Research on the Position Optimization of Tower Solar Heliostat Field Based on Optical Efficiency

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Abstract. Tower solar thermal power generation technology has multiple advantages such as high efficiency, environmental protection, rich resources, and economic feasibility, which is an important part of clean energy development. However, the power efficiency of tower solar thermal power generation system has obvious fluctuation and instability due to the arrangement mode, the size of each mirror and the distance between them. In the heliostat field, if all the heliostats have the same size and installation height, how to determine the location of the absorption tower and the location and size of the heliostat to maximize the annual average heat output per unit mirror area is a problem to be solved. The Campo layout is first used to generate the dense heliostat field as the initial mirror field before optimization. The optimized arrangement of the Campo layout is obtained by changing the distance between the heliostat and the central absorption tower and the distance between the heliostat and the adjacent heliostat. Secondly, the position coordinates of the initial absorber and the size of the heliostat were taken as decision variables. Taking the actual situation and the comprehensive efficiency of the heliostat field as the basic constraints, the constraint of the number of the heliostat is further analyzed. The optimization model was established by taking the formula of annual average thermal power output per unit mirror area as the objective function. In the Campo layout, the adaptive gravitational search algorithm is used to solve the experiment, and finally the relevant parameters under the optimization arrangement are obtained, which maximizes the annual average thermal power output per unit mirror area when the helostat field reaches its rated power.

Keywords: Adaptive gravitational search algorithm, Campo layout, Optical efficiency, Tower solar power system.

1. Introduction

At the beginning of the twentieth century, the world began to develop and explore a series of new renewable energy sources such as solar energy, wind energy, hydrogen energy, geothermal energy [1] and so on. As one of the new energy sources, solar energy, with its advantages of cleanliness and low cost, has become a key energy object for global development [2]. In the early stage of solar energy development, people mainly use photovoltaic power generation with photoelectric effect to collect and utilize solar energy [3], but with the radiation utilization rate can't be improved, photovoltaic power generation brought about by the environmental pollution and other problems bin to step to, the photothermal power generation has begun to enter into people's vision.

At present, photothermal power generation is mainly divided into point-focused power generation and line-focused power generation [4]. tower-type photothermal power generation system as one of the ways to utilize solar power generation, because of its high efficiency, the absorption tower can withstand a large temperature range, applicable to a variety of working conditions [5] is widely used. And the investment cost of the concentrating solar collector system, which is based on the heliostat mirror field, collector tower and heat absorber, accounts for more than half of the total investment of the tower solar thermal power plant [6]. Therefore, the optimization of the mirror arrangement of the heliostat mirror field and the selection of different mirror installation heights and sizes are of great practical significance.

At the present stage, most of the fixed-sun mirror fields are arranged in radial staggered radial grids [7]. In recent years, scholars in various countries have studied the optimization of the arrangement of heliostat mirror field to improve the comprehensive utilization efficiency of solar energy. Zhou Zhi et al. optimized the overall photothermal conversion efficiency to reach the highest by using the gradient descent method through the bionic-type arrangement method [8]. Yang Hongtao et al. simulated and optimized the multifocal point model through BP neural network and improved genetic algorithm to find the parameters that can make the heat absorber work safely and efficiently [9]. Caixia Lu et al. simulated the relevant parameters of Gemasolar power station in Seville by radial staggered radial grid arrangement to obtain the optimized arrangement of radial spacing of heliostats [10]. The optimization study of the relevant equipment for tower solar thermal power plant systems has been more mature, but the optimization study of the height, size, position and number of different mirrors between different mirrors in the heliostat field, such as the refinement parameters, is still in its infancy. The changes of these indexes will have a significant impact on the comprehensive utilization rate of heliostat mirrors.

