Research on Optimization Design of Heliostat Field Based on Genetic Algorithm

Jianqi Lu *

Engineering College, Yanbian University, Jilin, China, 133002

* Corresponding Author Email: lujianqi2003@163.com

Abstract. This article aims to design various variable parameters of the heliostat field while achieving the rated power of the heliostat field is an innovative solar heating system that focuses solar radiation on the absorption tower through a reflector, thereby generating high-temperature heat energy. This article mainly discusses the performance analysis and parameter optimization of the heliostat field to achieve optimal performance while meeting the rated power requirements. A simulated solar model was established using a three-dimensional Cartesian coordinate system, taking into account the effects of solar altitude angle and direct normal irradiance. The model in this paper comprehensively considers the effects of shadow occlusion loss, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance on the mirror field. To solve the problem, it is necessary to establish a three-dimensional coordinate system model, with the position of the absorption tower as the origin position of the coordinate system. Then, based on the size and installation height of the heliostat, the position of each heliostat is obtained, and optimized design is carried out to ensure that the total output thermal power is within the rated power range. Therefore, this article establishes a three-dimensional coordinate system model, taking the position of the absorption tower as the origin position of the coordinate system. Based on the size and installation height of the heliostat, the position of each heliostat is obtained. 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 optimized and solved using genetic algorithm.

Keywords: Heliostat field, Output thermal power, Solar energy, Genetic algorithm.

1. Introduction

Carbon peaking "and" carbon neutrality "are key strategies for addressing excessive carbon dioxide emissions [1]. with the rapid development of world industry and agriculture, global warming is accelerating, and carbon dioxide emissions are increasing day by day. Therefore, in order to achieve carbon emission control, it is first necessary to build a new type of power system with new energy as the main body. The vertical rotation axis of the base of the heliostat controls the azimuth angle of the reflector, while the horizontal rotation axis controls the elevation angle of the reflector. During operation, the planar reflector installed on the horizontal rotation axis rotates slightly in real-time according to the position of the sun, changing the normal direction of the mirror surface, so that the incoming sunlight (a beam of conical light) is reflected by the heliostat and directed towards the collector at the top of the absorption tower. The intersection point of the vertical and horizontal rotation axes is considered as the center of the heliostat. The installation height of the heliostat is the distance from the designated center of the heliostat to the ground, and the height of the absorption tower is the distance from the center of the collector to the ground.

2. Research on the parameters of the heliostat field

During the operation of the heliostat, its longitudinal rotation axis controls the azimuth angle of the reflector, and the horizontal rotation axis controls the elevation angle of the reflector. The planar reflector installed on the horizontal rotation axis rotates slightly in real-time according to the position of the sun, changing the normal direction of the mirror surface, so that the incoming sunlight (a cone-shaped beam of light) is reflected by the heliostat and directed towards the collector at the top of the

absorption tower. The position of the sun is constantly changing over time, and the direction of direct sunlight is constantly changing.

Therefore, this article first needs to establish a mathematical model of the sun's position and the output thermal power of the heliostat field based on the sun's altitude angle, sun azimuth angle, sun normal direction, longitude and latitude of the heliostat field, sun time angle, local time, sun declination angle, normal direct radiation irradiance, output thermal power of the heliostat field, optical efficiency, shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency, mirror reflectivity, etc Modeling optical efficiency, shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency, mirror reflectance, and other optical efficiencies.

The optical efficiency of the mirror field is the main indicator for evaluating the performance of the mirror field. Therefore, in the optimization design research of the heliostatic mirror field, it is essential to first model the efficiency of the mirror field. The accuracy of efficiency modeling also greatly affects the final result of mirror field layout optimization. Therefore, it is particularly important to establish an efficiency model of the heliostatic mirror field and ensure its accuracy. Therefore, this article mainly analyzes and models the solar position and mirror field efficiency, and proposes a more precise method for calculating shadow occlusion efficiency.

Both quantitative analysis and optimization design cannot be separated from the optical efficiency analysis of the mirror field, which is also an important indicator for evaluating the quality of mirror field design. Therefore, we model the optical efficiency of the mirror field and calculate the annual average optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area under the fixed sun mirror field, which also lays the foundation for subsequent optimization design.

