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Research on Heliostat Field Based on Multi-objective Optimization Intelligent Algorithm

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Abstract: By employing the discretization principle, ray tracing method, and coordinate system transformation technique, this paper has made significant advancements in optimizing heliostat field parameters. Through a comprehensive examination of the optical efficiency of the heliostat and utilizing genetic algorithm, systematic optimization of the heliostat field parameters is conducted to seek out the optimal solution. Firstly, it is essential to clarify the optimization criteria, which include the position coordinates of the absorption tower, size of the heliostat, installation height, number of heliostats, and their respective positions. To address multiple constraints effectively, an objective function is formulated based on the annual average thermal power output per unit mirror area. The position coordinates of absorbers are considered separately by calculating thermal power output for both (0,0) and non-(0,0) coordinates to determine optimal conditions through comparison. After that, using genetic algorithm and MATLAB software package enables obtaining optimized parameters for the heliostat field. In this optimal scenario, the absorption tower's position coordinate is (0, 0), each heliostat measures 8m*8m with an installation height of 4; there are a total of 2172 heliostats covering a combined area measuring 139008 m2. The innovation in this research methodology lies in its comprehensive utilization of the discretization principle while accurately analyzing optical properties through the ray tracing method. Additionally, the complex structure within the heliostat field is aptly described through clever coordinate system transformations. Finally, the combination that optimizes parameters for heliostat fields is effectively searched using genetic algorithms. This provides robust theoretical support for designing light energy utilization systems.

1. Introduction

In recent years, the problem of traditional energy shortage and environmental degradation has become increasingly prominent around the world. In order to deal with the energy crisis and improve the ecological environment, China has put forward a double carbon target, namely "carbon neutrality" and "carbon peak". In this context, the use of tower solar thermal power generation has become an important measure to achieve this ambitious goal. At the same time, the heliostat field as the energy input unit of the whole system, its comprehensive efficiency directly determines the highest performance level of the power generation system. The construction cost of the heliostat field accounts for 40% to 50% of the total investment in the power plant, and about 30% to 40% of the energy loss occurs in the heliostat field. Therefore, the heliostat field has become the main focus of the tower photothermal power station to achieve "cost reduction and efficiency improvement". By improving the efficiency of the heliostat field and reducing energy losses, the economic feasibility of the entire CSP plant can be significantly improved, promoting a more sustainable and efficient role of the plant in energy production.[1] At present, researchers have conducted a large number of studies on the condenser field. Nevertheless, there are still some problems. First, in the research, the mathematical model and optimized layout parameters are not elaborated enough, and the research is more focused on describing the performance improvement of the lens field after optimization. Secondly, when evaluating the mirror field performance, the optical efficiency is usually regarded as an important measure. However, for the shadow occlusion efficiency of optical efficiency, due to the complex calculation process, many studies do not provide specific calculation details.[2] Based on the above problems, this paper needs to consider the position coordinates of the absorption tower, the size of the heliostat, the installation height, the number of the heliostat, and the position of the heliostat, and combine the multi-objective optimization intelligent algorithm to optimize the key variables in the mirror field layout. The main research directions are as follows:

It is required to determine the various parameters of the heliostat field under the condition of meeting the design requirements, so as to maximize the annual average output thermal power of the heliostat field per unit mirror area. The calculation of optical efficiency includes shadow occlusion efficiency, cosine efficiency, atmospheric transmittance and collector truncation efficiency. Therefore, it is necessary to find the constraints in the problem and formulate an objective function about the annual average thermal power output per unit mirror area. Among them, the position coordinates of the absorption tower in the heliostat field optimization parameters should be optimized, which can be selected by comparison. Take the position coordinate of the absorber as (0,0), and arbitrarily take any point in the southeast and northwest direction as the position coordinate of the absorber, calculate the value of the average output heat power under different coordinate positions of the absorber, and compare it to solve the optimal coordinate of the absorber as (0,0). Finally, the genetic algorithm is used to optimize the model. (Original data source)

2. Heliostat field research related principles

2.1 Establishment of heliostat field coordinate system

In the coordinate system with the center of the circular area as the origin, the due east direction is defined as the X-axis forward direction, the due north direction is the Y-axis forward direction, and the direction perpendicular to the ground is the z-axis forward direction. The mirror field coordinate system is established. As shown in Fig 1:

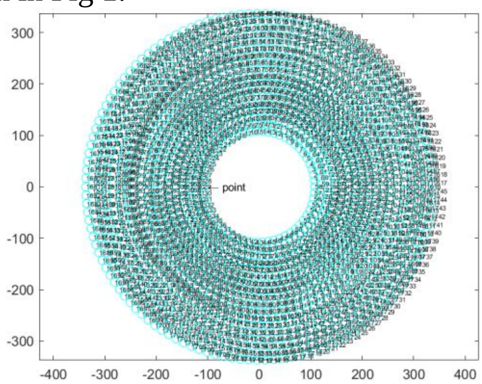

Figure 1: Heliostat position map in the heliostat field

2.2 Relevant formulas for heliostat field calculation

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

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

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

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

Where α_s is the solar elevation Angle,γ_s is the solar azimuth Angle,φ is the local latitude (positive north latitude),ω is the solar hour Angle,ST is the local time,δ is the solar declination Angle, and D is the number of days from the vernal equinox[3].

