

Design of optimal mirror field arrangement for heliostat based on objective optimization and particle swarm algorithm

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Abstract. In the study of tower-type solar thermal power generation technology, the size design of heliostat mirrors and the mirror field arrangement are crucial to the power generation efficiency. In order to investigate the optimal heliostat parameters and mirror field arrangement, a single-objective multivariate optimisation model is established with the rated annual average output power of 60MW as the objective function, and the heliostat size requirement and the spacing of the mirrors as the constraints. Considering that there are many variables affecting the objective function, particle swarm optimisation algorithm is used to solve the model, and then the reasonableness of the model is verified by combining the heat map of cosine efficiency distribution and the change rule of solar altitude angle. The results show that under the condition of the same size and installation height of the heliostat, the optimal width of the heliostat is 5.7m, the height is 3.5m, the total number is 1432, and the coordinates of the absorber tower is (16.9,13.3).

Keywords: Mirror field alignment, optical efficiency, cosine loss, ergodic search, particle swarm optimisation algorithm.

1. Introduction

Solar thermal power generation technology is a kind of high-temperature utilization of photothermal resources. Compared with photovoltaic power generation, solar thermal power generation technology is more energy-efficient and environmentally friendly, with photovoltaic power conversion in a physical way and low environmental impact. According to the different ways of heat collection, solar thermal power generation technology can be divided into Fresnel type, butterfly type, trough type and tower type [1-2]. Among them, tower-type power station collects heat with high efficiency, high thermal conversion efficiency, large cost reduction space, suitable for large-scale application and other advantages and become the main direction of application [3].

Tower solar thermal power generation technology using fixed sun mirror field collection of sunlight, and reflection convergence to the top of the absorber tower collector, through the light and heat conversion to achieve thermal power generation [4], can be continuous and stable output of electricity, has a better scale cost advantage, so by the countries more and more attention and attention, is the future of new energy in one of the most considerable directions of development. In a tower solar thermal power system, a heliostat is used as a solar focuser. The mirror reflects and focuses the sun's rays onto a collector, which heats up the mass (usually water or oil) and converts it into steam, which then drives a turbine to generate electricity. Thus, the role of the heliostat is to focus the solar energy efficiently onto a central receiver, thus providing sufficient thermal energy to generate electricity [5-6].

Heliostats play a key role in tower solar thermal technology by improving the efficiency of light energy utilisation and increasing the system's generating capacity. By precisely adjusting and controlling the position and angle of the heliostat, the optimal solar focusing effect can be achieved, thus increasing the power generation efficiency and capacity. Therefore, the design and layout of heliostats are critical to the operation and performance of tower solar thermal power systems. In this paper, assuming that all heliostats have the same dimensions and mounting height [7], the following parameters of the mirror field are designed: the positional coordinates of the absorber tower, the dimensions of the heliostats, the mounting height, as well as the number and position of the heliostats,

so that the mirror field achieves the largest possible annual average thermal power output per unit mirror area under the condition of a rated power of 60 MW [8-9].

Therefore, this paper takes the average output power per unit area of heliostat as the objective function, and the output power is greater than 60MW as the constraints, and then the constraints are derived according to the size requirements of the placement area of the heliostat mirror field, the requirements of the spacing of the heliostat mirrors, and the expressions of the optical efficiency of the heliostat mirrors and the output power to set up a single-objective optimisation model, considering that there are too many factors affecting the output power of the heliostat mirrors per unit area and that it is necessary to optimally solve the optimisation model. The single-objective optimisation model is established. Therefore, the particle swarm optimisation algorithm is used to solve this single-objective optimisation model [10].

2. Optimisation model building and solving

2.1. Model building

Under the condition that the annual average output power of the heliostat is greater than the rated output power $60MW$, the annual average output thermal power of the heliostat per unit mirror area should be as large as possible, so the annual average output thermal power per unit area should be taken as the objective function, and the optimisation model should be set up with the constraints of the installation distance of the heliostat and its boundaries, the requirements of the mirror surface dimensions, and the efficiency and the output power, and the particle swarm optimisation algorithm should be used for the solving of the model.

