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Study on the Optimal Design of Fixed-Sun Mirror Field Based on Variable Step Size Traversal Methods

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Abstract: *China has always made renewable energy an important part of its national energy strategy. In the flood of the times, China has carried out active research and development and innovation in tower power plant and fixed-sun mirror field technology, and has a complete solar energy industry chain. In this paper, a multivariate single-objective optimization model is established by using the geometric projection algorithm, the control variable method, and the variable step size traversal method, etc. The annual average optical efficiency parameter value and the annual average output thermal power in the known data heliostat mirror field are computed and extended to the unit area, which solves the problems of parameter design and mirror field layout setting under the condition that the variables are fixed in the known area heliostat mirror field.*

Keywords: *Step-Size Traversal Method, Heliostat Field, Control Variable Method, Nonlinear Programming*

1. Introduction

The heliostat is the basic component for collecting solar energy in tower solar thermal power station (hereinafter referred to as tower power station), and its base consists of a longitudinal rotating axis and a horizontal rotating axis, and the plane reflector is mounted on the horizontal rotating axis. The axis of the longitudinal axis is perpendicular to the ground, which can control the azimuth angle of the mirrors. The axis of the horizontal rotary axis is parallel to the ground, which controls the pitch angle of the reflector, the heliostat and the base. The intersection of the two rotating axes (also the center of the fixing mirror) from the ground is called the height of the installation of the fixing mirror. Tower power stations utilize a large number of heliostats to form an array called a heliostat field [1-4].

The sunlight in the reflection process of heliostat field is not a parallel ray, but a bunch of conical rays with a certain cone angle, so the reflected ray of the sun's incident ray through any point of the heliostat is also a bunch of conical rays.

2. Modeling and solving the annual average optical efficiency and output power of a heliostat mirror field

2.1 Modeling of solar cones

The beam of light directed from the Sun to the surface of the Earth is not parallel, but a cone of light with a cone angle of 32°, known as the solar tensor angle. According to the law of reflection of light, the cone of light, after being reflected by a heliostat, will be focused on the surface of the heat absorber into another conical beam with a certain divergence. The half-angle spread of a cone of light emitted from the Sun to the Earth is typically 4.65 mrad. A number of rays are uniformly traced within the solar divergence angle to be used as the incident beam. The uniform tracing is done by dividing the steps in the direction of the half-angle spread by a uniform angle, and similarly in the circumferential direction by a uniform angle. Similarly, the reflection process divides the step length of the reflected beam by a uniform angle. Therefore, the right-handed right-angle coordinate system is used as the basis to establish the coordinate system for the reflection of the light cone through the heliostat as shown in Figure 1.

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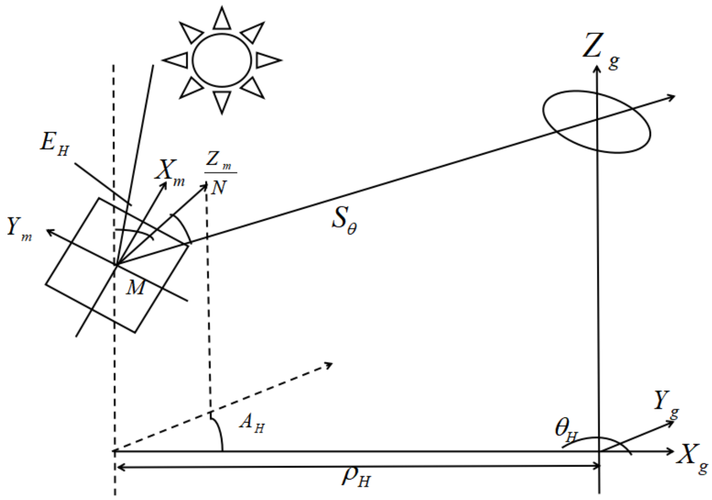


Figure 1: Light cone via heliostat reflection coordinate system

Suppose a ray in a cone of light from the sun makes an angle of θ with the main ray, τ with the x-axis. Then there is:

$$\vec{S} = \left(\sin\theta\cos\tau, \sin\theta\sin\tau, \cos\tau\right) \tag{1}$$

Since a cone of light is made up of an infinite number of rays, to analyze the cone of light, it is necessary to traverse all the rays of the entire cone.

