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Research on optical efficiency of heliostat field based on cosine loss model and shadow light blocking efficiency model

Kai Kang[1,*,#], Yixin Li[2,#]

[1]School of Mechanical and Equipment Engineering, Hebei University of Engineering, Hebei, Handan, 056038, China
[2]School of Management Engineering and Business, Hebei University of Engineering, Hebei, Handan, 056038, China
[*]Corresponding author: 3241153039@qq.com
[#]These authors contributed equally.

Abstract: *With the development concept of green and environmental protection deeply rooted in people's hearts, the heliostat field has moved from theoretical knowledge to production practice with its high utilization of solar energy. In order to accurately calculate the optical efficiency of the heliostat field, it is necessary to construct the mirror field coordinate system[1] and the heliostat coordinate system, and determine the information of the sun's declination angle, sun's hour angle, sun's altitude angle, and sun's azimuth angle. Based on these angles, the direction vector of incoming and outgoing rays and the direction vector of reflected rays are calculated, and the cosine loss model is used to solve the cosine loss efficiency. When calculating shadow occlusion loss, a theoretical model of shadow occlusion efficiency was established. Coordinate transformation was used to determine whether the light in heliostat A can enter heliostat B. The occlusion efficiency of heliostat was determined by the ratio of the shadow area formed by the light entering B to the area of heliostat B. At the same time, the average optical efficiency of the heliostat field is obtained by combining the optical efficiency formula, and on this basis, the average output thermal power per unit area of the heliostat field is obtained. Through the above analysis, it was calculated that the annual average optical efficiency of a circular heliostat field which is located at 98.5 degrees east longitude, 39.4 degrees north latitude, an altitude of 3000 meters, and is a circle with a radius of 350 meters is 0.647. Its the annual average thermal output power is 36.273MW and the annual average thermal output power per unit mirror area is 0.096MW/m^2. Finally, a more accurate optical efficiency calculation method was proposed, which can be used to calculate the optical efficiency of different scale heliostat fields.*

Keywords: *Optical Efficiency, Cosine Loss, Light Blocking Efficiency Model, Optimize and Design*

1. Introduction

Tower type solar thermal power plant is a process where a large number of heliostats gather solar energy to reflect low-density solar energy onto a heat absorber located at the top of the tower, forming high-density solar energy. The heat absorber converts the light energy into working fluid heat energy, and then converts the heat energy into electrical energy through a steam turbine generator set[2]. Due to the high investment cost of the heliostat field, it is difficult to change its layout and related parameters after the construction of the field is completed. Therefore, optimizing the layout of the field is an indispensable step in the design process[3]. The optimized heliostat field can achieve maximum utilization of solar energy, achieve more average annual efficiency of the field, and reduce investment and power generation costs, which is of great significance for improving the comprehensive cost-effectiveness of power plants. Assuming that the intersection point between the axis of the absorption tower and the ground is taken as the origin, the x-axis and y-axis are set to the east and north directions respectively, and the z-axis is set vertically to the ground. A ground coordinate system is established, and all heliostat coordinates, dimensions, and heights are known. Calculate the annual average optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area of the heliostat field under given conditions.

ISSN 2706-655X Vol.5, Issue 12: 40-49, DOI: 10.25236/IJFET.2023.051208

2. Material and Method

2.1. Data acquisition and preprocessing

Obtain the position coordinates of a heliostat field in Gansu Province through online search and on-site investigation. And by visualizing the obtained coordinates, it was found that the overall distribution of the heliostat exhibits an elliptical pattern.

2.2. Research methods

According to literature on optical efficiency[4],it can be seen that the optical efficiency of a heliostat is influenced by shadow occlusion loss, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance. Among these five influencing factors, the specular reflectance is a constant, which can be directly incorporated into the formula for calculation. Secondly, what is easy to solve is the atmospheric transmittance, which can be calculated by substituting the distance from the heliostat mirror surface to the center of the collector into the formula. Then, calculate the cosine efficiency. Combining local latitude and time information, determine the unit vectors of the sun's altitude angle, sun's azimuth angle, incident light, and reflected light to obtain the cosine loss value. For the collector truncation efficiency and shadow occlusion efficiency, the shadow occlusion loss needs to be determined for the collector truncation efficiency, So let's first solve for the shadow occlusion efficiency. The shadow occlusion efficiency is determined based on the ratio of the projection formed by the sunlight incident on mirror A and reflected on mirror B to the area of mirror B. Finally, to solve the truncation efficiency of the collector, it is necessary to consider the energy loss caused by shadow occlusion and determine the relationship between the collector coordinates and the total standard deviation of the collector.

