Research on optimization model based on heliostat field

Kaiwen Xu#, Hui Xu#, Jihui Fan*

School of Integrated Circuits, Shandong University, Jinan, 250101, China

* Corresponding Author Email: fanjihui@sdu.edu.cn

#These authors contributed equally.

Abstract. Tower solar power system (SPT) is a new type of clean energy technology with low carbon and environmental protection. In this context, it is very meaningful to explore how to arrange an efficient heliostat field and set the heliostat parameters, because the improvement here can improve the average optical efficiency of the heliostat field and collect thermal energy. In this paper, under the constraint of circular layout area, the solar energy transmission model of heliostat and the comprehensive optical efficiency model of heliostat field are established by coordinate system transformation method, Monte Carlo algorithm and HFLCAL calculation model. Then, considering the optimal layout scheme of the heliostat field, the EB layout is used to establish the basic layout of the heliostat field, and the heliostat with high comprehensive optical efficiency and meeting the actual use requirements is selected by the step-by-step traversal algorithm. Subsequently, the heliostat height, heliostat width, installation height and heliostat installation height difference between adjacent areas are introduced into the optimization model as particles, and then the PSO-GA hybrid optimization algorithm is used to approximate the optimal design of the SPT system. The goal of optimizing the comprehensive optical efficiency of the heliostat field and the output thermal power per unit area of the SPT system is achieved.

Keywords: Heliostat Field, Monte Carlo Algorithm, HFLCAL Calculation Model, PSO-GA Hybrid Optimization Algorithm.

1. Introduction

In recent years, achieving carbon emission reduction targets has gradually become an important decision for mainstream countries. According to the statistics of the IEA, fossil fuels continue to account for 80% of the total global energy supply, and the role of new energy technologies in combating climate change has become increasingly prominent[1]. With the advantages of high efficiency, cleanliness and no noise, SPT system has received extensive attention as a new energy technology. The heliostat reflects the solar radiation onto the collector at the top of the absorption tower. The heat conduction medium in the collector is heated, and the power is generated through the thermodynamic cycle to synthesize solar fuel or supply industrial processes. In practical project, the heliostat field is one of the key factors for the energy collection efficiency of the SPT system. Therefore, it is very important to obtain the optimal design of the heliostat field.

The comprehensive optical efficiency is an important index to measure the heliostat field design. It can be solved by shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency and specular reflectivity. For shadow occlusion efficiency, it is appropriate to choose the Monte Carlo method for this study because it allows the simulation of complex geometries and becomes particularly useful when a large number of parameters are involved. Therefore, this work proposes to use an effective Monte Carlo algorithm to solve the shadow occlusion efficiency based on the theoretical model proposed in [2]. For the truncation efficiency of the collector, this work deeply considers the solar light as a conical light, and combines the HFLCAL calculation model [3] to establish a solar light transmission model to solve the truncation efficiency. The algorithm will provide an accurate estimation of the integrated optical efficiency of the heliostat field. In order to design the optimal heliostat field layout and heliostat parameters, the previously determined comprehensive optical efficiency solution model is coupled with a hybrid algorithm based on population and genetic, that is, PSO-GA hybrid optimization algorithm[4]. The section 2 describes the integrated optical efficiency model of the heliostat field, and gives the solution results of the model at a known position. In section 3, the basic layout scheme based on EB mirror field and the optimization scheme of heliostat field based on PSO-GA algorithm are introduced. The optimization results are given in the section 4.

2. The model for the comprehensive optical efficiency of the heliostat field

The ratio of the energy received by the collector to the total energy of the thermal optics is called the optical efficiency of the heliostat.[6] In this paper, Monte Carlo algorithm and HFLCAL calculation model are used to solve the shadow occlusion efficiency and collector truncation efficiency respectively, and the comprehensive optical efficiency model of mirror field is established by combining cosine efficiency[7], atmospheric transmittance and specular reflectivity[8].

2.1. The model of annual average shadow occlusion efficiency

Shadow occlusion loss can be divided into three parts :

1. the shadow loss caused by the absorption tower shielding the incident light of the heliostat ;
2. the shadow loss caused by the incident light received by the rear heliostat being blocked by the front heliostat ;
3. the light reflected by the rear heliostat is blocked by the front heliostat, resulting in light blocking loss.