In this paper, the annual average output thermal power per unit mirror area of the heliostat mirrors in the heliostat field is used as a reference index to calculate the instantaneous optical efficiency of each heliostat using the factors of truncation efficiency, cosine efficiency, and shadow shading efficiency. The Campo layout [11] is used as the initial heliostat field so that all the heliostats have variable but identical dimensions and mounting heights, and the radial staggered radial grid arrangement is optimized, and parameters such as the position coordinates of the absorber tower, heliostat dimensions and mounting heights, number of heliostats, and position of heliostats are taken as decision variables, so that by changing the layout of the heliostats, the distances of the heliostats from the central absorber tower or the distances of the heliostats from adjacent heliostats can be changed, thus improving the optical efficiency by reducing the shading ratio. mirrors, so that the optical efficiency of the mirror field can be improved by reducing the shading rate, and the annual average output thermal power per unit mirror area can be increased. The solution is combined with the adaptive gravitational search algorithm [12].

2. Relevant theory

First calculate the optical efficiency of the heliostat η_i

$$\eta_{imn} = \eta_{sbi}\eta_{icos}\eta_{ati}\eta_{trunci}\eta_{ref} \tag{1}$$

Where η_{sbi} is the shading occlusion efficiency. The mirror area of any one fixed-sun mirror is divided into a number of sufficiently small area micro-element ds_i, can be calculated to the incident light and the absorption tower plane intersection of the area of micro-elements, at the same time can be obtained incident light, reflected light and the mirror field of any one of the other fixed-sun mirror coordinates of the intersection of fixed-sun mirrors, fixed-sun mirrors on the *i* of all the area of micro-elements that can be received light can be obtained by the sum of the area of the effective acceptance of the light area can be obtained for the efficiency of the incident light for the

$$\eta_{1i} = \frac{2 \cdot K_1 \cdot ds_i}{DM_i^2 sin2\beta_i} \tag{2}$$

Where K_1 is the number of area microelements that can receive the light. Similarly, the total area of all effectively reflected light can be found, then the reflected light efficiency is

$$\eta_{2i} = \frac{2 \cdot K_2 \cdot ds_i}{DM_i^2 sin2\beta_i} \tag{3}$$

Where K_2 is the number of area microelements capable of reflecting sunlight to the collector. From Eqs. (2) and (3), the final shadow shading efficiency is found to be

$$\eta_{sbi} = \eta_{1i} \times \eta_{2i} \tag{4}$$

η_{icos} is the cosine efficiency, let the angle of incidence of sunlight to the *i*th heliostat be θ_i, is the angle between the incident light line and the normal vector of the surface of the heliostat and the sun's altitude angle α_s the sun's azimuthal angle γ_s to satisfy the following relationship:

$$sin\alpha_s = cos\varphi cos\delta cos\omega + sin\varphi sin\delta, cos\gamma_s = \frac{sin\delta - sin\alpha_s sin\varphi}{cos\alpha_s cos\varphi} \tag{5}$$

Where φ is the local latitude, ω is the solar time angle, and δ is the solar declination. were

$$\omega = \frac{\pi}{12}(ST - 12), sin\delta = sin\frac{2\pi D}{365} \cdot sin(\frac{2\pi}{360} \cdot 23.45) \tag{6}$$

Where *ST* is the local time and *D* is the number of days with spring equinox as day 0. Then the vector of incident light direction is

$$\vec{I} = (cos\alpha_s sin\gamma_s, -cos\alpha_s cos\gamma_s, -sin\alpha_s) \tag{7}$$

Let h_t be the height difference from the center of the heliostat to the center of the collector, which is $80 - 4 = 76m$. Then the unit vector of the reflected light at any point on the heliostat with coordinates (x_i, y_i, h_i) is

$$\vec{R} = (\frac{-x}{\sqrt{x^2+y^2+h_t^2}}, \frac{-y}{\sqrt{x^2+y^2+h_t^2}}, \frac{h_t}{\sqrt{x^2+y^2+h_t^2}}) \tag{8}$$