After averaging the values of shadow occlusion loss, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance corresponding to 9:00, 10:30, 12:00, 13:30, and 15:00 on the 21st of each month, the average optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area were obtained.

3. Results and analysis

3.1. Establishment of mirror field coordinate system

Mark the intersection point between the central axis of the absorption tower and the ground as D, and use point D as the origin of the mirror field coordinate system. Establish a coordinate system with the east direction as the X-axis positive half axis, the north direction as the Y-axis positive half axis, and the zenith direction as the Z-axis positive half axis.

3.2. Establishment of heliostat coordinate system

Using the center point O of the heliostat as the origin, establish a three-dimensional coordinate system for the heliostat. The axis and axis are located within the mirror surface, coincident with the horizontal axis of the heliostat, perpendicular to the axis, and coincident with the normal vector of the mirror surface center.

3.2.1. Determination of the normal azimuth and elevation angle of the center point of the heliostat

Firstly, provide some perspective information:

$$sin_{\sigma} = sin\frac{2\pi D}{365}sin(\frac{2\pi}{360}23.45) \tag{1}$$

σ represents the declination angle of the sun[5];

$$\omega = \frac{\pi}{12}(ST - 12) \tag{2}$$

ST indicates the local time,ω represents the solar hour angle[6];

$$\sin\alpha_s = \cos\sigma\cos\varphi\cos\omega + \sin\sigma\sin\varphi \tag{3}$$

α_s represents the solar altitude angle;

ISSN 2706-655X Vol.5, Issue 12: 40-49, DOI: 10.25236/IJFET.2023.051208

$$\cos\gamma_s = \frac{\sin\sigma - \sin\alpha_s \sin\varphi}{\cos\alpha_s \cos\varphi} \tag{4}$$

γ_s represents the azimuth angle of the sun.

Assuming the coordinates of the mirror center of mirror A is(X_{OA}, Y_{OA}, Z_{OA}), then the unit vector of reflected light is represented as:

$$R_{rA} = \frac{D - O_A}{|D - O_A|} = -\frac{(X_{OA}, -Y_{OA} J_z - Z_{OA})}{\sqrt{X_{OA}^2 + Y_{OA}^2 + (J_z - Z_{OA})^2}} \tag{5}$$

The unit vector of incident light R_{is} is represented as:

$$R_{is} = (x_i, y_i, z_i) \tag{6}$$

Establish the relationship between the sun's azimuth angle, sun's altitude angle, and incident light:

$$\begin{cases} x_i = \cos\alpha_s \cos(\gamma_s - 90°) \\ y_i = \cos\alpha_s \sin(\gamma_s - 90°) \\ z_i = \sin\alpha_s \end{cases} \tag{7}$$

Calculate the incident angle of the sun by using the unit vector of the incident light and the ray vector of the reflected θ is:

$$\theta = \frac{1}{2}\arccos(-R_{is} \cdot R_{rA}) \tag{8}$$

$$\sin\theta_s = \frac{X_{OA} - \cos\alpha_s \cdot \sin\gamma_s \cdot t}{\sqrt{X_{OA}^2 + Y_{OA}^2 + t^2 \cos\alpha_s^2 - 2\cos\alpha_s \cdot t(X_{OA} \cdot \sin\gamma_s - Y_{OA} \cdot \cos\alpha_s)}} \tag{9}$$

θ_s indicates the azimuth angle of the heliostat,$t = \sqrt{X_{OA}^2 + Y_{OA}^2 + Z_{OA}^2}$

