Design of heliostat field based on ray tracing

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Abstract. In the tower solar thermal power generation system, the optical efficiency of mirror field is the primary factor that determines the power generation efficiency of the whole system. Given the size and installation height of heliostat, in order to meet the requirements of rated Power 60MW, the parameters of heliostat field are designed and the model of tower solar thermal power generation system is established. Considering the cosine loss, shadow occlusion loss and truncation efficiency, and knowing that these three points are closely related to the position of the Sun, a method of ray tracing is proposed to calculate the sunshine accurately, the optimum parameters of helioscope field were determined by simulation. The simulation results show that the average thermal power output per unit mirror area can be increased by reducing the shadow occlusion between the heliostats.

Keywords: Ray tracing technology, Sensitivity analysis, Equilateral triangle layout, Absorption tower moving northward.

1. Introduction

In 2020, China clearly set the goals of "peaking carbon emissions" by 2030 and "carbon neutrality" by 2060, with solar energy as an important energy source for strategic goals. Rich solar energy resources plays an irreplaceable and important role in the field of new energy. Tower solar thermal power generation system is an important technology that utilizes solar energy for power generation. 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. Lv Tongxing [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. Zeng Jichuan [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 a 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. Guo Qing [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. This article adopts the ray tracing method to design various parameters of the heliostat field and establish a tower solar thermal power generation system model, while providing the size and installation height of the heliostat to achieve the rated power of 60MW.

2. Model establishment and solution

2.1. Model Preparation

Require the rated annual average output thermal power of the heliostat field to be 60MW, and all heliostat sizes to be 6m×6mThe design parameters for the heliostat field include the position coordinates of the absorption tower, the number of heliostats, and the position of the heliostats, with a height of 6m and an installation height of 4m [4]. Based on the shape and installation height of the heliostat, ensure that it does not touch the ground when rotating around the horizontal axis. Adopting a regular triangle arrangement, evenly distribute the heliostat in a circular area as shown in Fig 1, and consider the distance between adjacent heliostats to ensure that maintenance and cleaning vehicles can freely pass through.

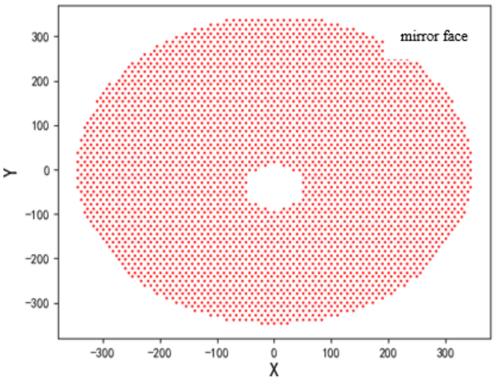

Fig 1. Schematic diagram of mirror installation position.

2.2. Modeling

2.2.1. Establishment of spotlight model

In order to simulate and optimize the focusing subsystem, it is necessary to accurately determine multiple key factors, including the position of the sun, the height of the absorption tower, the type and size of the collector, as well as the coordinates and specification parameters of the heliostat [5]. These factors collectively affect the focusing process, including how to adjust the angle of the heliostat to focus sunlight on the receiving surface of the collector and form the required imaging spot. Therefore, before conducting simulation of the focusing subsystem, it is necessary to accurately understand and define these key parameters. For the sake of analysis, a mirror field coordinate system (xyz) is established with the absorption tower as the origin coordinate, where the x-axis represents the due east direction, the y-axis represents the due north direction, and the z-axis represents the upward direction perpendicular to the ground. The coordinate system of the heliostat field is shown in Fig 2.

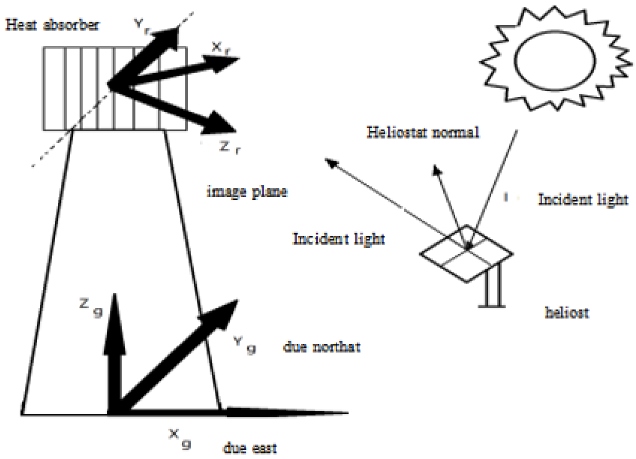

Fig 2. Heliostat Field Coordinate System.