Then the angle of incidence θ_i can be expressed as

$$\theta_i = \frac{1}{2}arccos(-\vec{I} \cdot \vec{R}) \tag{9}$$

The cosine efficiency is then found to be

$$\eta_{icos} = cos\theta_i \tag{10}$$

η_{trunci} is the collector truncation efficiency. in the accurate sun-earth model, the direct radiant light from the sun that strikes a point on the horizontal plane of the earth is not a parallel beam, but a conical light, and the cone angle of the sun's rays is $2\varepsilon \approx 9.3mrad$. at the same time, since all points on the sun's surface emit light in all directions, the the image of the sun observed at a point on the earth is circular. However, the image is not uniform and is called Solar Disk, giving an approximate representation of the image energy distribution function:

$$f(\alpha) = \begin{cases} S_0\{1 - \lambda(\frac{\alpha}{\alpha_s})^4\}, \alpha \leq \alpha_s \\ 0, \quad \alpha \geq \alpha_s \end{cases} \tag{11}$$

Where $f(\alpha)$ represents the energy flow density at any point in the observed image, $\lambda = 0.5138$ as a constant, α_s that is, half of the conical angle of light as $\varepsilon = 4.65$mrad α is the angle of the observation point to the sun at any point in the sun and the center of the sun line respectively. S_0 is the same as $f(\alpha)$. S_0 has the same unit and the value depends on the distance of the observation point from the sun. According to the optical reflection theorem, the incident light at a point on the heliostat is still conical after reflection. The truncation efficiency is related to the distribution of the reflected light from the heliostat on the collector, and the divergence of the light causes the energy on the collector to obey

$$F = S * P \tag{12}$$

Where "*" denotes convolution, *P* is the area formed by the projection of the heliostat mirror onto the collector plane, and *S* is the Solar Disk distribution with the distance from the mirror to the collector. Firstly, the distribution of a single conical beam of light is obtained, while considering that the sunlight is oblique to the mirror surface, after which multiple conical beams of light are superimposed, and finally the imaging superposition of multiple heliostats is carried out. See figure 1 below.

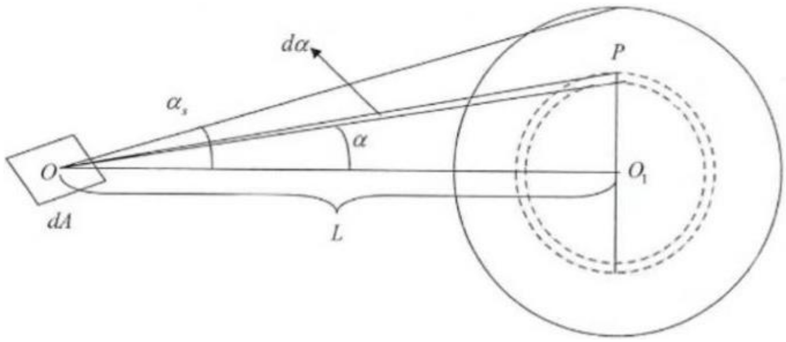

Figure 1. Schematic diagram of reflected light from a specular microelement

The microelement reflecting light with area *dA* in Fig. 1 is represented by a cone of light, and the outermost circle represents the range of the spot illuminated by the cone of light, with OO_1 perpendicular. In the light spot with *O* connected to OO_1 at an angle α of a circle, with the microelement method to express the area of this dashed circle is

$$dS = \pi(R_1^2 - R_2^2) = \pi L^2[tan^2(\alpha + d\alpha) - tan^2(\alpha)] \tag{13}$$

Where R_1 and R_2 are the radii of the outer and inner circles, respectively, and $d\alpha \approx 0$, so that we have

$$dS = 2\pi L^2 \cdot tan(\alpha)\, d\alpha \tag{14}$$

Then the energy of the whole spot is

$$E = \int_0^{\alpha_s} f(\alpha) \cdot 2\pi L^2 \cdot tan(\alpha) d\alpha = 2\pi L^2 S_0 \int_0^{\alpha_s} [1 - \lambda(\frac{\alpha}{\alpha_s})^4] \cdot tan(\alpha) d\alpha \tag{15}$$