The angle between the mirror center$O_i$and the collector center$J$in the relative vertical direction is denoted as λ, and J_z represents the height of the collector center relative to the mirror field plane. It can be obtained that:

$$\tan\lambda = \frac{X_{OA}}{J_z - Y_{OA}} \tag{10}$$

Finally, based on the above angle information, the formula for determining the normal azimuth angle A_H and elevation angle E_H of the center point of the heliostat is as follows:

$$E_H = \arccos\left(\frac{\sin\alpha_s + \cos\lambda}{2\cos\theta}\right) \tag{11}$$

$$A_H = \arctan\left(\frac{\sin\theta_s - \sin\lambda - \sin\gamma_s \cos\alpha_s}{\cos\theta_s \sin\lambda} - \cos\gamma_s \cos\alpha_s\right) \tag{12}$$

3.2.2. Establishment of theoretical model of shadow light blocking efficiency

According to literature review on optical efficiency calculation[7], it can be seen that:

The unit matrix for converting the heliostat coordinate system to the ground coordinate system is:

$$W = \begin{pmatrix} r_x & r_y & r_z \\ s_x & s_y & s_z \\ t_x & t_y & t_z \end{pmatrix} \tag{13}$$

(r_x, s_x, t_x),(r_y, s_y, t_y),(r_z, s_z, t_z) represent the vector representations of the three axes of the heliostat coordinates on the ground coordinates.

In the following calculation process, it is necessary to convert the vector in the heliostat coordinate system to the ground coordinate system. Based on the following formula:

$$E_H = \arccos\left(\frac{\sin\alpha_s + \cos\lambda}{2\cos\theta}\right) \tag{14}$$

$$A_H = \arctan\left(\frac{\sin\theta_s - \sin\lambda - \sin\gamma_s \cos\alpha_s}{\cos\theta_s \sin\lambda} - \cos\gamma_s \cos\alpha_s\right) \tag{15}$$

The transformation matrix from the heliostat coordinate system to the mirror coordinate system can also be expressed as:

ISSN 2706-655X Vol.5, Issue 12: 40-49, DOI: 10.25236/IJFET.2023.051208

$$W=\begin{pmatrix}-\sin E_H & -\sin A_H\cos E_H & \cos A_H\cos E_H\\ \cos E_H & -\sin A_H\sin E_H & \cos A_H\sin E_H\\ 0 & \cos A_H & \sin A_H\end{pmatrix} \tag{16}$$

Assuming the coordinates of a point in mirror A are G_1=(x1,y1,0), find the coordinatesG_2= (x_2, y_2, 0) of the ray falling into mirror B. And determine if G_2 is within the B image.

To calculate the value of G2, first convert G_1 of Mirror A into a ground coordinate system and calculate its coordinates G_1' in the ground coordinate system.

$$G_1'=\begin{pmatrix}r_x & r_y & r_z\\ s_x & s_y & s_z\\ t_x & t_y & t_z\end{pmatrix}\cdot G_1+O_A=\begin{pmatrix}x_1'\\ y_1'\\ z_1'\end{pmatrix} \tag{17}$$

$O_A(x_A,y_A,\ z_A)$ is the coordinate value of the heliostat coordinate system in the ground coordinate system.

Next, convert G_1'in the ground coordinate system to G_1'' in the heliostat B coordinate system

$$G_1''=\begin{pmatrix}r_x & r_y & r_z\\ s_x & s_y & s_z\\ t_x & t_y & t_z\end{pmatrix}^{\mathrm{T}}\cdot(G_1'-O_B)=\begin{pmatrix}x_1''\\ y_1''\\ z_1''\end{pmatrix} \tag{18}$$

Convert the incident light named $\boldsymbol{R_{is}}$= (x_i, y_i, z_i) from the ground coordinate system to the heliostat B coordinate system, denoted as $\boldsymbol{R_{ik}}$:

$$\boldsymbol{R_{ik}}=G_1{}''=\begin{pmatrix}r_x & r_y & r_z\\ s_x & s_y & s_z\\ t_x & t_y & t_z\end{pmatrix}^{T}\cdot\boldsymbol{R_{is}}=(x_l,y_l,z_l) \tag{19}$$

Given point G_1'' in the heliostat B coordinate system and the ray vector R_{ik}=(x_1, y_1, z_1),the coordinate of G_2 is needed to konw .

The solution process is as follows:

$$\frac{x_2-x_1''}{x_l}=\frac{y_2-y_1''}{y_l}=\frac{-z_1''}{z_l} \tag{20}$$

Simplification can lead to:

$$\begin{cases}x_2*z_l=z_l x_1{}''-x_l z_1{}''\\ y_2*z_l=z_l y_1''-y_l z_1{}''\end{cases} \tag{21}$$

It can be determined whether G_2 falls within the mirror B range.

