# Research on Optimization Design of Heliostat Field Based on Ray Tracing

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**Abstract.** In tower-type solar thermal power generation systems, the optical efficiency of the mirror field is the primary factor determining the overall system's power generation efficiency. In order to meet the requirement of a rated power of 60MW with different heliostat sizes and installation heights, optimize the various parameters of the heliostat field, establish a tower-type solar thermal power generation system model, and evaluate the model. Taking the maximum annual average output power per unit mirror area as the optimization objective, through simulation, it is found that the heliostat with a side length of 6 meters, a gradient design of installation height, a regular triangular layout, and the use of ray tracing technology can efficiently capture solar energy. The average optical efficiency, average cosine efficiency, average shadow blocking efficiency, average truncation efficiency, and average thermal power factor per unit area mirror are analyzed. The research results show that there is an optimal combination of absorber northward movement, heliostat size, equilateral triangle arrangement, installation height gradient design, and solar trajectory, which enables the annual average output thermal power to reach or even exceed the rated power of 60MW.This model and algorithm compared and analyzed genetic, greedy, and simulated annealing algorithms on the same dataset. The runtime is approximately 8-10 minutes, with CPU utilization around 60%.

**Keywords:** Ray Tracing Technology, Sensitivity Analysis, Equilateral Triangle Layout, Taichi Technology.

## 1. Introduction

The layout, simulation, and optimization of the heliostat field in tower solar thermal power generation systems are important aspects of research by scholars at present. Reference [1] established a calculation model for the solar altitude angle and azimuth angle, studied the sun position tracking method of the azimuth elevation angle of the heliostat in the coordinate system of the focusing mirror field, and analyzed the factors affecting the focusing efficiency. Reference [2] proposed a thermal efficiency evaluation method based on the difference in normal direct irradiance (DNI) between different dates by analyzing the energy balance during stable operation of the heat absorber. This method requires less control of the heliostat field and does not interfere with the normal operation of the heat absorber. The variation law of heat dissipation loss and thermal efficiency of the heat absorber under different operating conditions was analyzed. Reference [3] adopted a non-contact visual detection method and tested the tracking accuracy of the heliostat. By adjusting the aperture, focal length, magnification, elevation, and azimuth angle of the CCD camera, the target can fill the entire field of view of the camera. Reference [4] proposes a genetic algorithm based pointing point design and optimization control strategy, which transforms the dynamic scheduling problem of tower solar thermal power plants into a genetic algorithm optimization problem. The results obtained from modeling and solving optimize the uniformity of energy distribution on the panel of the heat absorber while ensuring the normal service life of the heat absorber, effectively improving truncation efficiency, in this article, the design of the heliostat still revolves around the absorption tower, and n heliostats will be arranged with m circles of heliostats [5]. The problem is simplified as the size of the same circle of heliostats is the same, while the size of the inner heliostat is the smallest, with a size increment from the inside to the outside; Arrange as densely as possible, ensuring no contact with the ground. The heliostat should be square, with a required size of 2-8m and an installation height of>=4m; Determine the initial size, size increment, and number of inner heliostats, and use this as input data to calculate the heliostat coordinates, heliostat size, and which circle the heliostat is located in. Grid search for the number and area of heliostats, find the maximum annual average output thermal power per unit mirror area, and output the result. This article calculates the optical efficiency, thermal power output, etc. of a heliostat tower power station under various conditions, optimizes the design of the heliostat field, and improves the working efficiency of the heliostat tower power station under certain conditions. (Data sources: https://www.nmmcm.org.cn)

# 2. Model establishment and solution

## 2.1. Model preparation

Take the absorption tower as the coordinate origin, which is the center of the circle. Evenly distribute the heliostats in a circular space and arrange them in an equilateral triangle. Because the size of the heliostat and the height of the mounting plate can be adjusted, this article adopts a gradient from the outside to the inside to lower the installation height [6]. The installation height of the heliostat near the outer edge of the heliostat field is higher, while the installation height of the heliostat near the center of the absorption tower is lower. Simulate and analyze this design scheme using optical simulation software. In the project, solar rays at different time points were simulated to determine how the heliostat focuses on solar energy.

