overlap, calculate the area of the overlap and add it to the shadow loss.

3. Determine whether the shadow overlaps with other shadows: Perform a second traversal to check whether the current shadow overlaps with other heliostats. Use the coordinates of the endpoints of the shadow and the coordinates of other fixed-sun mirrors to make a geometric judgment and check whether the shadow has intersection with other fixed-sun mirrors. If there is an intersection, calculate the area of the intersecting part and add it to the shadow loss.

2.4. Model Solving and Analysis

After mathematical calculations, we obtained the data as shown in Tables 1 and 2:

Table 1. calculation result

Data	Average Optical efficiency	Average Cosine efficiency	Average Shadow Occlusion Efficiency	Average Truncation efficiency	Average output per unit area of mirror Thermal power (kW/m^2)
1.21	0.889	0.902	1.000	1.000	1.776
2.21	0.888	0.902	1.000	1.000	2.351
3.21	0.887	0.901	1.000	1.000	14.589
4.21	0.886	0.999	1.000	1.000	0.482
5.21	0.885	0.999	1.000	1.000	0.662
6.21	0.885	0.998	1.000	1.000	0.711
7.21	0.885	0.999	1.000	1.000	0.660
8.21	0.886	0.999	1.000	1.000	0.470
9.21	0.887	0.990	1.000	1.000	10.915
10.21	0.888	0.992	1.000	1.000	2.221
11.21	0.889	0.993	1.000	1.000	1.752
12.21	0.889	0.993	1.000	1.000	1.675

Table 2 Fixed-heaven mirror field output

Average annual optical efficiency	Average annual cosine efficiency	Average annual shadow masking efficiency	Average annual truncation efficiency	Average annual thermal power output (MW)	Average annual output per unit area of mirror Thermal power (kW/m^2)
0.887	0.975	1	1	200.299	3.188

3. Particle swarm optimization

3.1. Model building

Particle swarm optimization (PSO) is a stochastic optimization algorithm based on group intelligence. The algorithm is inspired by the intelligent collective behavior of some animals and improves the candidate solutions by iteratively trying a given quality metric. The core idea is to utilize the information sharing of individuals in the group, so that the movement of the whole group in the problem-solving space, resulting in the evolution process from disorder to order, thus obtaining the global optimal solution [4].

The absorber tower is placed at the center of the circular area, and the particles in the model are initialized in these rings by placing some rings composed of heliostats radially in the circular arc with radius from 100m to 350m. The distance between the radial and tangential neighboring heliostat base centers is required to be 5m more than the mirror width.

3.2. Model Solving and Analysis

Firstly, the PSO particles are initialised using only the heliostats in the smallest circle. Each particle represents a possible heliostat arrangement, and each particle is assigned two kinematic properties in the algorithm, namely position X and velocity V. The optimal solution is obtained by iteratively eliminating inferior solutions. The optimal solution is obtained by iteratively eliminating inferior solutions.

$$X_i(t)=(X_{i1}(t),...,X_{iD}(t)) \tag{12}$$

$$V_i(t)=(V_{i1}(t),...,V_{iD}(t)) \tag{13}$$

For each particle, its fitness value is calculated using the evaluate fitness function. The location of the optimal fitness value experienced by the ith particle is noted as the individual historical optimum. The height and size of the heliostat mirror D will be determined by the location of the particle. And it is guaranteed that the distance between the centers of adjacent heliostat bases is more than 5m more than the width of the mirror.