The light beam emitted by the sun forms a light cone[8]. However, during the propagation process, due to the very long distance from the sun to the heliostat, when the sun beam propagates to the mirror surface, it can be approximately regarded as a point. During the reflection process, the light beam diverges and forms a light cone with the reflection point as its vertex. As shown in Figure 1:

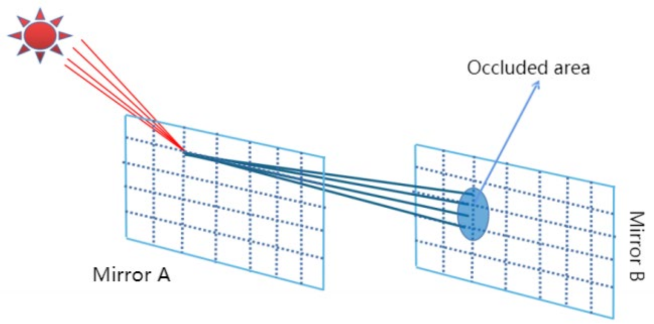

Figure 1: Reflectance map

When calculating shadow occlusion loss, the area of the light cone received by the second mirror is used as the occlusion area, as shown in Figure 2:

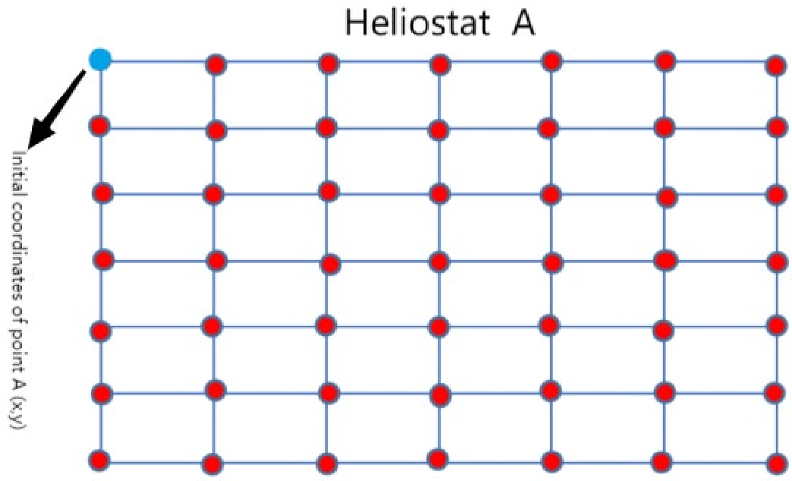

Figure 2: Heliostat A grid distribution plot

When calculating shadow occlusion loss, the area of the light cone received by the second mirror is used as the occlusion area, as shown in Figure 3:

