Study on Optical Efficiency of Heliostats Based on Different Models

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Abstract. A tower-type solar power station comprised of heliostats and a collector stands as a pivotal solution for harnessing solar energy and transforming it into thermal energy, facilitating clean energy production. In the preliminary stages of constructing tower solar thermal power stations, optimizing the layout of heliostat fields emerges as a critical concern. This paper delves into the investigation of various parameters such as annual average optical efficiency, annual average thermal output, and annual average thermal output per unit mirror area of the heliostat field. Through the establishment of a mirror coordinate system, cosine efficiency model, atmospheric attenuation model, and truncation efficiency model based on predefined heliostat dimensions and positions, we meticulously calculate shadow shading efficiency, cosine efficiency, atmospheric attenuation efficiency, and truncation efficiency of the heliostat field. These analyses contribute significantly to the design and optimization of heliostat fields, enhancing the overall performance and efficiency of tower-type solar power stations.

Keywords: Solar Power Generation, Heliostat Field, Optimization Design, Optical Efficiency.

1. Introduction

Tower-type solar thermal power generation systems are irreplaceable in China's crucial clean energy technologies to achieve carbon emission reduction. The core of these systems is how to use heliostats to efficiently capture and convert solar energy into electrical energy. Further enhancing the optical utilization efficiency of heliostat fields is vital for promoting the energy utilization efficiency of these systems.

In previous research, many scholars have conducted in-depth exploration on the optical efficiency of heliostats. For instance, Gao et al. proposed an optimization layout method based on the adaptive gravity search algorithm and confirmed its effectiveness with the case study of the Gemasolar power station's heliostat field in Seville [1]. They calculated and analyzed the optical efficiency of heliostat fields with different arrangements, providing a new perspective. Deng and his team introduced a decomposed multi-objective evolution for the optimization of heliostat field layout [2], providing a more efficient solution for field configuration. Yin et al. focused on the dynamic characteristics of heliostats and verified the effect of dynamic absorbers in reducing heliostat vibration through dynamic simulation experiments [3], thereby filling the gap in this research field. Wei and his team used the principles of photographic imaging to accurately detect errors in the tilt angle of heliostats [4], further improving efficiency. Zhang and his team approached the issue from the perspective of tower-groove coupling and conducted optical efficiency optimization research on heliostat fields [5], providing strong theoretical support for improving photo-energy conversion efficiency.

Despite these many excellent studies, how to improve the optical efficiency of heliostats is still an area worth exploring. Existing methods have achieved certain results in optimizing layout, reducing vibration, and correcting errors, but all methods still have their limitations. The effectiveness and feasibility of each method are often determined by many factors, such as geographical location, weather conditions, characteristics of the heliostat itself, etc. Therefore, we need a more adaptable and flexible method for different scenarios and conditions.

In addition, although previous studies have proposed many useful optimization methods, they often lack quantitative efficiency calculation models, limiting the repeatability and universality of research. What we need is a more general calculation model that can accurately describe the efficiency of heliostats under different conditions.

Therefore, we believe it necessary to conduct targeted research to explore how to improve the optical utilization efficiency of heliostats and establish accurate efficiency calculation models. In this article, we will analyze and establish heliostat models of different efficiencies to explore the optical efficiency of heliostats more comprehensively and in-depth. We hope that this research can provide feasible solutions for tower-type solar thermal power generation technology and contribute to the development of clean energy worldwide.

2. Research on the Optical Efficiency of Heliostats.

2.1. Theory Model of Shadow Shading Efficiency

Assuming that the weather conditions during the operation of the heliostat field do not cause energy loss in the incident sunlight and that the arrangement of heliostats does not result in the reflection of sunlight from rear heliostats being obscured by front heliostats, the shadow shading loss can be considered in two parts:

Loss caused by obstruction by the tower when sunlight illuminates the heliostats along its propagation path.

Loss caused by obstruction by front heliostats when sunlight illuminates rear heliostats.