2.1. Establishment of Sun Position Model

Due to the close relationship between the establishment of the horizon coordinate and the observation point, and the movement of the heliostat relies on the adjustment of the position angle and height angle of the other side, this article takes a more intuitive and vivid horizon coordinate system as a reference, and uses the sun's altitude angle (the angle between the sun and the plane where the observation point is located) and the sun's azimuth angle (the angle between the sun's projection point on the ground plane of the observation point and the y-axis direction after it is connected to the observation point, which is for ease of understanding and calculation) Represent the position of the sun and substitute it into solving relevant mathematical models. The solar position model established in the horizontal coordinate system [1] is shown in Fig 1.

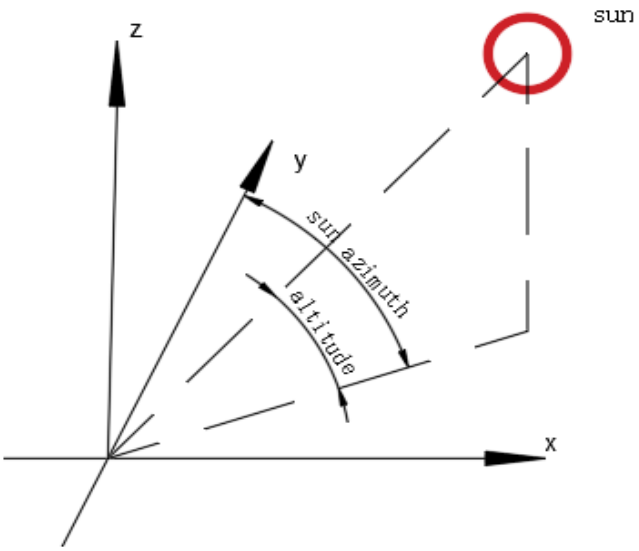


Figure 1. Schematic diagram of the sun position model

2.2. Composition of optical efficiency of heliostats

The sunlight is reflected once by the heliostat field and propagates to the surface of the collector. The low energy density solar beam is collected by the heliostat field and transformed into a high energy density beam, which is then converted from solar radiation energy to thermal energy on the surface of the collector. The ratio of the energy that can be received by the collector to the total energy of thermal optics is called the optical efficiency of the heliostat. The optical efficiency of a heliostat is influenced by factors such as the position of the sun, the arrangement rules of the heliostat, atmospheric conditions, the material of the heliostat, the geographical location of the factory, and the shape of the collector. It is an important standard for measuring the focusing ability of a heliostat field. The optical efficiency of a heliostat field consists of six parts: cosine efficiency $\eta_{\cos}$, atmospheric attenuation efficiency η_{at}, overflow efficiency η_{int}, shadow occlusion efficiency η_{sb}, mirror reflectivity η_{ref}, and mirror cleanliness η_{clc}. At any time, the optical efficiency of the mirror field is calculated by multiplying the six parts above:

$$\eta_{field,t} = \eta_{cos} \cdot \eta_{at} \cdot \eta_{int} \cdot \eta_{sb} \cdot \eta_{ref} \cdot \eta_{clc} \quad (1)$$

When calculating, mirror reflectivity and mirror cleanliness are usually considered as constants, with a focus on the remaining four parts [2].

2.3. Efficiency Model

2.3.1. cosine efficiency model

In order to reflect sunlight onto the heat absorber at the top of the absorption tower, the plane of the heliostat must not be perpendicular to the incident light. Only when the mirror surface is perpendicular to the light, the actual reflection area is equal to the mirror surface area [3]. As the mirror tilts, the lighting area of the heliostat also changes. As shown in the diagram, the actual lighting area of the heliostat is at the angle between the mirror's normal and the incident light θ Regarding. Its current lighting area is the mirror area andθThe product of the cosine values of the angle, and the cosine efficiency isθThe cosine value of an angle. The cosine efficiency diagram is shown in Fig 2 and 3.