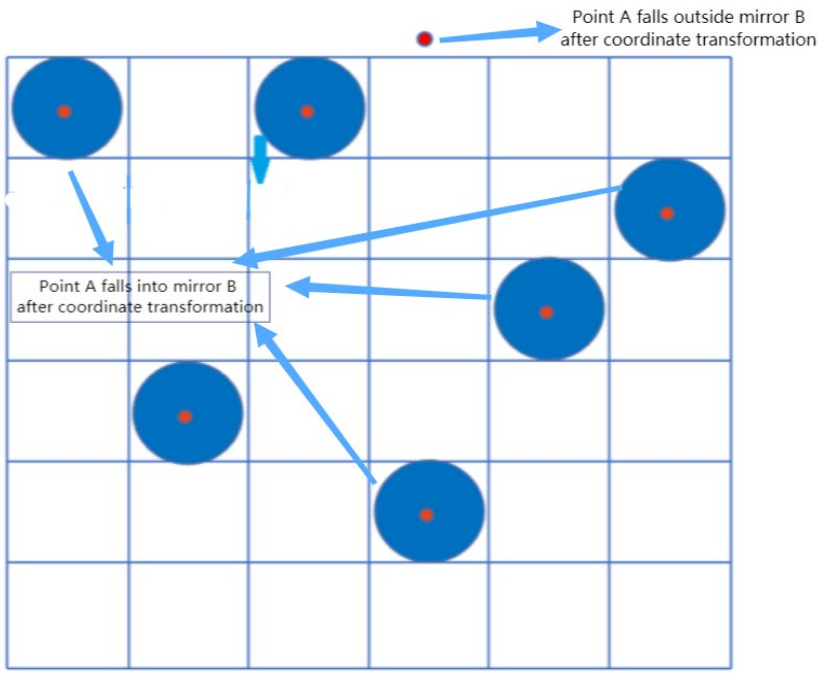

Figure 3: Heliostat B receiving diagram

The first scenario is that after reflection, the light cone reaches the mirror surface of the heliostat, and its shadow occlusion area can be approximately represented by the square area. In the second case, after reflection, the light cone does not reach the surface of the heliostat, and the light is completely reflected without loss. At this point, it is necessary to divide the mirror surface and mirror surface into several equilateral small squares. The width and height of the mirror surface and mirror surface are 6 meters respectively. When dividing, if 2 meters are selected as the width of each grid, there is a significant error in calculating the beam area received on the mirror surface. To reduce errors, the width of the grid should be minimized as much as possible, so each positioning mirror should be divided into 0.25m × For a 0.25m small grid, the vertex coordinates of each small grid are taken into equations (17) and (19) to calculate the number of points falling into the mirror, and the corresponding area is calculated. The shadow occlusion efficiency can be expressed as:

$$\eta_{sb} = \frac{S_1}{S} \tag{22}$$

S_1 represents shadow occlusion loss, and S represents the total area of the heliostat.

ISSN 2706-655X Vol.5, Issue 12: 40-49, DOI: 10.25236/IJFET.2023.051208

3.2.3. Computational model of cosine efficiency

During the process of sunlight reflecting from the heliostat to the central collector, there is an angle θ between the incident light and the normal direction of the mirror reflection point, and the cosine efficiency value $\cos\theta$ can be expressed as.According to the law of light reflection, the incident light, reflected light, and normal are collinear. Therefore, for each mirror, the smaller the angle between the incident light and the normal direction of the reflection point on the mirror, the greater the corresponding cosine efficiency value. When the incident light is perpendicular to the mirror, that is, when the incident light is parallel to the normal of the mirror, the cosine efficiency is maximum.

Consider a mirror as an ideal plane, and the cosine efficiency of each mirror can be represented by establishing the unit vector of incident light and the unit vector of reflected light:

$$\eta_{cos} = \cos\theta \tag{23}$$

$$\theta = \frac{1}{2}\cos^{-1}(-\mathrm{R_{is}} \cdot \mathrm{R_{rA}}) \tag{24}$$

3.3. Computational model for truncation efficiency

The truncation efficiency can be expressed as the ratio of the energy absorbed by the collector to the energy reflected by the heliostat[9],due to the presence of occlusion, the energy reflected by the heliostat during the entire process is calculated by subtracting the energy loss caused by shadow occlusion from the total energy reflected by the heliostat mirror surface.

The calculation formula for truncation efficiency:

$$\eta_{\mathrm{trunc}} = \int_{x'}\int_{y'} \exp\left(-\frac{x'^2+y'^2}{2\sigma_1^2}\right) dy'dx' \tag{25}$$

x',y' represent the plane coordinates of the collector,σ_1 represents the total standard deviation of light on the collector.

The light received by the collector is influenced by the shape of the sun, light quality, light scattering, and light tracing. When considering the total standard deviation of the light on the collector, this article assumes that the first three factors have little impact, and only considers the standard deviation of the last tracking error. The standard deviation of the tracking error σ_2 is recorded as:

$$\sigma_2 = \frac{\sqrt{0.5(Q_t^2+R_s^2)}}{4F_{dr}} \tag{26}$$

Establish the relationship between the total standard deviation and tracking error, as shown in equation (25):

$$\sigma_1 = F_{dr}\sigma_2 \tag{27}$$

The reflection distance F_{dr} of the reflected light is expressed as equation (28):

$$F_{dr} = \sqrt{x^2 + y^2 + (J_z - Z_{OA})^2} \tag{28}$$

The dimensions of the collector in the meridional and sagittal directions are represented by $\mathrm{Q_t}$ and $\mathrm{R_s}$ respectively. The expression is:

$$Q_t = d\left|\frac{F_{dr}}{f} - \cos\theta\right| \tag{29}$$

$$R_s = d\left|\frac{F_{dr}}{f} - \cos\theta - 1\right| \tag{30}$$

$\mathrm{d} = \sqrt{\mathrm{a} * \mathrm{b}}$,a represents the length of the heliostat, and b represents the width of the heliostat. θ is the angle of incidence, f equal to F_{dr} .