2.2 Principle of calculating average optical efficiency by monthly averaging method

Optical efficiency can be expressed by the product of shadow shading efficiency, cosine efficiency, atmospheric transmittance, collector cutoff efficiency, and specular reflectance, i.e:

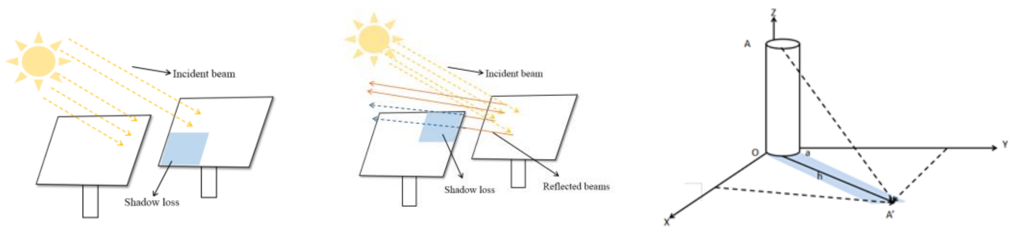
$$\eta = \eta_{sb}\eta_{\cos}\eta_{at}\eta_{trunc}\eta_{ref} \tag{2}$$

Solving for optical efficiency requires calculations for each of these parameters:

(1) Efficiency of shadow masking:

In a mirror field, the angle of the sun as well as the arranging pattern of the heliostats, etc., will produce a certain amount of shadow masking on the incident beam or reflected beam. Therefore, first of all, one heliostat A is arbitrarily selected as the subject, and the other heliostat B is selected as an example from the range that may have an effect on heliostat A. The shadow occlusion calculation can be categorized into the following three cases, as shown in Figure 2.

For the above three cases, the applicable solution is the plane projection method. The vertex coordinates are projected along the direction of the incident beam to the heliostat B. The coordinates obtained after projection are transformed using the Euclidean coordinate method, with the center of the heliostat B as the far point, the long side parallel to the x-axis, the short side parallel to the y-axis, and the z-axis parallel to the normal direction.



(a) (b) (c)

Figure 2: Schematic illustration of the different shadows of the heliostat (a. heliostat A receiving the solar beam is blocked by heliostat B; b. heliostat A is blocked by heliostat B while reflecting the beam outward; c. effects from the absorber tower and integrator)

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Then the shadow shading efficiency of each heliostat is satisfied:

$$\eta_{sb} = 1 - \sum \eta_{si} - \sum \eta_{bk} \tag{3}$$

where η_{si} is the shadow loss from each heliostat, and η_{bk} is the occlusion loss from the kth heliostat.

(2) Cosine efficiency:

If the angle of incidence of the solar beam is known to be, then the cosine efficiency is satisfied:

$$\eta_{\cos} = \cos\theta = \vec{i} \cdot \overrightarrow{S_n} \tag{4}$$

where $\vec{i}$ is the unit vector in the opposite direction of the incident beam, determined by the solar altitude angle and solar azimuth angle.

(3) Atmospheric transmittance:

Based on the definition given in the data survey, the atmospheric transmittance is calculated as follows:

$$\eta_{at} = 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} \times d_{HR}^2 \tag{5}$$

(4) Collector cut-off efficiency:

The truncation efficiency is part of the solar radiation energy reflected from the sun-setting mirror because it does not reach the surface of the heat absorber, and the loss of energy, the part of the heat is deducted, the heat absorber actually received by the solar energy efficiency of the solar radiation. The number of effective points as the collector to absorb light and heat capacity of the judgment criteria, let the number of effective intersection points be num, then the collector truncation efficiency η_{trunc} meets:

$$\eta_{trunc} = \frac{num}{n_{all} - (n_A + n_C)} \tag{6}$$

(5) Specular reflectance:

The specular reflectance η_{ref} can usually be obtained as a constant, and in this case the specular reflectance is taken as a constant of 0.92.

