Study and Optimization of the Optical Performance of Linear Fresnel Solar Systems: Postprint

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Abstract

To investigate and optimize the optical performance of linear Fresnel solar systems, this study employs the Monte Carlo Ray Tracing (MCRT) method to establish a self-programmed three-dimensional optical model of the entire system. Based on this model, the influence patterns of different mirror configurations, aiming positions, surface errors, and geographical locations on the system' s optical performance are analyzed, and the geometric parameters and aiming positions of the mirrors are optimized. The results demonstrate that an optimal performance value exists for each mirror configuration, at which point the optical performance of cylindrical and parabolic mirrors is nearly identical. Regarding the heat flux distribution on the absorber tube, uniformity can be enhanced by optimizing the design of mirror aiming lines, and certain surface errors can also improve this uniformity. Geographically, the system' s annual average optical efficiency ranges between 52%}37% within the latitude range of 20°-50°N, making it applicable in most regions of China.

Full Text

Preamble

Optical Performance Investigation and Optimization of a Linear Fresnel Reflector Solar Collector

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Abstract: A 3D Monte Carlo ray tracing model was developed in FORTRAN for a linear Fresnel reflector solar collector in order to investigate and optimize its optical performance. The performance of three typical mirrors, the effects of the mirror aim lines, slope error, and location, etc. were investigated. The results show that the optimal radius and focal length could be found for the cylindrical and parabolic mirrors, respectively. The optimized cylindrical mirror could achieve the same performance as that of the optimized parabolic mirror. The uniformity of the concentrated solar flux on the absorber tube could be improved by designing the aim lines and using the mirror with a certain slope error. In addition, the LFR system whose yearly mean optical efficiency ranges between 52% and 37% from N20° to N50° could be applied in most area of China.

Keywords: Solar energy; Linear Fresnel reflector; Compound Parabolic Collector (CPC); Monte Carlo ray tracing (MCRT); Optical performance

0 Introduction

In recent years, linear Fresnel reflector solar thermal power technology has experienced rapid development, with multiple power generation systems having been successively commissioned. The optical performance of linear Fresnel systems represents a key parameter for evaluating overall system performance, directly influencing the photothermal conversion process and subsequent power generation efficiency. Consequently, fundamental research in this area has attracted widespread attention. Häberle et al. [1] investigated the optical performance of Solarmundo, the world's first linear Fresnel demonstration system, obtaining the radiative heat flux distribution on the absorber tube under normal incidence and the optical-thermal efficiency under typical operating conditions. Du et al. [2] explored methods for reducing shadowing and blocking losses in mirror fields, deriving an optical geometric method for designing east-west oriented systems free from shadowing and blocking losses. Abbas et al. [3] comparatively analyzed the spot distribution characteristics on planar absorbers for linear Fresnel systems employing cylindrical and parabolic reflectors. Grena et al. [4] proposed a linear Fresnel system with dual-wing secondary reflectors and investigated its optical performance and heat flux distribution characteristics. Currently, however, research on optical performance prediction for linear Fresnel systems and the influence of key parameters remains relatively limited, with the underlying mechanisms still not fully understood.

To investigate and optimize the optical performance of linear Fresnel systems, this paper derives the mirror tracking equations and ray tracing equations, and establishes a dynamic optical model using the Monte Carlo ray tracing method (MCRT) [5-7]. Based on this model, a series of analyses and optimization studies are conducted.

1 Physical Model

The linear Fresnel system investigated in this paper is illustrated in Figure 1 [Figure 1: see original paper]. The system primarily consists of a linear Fresnel reflector (LFR) field, a compound parabolic collector (CPC) secondary reflector, an absorber tube with selective coating, and a glass cover plate. The main system parameters are listed in Table 1 . The reflector field comprises horizontally arranged strip mirrors with identical geometric parameters. Each mirror group independently tracks the sun' s position to reflect sunlight into the fixed CPC cavity. The mirror field is arranged symmetrically in the east-west direction, with east-side mirrors labeled M1-M25 from west to east, and west-side mirrors labeled M26-M50 from east to west. The CPC profile is left-right symmetric, composed of an involute curve AB and a parabolic curve BC, as shown in Figure 1. The general equation for the profile is given in Equation (1) [8].