2.1.1. Determination of the optimisation model

The average annual thermal power output per unit area is taken as the objective function:

$$\max(E_s) \quad (1)$$

Where, E_s is the average thermal power output per unit area.

The expression for the average output thermal power per unit area is

$$E_s = \frac{E_{field}}{Nd_a d_h} \quad (2)$$

Where N is the number of fixed-sun mirrors, d_a is the mirror width, d_h is the mirror height, for the shadow shading efficiency model, using the traversal search solution, first solve the absorption tower and collector Total shadow length, determine whether the shadow length at each moment falls into the circular area of the fixed-sun mirror placement, if the shadow length is less than 100 m, the fixed-sun mirror will not be absorber tower shadow shading; otherwise, it is considered that there is a shadow shading, and the shading loss is approximated as the ratio of the shadow area to the area of the circular placement area. The mutual shading between the heliostats is then solved to determine whether the reflected light will be shaded by the neighbouring heliostats, and the approximation of such a shadow shading loss is derived. Finally, the shadow shading efficiency is calculated by superimposing the two shadow losses.

Similarly, the optical efficiency of heliostats is processed using an ergodic search, resulting in the cosine efficiency as a two-dimensional matrix, with the rows of the matrix representing the different states of heliostats at the same moment, and the columns of the matrix representing the different states of the same heliostat at 60 moments. According to the relationship between radiant irradiance and output thermal power is further solved, in solving the output thermal power of the heliostat mirror,

taking into account the angle of the heliostat mirrors in different positions and the distance from the neighbouring mirrors are unequal, in order to facilitate the calculation, it is considered that the product obtained by multiplying the shadowing efficiency by the area of the heliostat mirrors is approximated to be equal to the effective light-gathering area of the mirrors, and the output power of heliostat mirrors is calculated by using this approximation of the area E_{field} .

2.1.2. Constraints on the placement of heliostats

Remember that the mirror centre coordinates are $O_n(x_n, y_n, z_n)$, the fixed-sun mirror must be placed in the circular region, and the mirror width and mirror height should meet the requirements, the collector centre coordinates are $H(x_1, y_1, h)$ and the mirror centre coordinates should satisfy the:

$$100^2 \leq x_n^2 + y_n^2 \leq 350^2 \tag{3}$$

The width of the mirror is usually not less than the height of the mirror and there is a distance requirement to be met from the centre of adjacent mirrors:

$$2 \leq d_h \leq d_a \leq 8 \tag{4}$$

$$\sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2} \geq d_a + 5 \tag{5}$$

In order to ensure that the mirror does not touch the floor when rotating, the mounting height z_n needs to meet the:

$$2 \leq z_n \leq 6 \tag{6}$$

$$\frac{d_h}{2} \leq z_n \tag{7}$$

2.1.3. Rated power constraints

The average annual output power is greater than $60MW$, so it is necessary to solve for the average annual output thermal power of the fixed-sun mirror:

$$E_p = \frac{\sum_{i=1}^{60} \left(DNI_i \sum_{n=0}^N A_n \eta_n \right)}{60} \tag{8}$$

Combining the models and formulas for solving each of the efficiencies, the optimisation model is derived as:

$$\max(E_s) \tag{9}$$

$$\left. \begin{aligned}
 &100^2 \leq x_n^2 + y_n^2 \leq 350^2 \\
 &\sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2} \geq d_a + 5 \\
 &2 \leq d_h \leq d_a \leq 8 \\
 &2 \leq z_n \leq 6 \\
 &\frac{d_h}{2} \leq z_n \\
 &E_p = \frac{\sum_{i=1}^{60} \left(DNI_i \sum_{n=0}^N A_n \eta_n \right)}{60} \geq 60MW \\
 &E_s = \frac{E_{field}}{Nd_a d_h} \\
 &\cos 2\theta_n = \frac{(x_1 - x_n) \cos \alpha_s \sin \gamma_s + (y_1 - y_n) \cos \alpha_s \cos \gamma_s + (h - z_n) \sin \alpha_s}{(x_1 - x_n)^2 + (y_1 - y_n)^2 + (h - z_n)^2} \\
 &\eta_{\cos} = \sqrt{\frac{1 + \cos 2\theta_n}{2}} \\
 &\eta_{at} = 0.99321 - 0.0001176d_{HR} + 1.97 \times 10^{-8} \times d_{HR}^2 \\
 &d_{HR} = \sqrt{(x_1 - x_n)^2 + (y_1 - y_n)^2 + (h - z_n)^2}
 \end{aligned} \right\} s.t.$$