Starting the iteration, each solution during the iteration modifies the position and velocity of each particle according to (15) and (16)

$$V_i(t+1)=V_i(t)+r_1c_1[X_{ibest}(t)-X(t)]+r_2c_2[X_{genbest}(t)-X(t)] \tag{14}$$

Where i is the ith possible solution, c_1, c_2 are two constants between (0,2), and r_1, r_2 are two random numbers between (0,1). After modifying the positions and velocities for all possible solutions, the components of some possible solutions are randomly selected to be adjusted in order to jump out of the local optimum. Update the individual historical optimum X_{ibest}, for all possible solutions after the random adjustment, and update the population historical optimum $X_{genbest}$ based on the historical optimum of all possible solutions. After each PSO iteration, add a new heliostat ring to each particle swarm. This can be accomplished using the "*initialize_mirrors_on_ring*" function, and only one outer ring is added at a time. When the maximum number of iterations is reached or other termination conditions are met, the optimization is ended and the particle positions with the best fitness values are output as the design solution for the mirror field. The results are shown in Table 3 and 4

Table 3 Fixed-heaven mirror field output

Average annual optical efficiency	Average annual cosine efficiency	Average annual shadow masking efficiency	Average annual truncation efficiency	Average annual thermal power output (MW)	Average annual output per unit area of mirror Thermal power (kW/m^2)
0.977	0.987	1.000	1.000	63.637	3.512

Table 4 Design of Fixed-Day Mirror Fields

Absorption tower position coordinates	Dimensions of heliostat (width × height)	Installation height of heliostat m	Total number of mirrors	Total area of fixing mirror (m^2)
(0,0)	5×4	4	906	18120

4. Case studies

By analyzing the altitude and latitude of the heliostat field and combining the design experience of existing heliostat fields in the industry, we specify the aspect ratio of the rectangular heliostat, and the aspect ratio of the mounting height to the length of the heliostat. By substituting different combinations of dimensions into the optimization algorithm, the optimal heliostat field design is obtained, including the optimal total number of mirrors, mirror dimensions, mounting height, and mounting position and other parameters.

The design of the heliostat field scheme is based on the PSO algorithm. We redesigned the radial alignment scheme of the heliostat mirrors, i.e., after completing the alignment of a ring of heliostats, the position of the next mirror ring is determined based on the heliostat with the largest size on the ring [5].

Since the PSO algorithm is designed to optimize the adjustment of mirror positions, it is also necessary to constrain the heliostat mirrors according to the requirements of the target mirror field, including the coordinate constraints of a single heliostat and the spacing constraints of the radial heliostat rings. When solving practical problems, it is often necessary to adjust and customize the standard optimization algorithm according to specific physical constraints or other requirements. The model not only implements standard particle swarm optimization methods, but also incorporates constraints specific to the problem to ensure that a feasible solution is found.

The solution of the model is shown in Algorithm 1, which is a particle swarm optimization algorithm that aims at placing heliostats of different sizes, each corresponding to a particle, in a fixed annular region. Each particle's attributes (e.g., position and velocity) are updated during the optimization process to find the optimal layout. According to the above algorithm, we obtain the solutions as in table 5 and table 6.

Table 5 Fixed-heaven mirror field output

Average annual optical efficiency	Average annual cosine efficiency	Average annual shadow masking efficiency	Average annual truncation efficiency	Average annual thermal power output (MW)	Average annual output per unit area of mirror Thermal power (kW/m^2)
0.912	0.924	1.000	1.000	92.712	3.278

Table 6 Design of Fixed-Day Mirror Fields

Absorption tower position coordinates	Dimensions of heliostat (width × height)	Installation height of heliostat m	Total number of mirrors	Total area of fixing mirror (m^2)
(0,0)			1650	28283

5. Conclusion

Through the empirical analysis in this study, we derive an optimisation scheme for the layout of a heliostat mirror field based on the particle swarm optimisation algorithm, which can significantly improve the overall efficiency of the mirror field in the use of solar energy. By optimising the distribution of the heliostats and the location of the absorber towers, we achieved an increase in the annual average optical efficiency and annual average output thermal power of the mirror field, which provides useful insights for the design and operation of solar PV power generation systems. Future research could further consider optimisation schemes for different geographical locations and climatic conditions to achieve more efficient use of solar energy resources and to promote further development of solar PV power generation technology. The research results provide an important theoretical basis and practical value for the practical application in the field of solar photovoltaic power generation and make a positive contribution to the promotion of the sustainable use of renewable energy.

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