Performance Evaluation of Fixed-Sun Mirror Field Configurations for Tower Solar Photovoltaic Power Plants

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Abstract. For the performance evaluation of tower solar thermal power plant with fixed-sun mirror field configuration, this paper firstly establishes the equations about the sun position and input thermal power. Then, the direction vector of incident light is obtained through the calculation of the sun angle, and then the angle between the two vectors can be obtained through the known direction vector of reflected light, and the half-angle cosine is the cosine efficiency. Next, the spot flux on the collector can be approximated as a two-dimensional normal distribution, and the truncation efficiency can be approximated using the definite integral. Next, the real-time optical efficiency of each heliostat can be obtained by calculating the known atmospheric projection efficiency and reflection efficiency. Finally, through the above calculation method, the annual average optical efficiency of the heliostat mirror field was calculated as 0.33, the annual average cosine efficiency as 0.76, the annual average truncation efficiency as 0.55, the annual average thermal power output (mw) as 26.23 mw, and the annual average thermal power output per unit area of the mirror surface (kw/m^2) as 0.42 kw/m^2, which effectively evaluates the configuration of the heliostat mirror field for the tower-type solar photovoltaic power plant. performance was effectively evaluated.

Keywords: Tower Solar Thermal Power, Mirror Field, Mirror Reflection.

1. Introduction

With the aggravation of energy crisis and environmental pollution, the development and utilization of clean energy has become one of the major challenges facing the world today [1]. Solar energy, as an infinitely renewable, non-polluting and carbon-emission-free energy source, has enormous development potential and application value [2-3]. Therefore the development and wide application of new energy technologies become especially critical. Among them, tower solar thermal power generation technology, as a low-carbon and environmentally friendly clean energy technology, has great potential and is rapidly emerging in the field of power production [4]. The construction cost of the heliostat field of a tower solar thermal power plant accounts for 30%~50% of the total investment of the whole plant, so it is important to accurately evaluate the performance of the heliostat field configuration [5-6].

In this paper, the annual average optical efficiency, the annual average output thermal power, and the annual average output thermal power per unit mirror area of a heliostat field are solved, taking into account a number of factors, such as the solar position, mirror reflection, and atmospheric transmittance. In this paper, a model is built based on the provided heliostat location data to simulate the reflection and convergence process of sunlight on heliostats in order to calculate the optical efficiency of each heliostat. The performance of the fixed-sun mirror field configuration of the tower solar thermal power plant was effectively evaluated by calculating the annual average optical efficiency, annual average cosine efficiency, annual average truncation efficiency, annual average output thermal power, and annual average output thermal power per unit area of mirror.

2. Modeling and solving

2.1. Calculation of sunlight angle

In the optimal design of circular heliostat fields, solar angle formulas are very important tools that are used to determine the position of the sun in the sky so that the angle of the heliostat can be precisely adjusted to maximize solar energy capture [7].

A circular heliostat field is planned to be constructed in a circular area centered at 98.5°E, 39.4°N, with an elevation of 3000 m and a radius of 350 m. A coordinate system is established with the center of the circular area as the origin and the x-axis as the y-axis as the z-axis. A coordinate system is established with the center of the circular area as the origin, due east as the x-axis positive, due north as the y-axis positive, and perpendicular to the ground upward as the z-axis positive, in order to calculate the four key angles of the sun. As shown in figure 1 below.

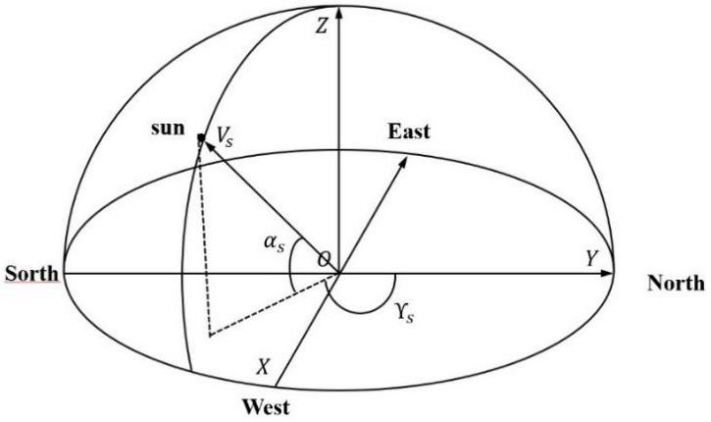


Figure 1. Sun angle calculation

The solar altitude angle is the vertical position of the sun in the sky, based on the horizon. This angle determines the sun's elevation in the sky and is important for the tilt angle of the heliostat to ensure maximum sunlight capture, which is calculated as follows, where φ is the local latitude and north latitude is positive.