The range of shadow occlusion varies with the position of the sun throughout the day. Considering the irregularity of the occlusion area, this paper use the Monte Carlo method to calculate. If a point on the mirror is selected, if there is an intersection between the reverse extension line along the direction of the incident light and the cross section of the absorption tower, the point is shaded. The first part of the occlusion area can be characterized by the ratio of the number of occluded points to the total number of randomly selected points, that is:

$$S_1 = S_{mirror} \cdot \frac{m_{block}}{m_{total}} \tag{1}$$

Where S_{mirror} is the total area of a single mirror, m_{total} is the total number of points selected, and m_{block} is the number of points that are occluded. The Monte Carlo method has randomness when taking points, and can cover irregular shapes well.

For the shadow area of parts 2 and 3, this paper mainly consider the occlusion caused by 12 heliostats with the shortest distance from the target heliostat. Using coordinate system transformation and plane projection method, the occlusion area can be calculated[6].

Let a vertex of the mirror surface of the heliostat A that blocks the incident light be H_1, and the point of its projection on the heliostat B along the incident light be H_2. The mirror coordinate system is established on the two mirrors respectively, and then in the A mirror coordinate system $H_1\colon (x_1, y_{1,} 0)$ under the B mirror coordinate system $H_2\colon (x_2, y_{2,} 0)$.

Identity matrix T can convert the mirror coordinate system to the ground coordinate system:

$$T = \begin{pmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\cos\beta\sin\alpha & \sin\alpha\sin\beta \\ \sin\alpha & \cos\alpha\cos\beta & -\cos\alpha\sin\beta \\ 0 & \sin\beta & \cos\beta \end{pmatrix} \tag{2}$$

Where α and β satisfy:

$$(\cos\alpha, \sin\alpha, 0) \cdot \vec{n} = 0 \tag{3}$$

$$(0,0,1) \cdot \vec{n} = \cos\beta \tag{4}$$

Where $\vec{n}$ is the normal vector of the mirror surface.

Convert $H_1\colon (x_1, y_1, 0)$ to $H_1{}'$ and $H_1{}'$ to $H_1{}''$:

$$H_1^{'} = \begin{pmatrix} l_x & l_y & l_z \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{pmatrix} \cdot H_1 + O_1 = \begin{pmatrix} x_1^{'} \\ y_1^{'} \\ z_1^{'} \end{pmatrix} \tag{5}$$

$$H_1^{''} = \begin{pmatrix} l_x & l_y & l_x \\ m_x & m_y & m_z \\ n_x & n_y & n_z \end{pmatrix}^T \cdot (H_1 - O_2) = \begin{pmatrix} x_1^{''} \\ y_1^{''} \\ z_1^{''} \end{pmatrix} \tag{6}$$

Where O_1 and O_2 are the coordinates of the center points of heliostats A and B in the ground coordinate system, respectively.

Consider that $H_2: (x_2, y_2, 0)$ satisfies the following conditions:

$$\frac{x_2 - x_1^{''}}{a} = \frac{y_2 - y_1^{''}}{b} = \frac{-z_1^{''}}{c} \tag{7}$$

The coordinates can be calculated as follows :

$$\begin{cases} x_2 = \dfrac{cx_1^{''} - az_1^{''}}{c} \\ y_2 = \dfrac{cy_1^{''} - bz_1^{''}}{c} \end{cases} \tag{8}$$

Similarly, the projection points of other vertices of the heliostat A on the heliostat B are calculated in turn to obtain the projection surface. The projection surface is approximated as a trapezoid or a rectangle. Assuming that the shadow areas formed by 12 heliostats do not overlap with each other, the shadow occlusion area can be calculated cumulatively.

Considering the occlusion area of the above three parts, the shadow occlusion efficiency of a single heliostat can be calculated.

2.2. The model for annual average truncation efficiency

The reflected light of the heliostat is a beam of conical light[9].Since the heliostat is far away from the collector, the cross section of the conical light is large, which exceeds the range of the collector, resulting in that the light energy cannot be completely absorbed by the collector, which is the truncation loss. The ratio of the energy absorbed by the collector to the entire conical light energy is the truncation efficiency, which can be calculated using the HFLCAL model.