3.4. Analysis of experimental results

3.4.1. The law of change in the position of the sun

There is a close relationship between the optical efficiency of the heliostat field and the position of the sun. Therefore, in order to obtain the distribution of optical efficiency at different positions in the mirror field, it is necessary to first calculate the position of the sun in the region and simulate the changing trajectory of the sun's motion trajectory in the region. This article takes the position of 98.5 degrees east longitude and 39.4 degrees north latitude as the simulation location, and simulates the position of the sun every 0.5 hours during the period from January to December, starting from the mirror field on the 21st of each month until the end of work. The changes in the sun's altitude angle and azimuth angle over time during this period are recorded, and the simulation results are shown in Figure 4:

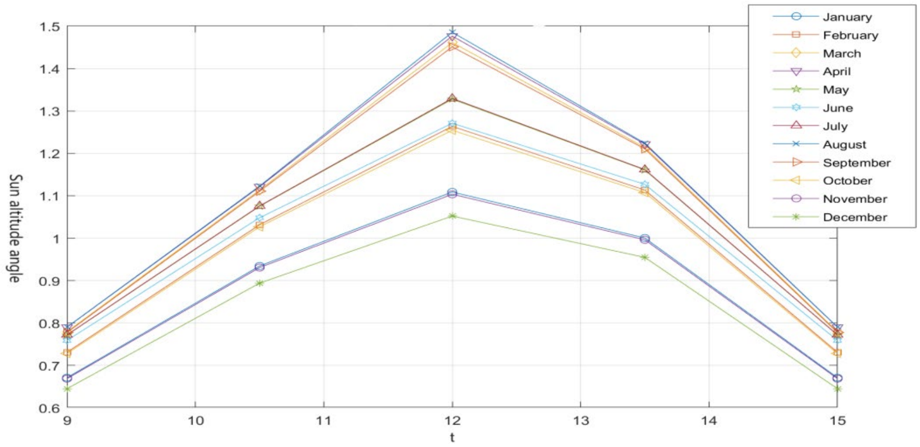

Figure 4: Variation Law of Solar Altitude Angle

From Figure 4, it can be seen that the height angle of the sun shows a trend of first increasing and then decreasing within a day, reaching its maximum value at 12 o'clock. The variation curve of the sun's height angle is basically symmetrically distributed at noon. At the same time in different periods, the solar altitude angle also varies. On June 21st, the solar altitude angle is the largest, and on December 21st, the solar altitude angle is the smallest. The curves basically coincide on March 21st and September 21st.

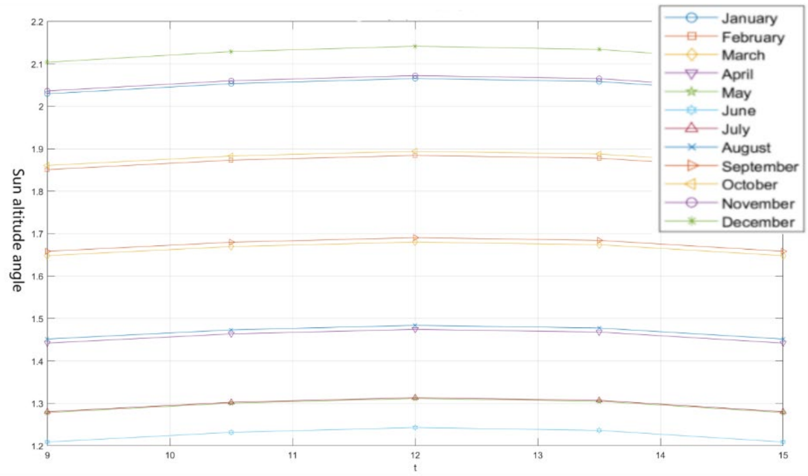

Figure 5: Variation Law of Solar Sun orientation

Figure 5 shows the variation curve of the sun's azimuth angle: the variation law of the sun's azimuth angle shows an upward trend within a day. The time span and sun's azimuth angle of the curve corresponding to December 21 (winter solstice) are the smallest, and the time span and sun's azimuth angle corresponding to June 21 (summer solstice) are the smallest. The variation law of the sun's azimuth angle is basically the same on March 21 (spring equinox) and September 21 (autumn equinox).