## 2.2. Sun position

Calculating the position of the sun is the key to spotlight simulation, and the position of the sun can be determined by the solar altitude angle and azimuth angle of the observation point. α Represents the angle between the sunlight and its projection on the ground, with a range of 0 to 90 degrees, γ Represents the angle between the projection of sunlight on the ground and the due north direction. The calculation formulas are Formula (1) and Formula (2).

$$sin\,\alpha_s = cos\,\delta\,cos\,\emptyset\,cos\,\omega + sin\,\delta\,sin\,\emptyset \quad (1)$$

$$cos\,\gamma_s = \frac{cos\,\delta - sin\,\alpha_s\,sin\,\emptyset}{cos\,\alpha_s\,cos\,\emptyset} \quad (2)$$

The declination angle of the sun refers to the angle between the line connecting the sun and the center of the earth and the equatorial plane of the earth. The declination angle changes over time, and due to the Earth's annual rotation around the Sun, the point of direct sunlight moves back and forth between the north and south latitudes of the Earth, causing seasonal changes in the position of the Sun. The calculation formula is formula (3).

$$sin\,\delta = sin\left(\frac{2\pi}{365}D\right)sin\left(\frac{2\pi}{360}23.45\right) \quad (3)$$

The solar time angle is the time angle at the center of the sun's surface, which is a parameter describing the apparent motion of the sun. It is defined as the angle from the observation point of the celestial meridian along the celestial equator to the time circle where the sun is located. Due to the fact that the Earth rotates at an angle of 360°, 24 hours a day corresponds to a solar time angle of 15 ° per hour. Among them, if the sun's hour angle at 12:00 noon is set to 0 °, then the sun's hour angle is negative in the morning and positive in the afternoon. The calculation formula is formula (4).

$$\omega = \frac{\pi}{12}(ST - 12) \quad (4)$$

Among α: Sun altitude angle, γ: Sun azimuth, δ: Zodiac Corner (date related), φ: The latitude of the observation point, ω: Suntime angle, δ: Sun declination angle, ST: local time. D: The vernal equinox is the number of days counted from day 0. For example, if the vernal equinox is on March 21st, then April 1st corresponds to D=11.

The above formula can be used to calculate the position of the sun for any given date and observation point. The altitude and azimuth of the sun are crucial for the focusing process of heliostats, as they determine the angle of incidence of sunlight, thereby affecting the reflection and focusing of light.

### 2.3. Optical efficiency of heliostats

During the focusing process, the solar focusing system will face various loss factors, such as the angle of the incident light, atmospheric conditions, the position and characteristics of the heliostat, the receiving area of the heat absorber, and the properties of the mirror surface. To evaluate these losses, this article defines the optical efficiency of a heliostat, which represents the ratio of the actual solar radiation energy received by the heat absorber to the theoretically maximum solar radiation energy that can be received [7]. The optical efficiency includes five aspects: cosine efficiency, atmospheric transmission efficiency, shadow occlusion efficiency, truncation efficiency, and reflectivity, which comprehensively affect the performance of the spotlight system. Optical efficiency of heliostats ŋ the calculation formula is formula (5).

$$ŋ = ŋ_{cos}ŋ_{\alpha t}ŋ_{sb}ŋ_{trunc}ŋ_{ref} \quad (5)$$

Among them, ŋ Cos: cosine efficiency, ŋα t: Atmospheric transmittance, ŋ SB: Shadow occlusion efficiency, ŋ Trunc: The truncation efficiency of the collector, ŋ Ref: Mirror reflectance (usually a constant of 0.92).

(1) Cosine efficiency. In order to effectively focus the sunlight on the receiving surface of the heat absorber, the solar heliostat needs to continuously adjust the angle of its mirror surface to ensure the optimal angle between the incident light and the mirror surface. The optimal angle will cause the projected area of the mirror in the direction perpendicular to the incident light to be smaller than the actual mirror area, resulting in a loss of solar radiation energy, which is called cosine loss. In the solar tower mirror field, cosine loss has a significant impact on optical efficiency [8]. In order to calculate cosine efficiency, this article defines the angle between the incident sunlight and the normal of the heliostat mirror surface ɵ Is the cosine angle, and the cosine efficiency is ɵ the cosine value of an angle can be calculated by the relationship between the incident ray vector and the reflected ray vector. The calculation formula is formulas (6), (7), and (8).

$$ŋ_{cos} = cos\,\theta = \left|\sqrt{(1 + cos(2\theta))/2}\right| = \left|\sqrt{(1 - I \times R)/2}\right| \quad (6)$$

$$I = (-\cos\alpha_s \sin\gamma_{s'} - \cos\alpha_s \cos\gamma_{s'} - \sin\alpha_s) \quad (7)$$

$$R = (-x, -y, H - Z)/\sqrt{x^2 + y^2 + (H - Z)^2} \quad (8)$$

Among them, I am the unit vector of incident light, pointing from the direction of the sun towards the center of the heliostat; R: Reflected light unit vector, pointing from the center of the heliostat to the focal point of the heat absorber; (x, y, z) is the center coordinate of the heliostat; H: The height of the heat absorber's focal point, in meters.