2.1 Mirror Tracking Equation

To investigate the system' s optical performance, the tracking angle m of each mirror group at any given time must first be determined. To this end, a right-handed Cartesian coordinate system is established, including the incident coordinate system XiYiZi, mirror coordinate system XmYmZm, ground coordinate system XgYgZg, and receiver coordinate system XrYrZr, as shown in Figure 1. The tracking angle m is defined as the angle between the positive Ym direction and the positive Yg direction after the mirror rotates about Xm, with positive values for counterclockwise rotation of Xm. The angle m can be determined from the aim line (xg, yaim, zaim) of the central reflected ray from the mirror, as shown in Figure 1. When $\pi \leq \mathrm{A} \leq 3\pi/2$ and the random tracking error Rte follows a normal distribution N(0, σte), the tracking angle m for west-side mirrors can be obtained from Equation (2). Similar derivations apply to other cases.

In the equation, $ $1 and $ $2 are shown in Figure 1, σte is the standard deviation of tracking error, ym is the y-coordinate of the mirror axis in the XgYgZg system, and α and A represent the solar altitude and azimuth angles, respectively, which can be calculated from the local latitude ϕ, solar time ts, and day number Nday [9].

The geometric and optical parameters of the system are summarized in Table 1 [1][4], which includes: number of mirrors nm, mirror width Wm = 0.598 m, mirror length Lm = 9.805 m, mirror spacing dm = 0.10 m, tube height Ht = 1.5 m, tube radius r1 = 0.035 m, r2 = 0.04 m, r3 = 0.07 m, maximum acceptance angle max = 60°, maximum rim angle omax = 1.047 rad, glass plate width = 0.5 m, glass plate thickness = 0.004 m, glass plate height Hglass = 0.7 m, mirror reflectivity 1 = 0.95, glass transmissivity τ = 0.95, glass refractive index = 1.5, CPC reflectivity 2 = 0.95, and absorber tube absorptivity αt = 0.95.

2.2.1 Random Photon Initialization

In the Monte Carlo ray tracing process, each reflecting mirror surface is treated as a random photon emission surface. Assuming uniform solar radiation distribution across the mirror surface, the intersection point of an incident ray with the mirror in the mirror coordinate system can be expressed as Pm, as given in

Equation (4). Considering the sun' s non-parallel angle $\delta = 9.30$ mrad, the incident vector in the XiYiZi system can be expressed as Ii, also given in Equation (4).

In the equations, fm(y) represents the mirror cross-section profile equation in the YmZm plane, and all variables throughout this paper follow a uniform distribution U[0,1]. The energy carried by each photon on a given mirror can then be expressed as:

$$W = \frac{DNI \cdot L_m \cdot W_m \cdot \eta_{cos}}{n_p}$$

where cos is the mirror cosine efficiency, np is the number of photons traced on the mirror, and DNI is the direct normal irradiance [9].

2.2.2 Photon Reflection on Mirrors or CPC

The reflection process is illustrated using photon reflection on a mirror as an example. First, the incident vector Ii is transformed into Ig in the XgYgZg system and Im in the XmYmZm system through coordinate transformations. A random number is then generated to determine whether reflection occurs; if $<$ 1, reflection takes place, and the reflected vector Rm in the XmYmZm system can be obtained from Equation (7). Finally, Rm is transformed into Rg in the ground coordinate system.

$$R_m = I_m - 2(N_m \cdot I_m)N_m$$

where Nm is the unit normal vector at point Pm, m and ϕm are the radial and tangential angular deviations of the mirror normal caused by surface slope error σse [10], and km is the slope of the mirror profile at Pm. A similar approach can be used to calculate the reflection process on the CPC.

2.2.3 Shadowing and Blocking

When incident rays are blocked by adjacent mirrors, they cannot reach the mirror surface, creating shadows. The method for determining whether a ray is blocked is illustrated using the shadowing process shown in Figure 1. First, the intersection point Pa of the incident ray with mirror a in mirror a' s coordinate system is transformed into Pab in mirror b' s coordinate system, as expressed in Equation (9). Then, the incident vector Ig is transformed into Ib in mirror b' s system, as given by Equation (10). From Pab and Ib, the incident ray equation in mirror b' s system can be obtained. By simultaneously solving this ray equation with the surface equation of mirror b in its coordinate system, the intersection point Pb of the ray with mirror b can be found. If Pb lies on mirror b, the ray is blocked. A similar method can be used to determine whether incident rays are blocked by the absorber tube and whether reflected rays are blocked by adjacent mirrors.