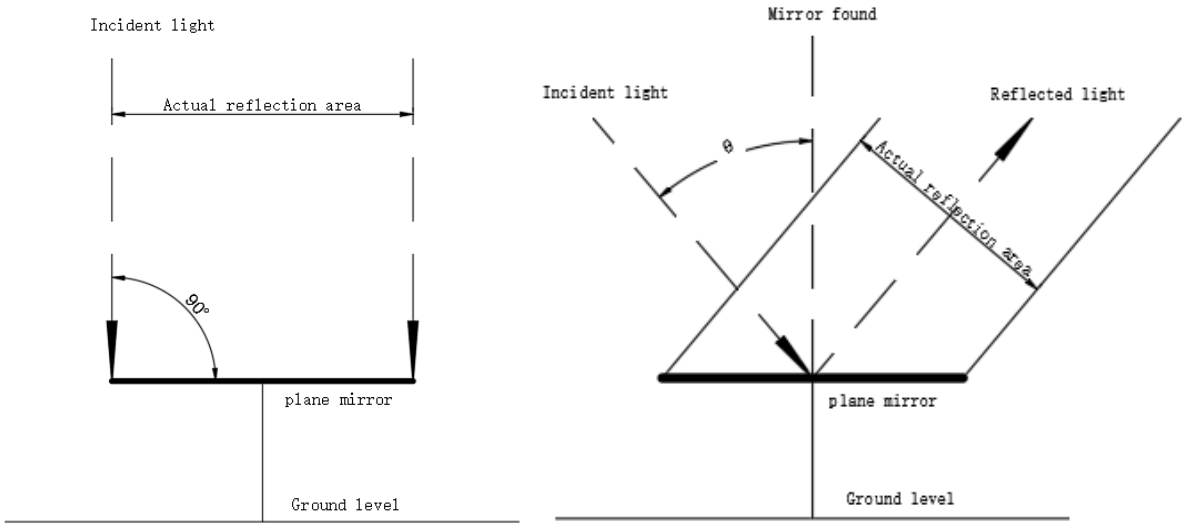


Figure 2. Schematic diagram of cosine efficiency

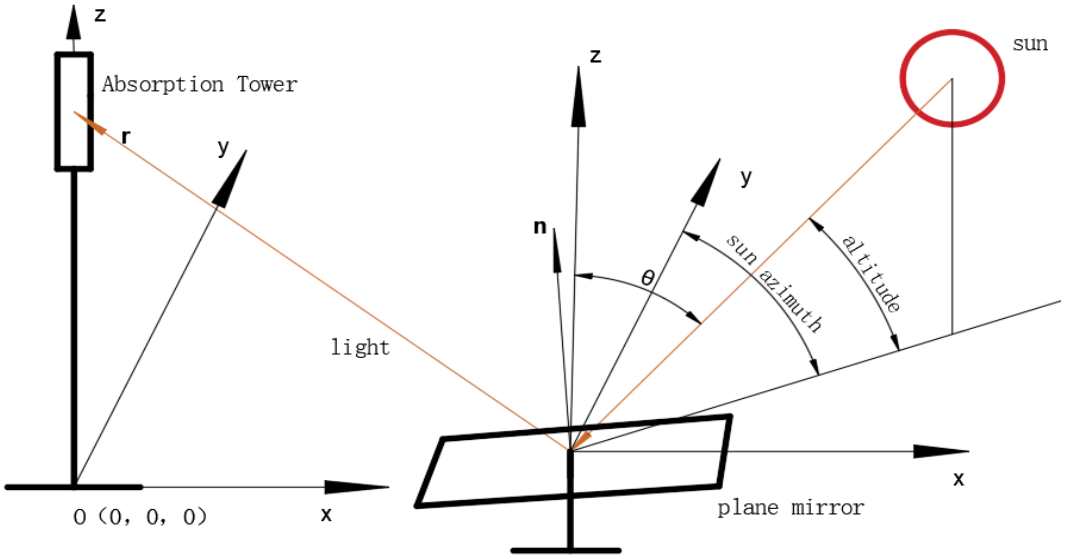


Figure 3. Schematic diagram of planar mirror reflection

The formula for calculating cosine efficiency is:

$$\eta_{cos} = cos\theta = \left|\sqrt{\frac{(1+cos2\theta)}{2}}\right| = \left|\sqrt{\frac{(1+s\cdot r)}{2}}\right| \tag{2}$$

$$r = \frac{-x,-y,H-z}{\sqrt{x^2+y^2+(H-z)^2}} \tag{3}$$

$$s = (-\cos\alpha_s \sin\alpha_s, -\cos\alpha_s \cos\gamma_s, -\sin\alpha_s) \tag{4}$$

The vector s is the unit vector of the incident rays of the sun, the r vector is the unit vector of the specular reflected rays, and the dot product of the s vector and the r vector is the cosine value of the angle between the incident rays and the reflected rays, which is divided equally by the specular normal vector n. Each angle is θ, the included angle is 2θ. The cosine value's double angle formula can be used to calculate cos θ, That is the cosine efficiency. The solar altitude angle and azimuth angle at 9:00, 10.5:00, 12:00, 13.5:00, and 15:00 on the 21st of each month are known, and the coordinates of each heliostat are known. The cosine efficiency at these moments can be calculated as the daily average cosine efficiency. The 21st of each month is the average cosine efficiency in the middle of each month, which can be used as the monthly average cosine efficiency, The annual average cosine efficiency is obtained by adding up the monthly average cosine efficiency on the 21st of each month and dividing it by 12.