The energy flux density of any point (x_r, y_r) on the conical section is :

$$q_{\mathrm{HF}}(x_r, y_r) = \frac{P_{\mathrm{m}}}{2\pi\sigma_{\mathrm{HF}}^2} \mathrm{e}^{-\frac{(x_r - x_{Ar})^2 + (y_r - y_{Ar})^2}{2\sigma_{\mathrm{HF}}^2}} \tag{9}$$

Where:

$$P_{\mathrm{m}} = DNI \cdot \mathrm{S} \cdot n_{\cos} f_{\mathrm{at}} \eta_{\mathrm{ref}} \tag{10}$$

$$\sigma_{\mathrm{HF}} = \sqrt{d_{HR}^2 \left(\sigma_{\mathrm{sun}}^2 + \sigma_{\mathrm{bq}}^2 + \sigma_{\mathrm{ast}}^2 + \sigma_{\mathrm{track}}^2\right)} \tag{11}$$

$$\sigma_{\mathrm{bq}}^2 = (2\sigma_{\mathrm{s}})^2 \tag{12}$$

$$\sigma_{\mathrm{ast}} = \sqrt{0.5(H_t^2 + W_t^2)/4d} \tag{13}$$

$$H_t = \sqrt{L_{\mathrm{W}} \times L_H} \left| \frac{d_{HR}}{f} - n_{\cos} \right| = \sqrt{\mathrm{L_w} \times L_H} \cdot n_{\cos} \tag{14}$$

$$W_t = \sqrt{L_W \times L_H} \left| \frac{d_{HR}}{f} n_{cos} - 1 \right| = \sqrt{L_W \times L_H} \tag{15}$$

$$f_{\mathrm{at}} = 0.99321 - 0.0001176d + 1.97 \times 10^{-8} \times d^2 \tag{16}$$

In the formula, L_W is the width of the heliostat, L_H is the height of the heliostat, d is the distance from the light source to the target point, and (x_{Ar}, y_{Ar}) is the coordinate of the intersection point of the reflected light passing through the center of the mirror and the heat absorbing surface. Referring to the data obtained from the PSA platform and the SENER heliostat test, take $\sigma_{\text{sun}} = 2.51$ mrad, $\sigma_{\text{s}} = 0.94$ mrad, $\sigma_{\text{track}} = 0.63$ mrad.

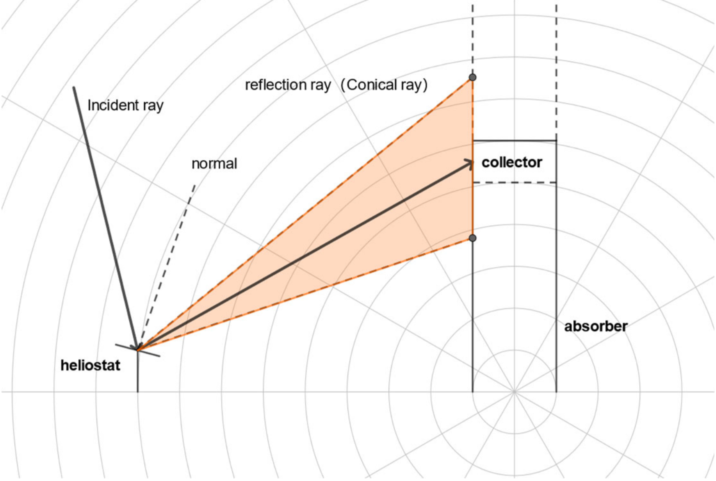

Fig. 1 Truncation efficiency calculation diagram

It is assumed that the conical light is emitted from the center point of the mirror. Considering that the heat absorbing surface is the cross section of the collector axis, the cross section of the reflected light on the heat absorbing surface is an ellipse A, and the cross section of the collector on the heat absorbing surface is a rectangle B. As shown in Fig 1.

The energy absorbed by the collector is :

$$\mathrm{W}_{\text{absorb}} = \iint q_{\text{HF}}(x_r, y_r)dxdy \tag{17}$$

The integral region is the overlapping region of ellipse A and rectangle B.