2.2.4 Photon Refraction in Glass Plate

If a reflected photon is not blocked, the intersection point with the glass plate is then determined. First, the intersection point Pm of the reflected ray with the mirror surface is transformed into Pg in the ground coordinate system, as expressed in Equation (11). Combined with Rg, the reflected ray equation in the ground coordinate system can be obtained. By simultaneously solving this reflected ray equation with the equation for the lower surface of the glass plate in the XgYgZg system, their intersection point can be found. A random number is then used to determine whether refraction occurs; if $< \tau$, refraction takes place. If refraction occurs, the refracted vector Rt in the glass can be calculated from Equation (12). The intersection point of the refracted ray with the upper surface of the glass plate can then be determined, while the photon vector remains unchanged as Rg after transmission.

2.2.5 Photon Absorption and Statistics on Absorber Tube

When a photon passes through the glass plate or is reflected by the CPC and strikes the absorber tube, a random number is generated to determine whether absorption occurs; if $< \alpha$t, the photon is absorbed. The absorbed photons on the absorber tube are then statistically distributed among Nc circumferential grids on the tube surface.

2.2.6 Definition of Optical Performance Evaluation Parameters

Through ray tracing and statistical analysis of photon distribution on the absorber tube, performance parameters such as non-uniform heat flux distribution and system optical efficiency can be obtained. To evaluate the system’ s optical performance, the following parameters are defined: the circumferential heat flux non-uniformity coefficient σq [11], the local concentration ratio (LCR) of axial heat flux on the absorber tube, instantaneous optical efficiency iopt, daily average optical efficiency dopt, and yearly average optical efficiency yopt.

The local concentration ratio is defined as:

$$LCR = \frac{q_k}{DNI}$$

where qk is the local heat flux density in the k-th circumferential grid of the absorber tube. The instantaneous optical efficiency is given by:

$$\eta_{iopt} = \frac{\sum_{j=1}^{N_{day}} \sum_{i=1}^{N_{time}} Q_{ij}}{\sum_{j=1}^{N_{day}} \sum_{i=1}^{N_{time}} DNI_{ij} \cdot L_m \cdot W_m \cdot n_m}$$

where Qij and DNIij are the heat absorbed by the absorber tube coating and the direct normal irradiance at time i on day j, respectively.

3 Model Validation

A three-dimensional optical model of the system was developed using Fortran programming based on the aforementioned methods. To verify the accuracy of the method and model, comparisons were made with simulation results from TracePro [13] and SolTrace [14] software, following a similar approach to Chemisana et al. [12]. TracePro is a widely used commercial software, while SolTrace is a solar simulation software developed by NREL, both capable of analyzing the transient performance of optical systems. The validation was performed in two parts: first, the LCR distribution of radiation absorbed by the absorber tube was compared with TracePro for a case with $\alpha = 90°$, flat mirrors, and aim lines of (xg, -0.15, 10) and (xg, 0.15, 10) for west and east mirrors, respectively; second, the LCR distribution of incident radiation on the lower surface of the glass plate was compared with SolTrace for the same parameters but with σse = 2.5 mrad. The comparison results are shown in Figure 2 [Figure 2: see original paper]. As can be seen, the LCR curves match well in both cases, verifying the accuracy of the method and model presented in this paper.

4 Results and Discussion

4.1 Performance Comparison and Optimization of Three Typical Mirrors

Mirrors are the concentrating elements of the system, accounting for more than half of the total system cost, and their geometric parameters directly affect system performance. To investigate the influence of mirror geometric parameters on system performance and explore approaches to reduce system cost, this section compares systems using flat mirrors, cylindrical mirrors, and parabolic mirrors. The mirrors and CPC are assumed to have the same surface slope error σse. In this section, the aim line is (xg, 0, 10), σse = 2.5 mrad, and DNI = 1000 $\mathrm{W \cdot m^{-2}}$.