2.3.2. Atmospheric attenuation efficiency

When light propagates in the atmosphere, it is affected by local altitude and atmospheric conditions (such as humidity, dust, etc.), resulting in the loss of some radiation. The atmospheric attenuation efficiency refers to the ratio of the radiation energy of the light reaching the heat absorber to the radiation energy reflected by the heliostat [4]. The formula for calculating atmospheric attenuation efficiency is:

$$\eta_{at} = 0.99321 - 0.000117 d_{HR} + 1.97 \times d_{HR}^2 (d_{HR} \leq 1000) \tag{5}$$

Among them, dHR is the mirror reflection distance, which is the distance from the center point of the heliostat to the center point of the heat absorber.

2.3.3. Spillover efficiency

When reflected light shines on the heat absorber, the characteristics of the spot and the accuracy or shaking of the heliostat may cause the spot to shift or overflow, resulting in some light shining outside the heat absorber. The truncation efficiency is the ratio of the actual spot to the ideal spot formed by the reflected light on the heat absorber.

2.3.4. Shadow occlusion efficiency

There are various forms of heliostat field layout, one of which is a linear arrangement, which is relatively simple in layout. The heliostat mirror is arranged in an equidistant and regular manner, and this arrangement can have a mirror density of up to 48%. However, it also has its drawbacks, which can cause significant shadow and occlusion losses [5]. Therefore, to improve mirror field efficiency and reduce shadow and occlusion losses, we need to adjust the size of the heliostat plane mirror at different positions.

Compared to the linear layout, the radial grid arrangement is more widely used [6]. In this layout, the heliostat is installed on multiple circular rings with different distances as radii centered on a heat absorbing tower [7], and the front and rear heliostats on adjacent mirror rings need to be staggered by a certain angle. At the same time, the radius of the first mirror ring needs to be determined by tower height data.

The efficiency of shadow occlusion is mainly affected by the arrangement of the mirror field [8]. Currently, the existing arrangement of heliostats cannot achieve a shadow occlusion efficiency of 1, which means there is shadow loss and cannot be ignored. Therefore, this article uses the geometric projection method to calculate the efficiency of shadow occlusion [9], and Fig 4 is a schematic diagram of shadow occlusion analysis.

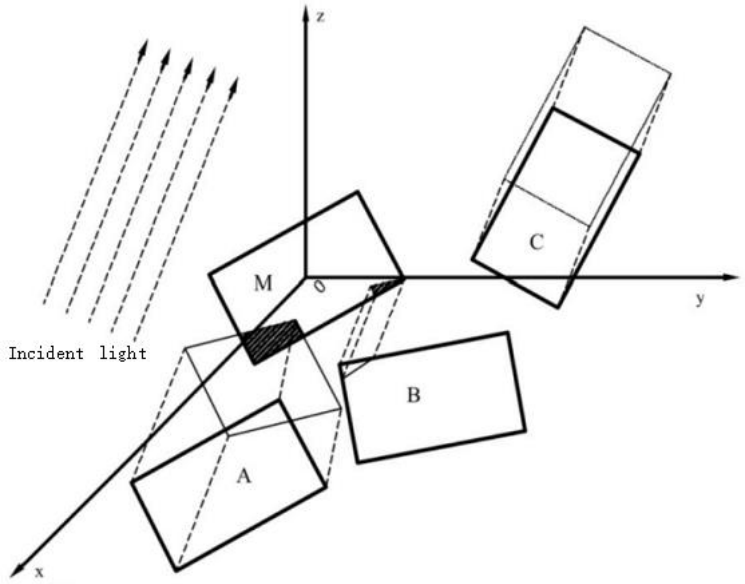


Figure 4. Schematic diagram of shadow occlusion analysis

3. Research on optimizing the field parameters of heliostats using genetic algorithms

3.1. Assumptions for Optimizing Design

Assuming that there is no secondary reflection of sunlight on the plane reflector of the heliostat. Assuming that the impact of reflection in the air is not considered, and the loss during reflection is not taken into account. The plane reflector of the fake sun mirror will not bend and always maintains a plane. Assuming that the sunlight reflected onto the heat absorber does not overflow. Assuming that the distribution of energy flow density on the heat absorber meets the design requirements, it will not affect the overall efficiency of the mirror field in utilizing solar energy. Assuming that the reflection performance of the mirror itself is good, and the mirror surface exposed to air is free of dirt, it does not affect the reflectivity and mirror field efficiency of the mirror surface. Neglecting the actual engineering gap between the horizontal and vertical rotation axes during installation, assume that the intersection point of the two rotation axes is the center of the heliostat.