$$\bar{\eta} = \frac{\sum_{month=1}^{12} \int_{t_1}^{t_2} I_b \eta^{(t)} dt}{\sum_{month=1}^{12} \int_{t_1}^{t_2} I_b dt} \tag{7}$$

Where t_1, t_2 is the time when the mirror field starts working and stops working, $month$ is the date month involved. Guidelines for the calculation of direct solar radiation provide that direct solar radiation is numerically equal to normal direct radiation, i.e., there is $|I_b| = |DNI|$, η which represents the instantaneous optical efficiency of the mirror field.

2.3 Principle of calculation of average annual thermal power output

Calculating the annual average output thermal power with a target of 365 days in a year, also using the monthly averaging method for the operation, the output thermal power of the fixed-day mirror field can be calculated as:

$$E_{field} = DNI \cdot \sum_{i}^{N} A_i \eta_i \tag{8}$$

The three parameters are irradiance of direct normal radiation, daylight area of heliostat and optical efficiency of heliostat.

According to the given coordinate data, the number of heliostats in the whole heliostats field can be determined, and the daylighting area A_t of all heliostats can be calculated according to the specification parameters of each heliostat. The average annual output thermal power per unit mirror area can be obtained by comparing the obtained average annual output thermal power with the known heliostat area.

2.4 Model solving

For the distribution of the initial heliostatic field as shown in Figure 3, according to the process of model building, the optical efficiency of each moment was calculated by shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency and mirror reflectivity, and the daily optical efficiency was obtained by adding them together.

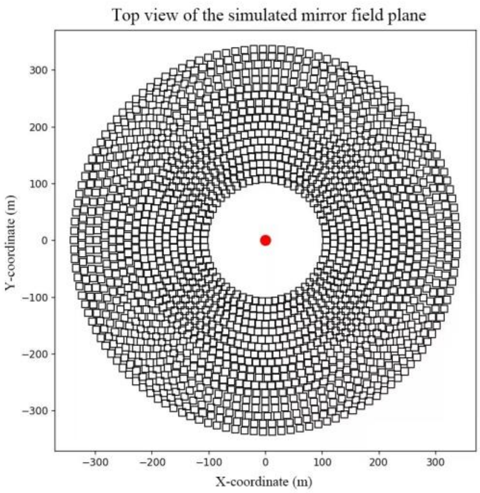

Figure 3: Initial layout of heliostat field

Since the atmospheric perspective is not closely related to the date, it is believed that the atmospheric perspective on the 21st day of each month is equal, and there is a certain deviation in the atmospheric transmittance of heliofixed lenses at different directions at each moment. The specific correlation degree and the obtained DNI of direct normal radiation are shown in Figure 4.

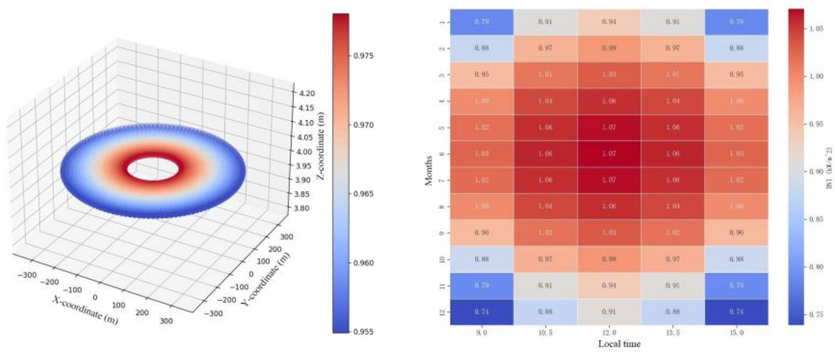

Figure 4: The correlation between atmospheric transmittance and heliostat and normal direct radiation irradiance

The data of average output thermal power per unit mirror area of the heliostat field can be obtained by synthesizing the above parameters, as shown in Table 1 below.