Atmospheric transmittance. When sunlight is reflected, it is affected by various factors such as geographical altitude and atmospheric conditions, such as dust, water vapor, carbon dioxide, etc., resulting in the loss of solar radiation energy when passing through the atmosphere. This loss is called atmospheric transmission loss. The atmospheric transmission efficiency refers to the ratio of solar radiation energy transmitted through the atmosphere to the solar radiation energy reflected by a heliostat. Under clear weather conditions, the atmospheric transmission efficiency is expressed as a function of the distance d from the center of the heliostat to the target point of the heat absorber. The calculation formula is formula (9).

$$ŋ_{\alpha t} = 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} \times d_{HR}^2 (d_{HR} \leq 1000) \quad (9)$$

Where dHR: represents the distance from the center of the mirror to the center of the collector (in meters).

(2) Shadow occlusion efficiency. In the layout of the heliostat field, due to the close distance between the various heliostats, some mirror surfaces may be in the shadow area of adjacent heliostats, or the heliostats may not fully receive sunlight under the obstruction of the absorption tower, resulting in so-called shadow loss. In addition, during the process of sunlight reflecting onto the heat absorber, the light reflected by some heliostats may be cut off by the back of other nearby heliostats, resulting in occlusion loss. This is different from cosine efficiency and atmospheric transmission efficiency, as shadow and occlusion efficiency rely more on the spatial layout relationship between heliostats.

The Ray Tracing algorithm is used to calculate shadow transmittance. The principle of the Ray Tracing algorithm is to track the main ray from the eye to the pixel centerline, then calculate all the intersections between the main ray and the objects in the scene, obtain the closest intersection point from the viewpoint, and calculate the ray casting at the near intersection point based on the local lighting model. The shadow shading determination in this article is achieved by determining whether the light intersects with obstacles and whether it is within a specified height range. Provide the following specific parameters.

P: The starting point of the ray, with coordinates (x, y, z); F2: Direction vector of light rays, coordinates are (x, y, z); H1 and h2: the height range of the heliostat field; r: Obstacle radius.

The shadow masking judgment can be carried out according to the following steps:

① Calculate the intersection point between the light and the obstacle sphere. By solving the intersection point between a ray of light and a sphere, the specific calculation of the intersection point between the spherical equation and the ray equation is achieved.

② Determine whether the coordinate z of the intersection point is within the specified height range [$h_1$, $h_2$]. If it is within the height range, it is considered that there is shadow shading, and the return flag is 1; Otherwise, the return flag is 0, indicating no shading.

This shadow shading determination algorithm is based on the geometric relationship between light and obstacles, and determines the presence of shadow shading by comparing the height range of intersection points. It is achieved by calculating and simulating the altitude angle, azimuth angle, and direct normal irradiance (DNI) of the sun. The calculation of altitude and azimuth angles involves daily and seasonal variations in the position of the sun, while direct normal irradiance is estimated based on atmospheric conditions and altitude. The main loop calculates the shadow occlusion of each pixel by traversing the pixels of the heliostat field. For each pixel, first calculate the distance and direction between the ray and the pixel, and then check for shadow occlusion. If there is no shading, the value of SB will be increased and the trc variable will be accumulated to calculate the collector truncation [9].

Among them, SB: an integer variable used to record whether a shadow exists on a certain pixel. 1 indicates the presence of shadows on the pixel, 0 indicates the absence of shadows on the pixel; TRC: A variable that records the incidence rate, used to represent the proportion of light rays passing through the collector, and represents the transmittance of light rays passing through the collector at a certain pixel, that is, the penetration rate of light rays in the collector. This value is usually used in solar thermal collection systems to calculate energy transfer and loss.