The total energy of the light reflected by the heliostat is :

$$\mathrm{W}_{\text{total}} = \iint q_{\text{HF}}(x_r, y_r)dxdy \tag{18}$$

The final truncation efficiency is calculated as follows :

$$\eta_{\text{trunc}} = \frac{\mathrm{W}_{\text{absorb}}}{\mathrm{W}_{\text{total}}} \tag{19}$$

2.3. Model measurement

In order to verify the accuracy of the model, an actual heliostat field is selected for verification analysis. The center of the field is located at 98.5 ° E, 39.4 ° N, with an altitude of 3000 m and a radius of 350 m. The height of the absorption tower is set to 80 m, and the collector is a cylinder with a height of 8 m and a diameter of 7 m, as shown in Fig.2.

Fig. 2 The actual heliostat field image

Using MATLAB to establish the above mathematical model, the key optical efficiency at different times is calculated, and the optical efficiency of each heliostat in the mirror field is obtained. Figs.3 to 6 show the optical efficiency distribution at 9 : 00 on December 21.

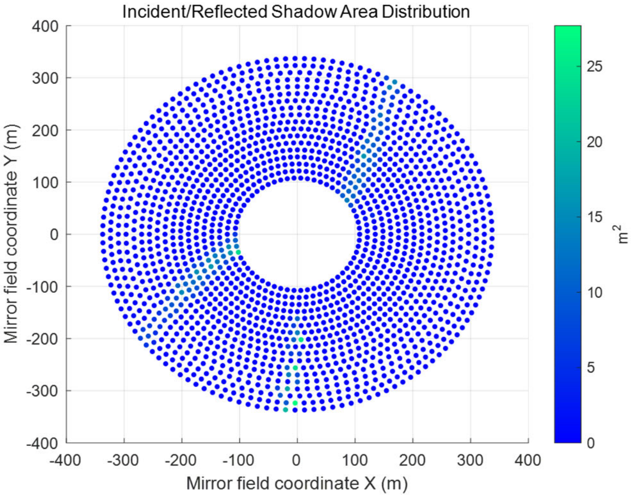

Fig. 3 Occlusion shadow area distribution

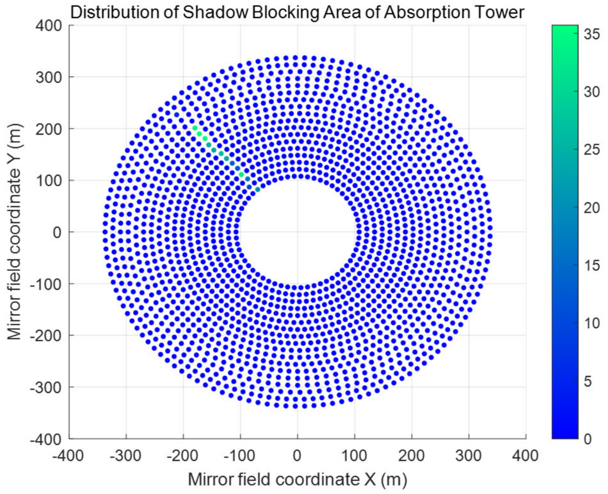

Fig. 4 Shadow area distribution of tower

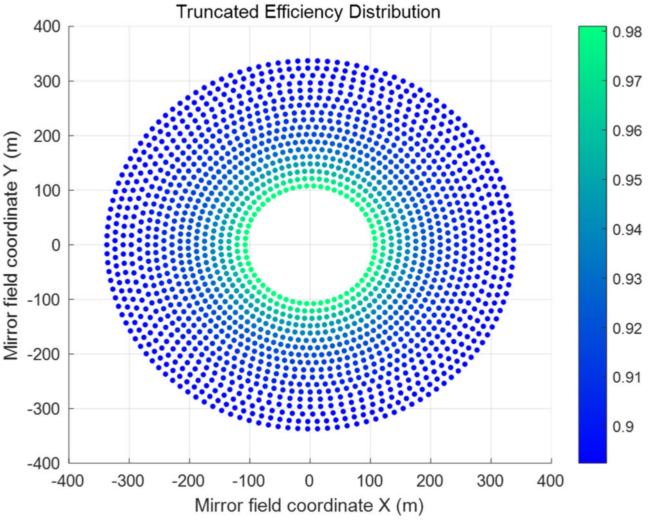

Fig. 5 Truncation efficiency distribution

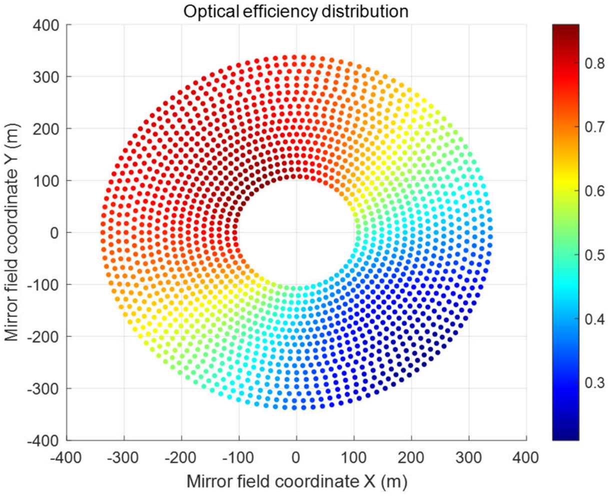

Fig. 6 Optical efficiency distribution

The optical efficiency of each heliostat in the mirror field is obtained by multiplying the five parts of efficiency. The calculation results of the model are close to the actual optical efficiency of the mirror field.

3. Optimization

For the layout of the heliostat field, the main parameters considered are the position coordinates of the absorption tower, the size of the heliostat, the installation height, the number of heliostats, the position of the heliostat, etc. In fact, this problem can be summarized as a multi-objective optimization calculation problem. In order to reduce the computational dimension, this paper propose to establish the basic layout of the heliostat field first, and then calculate it when the heliostat