Where $f(\alpha)$ is the Solar Disk approximation, the total spot energy can also be

$$DNI \times dA = 2\pi L^2 S_0 \int_0^{\alpha_s} [1 - \lambda(\frac{\alpha}{\alpha_s})^4] \cdot tan(\alpha) d\alpha \tag{16}$$

The couplings (15) and (16) can be obtained as S_0

$$S_0 = 1.206 \times \frac{DNI \times dA}{\pi tan^2(\alpha_s) L^2} \tag{17}$$

Using Eqs. (11) and (17), the energy flow density *I* at each point in the spot can be found, and there is a relationship between the energy flow density and the truncation efficiency

$$I = DNI \cdot \eta_{trunci} \tag{18}$$

In summary, the collector truncation efficiency η_{trunci} can be obtained by combining Eqs. (11), (17) and (18). And the specular reflectivity efficiency satisfies: $\eta_{ref} = 0.92$. The atmospheric transmittance η_{ati} calculation relationship [13] is

$$\eta_{ati} = 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} \times d_{HR}^2 \qquad (d_{HR} \le 1000) \tag{19}$$

Combining equations (1), (4), (10), (18) and (19), the optical efficiency of a certain heliostat can be found. Accordingly, the annual average optical efficiency can be obtained

$$\eta_{year} = \frac{1}{1746 \times 60} \sum_{i=1}^{1746} \sum_{m=1}^{12} \sum_{n=1}^{5} \eta_{imn} \sum_{i=1}^{1746} \tag{20}$$

Next, the average annual thermal power output per unit of mirror area is calculated and can be expressed as

$$E_{year} = \frac{1}{60} \sum_{m=1}^{12} \sum_{n=1}^{5} E_{field_{mn}} \tag{21}$$

Where E_{field} is the instantaneous output thermal power of the heliostat field, denoted as

$$E_{field} = DNI \cdot \sum_{i=1}^{1746} A_i \eta_i \tag{22}$$

Where A_i is the light harvesting area of the ith heliostat, η_i is the optical efficiency of the ith heliostat, and *DNI* is the normal direct radiant irradiance, which can be approximated by the following formula[14]

$$\begin{gathered} DNI = G_0 (a + b e^{-\frac{c}{sin\alpha_s}}) \\ a = 0.4237 - 0.00821(6-H)^2 \\ b = 0.4237 - 0.00821(6-H)^2 \\ c = 0.4237 - 0.00821(6-H)^2 \end{gathered} \tag{23}$$

Where G_0 is the solar constant, which takes the value of 1.366kW/m^2, and H is the altitude. According to Eqs. (20)-(23), let S_m be the sum of all the heliostat light-gathering areas, expressed as

$$E_{single} = \frac{E_{year}}{S_m} \tag{24}$$

Then the average annual thermal power output per unit mirror area can be expressed as

$$S_m = \sum_{i=1}^{1746} S_i \tag{25}$$

Finally, an optimization model is built with a Campo layout, starting with the first heliostat in the due north direction of the innermost circle, and providing for the transformation of the region when the azimuthal spacing between adjacent heliostats in the last row of the previous region layout reaches two-thirds of the heliostat's characteristic diameter. And so on, generating a dense heliostat field. Wherein the characteristic circle refers to a circular region that is related to the size of the heliostat and satisfies the safety distance of the heliostat. The azimuthal angle between the centers of adjacent heliostats can be obtained as

$$\Delta\alpha_1 = 2arcsin(\frac{DM}{2R_1}), DM = DH + D_s \tag{26}$$

Where the diameter of the characteristic circle of the heliostat is denoted as *DM*, the radius of the nth row of aligned heliostats from the center point is denoted as R_n, the safety distance is denoted as D_s, the length of the diagonal of the heliostat is denoted as *DH*, and the azimuthal angle between the neighboring heliostats in the first row is denoted as $\Delta\alpha_1$. It can be seen that, by the staggered arrangement of the odd-numbered rows and the even-numbered rows, the numbers of the heliostats of the rows within the same region are the same, and the radial distances of the neighboring heliostats of the same rows are the same. Make a schematic diagram of the campo layout as shown in Figure 2 below.