2.2. Model solution

In order to solve the optimisation model developed above, the particle swarm optimisation algorithm is used considering the large number of variables affecting the power output per unit area. In the particle swarm optimisation algorithm, each problem solution is considered as a bird, called a "particle", which searches in a multi-dimensional space. Each particle evaluates the goodness of the current position based on a fitness function (i.e., an objective function). Each particle has a memory function that remembers the optimal position it has searched. In addition, each particle has a velocity, which is used to determine the distance and direction of its flight. The velocity of the particle is dynamically adjusted according to its own experience and the experience of its companions.

2.2.1. Principles of Particle Swarm Algorithm

Suppose that there is an n-dimensional space and that there are m particles that form a cluster of particles. Each particle is described by an n-dimensional vector describing its position in the solution space, and the position of the *i* particle in the solution space is denoted as X_i . That is, the position vector of each particle represents the solution of the optimisation model. Substituting the position vectors into the objective function, the fitness value of each particle can be calculated, and the magnitude of the fitness value is used to measure its merit. The optimal position that each individual passes through is denoted as p_{best} , so the optimal position of the particle is denoted as g_{best} , and the velocity of the particle is denoted as V_i , and the process of the particle swarm can be described as:

$$\begin{cases}
 V_{ij}(t+1) = V_{ij}(t) + c_1 r_1(t) [P_{ij}(t) - x_{ij}(t)] + c_2 r_2(t) [p_{ij}(t) - x_{ij}(t)] \\
 X_{ij}(t+1) = x_{ij}(t) + V_{ij}(t+1)
 \end{cases} \tag{10}$$

Where *i* denotes the first *i* particle, *j* denotes the first *j* dimension, *t* denotes the number of iterations, and c_1 and c_2 are the acceleration factors.

According to this evolutionary equation, the velocity of the particle is adjusted according to its own inertia, the optimal position of the individual, and the optimal position of the group, thus updating the position vector of the particle.

2.2.2. Particle swarm calculation step

(1) Random initialization of particle swarms: set the number of particle swarms to 50 and the number of iterations to 150 times. Evenly distributed within the constraints, randomly generate the initial position and velocity of each particle.

(2) Calculate fitness: For each particle, calculate the area corresponding to its position as its fitness value.

(3) Update individual and global optimal solution: compare the fitness value of each particle with the fitness of its individual historical optimal solution, and update the individual optimal solution if the current fitness is good. At the same time, the fitness of each particle is compared with the fitness of the global optimal solution, and if the current fitness is good, the global optimal solution is updated.

(4) Update the inertia weight, velocity and position of particles: Update the inertia weight, velocity and position of each particle according to a preset formula. The inertial weights control the exploration and utilization ability of particles in the search space, and the update of speed and position is guided by the individual historical optimal solution and the global optimal solution.

(5) Determine the termination condition: check whether the current number of iterations reaches the preset number of iterations. If achieved, the algorithm is ended and the global optimal solution is output. Otherwise, continue iterating and return to step 3.

Through the above steps, the particle swarm optimization algorithm continuously updates the velocity and position of particles to find the optimal solution. In the iterative process, the particles gradually optimize the fitness value through the guidance of the individual optimal solution and the global optimal solution, and finally find the optimal solution. Finally, the optimal parameters of the heliostat and absorption tower were obtained by MATLAB solution, as shown in Table 1.

Table 1. Design parameter table

Absorption tower location coordinates	Heliostat size (width and height)	Heliostat mounting height (m)	Total number of faces of the heliostat	Total heliostat area (m ²)
(16.9,13.3)	5.7、3.5	5.7	1432	28568.4

Due to the length of this article, some mirror center coordinate values and some heliostat parameters are given, see Table 2.