To compare the performance of the three mirror types, the radius (r) of cylindrical mirrors and focal length (f) of parabolic mirrors were optimized. Figure 3 [Figure 3: see original paper] shows the optimization results for a system located on the Tropic of Cancer, with the optimization objective function being dopt and the calculation period from 7:30 to 16:30 on the summer solstice. The results show that dopt initially increases rapidly with r or f to a maximum value (at r = 27.5 m or f = 14 m), then gradually decreases, eventually approaching the flat mirror daily efficiency of 52.52%. Analysis reveals that within the ranges r = 25.5-32 m or f = 12.7-15.7 m, the dopt values for the two mirror types vary by less than 0.1%, indicating that the system is insensitive to changes in r or f within these ranges, which provides convenience for system design and manufacturing.

Figure 4 [Figure 4: see original paper] presents the heat flux distribution on the absorber tube for systems using the optimized three mirror types, with $\alpha = 90°$. The results show that the optical performance of optimized parabolic and cylindrical mirrors is very similar, with their LCR curves on the absorber tube nearly overlapping and their iopt values differing by less than 0.1%, which is 9.8% higher than that of flat mirrors. Verification analysis confirms that this characteristic holds for other aiming strategies as well. This conclusion demonstrates that optimized cylindrical mirrors can achieve the same performance as parabolic mirrors in LFR systems. Since cylindrical mirrors are relatively easier to manufacture and less expensive, they can effectively reduce system costs. Cylindrical mirrors are used in all subsequent studies.

4.2 Influence of Mirror Aim Lines on Optical Performance

Under the aiming scheme shown in Figure 4, the maximum LCR of the cylindrical mirror system is more than twice that of the flat mirror system, increasing the risk of absorber coating failure. This section aims to achieve more uniform heat flux distribution by designing appropriate aiming schemes while maintaining high optical efficiency, with σse = 2.5 mrad and zaim = 9.805 m.

First, the mirror radius was optimized for five different aiming schemes (with west and east mirror aim lines symmetric about the xgzg plane) as shown in Table 2 . The optimization results are presented in Table 2. Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper] compare the optical performance of the five optimized schemes. Figure 5 shows that LCR can be reduced by dispersing aim lines while maintaining high optical efficiency. The comparison indicates that both Scheme 4 and Scheme 5 achieve relatively high iopt values (65.90% and 67.5%) and low σq values (36.50% and 57.34%). As shown in Figure 6, Scheme 4 reduces the maximum LCR by 36% compared to Scheme 1, while capturing 35% of the energy on the upper half of the absorber tube; Scheme 5 reduces the maximum LCR by 22% while capturing 20% of the energy on the upper half. To avoid local overheating of the absorber tube while ensuring high efficiency, LFR systems could employ Scheme 5 in low-temperature sections and Scheme 4 in high-temperature sections. Subsequent studies use Scheme 4 as an example.

Table 2 Five mirror aim schemes

Scheme	yaim (m)	σse (mrad)	iopt (%)
1	0.006	2.5	67.50
2	0.09	2.5	67.09

Scheme	yaim (m)	σse (mrad)	iopt (%)
3	-0.01	2.5	66.03
4	0.11	2.5	65.90
5	0.11	2.5	67.50

4.3 Influence of Slope Error on Optical Performance

Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] compare the instantaneous optical performance of systems with different surface slope errors σse, with $\alpha = 90°$. As shown in Figure 7, as σse increases (0–3.5 mrad), σq gradually decreases, indicating improved heat flux uniformity on the tube wall, while iopt also decreases but only slightly (by 3.9%). Combined with Figure 8, the maximum LCR is reduced by 20% relatively. This demonstrates that using mirrors with a certain σse can significantly improve heat flux uniformity with only a small efficiency penalty, while also reducing manufacturing costs. In subsequent studies, σse = 2.5 mrad is used.

4.4 Optical Efficiency at Different Latitudes

Figure 9 [Figure 9: see original paper] compares the daily average efficiency dopt and yearly average efficiency yopt of the system at different latitudes. The results show that dopt varies with day number Nday and latitude ϕ, with all dopt curves at different ϕ values exhibiting a bell-shaped variation with day number. Systems south of the Tropic of Cancer in the Northern Hemisphere show two peaks in their dopt curves, while systems north of the Tropic of Cancer show only one peak on the summer solstice. Meanwhile, yopt gradually decreases as ϕ increases. Within the latitude range of 20°N to 50°N, the yopt of this linear Fresnel system varies from 52% to 37%. This indicates that the system maintains relatively high optical efficiency and can be applied in most areas of China.

