Optimal design and application of heliostat field based on radial staggered radiation grid layout

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Abstract. To meet the actual requirements and maximize economy and efficiency, the size of heliostats is designed, and efficiency optimization is achieved through a reasonable layout. In this study, linear and nonlinear programming models are constructed. With the objective function of minimizing the shadow occlusion between heliostats, the optimal size and height of heliostats and the shadow length are obtained. Combining the circular layout strategy of radial staggered radiation grids and the simulated annealing algorithm, with the annual average thermal power output per unit mirror area as the optimization target, the target of a rated power of 60 MW is achieved. The research results show that the annual average optical efficiency of the optimized heliostat field is 29.91%, and the average yearly thermal power output per unit area is 341.78 kW/m², providing an important basis for the design and construction of solar thermal power plants.

Keywords: Linear Programming, Simulated Annealing Algorithm, Optimal Design, Radial Staggered Radial Circular Layout.

1. Introduction

Currently, with the rapid growth of energy demand and the gradual depletion of traditional fossil fuel resources, environmental pollution problems have become increasingly severe. To address the global energy crisis and climate change challenges, clean and renewable energy development and utilization have become an important direction for future energy strategies. Due to its abundant resources and environmental-friendliness, solar energy has gradually become a renewable energy source that has attracted much attention. Among various solar power generation technologies, tower-type heliostat solar thermal power generation has become a research hotspot because of its high conversion efficiency and good prospects for large-scale development.

The tower-type heliostat system has a relatively high heat-collection efficiency, but its performance highly depends on the layout of the heliostat field and the design of specific dimensions. In recent years, research on optimizing the layout of heliostat fields to improve energy conversion efficiency has attracted much attention [1]. Francisco J calculated various parameters of the heliostat field at noon on the vernal equinox [2]. They defined the ground utilization efficiency through the product of three items to limit the layout range of the heliostat field, providing a preliminary plan for the layout of the heliostat field [3]. However, selecting this specific time limits the accurate reflection of the annual efficiency. Current research shows that the efficiency can be maximized under non-blocking conditions [4]. Sun et al. and Leng et al. and Leng et al. further explored the daily, monthly, and annual efficiencies, indicating that the solar elevation angle has a significant impact on the layout and provides different optimization directions for practical applications [5,6]. The research team established the maximization of solar-to-chemical energy conversion efficiency as the objective function, and proposed a novel circular layout scheme of radially staggered heliostat field arrangement through an analytical model using annual fuel productivity as the evaluation criterion. The study particularly emphasized the coupling relationship between heliostat field and receiver design parameters, achieving significant improvement in overall system conversion efficiency through their synergistic optimization [7]. However, a high-efficiency layout does not necessarily achieve maximum economic benefits. Some people believe that starting from the actual economic perspective is necessary, reducing costs while ensuring conversion efficiency. Therefore, the current problem is: how to optimize the layout of the heliostat field according to the actual terrain, heliostat size, target efficiency, and layout design.

In response to the problem that the existing research has not effectively resolved, which is the balance between the efficiency and economy of the solar energy system, this paper proposes an optimized model of a radial staggered radiation grid for the heliostat field based on a circular layout. It is mainly designed for a 60MW-level photovoltaic power generation system. By optimizing the mirror field size, installation height, and layout configuration, this research has important application value in improving the annual average output power per unit area. At the same time, it can effectively enhance the optical efficiency and economy of the system, providing a theoretical basis and technical guidance for related fields.

2. Establishment and solution of the model

2.1. Objectives of model construction

The data used in this study are sourced from www.mcm.edu.cn. By calculating the solar altitude angle and azimuth angle, the layout of the photovoltaic array is designed, and linear and nonlinear programming models are constructed. Combining the geometric characteristics of solar radiation with the structure of the photovoltaic array, we aim to optimize the layout and energy output of the photovoltaic array. In this process, the simulated annealing algorithm is utilized to achieve the optimal layout and maximum energy output of the photovoltaic array.

$$\sin \partial_s = cos\delta \cos \varphi \cos \varpi + \sin \delta \sin \varphi \tag{1}$$

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

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

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

Where φ represents the local latitude (positive for northern latitudes). ω denotes the solar hour angle. ST corresponds to local time. δ is the solar declination angle. ∂_s indicates the solar elevation angle, and D defines the number of days counted from the vernal equinox. with day 0 being the equinox itself.