(3) The cutoff efficiency of the collector. Truncation efficiency is the loss of solar energy caused by the failure of the sunlight reflected by the heliostat to fully reach the receiving surface of the heat absorber, known as overflow loss. The main reasons for this overflow loss are the natural divergence of sunlight and the focusing efficiency of the heliostat, which causes the light spot to be too large to fall entirely on the receiving surface of the heat absorber, and the inaccurate focusing point, which causes the light to not be fully concentrated on the receiving surface of the heat absorber. The calculation formula is formula (10).

$$\eta_{trunc} = \frac{\text{The collector receives energy}}{\text{Mirror total reflection energy - Shadow occlusion loses energy}} \tag{10}$$

### 2.4. Annual average thermal power output and unit mirror area annual average thermal power output calculation

From the meaning of the question, it can be inferred that: $\mathrm{DNI} = \mathrm{G}_0\left[\alpha + \mathrm{b}\exp\left(-\frac{\mathrm{c}}{\sin\alpha_s}\right)\right]$; $0.4237 - 0.00821(6-\mathrm{H})^2$; $0.5055 + 0.00596(6.5-\mathrm{H})^2$; $0.2711 + 0.01858(2.5-\mathrm{H})^2$.

The formula for calculating the annual average thermal power output is Formula (11), and the formula for calculating the annual average thermal power output per unit mirror is Formula (12).

$$E_{fieled} = \frac{DNI \cdot \sum_{i=1}^{N} A_i \eta_i}{1000} (kw/m^2) \tag{11}$$

$$E = \frac{E_{fieled} \times 1000}{6 \times 6 \times N \times 5 \times 12} (kw/m^2) \tag{12}$$

After program calculation, the annual average output thermal power of the heliostat field is 22.39994713MW, and the average annual output thermal power per unit mirror is 32.5843kw/m2.

### 2.5. Modeling

(1) The absorption tower is moving northward. Due to its geographical location, moving the absorption tower slightly northward to better capture winter solar energy can help increase the annual heat output.

(2) The size of the heliostat. Choose a heliostat with a side length of 6 meters, which is of moderate size and can provide a good balance between solar capture and system cost.

(3) A regular triangle arrangement. Adopting a regular triangle layout, utilizing equal distances between mirrors to minimize occlusion between them. Automatically form uniform spacing without excessive calculation and adjustment. Easy to expand through modularization to increase system capacity.

(4) Installation height gradient design. Gradually reduce the installation height from the outside to the inside. The installation height of the peripheral heliostat is 6 meters. Lower the height layer by layer inward, with each layer reduced by 1 meter. The installation height of the innermost heliostat is 3 meters.

(5) Sun trajectory analysis. Through ray tracing, it is possible to simulate the sun's trajectory and light angle at different time points throughout the year, which can better understand the position of the sun in different seasons and time points, and adjust the angle of the heliostat.

(6) System optimization. The design of ray tracing technology optimization system, including the size, layout, and installation height of the heliostat. By simulating and analyzing different parameter combinations, find the optimal design solution to ensure that the system can operate efficiently under different conditions.

(7) The analysis results show that. Considered the reflection and refraction of light, as well as the focusing effect on the collector. The design scheme can efficiently capture solar energy for most of the time, with an average annual output thermal power of 60MW or more.

## 3. Model calculation process

(1) Based on known conditions, define the longitude and latitude of the central tower, the solar constant ($kW/m^2$), the number of days passed on the 21st day of each month, and the 5 time points on the 21st day of each month in the program. According to the operation process, first calculate the sun's time angle and declination angle and put the results into the set. Since the problem is given to calculate the 21st day of each month, the calculation of the time angle is to traverse the set of solar time points solar-times, that is, establish the calculation equation according to formula (4), The calculated result is placed in the time angle set omegas, and the condition for the completion of the traversal is the length of solar_times. When the length is 5, the traversal ends; Using the same method, according to formula (3), traverse the set of days for each year on the 21st of each month, DAYS-OF_YEAR, to obtain the declination angle set delta of the sun [10].

(2) The solar altitude angle and azimuth angle are related to the position of the heliostat in the spatial coordinate system. After importing the coordinate data provided in the question, first perform an outer loop on the declination angle set delta, take out the declination angle for each month, and then perform an inner loop on the time angle set omegas. Take out the declination angle and time angle for each time point on the 21st of the month, and take out the corresponding (x, y) coordinates for each heliostat. Calculate each heliostat separately using the declination angle, time angle, and (x, y) coordinates of the heliostat, using formulas (1) and (2) Calculate the altitude and azimuth of the sun, and use the DNI calculation formula for normal direct radiation irradiance provided in the appendix to calculate the DNI for each heliostat at the current time point.