coordinates are basically determined. This paper use the PSO-GA hybrid optimization algorithm to establish an optimization function with the parameters of each heliostat field as variables and the annual average output thermal power per unit mirror area as the goal. Under the condition of satisfying the constraints, the annual average output thermal power per unit mirror area is as large as possible to obtain the optimal solution.

3.1. The establishment of the heliostat field

The EB (Estimate Blocking) [10] mirror field has the advantages of low shadow loss efficiency and high land use efficiency under large mirror field radius, so the EB layout model is used to design the basic mirror field layout. The EB layout is shown in Fig.7.

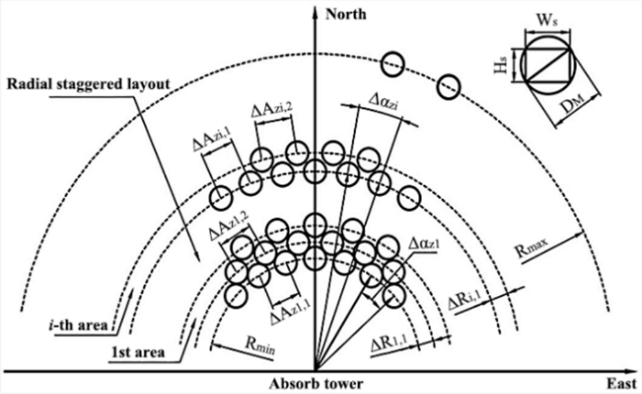

Fig. 7 EB layout diagram

The expression of the azimuth spacing of the heliostat of the first ring in each region of the mirror field is :

$$\varDelta A_{\mathrm{zi,1}} = A_{\mathrm{sf}} \cdot W_{\mathrm{S}} \tag{20}$$

$\mathrm{A_{zi,1}}$ is the azimuth spacing factor and is taken as constant 2.

Except for the first ring, the azimuth spacing of the other ring heliostats in each region can be obtained by the azimuth of the heliostats in this region. The expression is :

$$\varDelta A_{zi,j} = 2R_{i,j} \cdot \sin\left(\varDelta\alpha_{z,i}/2\right) \tag{21}$$

$\mathrm{A_{zi,j}}$ is the azimuth spacing of the j-ring heliostat in the i-zone of the mirror field.

The azimuth of the heliostat in the i region is :

$$\varDelta\alpha_{Z,i} = 2\arcsin\left[\varDelta A_{zi,1}/\left(2R_{i,1}\right)\right] \tag{22}$$

The radial spacing of the heliostat at the junction of adjacent mirror fields is set to D_M. $\triangle R_{1,1}$ denotes the radial distance between the first ring and the second ring in the mirror field first region, which is expressed as :

$$\varDelta R_{1,1} = \sqrt{D_{\mathrm{M}}^2 - \left(\varDelta A_{z1,1}/2\right)^2} \tag{23}$$

The radial distance between the heliostats of the adjacent rings in the same area is always set to $\triangle R_{1,1}$.