Let the vector of incident sunlight in the ground coordinate system be[6]:

$$\overrightarrow{V_0} = (a,\ b,\ c) \tag{1}$$

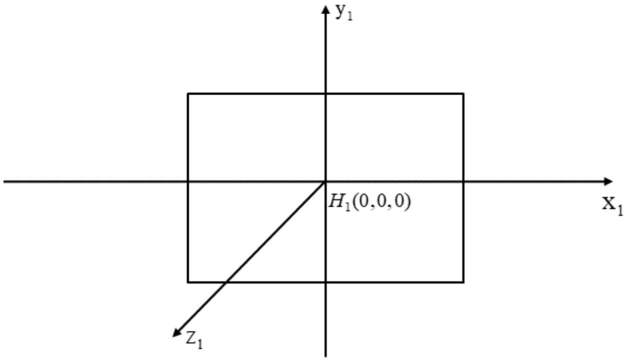

Fig 1: Mirror Coordinate System

Establishing the mirror coordinate system as shown in Fig 1, in the coordinate system of Mirror A, given a certain point $H_1 = (x_1,\ y_1)$ in Mirror A, we want to find the coordinates of this point after the light ray reflects onto Mirror B.

Let's denote the heliostat in the front row as Mirror A and the heliostat in the rear row as Mirror B. In the coordinate system of Mirror A, given a certain coordinate point $H_1 = (x_1,\ y_1)$, we aim to find the corresponding coordinate point $H_2 = (x_2,\ y_2)$ in the coordinate system of Mirror B after the light ray passes through point H_1. To compute the value of coordinate point $H_2 = (x_2,\ y_2)$, this paper follows the steps below:

The transformation matrix representing the conversion from the coordinate system of Mirror A to the ground coordinate system is:

$$T=\begin{pmatrix} m_x & m_y & m_z \\ n_x & n_y & n_z \\ p_x & p_y & p_z \end{pmatrix} \tag{2}$$

Where $(m_x, n_x, p_x), (m_y, n_y, p_y), (m_z, n_z, p_z)$ are the vectors representing the three coordinate axes of Mirror A in the ground coordinate system. Let $\overrightarrow{V_H}$ denote the vector representing the light ray in the coordinate system of Mirror A, and $\overrightarrow{V_0}$ represent the vector representing the light ray in the ground coordinate system. Then, the conversion relationship is as follows:

$$\overrightarrow{V_0}=\vec{T}\cdot\overrightarrow{V_H} \tag{3}$$

$$\overrightarrow{V_H}=\begin{pmatrix} m_x & m_y & m_z \\ n_x & n_y & n_z \\ p_x & p_y & p_z \end{pmatrix}^T \cdot\overrightarrow{V_0} \tag{4}$$

The paper first transforms the coordinates H_1 of heliostat A to the ground coordinate system, resulting in H_1'. Then H_1' is transformed to the coordinate system of heliostat B, resulting in H_1''. If O_A represents the coordinates of the origin of heliostat A's coordinate system in the ground coordinate system, then by Equation (4), we can obtain:

$$H_1'=\begin{pmatrix} m_x & m_y & m_z \\ n_x & n_y & n_z \\ p_x & p_y & p_z \end{pmatrix}^T \cdot H_1+O_A=\begin{pmatrix} x_1' \\ y_1' \\ z_1' \end{pmatrix} \tag{5}$$

Let O_B be the coordinates of the origin of heliostat B's coordinate system in the ground coordinate system. Then, H_1'' can be further transformed to:

$$H_1''=\begin{pmatrix} m_x & m_y & m_z \\ n_x & n_y & n_z \\ p_x & p_y & p_z \end{pmatrix}^T \cdot\left(H_1-O_B\right)=\begin{pmatrix} x_1'' \\ y_1'' \\ z_1'' \end{pmatrix} \tag{6}$$

Given the point $H_1''=\left(x_1'', y_1'', z_1''\right)$ in the coordinate system of heliostat B and the light ray vector V_H, we can derive the obscuration relationship between the front and rear rows of heliostats.

$$\frac{x_2-x_1''}{a}=\frac{y_2-y_1''}{b}=\frac{z_2-z_1''}{c} \tag{7}$$

Solving for:

$$\begin{cases} x_2=\dfrac{cx_1''-az_1''}{c} \\ y_2=\dfrac{cy_1''-bz_1''}{c} \end{cases} \tag{8}$$

Finally, calculating whether the coordinate point H_2 is within the range of Mirror B's surface will determine if the front row heliostat obscures the rear row heliostat.