(3) After calculating the solar altitude angle, azimuth angle, and DNI, put them into a set and traverse this set to calculate the shadow occlusion efficiency, cosine efficiency, atmospheric transmittance, and collector truncation efficiency of the current heliostat at that time point. Then, according to formula (5), calculate the optical efficiency and thermal power of the current heliostat.

### 3.1. Result Dataset Analysis

After calculation, the data for 5 time points on the 21st of each month were obtained, and the data was statistically analyzed and averaged. The annual indicator data is shown in Table 1.

**Table 1.** Annual Simulation Results Table

| Annual average optics efficiency | Annual average cosine efficiency | Annual average shadow occlusion efficiency | Annual average truncation efficiency | Annual average output thermal power (MW) | Mirror year per unit area Average output thermal power (kw/m2) |
|---|---|---|---|---|---|
| 0.9653 | 0.7749 | 0.7988 | 0.9091 | 59.6 | 0.4732 |

### 3.2. The relationship between truncation rate and distance azimuth angle

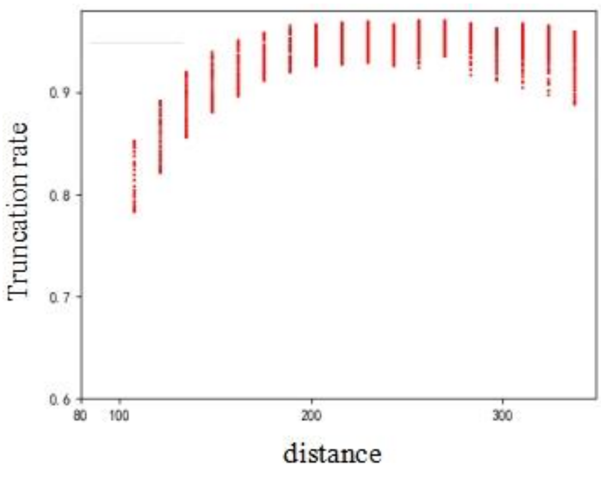


**Figure 1.** Truncation rate and distance

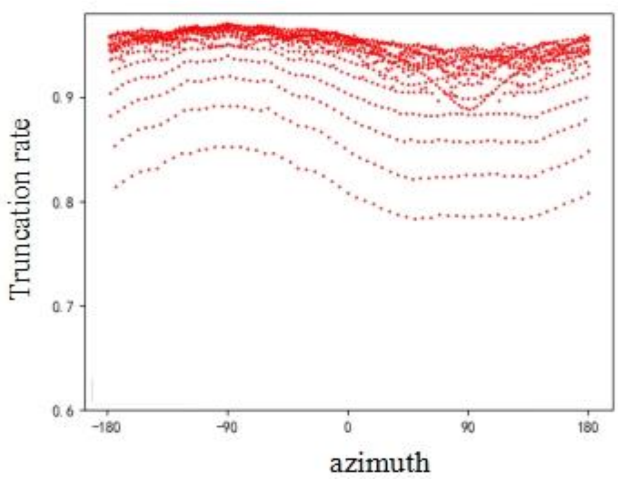


**Figure 2.** Truncation rate and azimuth angle

From Figs 1 and 2, it can be concluded that, when dHR is about 200, $\frac{d_{\eta_{trunc}}}{d_{d_{HR}}} \approx 0$ occurs, and the closer dHR is to 100, the greater the rate of change. Obviously, when optimizing the truncation rate, it is important to consider reducing the distance between the mirror surface and the center of the collector. Within a certain range, the smaller the dHR, the smaller the collector cutoff rate. As shown in Figs 3 and 4, the correlation between truncation rate and azimuth angle is clearly far inferior to the distance from the center of the mirror to the center of the collector.

### 3.3. The relationship between shadow occlusion efficiency and distance and azimuth

The efficiency of shadow occlusion is directly proportional to the distance between the central tower. The closer the heliostat is to the central tower, the higher the efficiency of shadow occlusion. The relationship between the efficiency of shadow occlusion and the orientation of the sun is calculated and fitted by the model, as shown in Fig 3. The efficiency of shadow occlusion is also related to the orientation of the sun. Through the model calculation, the relationship between the efficiency of shadow occlusion and the orientation of the sun is obtained, as shown in Fig 4.