Based on the EB layout principle, an algorithm can be designed to solve the initial layout of the heliostat field dense layout. Subsequently, the optimization algorithm is applied to gradually search and remove the heliostats that do not meet the constraints and low optical efficiency, and adjust the heliostat parameters to obtain the optimal layout model.

3.2. Hybrid optimization based on PSO-GA

The PSO-GA hybrid algorithm combines the particle swarm optimization algorithm with the genetic algorithm. The particle swarm optimization algorithm can preserve the historical state and the current state of the heliostat parameters. The reconstructed algorithm factor enables the individual to determine the mutation direction and span based on its own historical optimal solution and the historical optimal solution in the sub-population and the individual evolution speed. The algorithm can avoid falling into the local optimal solution while maintaining high convergence efficiency and high solution accuracy.

In this paper, GA is introduced into the PSO algorithm[11].The particle swarm optimization algorithm formula after the introduction of the operator is :

$$\begin{cases} \Delta x^{i}_{\max,t+1} = \Delta x^{i}_{\max,t} + c_1 r_1 \left(\Delta x^{i}_{\max} - x_{id}\right) + c_2 r_2 \left(\Delta x_{\max^{i}} - x_{id}(t)\right) \\ x_{id}(t+1) = x_{id}(t) + \Delta x^{m}_{\max,t+1} \end{cases} \tag{24}$$

x_{it} is used to replace x_{id} of PSO algorithm, which represents the position of the i th particle in N-dimensional space. The $x^{i}_{\max}$ corresponding to the historical optimal of the i th position is used to replace the P_{id} representing the individual optimal in the PSO algorithm. The global optimal point is replaced by the historical optimal solution $x^{j}_{\max}$ of the subpopulation. The reconstructed algorithm introduces the possibility of crossover and mutation, and strengthens the search ability of the global optimal solution.

In the calculation process, parameters such as mirror length, mirror width, heliostat installation height, absorber position, and heliostat coordinates are introduced as particles. There are usually thousands of mirrors in the heliostat field. If the parameters of each mirror are introduced as particles, the particle swarm size is large, which is not conducive to calculation and solution. Therefore, it is appropriate to simplify the model and reduce the particle dimension by field division and classified discussion in combination with the actual engineering situation.

For example, for the setting of the installation height of the heliostat, the heliostat field can be divided into five regions with unequal step size (100m 80m 40m 20m 10m) according to the distance from the heliostat base to the absorption tower, as shown in Fig.8.

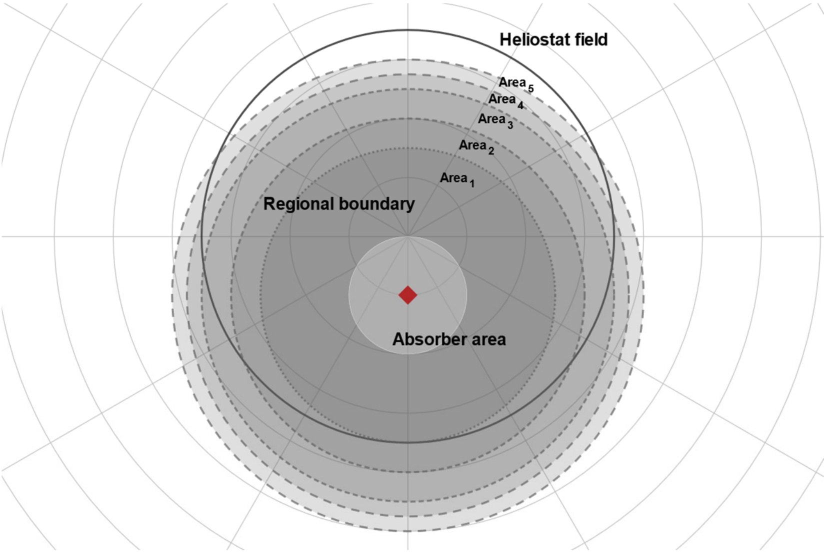

Fig. 8 Heliostat field plane partition diagram

The closest range to the absorption tower is the first area. The initial installation height of the heliostat is set to 2m, and the installation height difference between adjacent fields is. In order to reduce the loss of shadow occlusion, the installation height should gradually increase with the step from the inside to the outside of the field. Here, as a new particle, the optimization model is introduced to solve the optimal solution of the installation height. The processing of mirror size can also be carried out according to the partition of this field.