5 Conclusions

To investigate and optimize the optical performance of linear Fresnel systems, this paper establishes a three-dimensional optical model using the Monte Carlo ray tracing method, implements the algorithm in FORTRAN, and conducts a series of analyses and optimization studies. The main conclusions are as follows:

1. Optimized cylindrical mirrors can achieve almost the same optical performance as parabolic mirrors, with their radiation distribution curves on the absorber tube nearly overlapping. This conclusion provides a basis for replacing relatively expensive parabolic mirrors with cheaper cylindrical mirrors in LFR systems, promising to reduce system costs.
2. The uniformity of heat flux on the absorber tube can be improved by optimizing mirror aim lines with only a small sacrifice in efficiency, for

which two design schemes are presented in this paper. Additionally, there exists a stable high-efficiency range for cylindrical mirror radius, within which the efficiency is insensitive to radius variations, which can reduce the difficulty of system design and optimization.

3. The heat flux uniformity on the absorber tube improves with increasing mirror surface slope error σse. Using mirrors with a certain σse can improve heat flux uniformity while reducing manufacturing costs.
4. Within the latitude range of 20°N to 50°N, the system achieves high yearly efficiency (52%-37%) and can be applied in most areas of China.

References

[1] Häberle A, Zahler C, Lerchenmüller H, et al. The Solarmundo line focussing Fresnel collector. Optical and thermal performance and cost calculations[C]. Proceedings of the 2002 SolarPACES International Symposium. 2002.

[2] Du Chunxu, Wang Pu, Ma Chongfang, et al. Optical Geometric Method for LFR Mirror Field Arrangement Without Shading and Blocking[J]. Acta Optica Sinica, 2010, 11: 3276-3282.

[3] Abbas R, Montes M J, Piera M, et al. Solar radiation concentration features in Linear Fresnel Reflector arrays[J]. Energy Conversion and Management, 2012, 54(1): 133-144.

[4] Grena R, Tarquini P. Solar linear Fresnel collector using molten nitrates as heat transfer fluid[J]. Energy, 2011, 36(2): 1048-1056.

[5] He Y L, Xiao J, Cheng Z D, et al. A MCRT and FVM coupled simulation method for energy conversion process in parabolic trough solar collector[J]. Renewable Energy, 2011, 36(3): 976-985.

[6] Qiu Y, He Y L, Cheng Z D, et al. Study on optical and thermal performance of a linear Fresnel solar reflector using molten salt as HTF with MCRT and FVM methods[J]. Applied Energy, 2015, 146: 162-173.

[7] Cheng Z D, He Y L, Xiao J, et al. Three-dimensional numerical study of heat transfer characteristics in the receiver tube of parabolic trough solar collector[J]. International Communications in Heat and Mass Transfer, 2010, 37(7): 782-787.

[8] Oommen R, Jayaraman S. Development and performance analysis of compound parabolic solar concentrators with reduced gap losses-oversized reflector[J]. Energy Conversion and Management, 2001, 42(11): 1379-1399.

[9] He Y L, Cui F Q, Cheng Z D, et al. Numerical simulation of solar radiation transmission process for the solar tower power plant: From the heliostat field to the pressurized volumetric receiver[J]. Applied Thermal Engineering, 2013, 61(2): 583-595.

[10] Shuai Y, Xia X L, Tan H P. Radiation performance of dish solar concentrator/cavity receiver systems[J]. Solar Energy, 2008, 82(1): 13-21.

[11] Cheng Z D, He Y L, Cui F Q, et al. Comparative and sensitive analysis for parabolic trough solar collectors with a detailed MCRT ray-tracing optical model[J]. Applied Energy, 2014, 115: 559-572.

[12] Chemisana D, Barrau J, Rosell JI, et al. Optical performance of solar reflective concentrators: A simple method for optical assessment[J]. Renewable Energy, 2013, 57: 120-129.

[13] TracePro user' s manual release 5.0. Lambda Research Corporation, 2009.

[14] Wendelin T, Dobos A, Lewandowski A. SolTrace: a ray-tracing code for complex optical systems[R]. Denver West Parkway Golden, Colorado: National Renewable Energy Laboratory, 2013: 1-14.

Note: Figure translations are in progress. See original paper for figures.