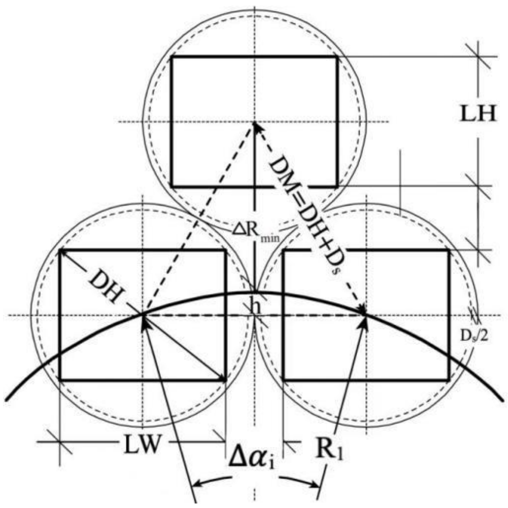

Figure 2. Schematic of the geometrical relationship between neighboring rows of fixed-heaven mirrors under Campo arrangement

From Fig. 2, the minimum increment of the radius of adjacent rows is calculated from the value of the half-angle cosine of the angle formed by the line joining the centers of any of the heliographs and the centers of the two heliographs tangent to its preceding row as

$$\Delta R_{\mathrm{min}i} = DM \cdot cos\tau - h_i \tag{27}$$

Where $cos\tau$ refers to the value of the half-angle cosine of the angle formed by the line connecting the centers of any heliograph and the centers of the two heliographs tangent to the preceding row; h_i refers to the difference between the line connecting the centers of the two adjacent heliographs in the preceding row and the radius of that row; and *DM* refers to the diameter of the characteristic circle. The radius of each row can be derived from the previous row, i.e.

$$R_{i+1} = R_i + \Delta R_{\mathrm{min}i} \tag{28}$$

The distance between the centers of any adjacent heliostats in row *i* is

$$L_i = 2R_i \cdot \sin\left(\frac{\Delta\alpha_1}{2}\right) \tag{29}$$

The half-angle cosine of the angle formed by the line joining the centers of two fixed-sun mirrors tangent to the center of any fixed-sun mirror and its preceding row is given by

$$cos\tau = \sqrt{1 - \left(\frac{L_i}{4R}\right)} \tag{30}$$

The difference between the line connecting the centers of two adjacent heliographs in the previous row and the radius of that row is

$$h_i = R_i - \sqrt{R_i^2 - \left(\frac{L_i}{2}\right)^2} \tag{31}$$

The arrangement can be arranged in this way to obtain a dense fixed heliostat field centered on the collector tower and starting from a radius of one hundred meters. This is then used as the initial heliostat field and optimized using an adaptive gravitational search algorithm.

3. Experiment

Decision variables:

Since it is to design the parameters of the heliostat field so that the annual average thermal power output per unit mirror area is as large as possible, the absorption tower position coordinates, heliostat dimensions, mounting height, number of heliostats, and location of heliostats are used as decision variables, i.e., the decision variables are: (x_0,y_0), *LW*, *LH*, h_i, *N*, (x_i,y_i).

Objective function:

$$f = \max_{(x_0,y_0)h_i(x_i,y_i)} E_{single} = max\,\frac{E_{year}}{S_m} \tag{32}$$

Where Esingle is the average annual thermal power output per unit mirror area; Eyear is the average annual thermal power output; and Sm is the total area of the heliostat.