Table 1: Annual average optical efficiency and output power meter

Average annual optical efficiency	Annual mean cosine efficiency	Average annual shading efficiency	Average annual truncation efficiency	Average annual thermal power output (MW)	Average annual thermal output per unit area (kW/m²)
0.55622261	0.7566482	0.91484868	0.904389858	31.15052682	0.943663646

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3. Solution and optimization of heliostat field design model based on variable step size traversal method

3.1 Optimal parameter selection of each index based on variable step size traversal method

When the heliostat surface is perpendicular to the solar incident beam, the goal of reflecting more solar radiation to the collector can be achieved, so that the energy can be maximized. But in fact, the sunlight cone and the heliostat surface must form a non-vertical Angle. In the energy conversion process, the mirror will be inclined to the incident beam, so the cosine loss is inevitable. In view of the above content, the heliostat field design should tend to arrange the heliostat in the area with high cosine efficiency. The cosine efficiency distribution of heliostat field is shown in Figure 5 below, where red represents the part with high cosine efficiency and blue represents the part with low cosine efficiency [5, 6].

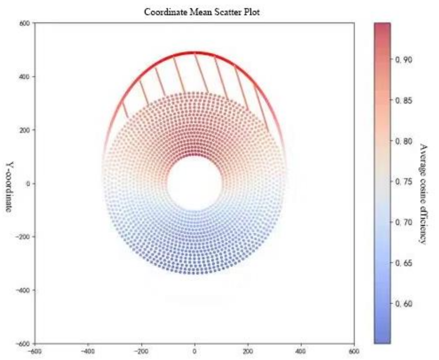

Figure 5: Cosine efficiency and extension region distribution of heliostat field

Combined with the distribution of cosine efficiency, the optimal solution can be obtained faster by increasing the number of helioscopes with the red region as the extension direction on the diameter of the centralized circular region.

The optimal parameter screening and exploration process of each index based on variable step size traversal is shown in Figure 6.

(1) The coordinate position of the absorption tower is determined

According to the preset heliostat field layout, the absorption tower is placed at a certain position on the diameter of the network spectrum, and the average output thermal power per unit heliostat mirror is calculated.

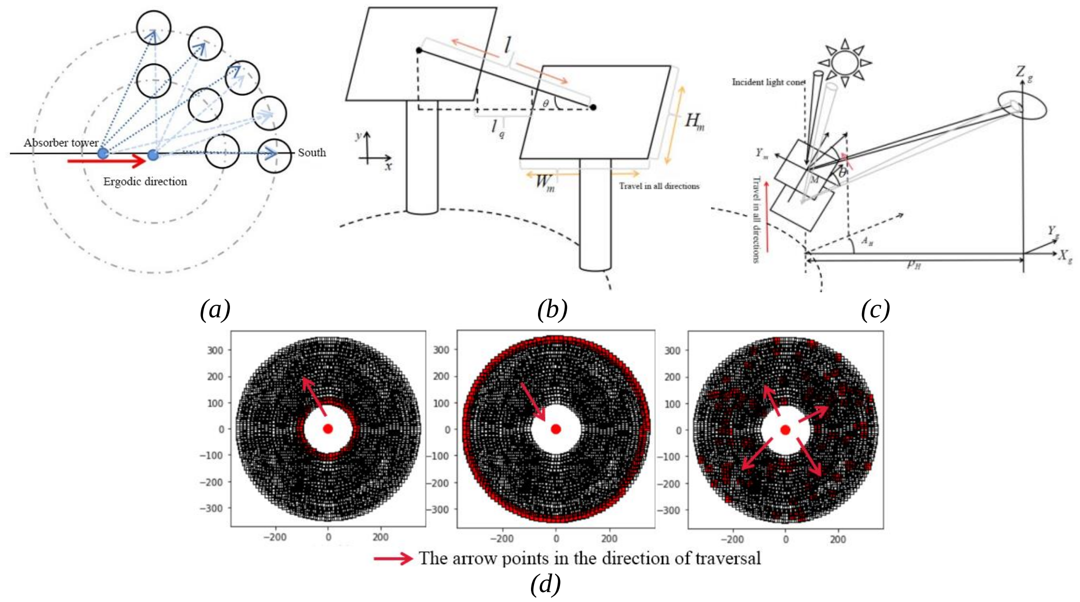

Figure 6: Diagram of the traversal process of each parameter index (a. Coordinate position of the absorber; b. Size of heliostat; c. Heliostat height; d. Number of heliostats)