3.4.2. Distribution law of cosine efficiency in heliostat field

In the optical efficiency of the heliostat field, the vast majority of efficiency losses come from cosine loss[10,11]. The cosine efficiency of a heliostat is the ratio of the effective reflected light area to the mirror area. For the entire heliostat field, the higher the cosine efficiency, the more light is reflected, and the mirror area in the field can be better utilized. The heliostat field can collect more energy. Therefore, the analysis of the cosine efficiency of a heliostat field is of great significance. Draw three-dimensional scatter plots of cosine efficiency and coordinates for different months based on the efficiency simulation results of the mirror field at 12:00 on the 21st of each month. The simulation results are shown in Figures

ISSN 2706-655X Vol.5, Issue 12: 40-49, DOI: 10.25236/IJFET.2023.051208

6 to 8:

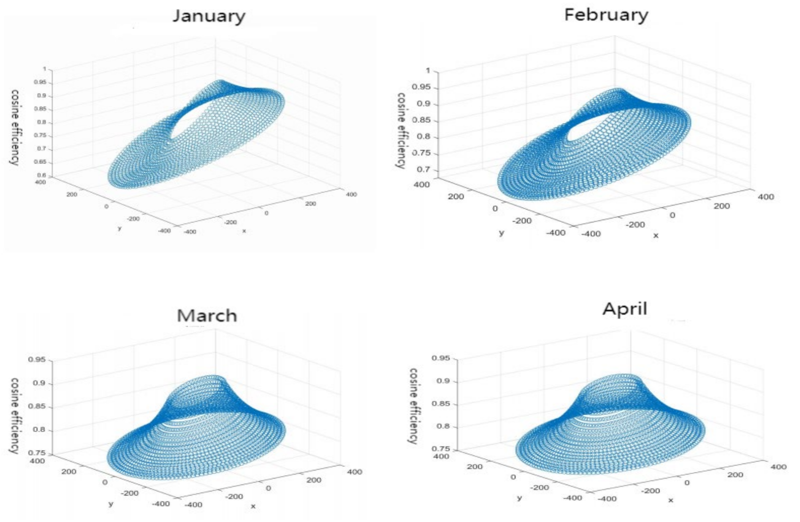

Figure 6: The 3D plot of cosine efficiency from Jan to Apr

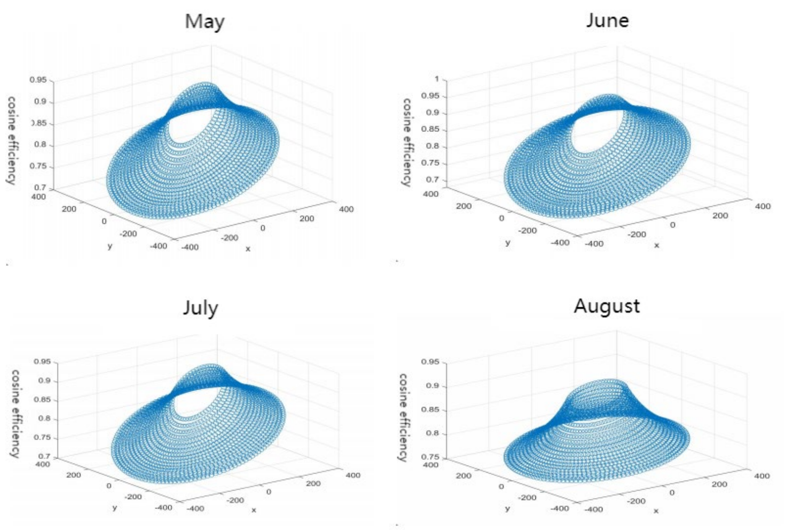

Figure 7: The 3D plot of cosine efficiency from May to Aug

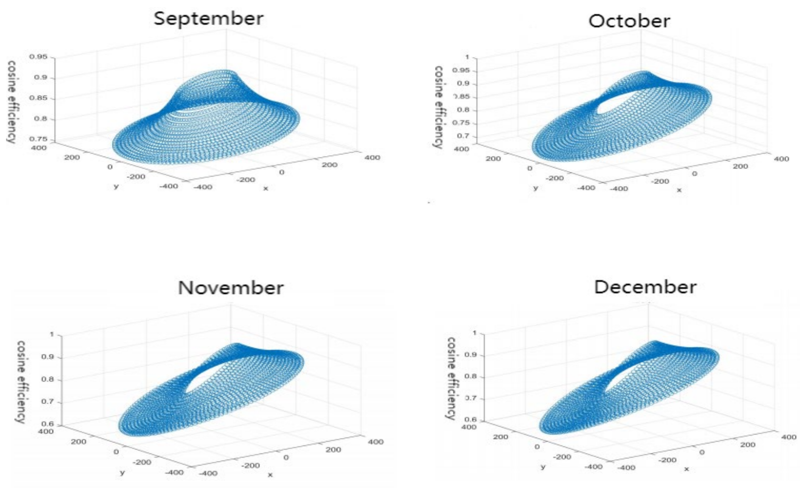

Figure 8: The 3D plot of cosine efficiency from Sept to Dec

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3.5. Results of the model

After averaging the values of shadow occlusion loss, cosine efficiency, atmospheric transmittance, collector truncation efficiency, and mirror reflectance corresponding to 9:00, 10:30, 12:00, 13:30, and 15:00 on the 21st of each month, the average optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area were obtained. The results are shown in Table 1:

Table 1: Monthly average

Date	Average optical efficiency	Average cosine efficiency	Average Shadow Occlusion Loss	Average truncation efficiency	Output thermal power per unit area
1.21	0.535	0.781	0.804	0.853	0.050
2.21	0.554	0.789	0.852	0.824	0.045
3.21	0.613	0.795	0.916	0.843	0.148
4.21	0.652	0.796	0.940	0.872	0.113
5.21	0.685	0.792	0.973	0.887	0.143
6.21	0.745	0.791	0.999	0.943	0.153
7.21	0.761	0.796	0.994	0.966	0.133
8.21	0.775	0.795	0.989	0.985	0.103
9.21	0.713	0.795	0.940	0.955	0.097