3.2. Principles of Genetic Algorithm

Genetic algorithm is an adaptive global optimization search algorithm that simulates the genetic and evolutionary processes of organisms in the natural environment [10]. It draws on Darwin's theory of evolution and Mendelian's theory of genetics. Essentially, it is a parallel, efficient, and global search method that can automatically acquire and accumulate knowledge about the search space during the search process, and adaptively control the search process to obtain the optimal solution.

As shown in Fig 5, the genetic algorithm operates according to the principle of "survival of the fittest" and generates an approximately optimal solution in the potential solution population step by step. In each generation of genetic algorithms, individual selection is based on the fitness values of individuals in the problem domain and the reconstruction methods borrowed from natural genetics to generate a new approximate solution. This process leads to the evolution of individuals in the population, resulting in new individuals that are more adaptable to the environment than the original individuals, just like modifications in nature.

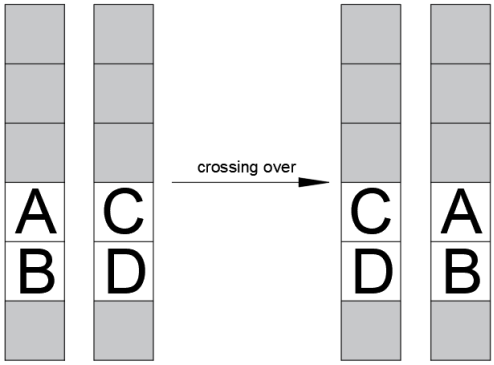


Figure 5. Cross exchange principle diagram

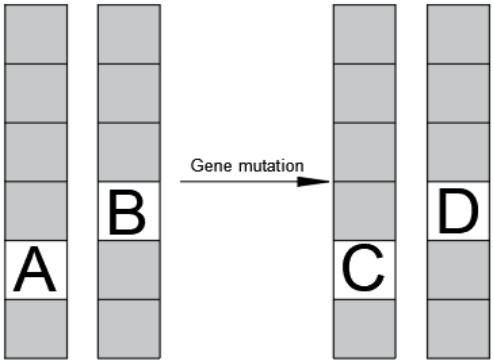


Figure 6. Schematic diagram of gene mutation

In genetic algorithms, binary encoding is the process of assigning a unique binary string to each numerical solution based on a given interval range and precision (the interval between two numerical solutions). For example, when the interval range of a given numerical solution is [1, 10] and the accuracy is given as 1e-5, the binary encoding is shown in Fig 6 and Fig 7.

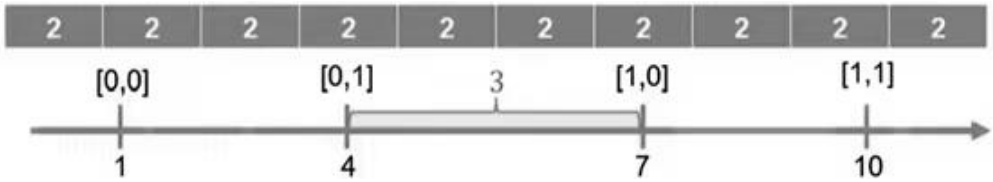


Figure 7. Schematic diagram of binary encoding

A string of length n that can represent the nth power of 2, with a numerical interval length of L and an accuracy of E, the length of a binary string is n. The relationship between the three is:

$$\frac{L}{2^n-1} \leq E \tag{6}$$

In the binary decoding process, generally, the interval range is [a, b], the interval length is L, that is, L=b-a, the string length is n, and the current string corresponds to a decimal T, then the corresponding real solution of the string is:

$$X = a + T \times \frac{b-a}{2^n-1} \tag{7}$$

3.2.1. Cross replication and variation

Mapping individual fitness size to probability for replication, individuals with higher fitness have a higher probability of replication, and the more copies they replicate - roulette wheel method. Copy the top N/4 individuals with high fitness, and then replace the bottom N/4 individuals with these individuals to generate elites. Randomly replace the next individual with a copy of the current

individual, which can be a "bad solution" or a high fitness solution. In order, there is a probability of crossover between two individuals, and multiple individuals can also cross each other. For the top N/2 or even N/4 individuals with high fitness, they can also cross each other.