$$\sin\alpha_s = \cos\delta\cos\varphi\cos\omega + \sin\delta\sin\varphi \tag{1}$$

The solar azimuth is the direction in which the sun is located in the sky, based on a due north direction, usually 0 degrees east. This angle tells us the direction in which the sun is located in the sky and helps in the orientation adjustment of the heliostat. It is calculated by the following formula, whereφ is the local latitude and north is positive.

$$\cos\gamma_s = \frac{\sin\delta - \sin\alpha_s\sin\varphi}{\cos\alpha_s\cos\varphi} \tag{2}$$

The solar hour angle is the angle of the sun relative to local noon and is used to describe the position of the sun in the sky. It is used to determine the sun's elevation and azimuth angles. The formula is as follows, where ST is the local standard time and longitude is the longitude of the location of the heliostat field.

$$\omega = \frac{\pi}{12}(ST - 12) \tag{3}$$

The angle of solar declination is the angle of the sun relative to the equator, which indicates the position of the sun on the celestial sphere and is used to calculate the solar altitude angle. The formula is as follows, where D is the number of days counted from the equinox as zero.

$$\sin\delta = \sin\frac{2\pi D}{365}\sin\left(\frac{2\pi}{360}23.45\right) \tag{4}$$

2.2. Output thermal power

The output thermal power represents the rate of thermal energy that the heliostat system obtains from solar radiation. In the design and optimization of a heliostat field, we first need to consider the normal direct radiant illuminance of solar radiation.

Normal direct radiant irradiance is the amount of solar radiation energy received per unit area of the earth in a plane perpendicular to the sun's rays, per unit time. It expresses the intensity of the sun's rays directed perpendicularly to the earth's surface, usually expressed in watts per square meter (W/m^2). The formula for its calculation is as follows:

$$DNI = G_0 \left[a + b \exp\left(-\frac{c}{\sin a_s} \right) \right] \tag{5}$$

$$\begin{cases} a = 0.4237 - 0.00821(6 - H)^2 \\ b = 0.5055 + 0.00595(6.5 - H)^2 \\ c = 0.2711 + 0.01858(2.5 - H)^2 \end{cases} \tag{6}$$

Where G_0 is the solar constant, which takes the value $1.366 kW/m^2$, H is the altitude (km).

Normal direct radiant illuminance tells us the intensity of the sun's rays in the vertical direction, but in a heliostat field we are interested in how efficiently these rays are collected and utilized. This is where the optical efficiency of the heliostat, which measures the mirror's ability to reflect and focus sunlight, needs to be considered.

By using the normal direct radiant illuminance and the optical efficiency, the output thermal power can be calculated, which helps to evaluate the performance of the heliostat system and to optimize the system design. The formula for this is:

$$E = DNI \cdot \sum_i^N A_i \eta_i \tag{7}$$

Where η_i is the optical efficiency of the ith mirror, and N is the number of fixed-sun mirrors (face), and A_i is the lighting area of the ith fixed-sun mirror.

2.3. Optical efficiency

The optical efficiency of a mirror field comprehensively characterizes the various performance indicators of the mirror field, including instantaneous optical efficiency and average optical efficiency throughout the year in terms of time characterization [8]. The efficiency of the mirror field includes the reflectivity of the mirror surface (including the reflective properties of the mirror surface itself and the staining of the mirror surface exposed to the air), the cosine loss due to the mirror surface and the incident sun line has a certain angle caused by the sunlight in the propagation process of the attenuation of the loss of the sunlight, the shadow caused by interference between the mirror and the light blocking, reflecting back to the heat absorber on the overflow of the sunlight and other sub-efficiencies. Its calculation formula is:

$$\eta = \eta_{sb} \cdot \eta_{cos} \cdot \eta_{at} \cdot \eta_{trunc} \cdot \eta_{ref} \tag{8}$$