The normal direct radiation irradiance DNI(unit: kW/m^2)refers to the received solar radiation energy per unit time in a unit area of the plane perpendicular to the sun on the Earth, which can be approximately calculated according to the following formula[4] :

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

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

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

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

Among them,G_0 is 1.366kW/m^2,H is 3000m, and the maximum DNI value was obtained at 12 o 'clock.

The formula for calculating the optical efficiency of the heliostat is as follows [5]:

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

Where,η is the optical efficiency,η_{sb} is the shadow occlusion efficiency,η_{cos} is the cosine efficiency,η_{at} is the atmospheric transmittance,η_{trunc} is the truncation efficiency,and η_{ref} is the specular reflectance (desirable constant 0.92).

Formula for shadow occlusion efficiency:

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

The heliostat cosine efficiency is expressed as [7]:

$$\eta_{\mathrm{cos}} = \cos\theta_i = \cos\left[\arccos\left(\vec{S} * \vec{R}\right)/2\right] \tag{11}$$

where $\vec{S}$ is the solar ray incident direction vector,and $\vec{R}$ is the reflected direction vector.

Formula of atmospheric projection rate [7]:

$$\eta_{\mathrm{at}} = 0.99321 - 0.0001176 d_{\mathrm{HR}} + 1.97 * 10^{-8} * \mathrm{d}_{\mathrm{HR}}^2 (d_{\mathrm{HR}} \le 100 \tag{12}$$

$$\mathrm{d}_{\mathrm{HR}} = \sqrt{\left(x_1 - x_2\right)^2 + \left(y_1 - y_2\right)^2 + \left(z_1 - z_2\right)^2} \tag{13}$$

Where,(x_1, y_1, z_1) is the heliostat coordinate,and (x_2, y_2, z_2) is the coordinate of the collector midpoint.

The output thermal power formula of the heliostat field [8]:

$$E_{field} = DNI\sum_{i}^{N} A_i \eta_i \tag{14}$$

Where, DNI is the normal direct radiation irradiance, A_i is the daylighting area of the ith heliostat, and η_i is the optical efficiency of the ith heliostat.

Formula of output thermal power per unit mirror area E_{avg} [9]:

$$E_{avg} = \frac{E_{field}}{N * S_N} \tag{15}$$

Where, N is the total number of heliostats. S_N is the area of unit heliostat.

2.3 Model establishment based on genetic algorithm

(1)Objective function: annual average output power per unit mirror area E_{avg}

$$E_{avg} = \frac{E_{field}}{N * S_N} = \frac{DNI\sum_{i}^{N} A_i \eta_i}{N * S_N} \tag{16}$$

(2) Constraints: the mirror (x_1) is not less than the mirror height (x_2), the mirror side length is between 2 m and 8 m, the installation height (x_3) is between 2 m and 6 m, and the installation height ensures that the mirror will not touch the ground when rotating around the horizontal axis; The distance between the center of the base of the two adjacent heliostats is more than 5m larger than the width of the mirror. Let d be the distance between the center of the base of the adjacent heliostats, and set the heliostats coordinate as (m_i, n_i), $i = 1, 2, 3, \cdots, n$.

That is:

$$\text{s.t.}\begin{cases} x_1 \geq x_2 \\ 2 \leq x_1 \leq 8 \\ 2 \leq x_2 \leq 8 \\ 2 \leq x_3 \leq 6 \\ x_3 \geq \dfrac{x_2}{2} \\ x_0 \leq 350 \\ y_0 \leq 350 \\ d - x_1 \geq 5 \\ d = \sqrt{(m_i - m_{i+1})^2 + (n_i - n_{i+1})^2} \end{cases} \tag{17}$$

2.4 Genetic algorithm model solution

Firstly, assuming that point (0,0) is the location of the absorption tower, the annual average output thermal power of the heliostat field is calculated, as shown in Fig 2:

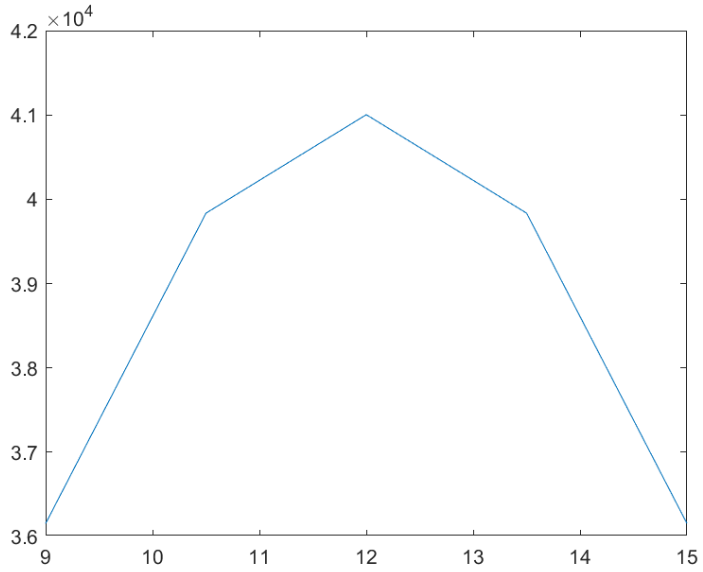

Figure 2: The output heat power diagram of the intermediate point of the origin

Then take a special case, choose a point from the four directions of the southeast and northwest as the position coordinates of the absorption tower. In this paper, take the south direction as an example, move the position of the absorption tower to the south by 4m, and calculate the annual average output heat power of the heliostat field, as shown in Fig 3:

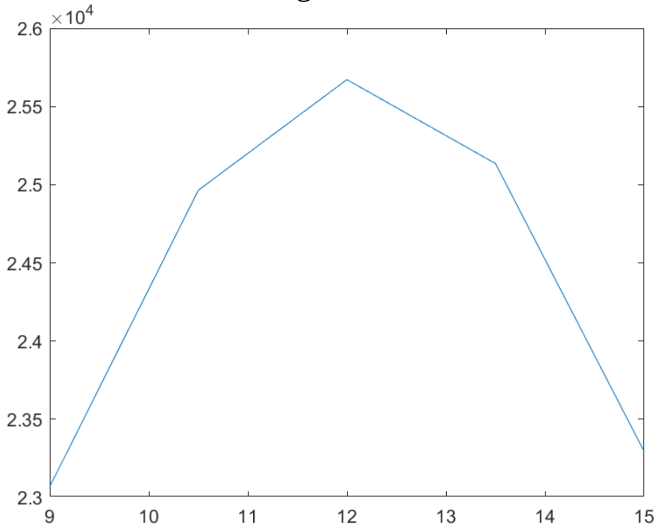

Figure 3: The output heat power diagram of each time point moving 4m south

Similarly, the output thermal power of the absorber in other directions can also be calculated; According to the comparison, when the absorber is located at (0,0), the output thermal power is larger. Therefore, in this paper, the position of the absorber is located at (0,0) as the optimal point.

2.5 Basic principle of genetic algorithm

The basic idea of genetic algorithm is to simulate the evolution process in nature, encode individuals in the solution space through "genes", and then use selection, crossover (cross-pairing), mutation and other genetic operations to produce new individuals, and finally find an excellent solution to the problem. These basic operations simulate the genetic mechanism in nature, in which the better individuals are more likely to be selected for reproduction, in order to gradually improve the individuals in the population through evolution, and find the optimal solution or better solution of the problem.

2.6 Analysis of experimental results

In this paper, GA genetic algorithm [10] is used to solve the problem, and the iteration number is set to 100 to obtain the iteration graph, as shown in Fig. 4 and Table 1. The flattening of the image indicates that the iteration number of 100 is appropriate.

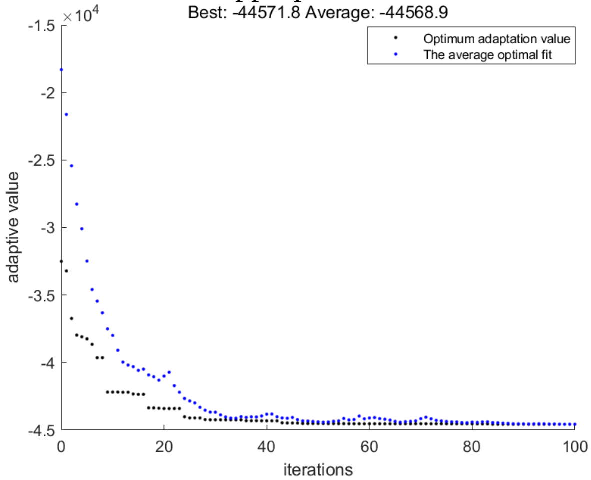

Figure 4: Iteration diagram of genetic algorithm

Table 1: Various parameters of the heliostat field after optimization

Absorber position coordinates	Heliostat dimensions	Height of heliostat installation	Total number of heliostats	Total area of heliostat
0,0	8*8	4	2172	139008

3. Conclusion

As a whole, the model conforms to the ideal state, considering multiple constraints and multiple constraint variables, and better describes the performance of the system. While establishing the model analysis problem, the problem is also simplified to ensure that the size of each heliostat is the same. The mirror of the heliostat is discretized to facilitate the analysis and solution. The genetic algorithm is used to solve the multi-objective optimization problem, which is solved by a large number of operations and iterations of intelligent algorithms, and the powerful data processing and prediction capabilities of MATLAB are fully utilized. The innovation of this research method is reflected in the comprehensive use of the discretization principle and the accurate analysis of the optical performance of the heliostat through the ray tracing model. At the same time, the complex structure of the heliostat field is more accurately described by the exquisite coordinate system transformation. The experimental results show that the optimal combination of the heliostat field parameters is found by the effective search of the genetic algorithm, which provides a solid theoretical support for the optimal design of the light energy utilization system.

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