2.2.2. Mirror field layout

The purpose of designing a heliostat layout is to increase the rated annual average output power of the heliostat field. This article sets the absorption tower as the coordinate origin (i.e. the center), and evenly distributes the heliostats in a circular space, arranged in equilateral triangles to minimize obstruction between mirror surfaces and allow for denser placement of heliostats. The output thermal power of the heliostat field is formula (1).

$$\eta_{field} = DNI \times \sum_{i}^{N} A_i \eta_i \tag{1}$$

Among them, DNI: normal direct radiation irradiance; N: Total number of heliostats (unit: face); AI: The lighting area of the i-th heliostat (unit: m2); ŋ i: The optical efficiency of the i-th mirror. This article uses mathematical simulation and optimization techniques, combined with the characteristics of the site and optimization objectives, to find the optimal design of the heliostat field. By adjusting the position, total number, size, and installation height of heliostats, different design schemes can be obtained and their performance can be evaluated [6].

In the northern hemisphere of the Earth, the sun usually rises and sets in the south, with more abundant sunlight in the south. The altitude angle of the sun and its position in the sky will affect the angle of incidence of light from the sun, which is related to the cosine law. The cosine law indicates that the cosine value between the incident angle and the surface normal determines the refraction and reflection of light. When the sun is located in the south of the sky, the incident angle is smaller and the cosine value is larger. That is, light from the sun shines on the surface at a more vertical angle, resulting in stronger sunlight. Therefore, when the sun is located in the south of the northern hemisphere, the cosine effect is greater, especially in clear weather conditions.

2.3. Simulation and Analysis

This article considers moving the absorption tower northward, reducing the reflective mirror surface area, expanding the central area, and adjusting the distance between the heliostat and the collector to calculate the rated power of the heliostat field. By calculating the power of the collector at different azimuth angles and visually analyzing the relationship between power and azimuth angle, as shown in Fig 3.

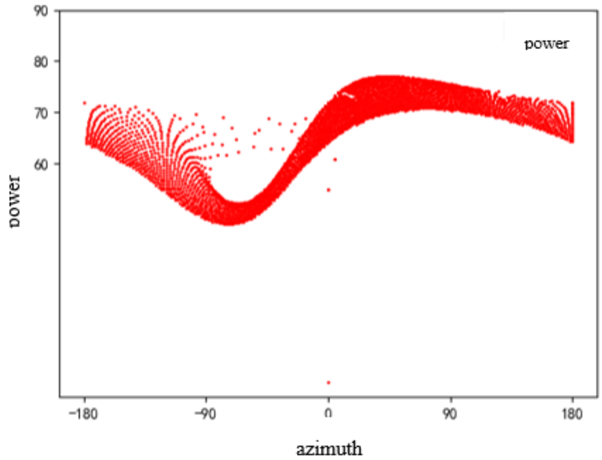

Fig 3. Power and azimuth angle.

The power of the collector was calculated by simulating the incidence of sunlight from different positions and directions of the heliostat. As shown in Fig 3, when the azimuth angle is around 45, the power reaches its maximum value. As the azimuth angle increases and the absolute value of azimuth decreases, the power also decreases from (-180, -80). Then, in the (-80, 45) range, as the azimuth angle increases and the absolute value of the azimuth angle increases, the power also increases. And it shows periodic changes [7]. The relationship between power and azimuth can be used to determine how the performance of a collector changes at different times and seasons. This helps optimize the orientation of the heliostat and the design of the collector to maximize the capture of solar energy.

By calculating the collector power at different distances between the heliostat and collector, and visually analyzing the relationship between power and distance, as shown in Fig 4. Usually, there is a certain relationship between the power of the collector and the distance of the heliostat. This relationship may be nonlinear, depending on the design of the heliostat and collector, as well as the angle of incidence of sunlight. From Fig 4, it can be seen that as the distance increases, the power change of the collector is not very significant. However, if the distance is too small, the efficiency will decrease sharply [8]. It can be seen that optimizing the arrangement distance of the heliostat is very important. And the maximum power is achieved at a distance of around 200.