2.4. Cosine efficiency

Cosine loss is the loss of received energy caused by the fact that the direction of incidence of sunlight is not parallel to the normal direction of the mirror's light-gathering port. Cosine efficiency is the energy loss caused by the angle between the angle of incidence of sunlight and the normal direction of the mirror's pickup port when receiving sunlight on the surface of the mirror or reflector. This efficiency factor takes into account the difference in angle at which the light is incident, since the more the angle of incidence deviates from the vertical, the lower the reflection efficiency and the greater the energy loss [9].

In a heliostat field, the heliostat is usually adjusted by two pivots, horizontal and vertical, to ensure that the sun's rays are reflected through the center of the heliostat and point towards the center of the

collector. This adjustment is made to minimize cosine losses and to direct the sun's rays as perpendicularly as possible to the reflecting surface, thereby increasing the reflection efficiency.

Since the position of the sun in the sky changes constantly, the heliostat must be able to adjust in real time to the changing position of the sun in order to maximize the capture of solar radiation. This requires a precise control system to control the rotation of the heliostat so that the angle of the sun's rays to the normal direction during reflection is as small as possible, thus minimizing cosine losses. As shown in figure 2 below.

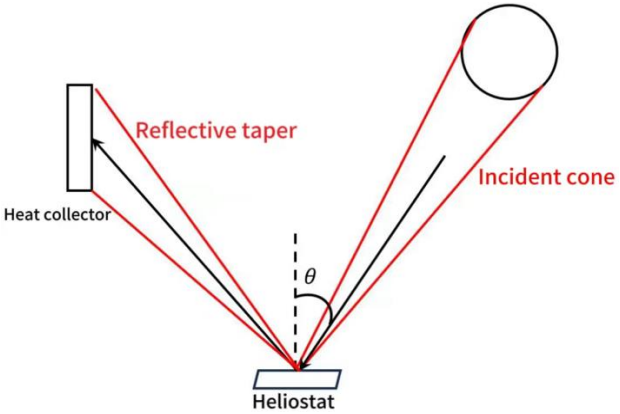


Figure 2. Schematic diagram of incident and reflected light cones

According to the vector dot product formula:

$$\cos\theta = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}|\cdot|\vec{b}|} \tag{9}$$

It's available:

$$\eta_{cos} = \cos\theta = \frac{\vec{n}\cdot\vec{s}}{|\vec{n}|\cdot|\vec{s}|} = \vec{n}\cdot\vec{s} \tag{10}$$

Where $\vec{s}$ is the unit vector from the center of the sun to the center of the heliostat, and $\vec{n}$ is the unit vector of the normal vector to the surface of the heliostat.

Set the coordinates of the heliostat as $P(x,y,z)$, the coordinates of the center point of the collector are $O_J\left(0,0,H_a+\frac{H_b}{2}\right)$ and H_a is the height of the absorber tower 80m, and H_b is the collector height 8m, and the unit vector from the center of the sun mirror to the center of the collector $\vec{t}$ is.

$$\vec{t} = \frac{O_M - I}{|O_M - I|} = \frac{\left(-x,-y,H_p+\frac{H_q}{2}-z\right)}{\sqrt{x^2+y^2+\left(H_p+\frac{H_q}{2}-z\right)^2}} \tag{11}$$

Next, calculate the unit vector from the center of the Sun to the center of the heliostat $\vec{s}$, due to the fact that the Sun is too far away relative to the Earth. To simplify the calculation, the light from the Sun directed to the origin and the light directed to the center of the heliostat are considered as parallel light. According to the spherical coordinate system, the unit vector from the center of the sun to the center of the heliograph $\vec{s}(x_s,y_s,z_s)$ can be expressed as:

$$\begin{cases} x_s = -\sin\left(\frac{\pi}{2}-\alpha_s\right)\cos\left(\frac{\pi}{2}+\gamma_s\right) \\ y_s = -\sin\left(\frac{\pi}{2}-\alpha_s\right)\sin\left(\frac{\pi}{2}+\gamma_s\right) \\ z_s = -\cos\left(\frac{\pi}{2}-\alpha_s\right) \end{cases} \tag{12}$$