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(2) Determine the size of the heliostat

In this process, the gap between the two heliostats changes accordingly, conforming to the relationship:

$$l_q = \frac{l}{\cos\theta} W_m \tag{9}$$

(3) Determination of heliostat height

Similarly, after controlling the parameters such as the position of the absorber, the installation height of 2 to 6 meters is adjusted in turn.

(4) Determination of the number of heliostats

The number of 1745 sets of heliostats is given. Based on this number, every 50 heliostats is formed into an adjustment unit. The adjustment direction is divided into positive and negative directions, increasing or decreasing the number of heliostats in turn, and taking out the most appropriate value range.

(5) Coordinate determination of heliostat

The heliostat field is selected to radiate from the absorption tower to the outer layer to form a circle. Each layer is numbered, the coordinates of the absorption tower are specified as (x_{ti}, y_{ti}), the coordinates of a certain helioscope are (x_{mi}, y_{mi}), and the number of layers is increased by one layer after layer for each outward expansion.

3.2 Multivariable target model building

Firstly, the parameters of the optimization model are defined, and then the objective function is established. According to the solving process of the annual average output thermal power, a model of the annual average thermal power per unit mirror area is established. Taking the calculation formula of the unit mirror area as the model, the output thermal power is controlled to be as large as possible, and a multi-variable single objective function is established. The objective function is as follows:

$$\max E_a = \frac{DNI}{A_t} \cdot \sum_{i}^{N} A_i \eta_i \tag{10}$$

Constraints need to be met:

(1) Due to the shadow occlusion of the absorption tower itself, the heliostat is not required to be installed within 100 meters around the absorption tower, that is, the distance between any absorption tower and the heliostat must exceed 100 meters.

(2) Since the operation range of 100 meters is left open for the shadow area, the circle radius of heliostat distribution in the heliostat field ranges from 0 to 250 meters:

(3) In order not to consider the influence of peripheral heliostats, the maximum value of the center distance between the two heliostats is applied to define the number of heliostats in each ring, thus, the calculation complexity can be reduced by associating the coordinates of the two heliostats.

(4) The specifications of the heliostat require that the side length of each mirror is between 2 and 8m, and usually the width of the mirror is not less than the length.

(5) Requirements for the installation height. The installation vertical axis should be between 2 and 6 meters, and it is necessary to ensure that the Tingri mirror will not touch the ground when the horizontal axis is rotating.

(6) In order to prevent collision between helioscopes during rotation, the distance between the center of the base of the adjacent heliostat should be maintained at more than 5m compared to the width of the mirror.

(7) The rated annual average output thermal power given in the title is 60kw, that is, the output thermal power of the heliostat field needs to be greater than or equal to the rated power.

(8) The interval distribution of heliostat needs to meet:

The distance between the front and rear heliostats is controlled according to the distance between

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different rings.

$$y \leq \left| \frac{\Delta r H}{L} \right| - \Delta r \tag{11}$$

(9) Parametric optical efficiency is included in the process of calculating the average output thermal power. In the case of the size of the heliostatic mirror and the position of the absorber and the height position, the spacing will be affected, resulting in a change in the atmospheric transmittance, which will affect the optical efficiency. Meet the conditions:

$$\begin{gathered} \eta_i = \eta_{sbi}\eta_{\cos i}\eta_{ati}\eta_{trunci}\eta_{refi} \\ \eta_{ati} > 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} d_{HR}{}^{2} \end{gathered} \tag{12}$$

3.3 Multivariable target model solving

A nonlinear programming model based on variable step size ergodic calculation is established. The helioscope layout obtained by the solution algorithm is shown in Figure 7 and the helioscope field parameters are shown in Table 2.