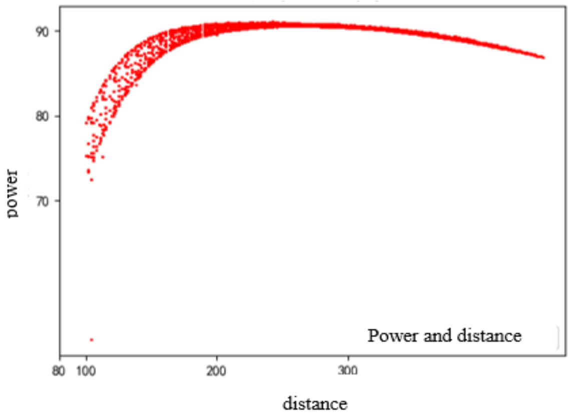

Fig 4. Power and Distance.

The absorption tower is moving southward, and the average efficiency of the heliostat field has been improved [9]. Through simulation, it was found that the smaller the mirror surface, the higher its truncation rate, but the improvement is limited. Moreover, the dense coverage of 4 * 4 mirrors cannot meet the design requirement of 60MW. Therefore, the mirror size adopts 5 * 5 or 6 * 6 mirrors, and the height of 4m has little or no effect [10]. Arrange the heliostat field as shown in Table 1, using 3471 pieces of 6m × A 6m heliostat is arranged around a circular area around the absorption tower in an equilateral triangle, and the average annual output thermal power per unit area of the mirror can be calculated to be 0.46kw/m2. The rated average output thermal power of the program operation of the heliostat field is close to the required 60MW, indicating that its design meets the requirements, as shown in Table 1.

Table 1. Design Parameters Table.

Absorption tower position coordinates	Heliostat size (width x height)	Installation height of heliostat	Total number of heliostat faces	Total area of heliostat(m^2)
(0, -76.903)	6x6	4	3471	124956

3. 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 indicator data for each factor are shown in Table 2, and the indicator data for the whole year are shown in Table 3.

Table 2. Simulation Results on the 21st of Each Month.

date	Average Optics efficiency	average cosines efficiency	Average Shadow Occlusion efficiency	Average truncation efficiency	Annual average thermal power output per unit area mirror (kw/m2)
January 21st	0.9652	0.7545	0.7606	0.8960	0.3886
February 21st	0.9652	0.7711	0.8008	0.9010	0.4584
March 21st	0.9652	0.7808	0.8067	0.9023	0.4873
April 21st	0.9652	0.7921	0.8090	0.9057	0.5193
May 21st	0.9652	0.7969	0.8099	0.9093	0.5360
June 21st	0.9652	0.7980	0.8102	0.9107	0.5410
July 21st	0.9652	0.7969	0.8099	0.9093	0.5358
August 21st	0.9652	0.7919	0.8089	0.9055	0.5181
September 21st	0.9652	0.7751	0.8039	0.9015	0.4708
October 21st	0.9652	0.7588	0.7752	0.8982	0.4796
November 21st	0.9652	0.7460	0.7252	0.8900	0.3428
December 21st	0.9652	0.7445	0.7171	0.8884	0.3335

Table 3. 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)	Annual average thermal power output per unit area mirror (kw/m2)
0.9651	0.7525	0.9190	0.9343	59.6	0.5503

3.1. Relationship between truncation rate and distance and azimuth

The relationship between truncation rate, distance, and azimuth is shown in Figs 5 and 6.

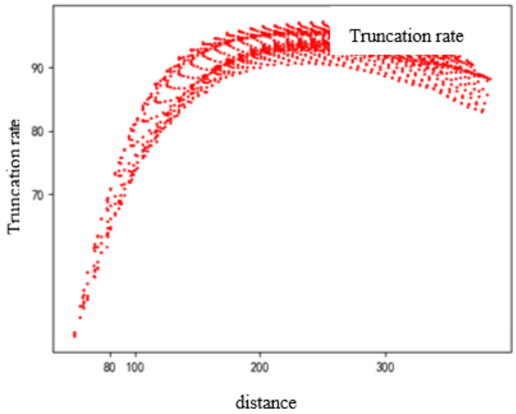

Fig 5. Relationship between distance and truncation rate.