2.2. Circular layout of radially staggered radiation grids

Numerous existing studies have shown that in the solar tower concentrated solar power system, the layout optimization of the heliostat field is crucial for improving the system efficiency and economic viability. Without area restrictions, placing the central tower at the center of the heliostat field and adopting a circular layout with a radial staggered arrangement can significantly increase the number of heliostats and enhance the overall system efficiency. This layout provides a more efficient and cost-effective solution for large-scalesolar power generation by reducing shadow and occlusion losses and optimizing land use[8,13]. The specific layout is shown in the following Figure 1.

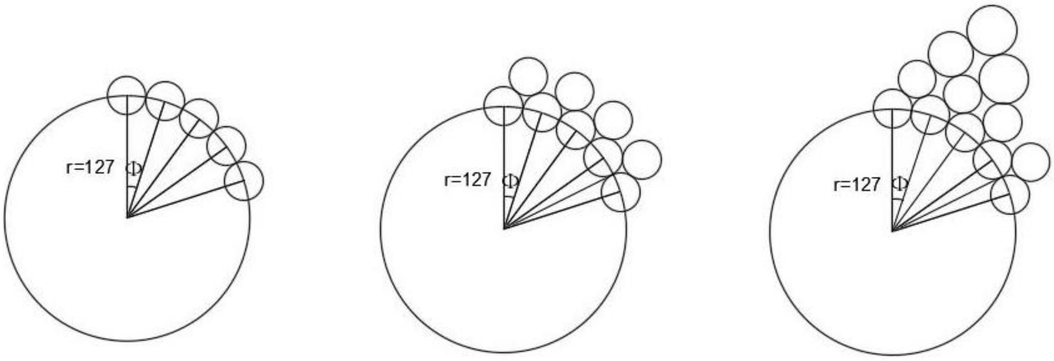

Figure 1. Circular layout of radially staggered radiation grids

In this layout, the heliostats are arranged radially around the tower collector and are laid out in a staggered manner to avoid mutual shading and improve the overall optical efficiency. This layout distributes the heliostats on multiple concentric circles through a radial grid structure. The number and position of the heliostats on each layer are precisely calculated to ensure that the shading between the heliostats is minimized at all angles and periods. The advantage of the staggered layout is that it allows the heliostats to be arranged at closer intervals while ensuring that each mirror can receive sufficient solar radiation, thereby improving the space utilization of the site and the annual average energy output.

In this layout, as shown in Figure 2, the heliostatic mirrors are arranged radially around the tower collector and are arranged in a staggered manner to avoid blocking each other and improve the overall optical efficiency. This arrangement distributes heliostats on multiple concentric circles through a radial grid structure. The number and position of each layer of heliostats are precisely calculated to ensure minimal shadows between the heliostats at all angles and periods. The advantage of the staggered layout is that it can make the heliostatic mirrors closer together, while ensuring that each mirror can get enough solar radiation, thereby improving the space utilization of the site and the annual average energy output.

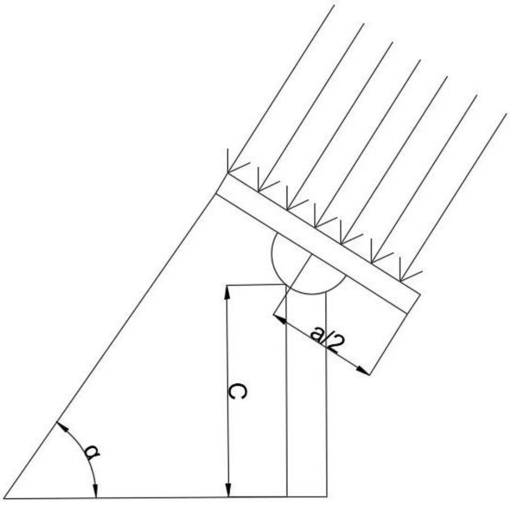

Figure 2. Partial enlarged view of the heliostat

2.3. Linear programming model

Based on the solar elevation angle and azimuth angle, a linear programming model was constructed to maximize the annual average thermal power output of heliostats per unit area. The constraints are the size and spacing of heliostats. As can be seen from Figure 2, when an extreme situation occurs, the heliostat is perpendicular to the ground at 90°, the shadow coverage length reaches the maximum. Thus, a linear programming model aiming to maximize the shadow area was determined.