Restrictive condition:

Considering the ratio of the finite area of the heliostat field to the area of the heliostat, and the ratio of the rated power to the maximum efficiency of the heliostat can be constrained to the total number of heliostats, and combining with the requirements, the following constraints are derived:

(1) Constraints on the upper limit of the total number of heliostats: The ratio of the estimated total area of the heliostat field to the area of the smallest heliostat is $350 \times 350 - 100 \times 100/(2\times 2) \approx 5000 \gg 1746$, so the upper limit of the heliostat is still 1746;

(2) Lower bound constraints on the total number of fixed-day mirrors:

$$N \geq \frac{60\times10^3}{64\times E'_{single}} \tag{33}$$

It indicates that the ratio of the total number of heliostats greater than or equal to the rated power to the maximum thermal power output of a single heliostat is approximately 147;

(3) Initial radius constraint: R1≥100;

(4) Safe distance constraints: Li≥LH+Ds;

(5) Heliostat height constraints: 2≤hi≤6, hi=hs. (i, s϶(1,1746));

(6) Constraints on the size of fixed-sun mirrors: 2≤LH, LW≤8, LWi=LWs. (i, s϶(1,1746));

(7) Heliostat safety height constraints: $LW/2\leq h_i$.

In summary, the final E_{single} optimization model is constructed as:

$$f = max_{(x_0,y_0)h_i(x_i,y_i)}E_{single} = max\frac{E_{year}}{E_m}$$

$$s.t.\begin{cases} R_1 \geq 100 \\ L_i \geq LH + D_s \\ 2 \leq h_i \leq 6 \\ h_i = h_s \\ \frac{LW}{2} \leq h_i \\ 2 \leq LW, LH \leq 8 \\ LW_i = LW_s \\ \frac{60\times10^3}{64\times E'_{single}} \leq N \leq 1746 \end{cases} \tag{34}$$

4. Results

Firstly, the Campo arrangement of the heliostat field is carried out by using Matlab to obtain the heliostat arrangement of the initial heliostat field. Then make optimization changes to its adjacent region radius and the radius of the characteristic circle of the heliostat to get the coordinated state of the shadow shading efficiency of the heliostat with other efficiencies, to improve the annual average optical efficiency, and to get the larger value of Esingle.

Using the adaptive gravitational search algorithm, the heliostat mirrors in the heliostat field are encoded, and the heliostat field composition data are divided into three parts: one is the radius of the heliostat rows in the mirror field; the second is the region of the heliostat field arrangement and the number of heliostat rows in each region; and the third is the number of heliostats in each row in each region. Among them, the radius of the heliostat rows will be used as the input variable of the algorithm, and the optimization will be solved by changing the value of R_n. Finally, E_{single} is used as the evaluation criterion to assess the rationality of the arrangement, and finally the optimal arrangement scheme is found. The results of the solution are shown in Tables 1 and 2 below.

Table 1. Average optical efficiency and output power table

Average annual optical efficiency	Average annual cosine efficiency	Average annual shadow shading efficiency	Average annual cut-off efficiency	Average annual thermal power output (MW)	Average annual thermal power output per unit area of mirror (kW/m^2)
6.153×10^{-1}	7.532×10^{-1}	9.014×10^{-1}	8.490×10^{-1}	6.215×10^{1}	5.310×10^{-1}

Table 2. Related equipment design parameter table

Absorption tower position coordinates	Size of Fixed Sun Mirror (*W*×*H*)	Installation height of fixed-sun mirror (m)	Total number of heliostats	Total area of the heliostat (m^2)
(0,0,80)	7.75×7.67	4.02	2.036×10^{1}	121040.97

The above results show that the absorption tower in the center of the heliostat field, taking into account the clearance from the ground as well as the convenience of repair and maintenance, mutual shading and other factors, the optimal height of the heliostat installation is 4.02m, the number of surfaces is 2036, at this time, to achieve the maximum unit area of the annual average efficiency.

5. Conclusion

Tower solar thermal power generation has gained wide attention for its advantages of large concentrating ratio, high heat collection temperature and high power generation efficiency. A mathematical model of the concentrating collector system of tower solar thermal power station is established, and the technical and economic evaluation index of the system is constructed to analyze the influence of the change of the parameters of the heliostat on the economy of the concentrating collector system. This paper provides a method to select the optimal arrangement when all the fixed-sun mirror parameters in the fixed-sun mirror field are the same. The results of the study can provide a reference for the selection of the sizes of the solar fixing mirrors in the tower-type solar concentrating collector system and the selection of the relevant parameters of the absorber tower.

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