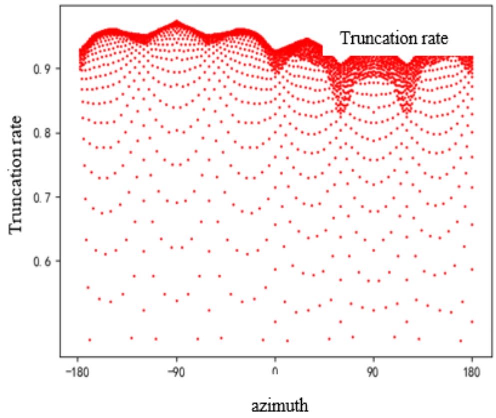

Fig 6. Relationship between azimuth and truncation rate.

3.2. The relationship between shadow occlusion efficiency and distance azimuth angle

The relationship between shadow occlusion efficiency and distance azimuth is shown in Figs 7 and 8.

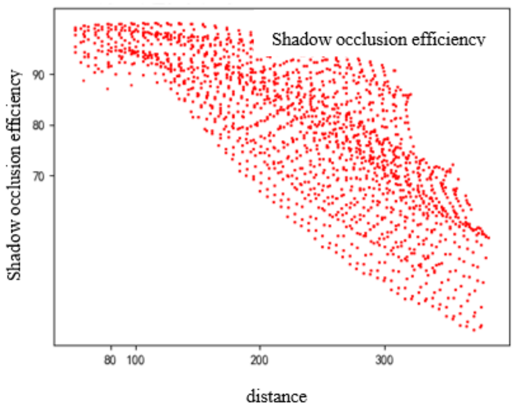

Fig 7. Relationship between distance and shadow occlusion efficiency.

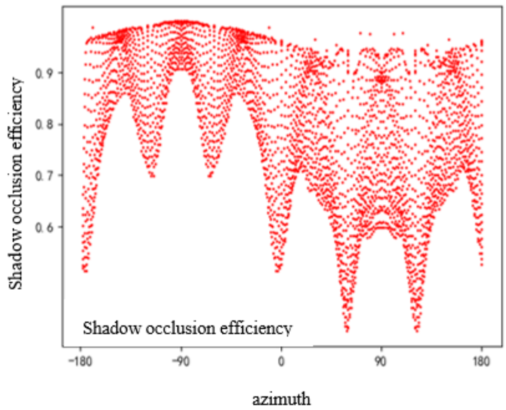

Fig 8. Relationship between azimuth and shadow occlusion efficiency.

3.3. Relationship between cosine efficiency and distance azimuth

The relationship between cosine efficiency and distance azimuth is shown in Figs 9 and 10.

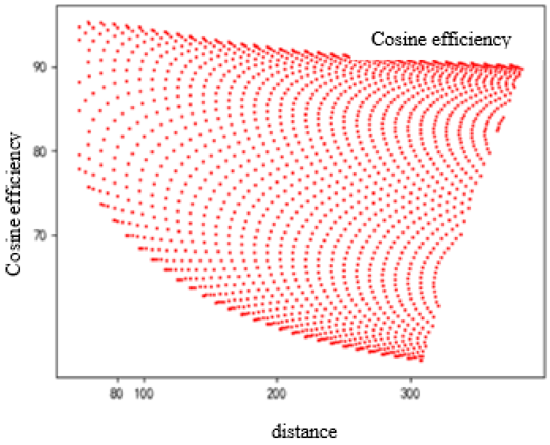

Fig 9. Relationship between distance and cosine efficiency

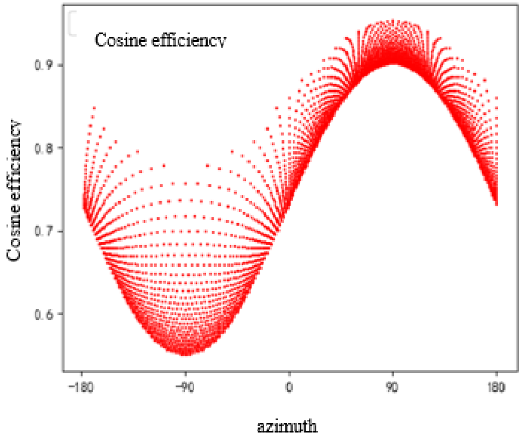

Fig 10. Relationship between azimuth and cosine efficiency

3.4. Relationship between atmospheric transmittance and distance azimuth angle

The relationship between atmospheric transmittance and distance azimuth is shown in Figs 11 and 12.