The final simplification yields:

$$\begin{cases} x_s = -\cos\alpha_s \sin\gamma_s \\ y_s = -\cos\alpha_s \cos\gamma_s \\ z_s = -\sin\alpha_s \end{cases} \tag{13}$$

As a result of $\vec{s}$ and $\vec{t}$ the angle between 2θ, using the doubling angle formula, it can be obtained:

$$\cos 2\theta = \frac{\vec{t}\cdot(-\vec{s})}{|\vec{t}|\cdot|\vec{s}|} = -\vec{t}\cdot\vec{s} \tag{14}$$

Finally, the cosine efficiency formula is derived:

$$\eta_{cos} = \cos\theta = \left|\frac{1+\cos 2\theta}{2}\right| = \sqrt{\frac{1-\vec{t}\cdot\vec{s}}{2}} \tag{15}$$

2.5. Atmospheric transmittance

Atmospheric transmittance is the ratio of the intensity of light reaching the ground surface or other receivers after being scattered and absorbed by molecules and particles in the atmosphere as the sun's rays pass through the atmosphere to the intensity of light from the original solar radiation, and is usually expressed as a ratio between 0 and 1, where 1 means that the light is not absorbed or scattered by the atmosphere, and 0 means that the light is completely absorbed or scattered [10].

Molecules and particles in the atmosphere cause scattering of the sun's rays, which means that the light rays are dispersed in all directions, not just in a straight line. This scattering effect causes the intensity of the light to be reduced, especially when the light travels over long distances, as is the case with sunlight in the atmosphere.

The atmospheric attenuation efficiency is the proportion of energy lost by the reflected beam on the surface of the solar mirror due to scattering and absorption in the atmosphere during the reflection process. This efficiency factor takes into account the energy loss of the sun's rays as they pass through the atmosphere.

Due to the scattering effect of atmospheric molecules, the reflected beam on the surface of the heliostat may be scattered during the reflection process, and the atmospheric attenuation efficiency:

$$\eta_{at} = \begin{cases} 0.99321 - 0.0001176 d_{HR} + 1.97\times10^{-8} d_{HR}^2, d_{HR} \le 1000m \\ \exp(-0.0001106 d_{HR}), d_{HR} > 1000m \end{cases} \tag{16}$$

Where denotes the distance from the center of the mirror to the center of the collector.

2.6. Collector cut-off efficiency

When the light spot reflected from the mirror field falls into the heat absorber receiving surface, due to the characteristics of the light spot and the accuracy or wobble of the heliostat may cause offset or overflow of the light spot, resulting in part of the light irradiated outside the heat absorber, and this part of the overflowed spot forms the truncation loss, and thus the truncation efficiency is defined as the percentage of the energy intercepted by the heat absorber to the energy converged by the mirror field.

For the calculation of truncation efficiency, many scholars have also done a lot of research, compared with the traditional calculation method, the HFLCAL model calculation speed is faster and the simulation accuracy is also guaranteed. In this paper, the HFLCAL model is used to calculate the overflow efficiency, and the circular Gaussian distribution is utilized to represent the energy flow density function on the surface of the heat absorber, and its calculation formula is as follows:

$$n_{int} = \frac{1}{2\pi\sigma_{tot}^2}\int_x\int_y exp\left(-\frac{x^2+y^2}{\sigma_{tot}^2}\right)dydx \tag{17}$$

The standard deviation of the elliptical Gaussian function is closely related to the fringes of the heliostat projection on the image plane, which is related to the properties of the conical light. According to the study, the nature of this standard deviation can be approximated as an effect of the shape of the sun, the quality of the beam, the astigmatism error, etc., as shown below:

$$\sigma = \sqrt{d_{HR}^2(\sigma_{sun}^2 + 4\sigma_s^2 + \sigma_{track}^2 + \sigma_c^2)} \tag{18}$$

Where, and is the solar shape standard deviation, the is the cone light standard deviation, and is the standard deviation of the beam quality. the reference value given in the PSA algorithm is the standard deviation of sun shape, and is the standard deviation of beam quality, is the standard deviation of sun shape, and is the standard deviation of beam quality.