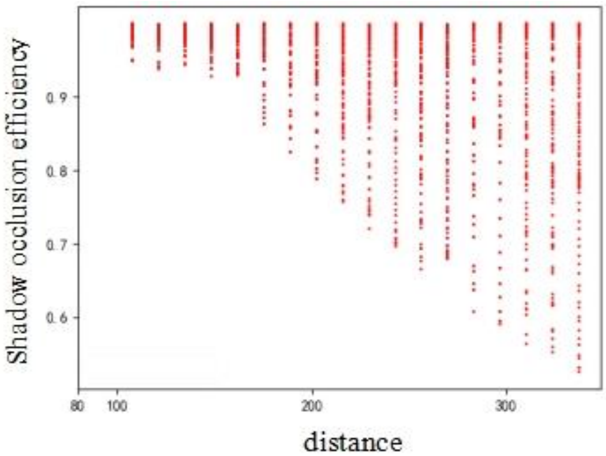


**Figure 3.** Shadow occlusion efficiency and distance

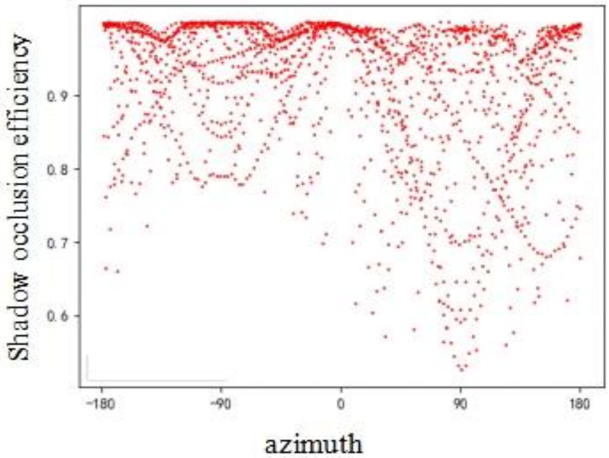


**Figure 4.** Shadow occlusion efficiency and azimuth

### 3.4. The relationship between cosine efficiency and distance and azimuth

The cosine efficiency is known from simulation. When the distance changes between 100 and 300 meters, the error of the cosine efficiency change is basically within an acceptable range, as shown in Fig 5. According to the cosine efficiency calculation formula, the efficiency is lower as it moves further south, as shown in Fig 6.

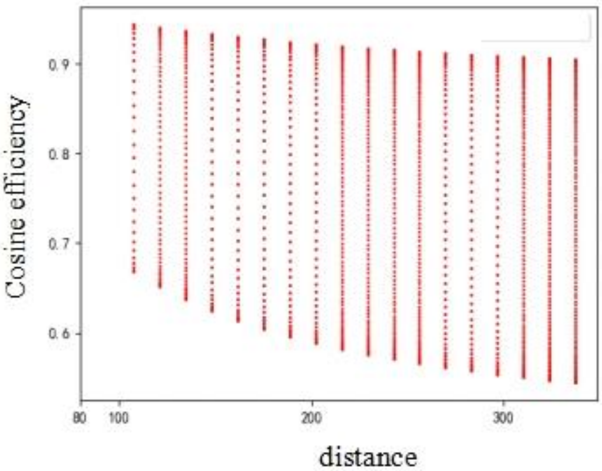


**Figure 5.** cosine efficiency and distance

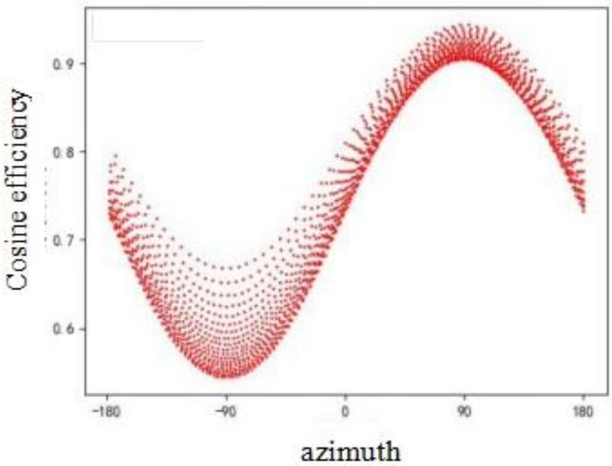


**Figure 6.** cosine efficiency and azimuth

### 3.5. The relationship between atmospheric transmittance and distance and azimuth

The relationship between atmospheric transmittance and distance is not significant. According to the model calculation shown in Fig 7, when the distance increases by 200 meters, the error is also between 0.02 and 0.03. The relationship between atmospheric transmittance and azimuth is also the same, regardless of the angle, it is basically between 0.97 and 0.99, as shown in Fig 8.