The particle setting of PSO-GA algorithm is efficient and flexible. In other aspects, it can also be adjusted according to the actual situation to further reduce the dimension.

4. Optimal results

If the heliostat installation height of the heliostat field is not considered, the population fitness convergence curve based on the PSO-GA hybrid optimization algorithm is shown in Fig.9. If the installation height of the heliostat field is considered, the convergence curve obtained is shown in Fig.10.

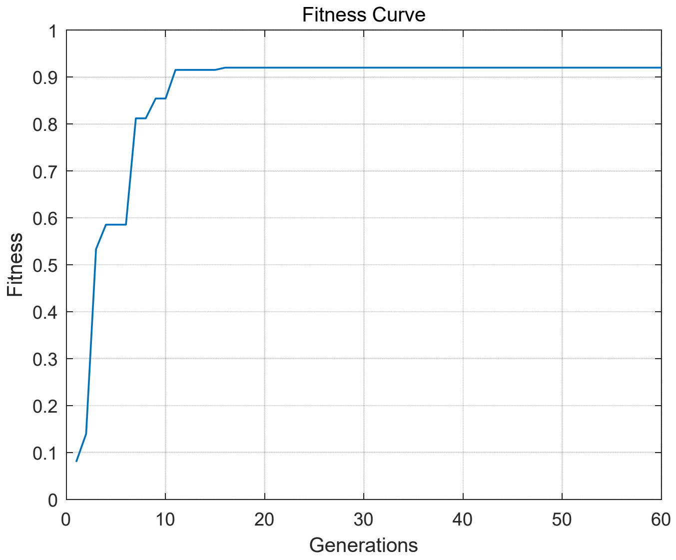

Fig. 9 Population fitness convergence curve

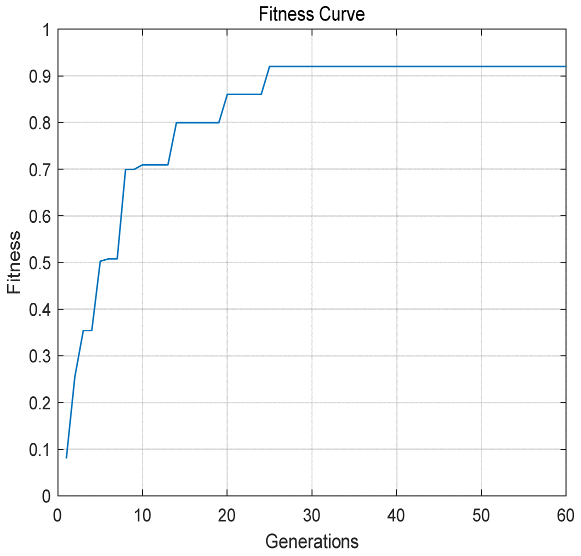

Fig. 10 Population fitness convergence curve

The mirror field parameters is shown in Table 1.Average optical efficiency and average output thermal power of the optimized model is shown in Table 2.

Table 1. mirror field parameters

Position coordinates of absorption tower	Total number of heliostats	Total area of heliostat (m^2)
(0,-246.5)	1315	77848

Table 2. Annual average optical efficiency and average output thermal power

Annual average optical efficiency	Average annual output thermal power (MW)	The average annual output thermal power per unit area of the mirror (kW / m^2)
0.6634	65.1842	0.8311

5. Conclusions

This work provides a new scheme for the optimal design of tower solar power generation system. When calculating the comprehensive optical efficiency of the mirror field, the Monte Carlo algorithm and the HFLCAL calculation model are used to improve the calculation accuracy of the comprehensive optical efficiency. In the design of heliostat field layout and heliostat parameters, the high-efficiency mirror field EB layout is used as the basic mirror field, and the basic mirror field layout satisfying the conditions is selected by the traversal algorithm combined with the constraints under the actual engineering application requirements. Then, the undetermined heliostat size, absorption tower position, and heliostat installation height are used as particles, and the PSO-GA algorithm is used to solve the optimal situation. The SPT system performance using this optimization scheme will be significantly improved. At the same time, the model has high accuracy and fast optimization speed. In the future work, the optimization model can integrate the actual plane concave and convex situation of the heliostat, the final power production and the investment cost of the SPT system, so as to further improve the optimization model.

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