$$\max L = \frac{\frac{1}{2}a + c}{\tan \alpha_s} \tag{5}$$

$$s.t.\begin{cases} 2 \le a \le 8 \\ 2 \le c \le 8 \\ c \le a \end{cases} \tag{6}$$

2.4. Solution process of the linear programming model

The minimum angle between October and December α_s is Set as 23.73^o, Use the simulated annealing algorithm to search for the optimal solution that maximizes L. When different heliostat sizes are selected, there will be differences in the shading area, and the power of the heliostat will also vary.

2.5. Nonlinear Programming Model

In conclusion, based on the heliostat field layout obtained through linear programming, a nonlinear programming model is further constructed to improve the overall optical efficiency and thermal power output of the heliostat field. In the solar tower photothermal system, after the initial optimization of the heliostat field layout through linear programming, constructing a nonlinear programming model can significantly improve the overall optical efficiency and thermal power output. According to the research of S.M. Besarati, Pargmann, and others, key parameters such as direct normal irradiance (DNI), shadow area, and the physical parameters of heliostats are accurately modeled through nonlinear equations, with the objective function of maximizing the annual average output thermal power. The optimized layout not only improves the efficiency in theory.

But also significantly increases the total annual output thermal power by reducing shadow and occlusion losses in practical applications, providing an efficient solution for the design and energy application of solar tower photothermal systems[14,15]. In this model, the annual average output efficiency and the total annual output thermal power are used as the objective functions, and the optimization goal is to maximize the annual average output power. From the above, the following research ideas can be derived: When the size of the heliostats is limited, the period is divided into two types according to the solar altitude angle and azimuth angle at different periods. After obtaining the specific size of the heliostats, according to the research results of S.M. Besarati et al and Guangdong Zhu, the specific arrangement and average thermal efficiency can be obtained by using the circular layout with the radial staggered arrangement.

As can be seen from the above - summarized research ideas, the period is divided into two types: The first period is from 9:00 to 10:30 and from 13:30 to 15:00. In the first period, DNI = DNI * 0.7. The second period is from 10:30 to 13:30, during which DNI remains unchanged.

$$\min -(DNI \times \eta_{at} \times 0.7 + DNI \times \eta_{at}) \tag{7}$$

$$s.t\begin{cases} d_{HR} \le 1000 \\ a < 8 \\ c < 6 \\ a \ge b \end{cases} \tag{8}$$

The detailed dimensions of the heliostat are obtained as follows: the mirror is 8 m in height, 6 m in width, and the installation height is 6 m.

The solution of the model also combines the simulated annealing algorithm. The layout parameters of the heliostat field for different periods are optimized. Then, by increasing the number of rings, the optimal values of the annual average optical efficiency and the output thermal power per unit area are finally achieved.

The algorithm flow is shown in Figure 3:

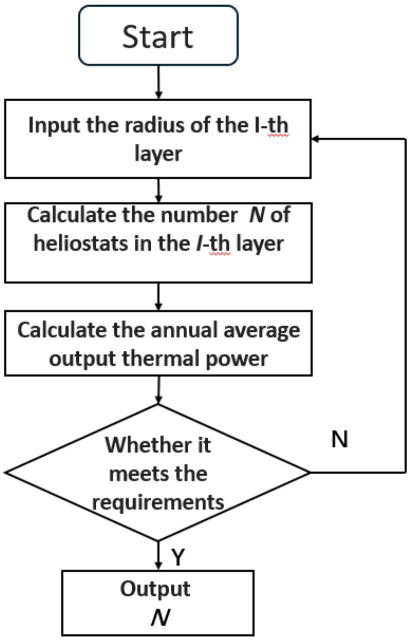

Figure 3. Optimize the algorithm flow chart.