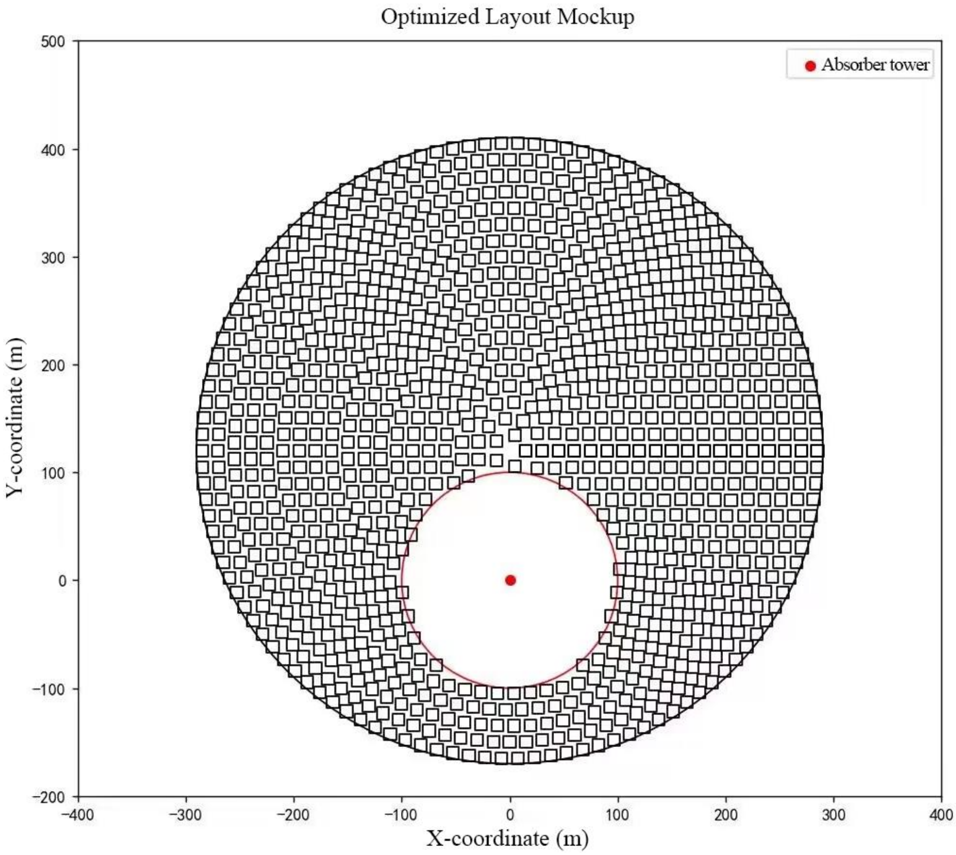

Figure 7: Layout of the final heliostat

Table 2: Heliostat field parameters design parameters

Absorption tower position coordinates	Heliostat size (W × H)	Heliostat mounting height (m)	Number of heliostats	Total heliostat area (m²)
(0,85)	7.32×7.56	4.526	1325	73324.44

4. Conclusions

In this paper, the design and optimization of heliostatic field is taken as the research goal. Firstly, the

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optical efficiency is taken as the starting point, and the shadow blocking efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency and mirror reflectivity are calculated and deduced by geometric projection algorithm according to the given formula, and the parameter system is established. According to the specifications of heliostats, the total lighting area of all heliostats can be calculated, and the average annual output thermal power per unit mirror area can be obtained. Then, the control variable method is used to determine the range of optimal parameter values by changing the position coordinates, heliostat size, installation height and heliostat number of the absorber in turn while other variables remain unchanged. The optimal parameter values of the four indicators are determined by an iterative method, and the resulting parameter setting range is set as the constraint conditions required by the objective function. Finally, the annual average output thermal power per unit mirror area is as large as possible as the objective function, and a multivariable programming model is established and solved to determine the design parameters of the heliostat. The model built in this paper adopts optimization methods such as geometric projection algorithm and variable step size traversal, which can efficiently search the parameter space and quickly find the optimal solution range, thus improving the calculation speed and accuracy of the model.

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