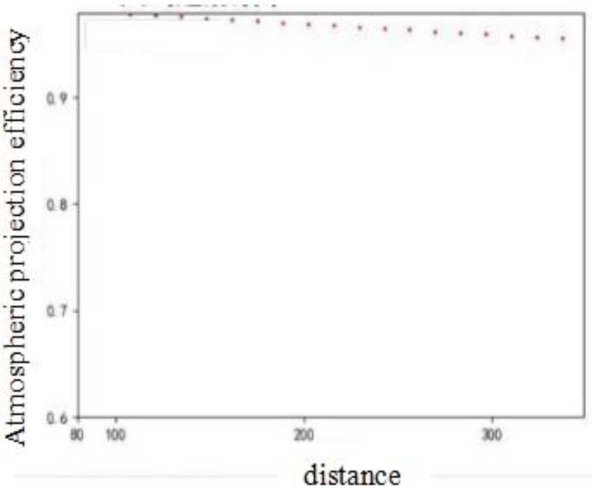


**Figure 7.** Atmospheric transmittance and distance

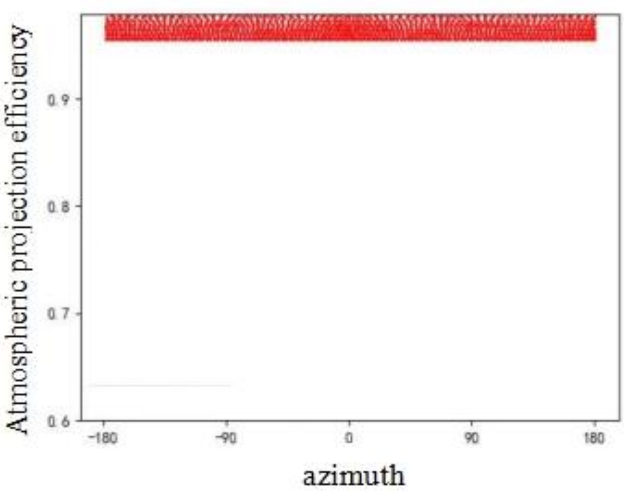


**Figure 8.** Atmospheric transmittance and azimuth

### 3.6. The relationship between total efficiency and distance and azimuth

According to the calculation method of thermal power, the total efficiency is related to the distance between the heliostat and the central tower. According to the model calculation results, as shown in Fig 9, within the range of 100 to 200 meters of the central tower, the trend of efficiency change is between 0.5 and 0.8, while the trend of efficiency change is between 0.1 and 0.7 in the range of more than 200 meters. The relationship with azimuth is also shown in Fig10, ranging from 0.1 to 0.7 in the positive direction and from 0.4 to 0.8 in the negative direction.