2.2. The cosine efficiency model

When a heliostat reflects sunlight onto the receiver, there will inevitably be an angle θ between the incident light ray and the normal direction at the reflection point on the mirror surface. The cosine of this angle, $\cos\theta$, represents the cosine efficiency value of the point on the heliostat[7], as shown in Fig 2.

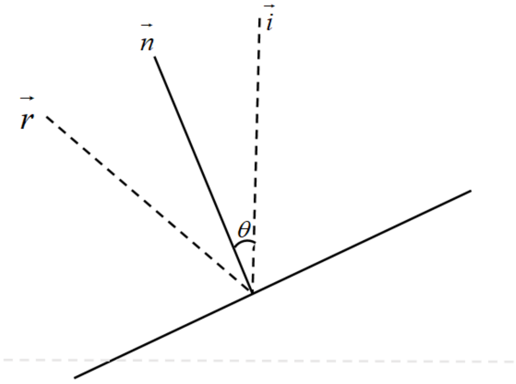

Fig 2: Schematic Diagram of Cosine Efficiency

Assuming the entire mirror surface is an ideal plane with the normal vector n, the unit vector in the direction opposite to the incident light ray is r, and the unit vector in the direction of the reflected light ray is i. The normal vector on each point of the heliostat mirror surface is equal. Therefore, the cosine efficiency of a single heliostat can be calculated by taking the dot product of the unit vectors of the incident and reflected light rays. The formula is as follows:

$$y_{\cos} = \cos\theta = \vec{n} \cdot \vec{i} \tag{9}$$

In this paper, the position of the sun in the ground coordinate system is represented by the zenith angle γ_s and the azimuth angle α_s. Therefore, the vector i can be expressed as:

$$\vec{i} = \left[-\cos(\alpha_s)\sin(\gamma_s), -\cos(\alpha_s)\cos(\gamma_s), -\sin(\alpha_s)\right] \tag{10}$$

From this, the value of the $\cos\theta$ can be calculated.

2.3. The atmospheric efficiency model

Kistler proposed a formula for atmospheric attenuation efficiency, and after some modifications, equations (11) and (12) can be obtained[8]:

When $Visi- \ bility = 23km$,

$$\eta_{att} = 0.99326 - 1.046 \times 10^{-4} d + 1.7 \times 10^{-8} d^2 - 2.845 \times 10^{-12} d \tag{11}$$

When $Visibility = 5km$,

$$\eta_{att} = 0.98707 - 2.748 \times 10^{-4} d + 3.394 \times 10^{-8} d^2 \tag{12}$$

When comparing these two mathematical models of atmospheric attenuation efficiency, assuming visibility is greater than or equal to 40 km, and the range of mirror reflection distance d is from 1 to 2000 meters. Fig 3 illustrates the relationship between atmospheric attenuation efficiency and mirror reflection distance.

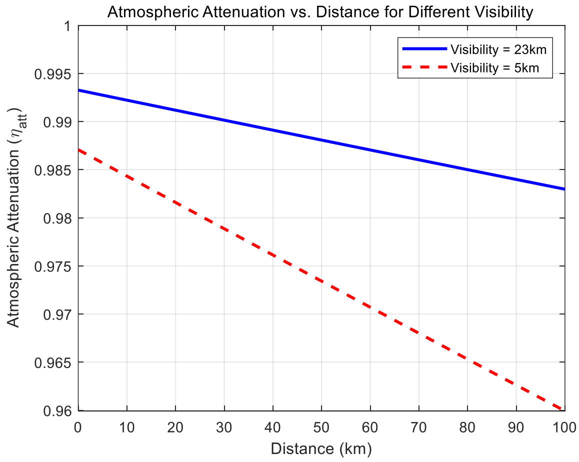

Fig 3: Relationship between Atmospheric Attenuation Efficiency and Heliostat Reflection Distance

As shown in Fig 3, the atmospheric attenuation efficiency decreases gradually in a linear trend as the mirror reflection distance increases.