Table 2. Some heliostat coordinates and parameter results

Heliostat serial number	Heliostat width (m)	Heliostat height (m)	Heliostat x coordinate (m)	Heliostat y coordinates (m)	Heliostat z-coordinates (m)
1	5.7	3.5	105.728	11.558	5.7
2	5.7	3.5	105.762	22.947	5.7
3	5.7	3.5	103.06	34.564	5.7
4	5.7	3.5	96.102	45.247	5.7
5	5.7	3.5	92.954	56.101	5.7
6	5.7	3.5	87.012	65.121	5.7
7	5.7	3.5	78.931	73.250	5.7
8	5.7	3.5	69.806	83.602	5.7
9	5.7	3.5	61.255	88.591	5.7
10	5.7	3.5	50.242	93.600	5.7
11	5.7	3.5	40.365	102.004	5.7
12	5.7	3.5	29.121	104.974	5.7
...

The optimal mirror field layout is plotted by the solved coordinates, as shown in Figure 1.

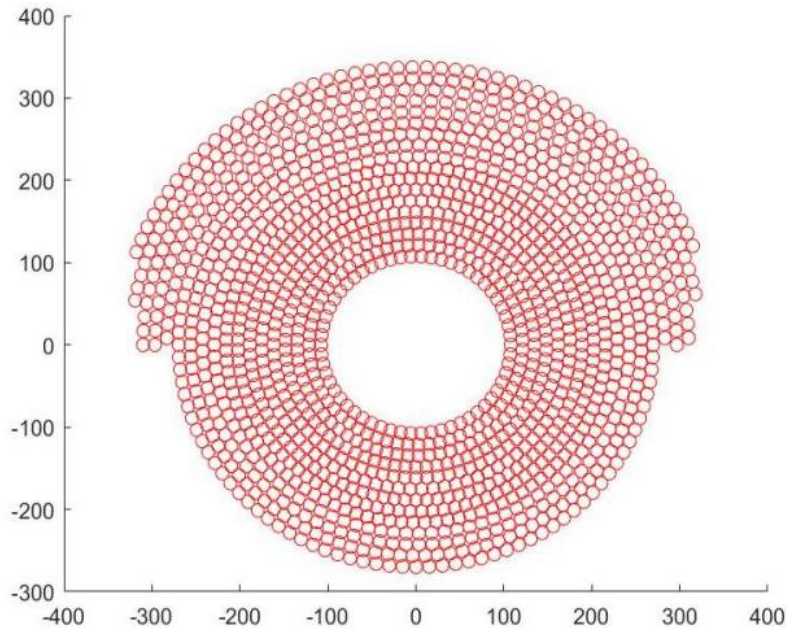


Figure 1. Mirror field arrangement under the same installation height and size

It is found that when optimizing the arrangement of heliostats in the mirror field, a part of the mirrors with lower optical efficiency is removed, and more heliostats are placed in the part with higher optical efficiency under a reasonable mirror size to improve the optical efficiency and output power per unit area of the mirror field.

3. Conclusion

To optimize the design of the heliostat mirror field, this paper establishes a single-objective multivariate optimization model of the mirror field coordinate system and heliostat mirror field through the use of geography-related background knowledge. The model takes into account various factors such as the position of the tower, the latitude and longitude of the site, and the angle of the sun at different times of the day and year.

The particle swarm optimization algorithm is used to carry out an optimization design study on the specific parameters of heliostat mirrors and the way of mirror field arrangement in different conditions. This algorithm is a popular optimization technique that is inspired by the social behavior of birds flocking or fish schooling. It involves a population of candidate solutions, known as particles, that move through the search space and adjust their position based on their own experience and the experience of their neighbors.

The results of the optimization study show that the size of the heliostat mirrors and the mirror field arrangement have a significant impact on the power generation efficiency of the tower solar thermal power generation system. The optimal design parameters vary depending on the specific conditions of the site, such as the latitude and longitude, the position of the tower, and the angle of the sun at different times of the day and year.

In conclusion, the design of the heliostat mirror size and the mirror field arrangement are crucial in influencing the power generation efficiency of tower solar thermal power generation technology. The use of a single-objective multivariate optimization model and the particle swarm optimization algorithm can help to identify the optimal design parameters for different site conditions. This research can contribute to the development of more efficient and cost-effective tower solar thermal power generation systems, which can play a significant role in meeting the growing demand for renewable energy.

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