In summary, collector truncation efficiency:

$$\begin{cases} \eta_{trunc} = \frac{1}{2\pi\sigma}\iint \exp\left[-\frac{1}{2}\left(\frac{x^2+\beta y^2}{\sigma^2}\right)\right] dxdy \\ \beta = 1 + \log_{10}\frac{LH}{LW} \end{cases} \tag{19}$$

2.7. Specular reflectivity

Specular reflectance is the ability of a mirror surface to reflect light and is usually expressed as a ratio of the amount of energy reflected back to the mirror as a proportion of the total energy of the incident light. A high specular reflectivity means that more of the sun's rays will be reflected back to the target region of the heliostat, improving the energy capture efficiency. In this paper, the specular reflectance can be taken as a constant, i.e.:

$$\eta_{ref} = 0.92 \tag{20}$$

3. Results

Data sources for this article are related to http://www.mcm.edu.cn/html_cn/node/c74d72127066f510a5723a94b5323a26.html. Taking the center of the circular area as the origin, the east direction as the x-axis positive, the north direction as the y-axis positive, and the perpendicular to the ground upward direction as the z-axis positive to set up a coordinate system, we obtained the positions of all the centers of heliostats, and then substituting the data into the model mentioned above, and the results of the calculations are shown in the table below. In order to simplify the calculation, all the "annual average" indicators in this problem are calculated at 9:00, 10:30, 12:00, 13:30 and 15:00 local time on the 21st day of each month, and the calculation results are shown in the Table 1 and Table 2 below.

Table 1. Average Optical Efficiency and Output Power on the 21st of each month

dates	Average optical efficiency	Average cosine efficiency	Average shadow masking efficiency	Average truncation efficiency	Average thermal power output per unit area of mirror (kw/m^2)
January 21	0.31	0.72	0.86	0.55	0.35
February 21	0.33	0.74	0.87	0.55	0.40
March 21	0.34	0.76	0.88	0.55	0.44
April 21	0.34	0.78	0.87	0.55	0.46
May 21	0.35	0.79	0.87	0.55	0.47
June 21	0.35	0.80	0.87	0.55	0.47
July 21	0.35	0.79	0.87	0.55	0.47
August 21	0.34	0.78	0.87	0.55	0.46
September 21	0.34	0.76	0.88	0.55	0.43
October 21	0.32	0.74	0.87	0.55	0.39
November 21	0.31	0.72	0.85	0.55	0.34
December 21	0.30	0.71	0.84	0.55	0.32

Table 2. Table of average optical efficiency and output power for question 1 year

Annual Average 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)
0.33	0.76	0.87	0.55	26.23	0.42

Observation of the average optical efficiency for each month reveals that the summer months (June, July, August) show a higher level of performance, while the winter months (December, November) perform poorly. This seasonal difference is closely related to changes in the sun's altitude angle. In the summer months, the sun is more highly overhanging and it is easier to focus the light on the heliostat, thus the optical efficiency is higher. Cosine and shadow shading efficiencies show similar seasonal trends, with higher cosine and shadow shading efficiencies in the summer months and lower ones in the winter months.

4. Conclusion

In this paper, taking into account the complex factors such as solar position, mirror reflection, atmospheric transmittance, etc., a model is established based on the provided data of heliostat position, and the annual average optical efficiency, annual average cosine efficiency, and annual average truncation efficiency of the heliostat field are found to be 0.33, 0.76, 0.87, 0.55, respectively, with an annual average thermal power output (mw) of 26.23 MW, and an annual average thermal power output (kw/m^2) of 0.42 kw/m^2 per unit area of the mirror. The thermal power (kw/m^2) is 0.42 kw/m^2. The model has a certain accuracy, but there are some shortcomings, and there may be some limitations in considering only the case of inclined planes when different sizes of heliostats are allowed to be used. This is because in practice, different sizes of heliostats may be suitable for different situations or tasks. For example, a tilted plane is suitable for some specific solar tracking applications, but in other scenarios a different type of heliostat, such as spherical or refractive, may be required.

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