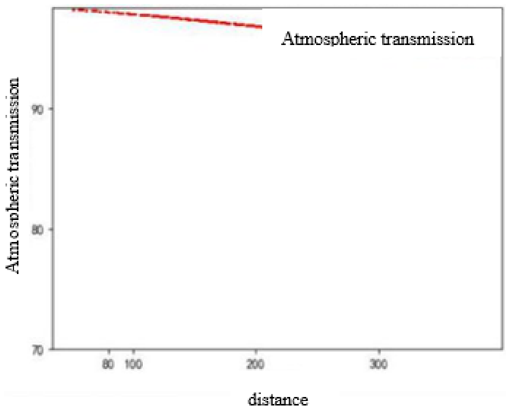

Fig 11. Relationship between distance and atmospheric projection efficiency

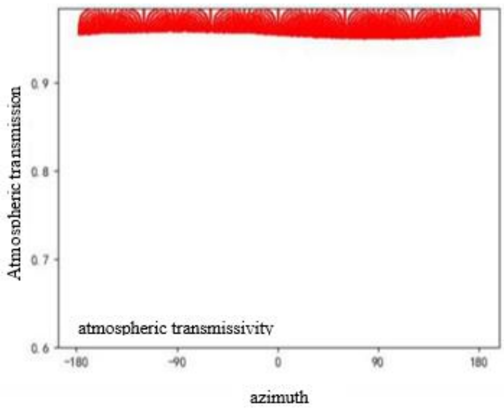

Fig 12. Relationship between azimuth and atmospheric projection efficiency

3.5. Relationship between power per square panel and distance azimuth angle

The relationship between power per square panel and distance azimuth is shown in Figs 13 and 14.

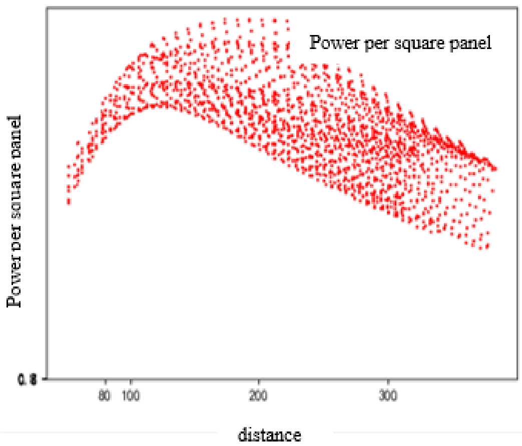

Fig 13. The relationship between distance and power per square panel.

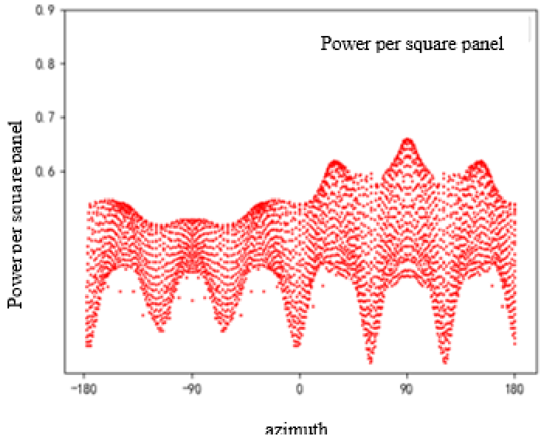

Fig 14. The relationship between orientation and power per square panel.

4. Conclusion

This article considers three points: cosine loss, shadow occlusion loss, and truncation efficiency. It is known that these three points are closely related to the position of the sun. A ray tracing method is proposed to accurately calculate the sunlight situation, and the optimal parameters of the heliostat field are determined through simulation. Taking the absorption tower as the origin, the heliostat field is placed in an equilateral triangle within the surrounding circular range. Simulation results show that reducing shadow occlusion between heliostats is to increase the average output thermal power per unit mirror area. Taking the absorption tower as the origin, 3471 pieces of 6m are used × a 6m heliostat is arranged around a circular area around the absorption tower in an equilateral triangle shape. By using ray tracing, the average annual output thermal power per unit area of the mirror can be calculated to be 0.46kw/m^2. The rated average output thermal power of the program operation of the heliostat field is close to the required 60MW, indicating that its design meets the requirements.

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