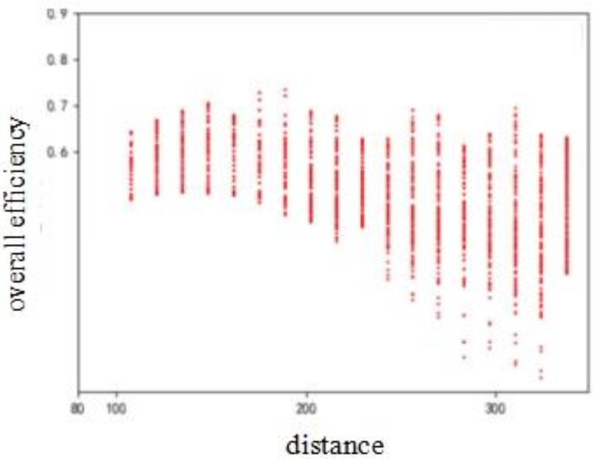


**Figure 9.** Total efficiency and distance

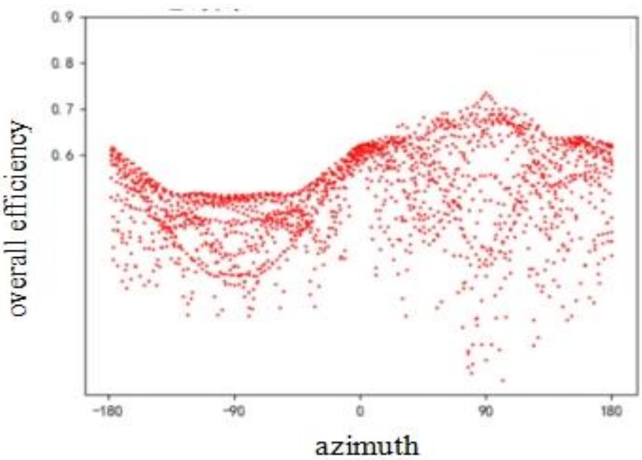


**Figure 10.** Total efficiency and azimuth

### 3.7. The relationship between power per square panel and distance, azimuth angle

According to the calculation method of thermal power, the power per square panel is related to the distance between the heliostat and the central tower. According to the model calculation results, as shown in Fig 11, the power per square panel is generally higher at a distance of about 150m. As the distance increases, the power begins to fluctuate significantly. In the image, it shows an increase in point distance and is more discrete, but it can also be seen that the peak value is also increasing; As shown in Fig 12, the power per square panel exhibits a certain periodicity with respect to the azimuth angle. The power is generally lower when the azimuth angle is -90, and higher when the azimuth angle reaches around 10-20. As the azimuth angle continues to increase, the power begins to fluctuate significantly, reaching its peak at around 90, but at this point, the distance between points is too large and the degree of dispersion is very high.

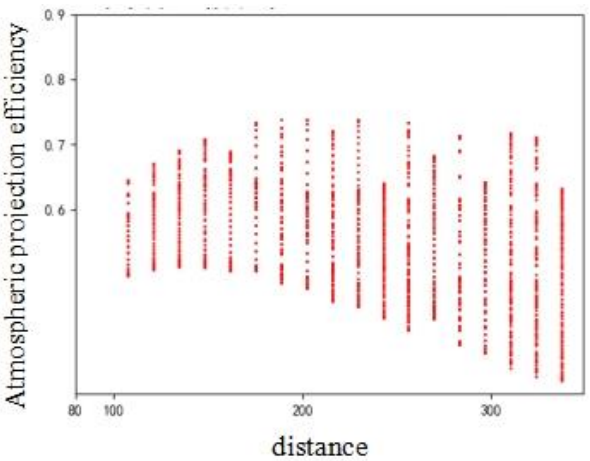


Figure 11. Power per square panel versus distance

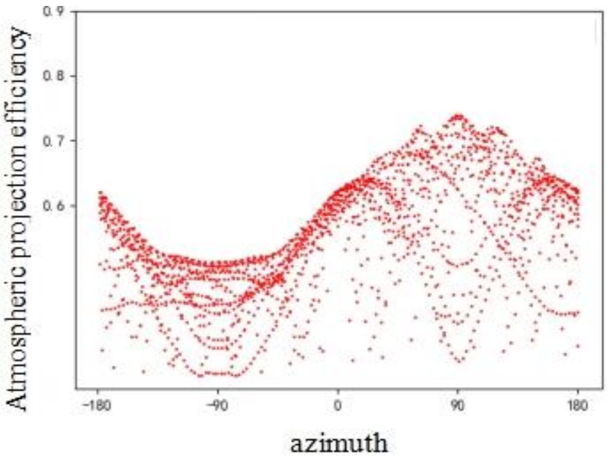


Figure 12. Power per square panel and azimuth angle

## 4. Conclusion

Given the size and installation height of the heliostat, this article designs various parameters for the heliostat field, and requires the designed heliostat field to achieve a rated power of 60MW, and the average annual output power per unit mirror surface area to reach the maximum. We should consider cosine loss, shadow occlusion loss, and truncation efficiency, which are closely related to the position of the sun. Therefore, it is proposed to use ray tracing method to accurately calculate the sunlight situation, and then determine the optimal parameters through simulation. After comparative analysis, the design takes the absorption tower as the origin and places the heliostat field in an equilateral triangle within the surrounding circular range. This can reduce shadow occlusion between heliostats and increase the average output thermal power per unit area.

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