Use the `coefficients` function in MATLAB to perform a cubic polynomial fitting between the number of turns N and the output power. Then, increase N by one in each iteration in a loop until the output power meets the rated power of 60 MW. It can be found that when N = 10, the condition is met, and the total annual output power is 66.77 MW, which is greater than the target of 60 MW. At this time, reduce the number of heliostats in the 10th layer until the target of 60 MW is just met. After the improvement, the calculation shows that $N=N_1+N_2+....+N_{10}=766$ The total annual output thermal power of the fixed - day field is 60.36 MW, reaching the rated output thermal power of 60 MW.

3. Results

3.1. Optimization Results

Select the minimum elevation angle. a_s Set as 23.73^o, Use the simulated annealing algorithm to search for the optimal solution that maximizes L, and finally obtain a =8m, c =6m, $L_{\max}$ =14.55m.

The results show that when the minimum elevation angle is constrained, the maximum distance between heliostats can be obtained to achieve no shadow occlusion, maximize the conversion efficiency, and thus ensure the minimum number of heliostats and the smallest floor area during layout planning.

3.2. Analysis of experimental results

From the mathematical model of the solution results, it can be seen that after optimization, the data of each indicator is more prominent compared with that of the original algorithm, especially the data of Annual average.

Thermal power output per unit area has increased by 31.54, as shown in Table 1.

Table 1. Comparison of power load forecasting of 403 line

	Before optimization	After optimization
Total power (MW)	55.20	60.36
Annual average optical efficiency (%)	26.15	29.91
Annual avg. thermal power output per unit area (KW/m²)	310.25	341.79
Width of the heliostat (m)	7	8
Height of the heliostat (m)	5	6
Spacing between heliostats (m)	15.5	14.55

By introducing the simulated annealing algorithm and the radial staggered radiation grid layout, new relational conclusions can be drawn. That is, on the premise of ensuring economic efficiency, the annual average thermal power output and optical efficiency of the heliostat field can be significantly improved.

By solving the non-linear programming model, the results are shown in Table 1. It shows that the total output thermal power of the heliostat field after optimal design reaches 60.36 MW, slightly higher than the set target of 60 MW. In addition, the annual average optical efficiency is 29.91%, and the annual average output thermal power per unit mirror area is 341.79 kW/m².

These results indicate that through the optimal design using the simulated annealing algorithm, the performance of the heliostat field has been significantly improved, especially in terms of enhancing the optical efficiency and thermal power output, which provides higher economic efficiency and sustainability for the tower - type solar thermal power generation system.

4. Conclusion

In this study an optimized design model for the heliostat field based on a radially staggered radiation grid layout was proposed. By integrating linear and nonlinear programming models and applying the simulated annealing algorithm, the optical efficiency and thermal power output of the tower-typesolar thermal power generation systemswere significantly enhanced.

The results show that the system's annual average optical efficiency reaches 29.91%, the total output power is 60.36 MW (slightly exceeding the 60 - MW rated target), and the annual average thermal power output per unit mirror area is 341.798 kW/m². This optimized design effectively enhances system efficiency while considering economic factors, demonstrating high practical value.

However, this study has limitations. It mainly focuses on existing heliostat designs, with insufficient exploration of new materials and shapes. Also, the experimental data collection and analysis methods have certain flaws. Future research should focus on optimizing heliostat materials and shapes. Selecting efficient optical materials and designing proper mirror shapes can boost heliostat optical efficiency and focusing stability, supporting solar thermal power technology development. Additionally, exploring dynamic layout adjustment strategies for different geographical and climate conditions can improve the system's overall performance and economic benefits.

The simulated annealing algorithm proved effective in this study. However,its performance depends on parameter settings and convergence speed. Thus, in practical use, careful parameter adjustment and computing resource management are needed for optimal results.Overall, this study offers new ideas for optimizing tower-typesolar thermal power generation systems and paves the way for future related research. With continuous exploration, solar thermal power generation technology can play a more crucial role in the global energy transition and sustainable development.

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