2.4. Truncation Efficiency Theoretical Model

Assuming the incident distribution of sunlight follows a conical distribution with a half-angle width of 4.65 milliradians[9]. Then, the sunlight reflecting from the heliostat mirror to the absorber surface also exhibits a conical shape. These rays are divided with uniform angular steps in both the direction of half-angle widening and azimuthal direction, as shown in Fig 4:

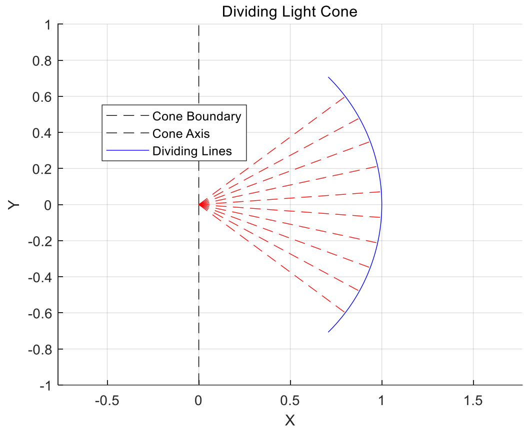

Fig 4: A Cone of Light Divided into Several Rays Using Angle Bisector Method

2.5. Total Optical Efficiency

According to Equation (13) [10]:

$$\eta_{fielde,t} = \eta_{\cos} \times \eta_{att} \times \eta_{\text{int}} \times \eta_{sb} \times \eta_{ref} \times \eta_{clc} \tag{13}$$

In the calculation, the mirror reflectivity and mirror cleanliness are often treated as constants.

With the heliostat shadow shading efficiency of 0.74, cosine efficiency of 0.89, truncation efficiency of 0.72, and atmospheric attenuation efficiency of 0.91, the total optical efficiency of the heliostat can be calculated as 0.43.

3. Conclusion

According to the formulas provided, the calculated annual average optical efficiency of the heliostat is 0.43, demonstrating notable efficiency in concentrating solar energy. The annual average shadow shading efficiency of 0.74 represents excellent performance in minimizing shadow shading, which facilitates maximum sunlight utilization. The high value of the annual average cosine efficiency of 0.89 illustrates that the mirror surface effectively captures and focuses sunlight. Moreover, the annual average truncation efficiency of 0.72 suggests a minimization of energy loss. Ultimately, the heliostat's annual average thermal output power is 28.5 MW, with an average thermal output power per mirror area unit of 0.42 kW/m², indicating an effective conversion of solar energy into thermal energy, hence providing a dependable energy source for diverse applications.

In summary, these calculated data showcase the exceptional performance of the heliostat, reflecting its high efficiency and reliability in solar energy utilization. The exceptional performance of the heliostat contributes significantly to the development of renewable energy, offering an encouraging outlook for the renewable energy sector.

However, improvements in optical efficiency are not achieved overnight. We must comprehend and acknowledge that there are a plethora of factors influencing the optical efficiency of heliostats. Beyond visible aspects like shadow shading efficiency, cosine efficiency, and truncation efficiency, many other factors also play a role in the optical efficiency of heliostats. This necessitates us having a comprehensive point of view and acute perception to fully grasp and understand these influencing factors.

Specifically, the design and layout of heliostats are among the key factors impacting their optical efficiency. Optimizing these aspects is vital for enhancing the overall optical efficiency of heliostats. For instance, by optimizing the spatial layout of heliostats, shadow shading can be minimized to make use of sunlight more effectively. At the same time, adjusting the angle and direction of the heliostats can effectively capture and focus sunlight, thereby increasing the thermal output power of the heliostats.

4. Outlook section

Furthermore, environmental factors also significantly affect the optical efficiency of heliostats. For example, geographical location, climatic conditions, and seasonal variations all impact the optical efficiency. This requires us to thoroughly consider the effects of these environmental factors when designing and operating heliostats to achieve maximum optical utilization efficiency.

Not only that, the maintenance and cleanliness of heliostats are critical factors impacting their optical efficiency. In their operation, the mirror surfaces of heliostats often accumulate dust and dirt, which lowers their reflectivity, consequently reducing their optical efficiency. Therefore, the regular cleaning and maintenance of heliostats are extremely crucial.

Through the aforementioned discussion, we see that to enhance the optical efficiency of heliostats, we need to approach from various angles. We need a profound understanding and mastery of the diverse factors affecting the optical efficiency of heliostat so we can better optimize these elements, advance the optical efficiency of heliostats, and further propel the development of solar thermal power generation technology.

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