Mutation is performed on the last N/4 individuals or last N/2 individuals with low fitness, mapped to probability variation based on fitness size, which can be a single locus variation or multiple model variations.

3.2.2. Implementation principle

The basic idea of roulette wheel betting is that solutions with higher fitness are more likely to be replicated, and the number of copies should be greater. For individual x, calculate the corresponding fitness:

$$f(x_i) > p_i = \frac{f(x_i)}{\sum f(x_i)} \tag{8}$$

3.3. The Function of Genetic Algorithm

(1) Function One - Randomly Generate Individuals.

(2) Function 2- Determine whether the current heliostat field has reached the rated power, using a loop statement, substitute the constraints of the optical efficiency model for the heliostat field. If the heliostat field reaches the rated power, exit the loop. So, it indicates that it has reached its maximum thermal output power, and the return value is one. If, at the end of the calculation, the heliostat field cannot reach the rated power, then the return value is zero.

(3) Function Three - Determine if the constraint conditions are met, the constraint conditions have been derived in the establishment of the optical efficiency model of the heliostat field, in simple terms, whether the rated power of the heliostat reaches its maximum.

4. Conclusion

The model overall conforms to the ideal state, considering multiple constraint conditions and variables, and well describes the performance of the system. While establishing a model to analyze the problem, the problem was also simplified to ensure that the size of each heliostat is consistent. The mirror surface of the heliostat was discretized for easy analysis and solution. Genetic algorithm is used in multi-objective optimization problem solving, which utilizes a large number of operations and multiple iterations of intelligent algorithms to fully utilize the powerful data processing and prediction capabilities of Matlab. The innovation of this research method is reflected in the comprehensive application of discretization principles, and the precise analysis of the optical performance of heliostats through ray tracing models. At the same time, the complex structure of the heliostat field was more accurately described through exquisite coordinate system transformation. The experimental results indicate that the optimal combination of heliostat field parameters has been found through effective search using genetic algorithms, providing solid theoretical support for the optimization design of light energy utilization systems.

References

[1] Yu Runze. Research on the Positioning of Solar Shadows [J]. Science and Education Guide (Mid-October), 2017 (29): 40 - 41.

[2] Zhang Ping, Xi Zhengwen, Hua Wenhan et al. Calculation Method for Optical Efficiency of Solar Tower Photothermal Mirror Field [J]. Technology and Market, 2021, 28 (06): 5 - 8.

[3] Ding Qi, Zeng Zhiyong, Chen Wuzhong, et al. An evaluation method for the effective mirror area of a heliostat field [J]. Journal of Solar Energy, 2021, 42 (09): 184 - 189.

[4] Du Yuhang, Liu Xiangmin, Wang Xingping, et al. Analysis of the impact of different focusing strategies on the heliostat of tower type photothermal power plants [J]. Journal of Power Engineering, 2020, 40 (05): 426 - 432.

[5] Gao Bo, Liu Jianxing, Sun Hao, et al. Optimization of heliostat field layout based on adaptive gravity search algorithm [J]. Journal of Solar Energy, 2022, 43 (10): 119 - 125.

[6] Gao Bo, Sun Hao, Liu Sheng. Optimization of mirror field layout for solar thermal power plants based on improved whale algorithm [J]. Journal of Solar Energy, 2023, 44 (10): 209 - 2017.

[7] Guan Hongyang, Zhang Yanmei, Liao Wenjun, et al. The influence of different arrangements of heliostat fields on the optical efficiency of the mirror field [J]. Equipment Machinery, 2017 (01): 6 - 10.

[8] Lv Caixia. The influence of heliostat parameters on the performance of tower solar concentrator systems [J]. Energy Conservation, 2023,42 (05): 34 - 37.

[9] Wang Wei, Cheng Song, Xie Wentao. Focusing strategy and application simulation of tower solar heliostats [J]. Shanghai Electric Technology, 2014,7 (03): 35 - 40.

[10] Gao Bo, Sun Hao, Liu Sheng. Optimization of mirror field layout for solar thermal power plants based on improved whale algorithm [J]. Journal of Solar Energy, 2023, 44 (10): 209 - 2017.