10.21	0.622	0.789	0.836	0.943	0.063
11.21	0.535	0.780	0.781	0.878	0.055
12.21	0.574	0.799	0.798	0.925	0.054

In order to obtain Table 2, the annual average values of the average optical efficiency, average output thermal power, and average output thermal power per unit mirror area obtained from Table 1 are calculated.

Table 2: Annual average

Annual average optical efficiency	Annual cosine efficiency	Average annual shadow occlusion loss
0.647	0.789	0.909
Annual truncation efficiency	Average annual thermal power output	Average annual thermal output per unit area
0.9063	36.274	0.096

4. Conclusions

The construction of tower solar power plants has a large scale, long cycle, and high cost. Optical efficiency is an important basis for determining whether the construction of solar power plants is reasonable and adjusting the layout of power plants. Optical efficiency is related to cosine loss efficiency, occlusion efficiency, and other factors. In order to accurately calculate the cosine loss efficiency, it is necessary to start from the coordinates of the power plant and heliostat, use information such as solar declination, solar hour, solar altitude, and solar azimuth, and combine the cosine loss model to obtain an annual average cosine loss efficiency of 0.789; Based on the theoretical model of shadow blocking efficiency, coordinate transformation is used to determine the blocking situation of light, and the annual average blocking efficiency of a heliostat is 0.909; In order to calculate the average optical efficiency of a solar power plant, it is necessary to combine the cosine loss efficiency and average occlusion efficiency with the optical efficiency formula to obtain a result of 0.647. Comparing the calculated results with actual data confirms the reliability of the calculation method. The calculation method proposed in this paper can be used to calculate the optical efficiency of tower solar power plants with different locations, different scales and shapes. At the same time, it provides a scientific theoretical basis for the construction of power plants.

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