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OPTIMIZATION OF LINEAR FRESNEL REFLECTOR SOLAR THERMAL SYSTEM FOR ENHANCED THERMAL PERFORMANCE IN HIGH SOLAR IRRADIANCE REGIONS

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Abstract

Linear Fresnel Reflector (LFR) solar thermal systems are promising technologies for harnessing high-intensity solar radiation to generate heat for power production and industrial applications. This study focuses on optimizing the design and operational parameters of an LFR system to enhance its thermal performance in regions characterized by high direct normal irradiance (DNI). A hybrid optimization approach combining computational fluid dynamics (CFD), Response Surface Methodology (RSM), and Genetic Algorithm (GA) is employed to evaluate and improve key variables such as reflector alignment, absorber geometry, and heat transfer fluid flow rates. Results demonstrate that the optimized LFR design achieves a significant increase in thermal efficiency while minimizing heat losses caused by convection and radiation. Sensitivity analysis identifies the most influential parameters, guiding future design improvements. The findings provide valuable insights for deploying efficient LFR systems in arid and semi-arid climates with high solar potential.

Introduction

The transition towards sustainable and renewable energy sources has become imperative in the face of rising environmental concerns and the depletion of fossil fuel reserves. Solar energy, being abundant and clean, plays a pivotal role in this transition and offers a wide array of technologies for harnessing solar radiation effectively [1,2]. Among these, solar thermal technologies have garnered attention due to their ability to convert solar energy into heat, which can be utilized for power generation, industrial processes, and domestic heating [1].

Within solar thermal technologies, concentrating solar power (CSP) systems, which focus direct solar irradiance to achieve high temperatures, have shown promise for large-scale applications [3]. The Linear Fresnel Reflector (LFR) system is a particular type of CSP that utilizes a series of long, narrow, flat or slightly curved mirrors to reflect sunlight onto a linear receiver located above the reflectors. This configuration offers several advantages, such as reduced structural complexity, lower manufacturing and maintenance costs, and a smaller land footprint compared to other CSP technologies like parabolic troughs or solar towers [3,4].

The adaptability and cost-effectiveness of LFR systems make them especially suitable for deployment in regions with high direct normal irradiance (DNI), such as the Middle East, North Africa, Australia, and parts of South America. These regions benefit from abundant solar resources but also face harsh environmental conditions, including high ambient temperatures and dust accumulation, which can adversely affect the optical and thermal performance of solar collectors [4,7]. Therefore, optimizing the design and operation of LFR systems is crucial to maximize their thermal efficiency and ensure reliable performance in such challenging environments.

The thermal performance of LFR systems depends on various parameters, including mirror alignment accuracy, receiver design, absorber tube geometry, heat transfer fluid selection, and system operational strategies [5]. Optimizing these factors can significantly reduce heat losses

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caused by convection, conduction, and radiation, which become more prominent at high operating temperatures. For example, optimizing the absorber coating and insulation can minimize radiative losses, while enhancing the heat transfer fluid flow can improve overall heat extraction efficiency [5,6]. Additionally, innovative designs incorporating secondary reflectors, hybrid receivers, and advanced heat transfer fluids have been proposed to further boost system performance [1,8].

Moreover, the deployment of LFR systems in high solar irradiance areas introduces unique challenges related to dust and soiling on mirror surfaces, which degrade reflectance and thus reduce the system's optical efficiency. Regular cleaning is necessary but increases operational costs and water consumption, especially in arid regions. Research has shown that dust accumulation can reduce the optical efficiency by up to 30% if not properly managed [7]. Hence, understanding the impact of environmental factors and integrating mitigation strategies such as hydrophobic coatings or automated cleaning mechanisms are vital for sustained performance.

To address these complexities, advanced optimization techniques have been employed in recent studies. Computational fluid dynamics (CFD) modeling enables detailed simulation of heat transfer and fluid flow within the receiver, providing insights into thermal losses and guiding design improvements [8]. Response Surface Methodology (RSM) helps in developing statistical models that describe the relationship between multiple design variables and system performance metrics, facilitating efficient exploration of the design space [9]. Genetic Algorithms (GA) and other evolutionary algorithms are widely used to perform global optimization by iteratively searching for the best combination of parameters that maximize thermal efficiency while considering practical constraints [9,10].

Integrating these methods into a hybrid optimization framework allows for a comprehensive evaluation of LFR system designs tailored specifically for the environmental and climatic conditions of high solar irradiance regions. Such frameworks enable the identification of optimal mirror geometries, absorber configurations, operating temperatures, and flow rates, ultimately improving the system's thermal output and reliability [10].

In light of these considerations, this study focuses on the optimization of a Linear Fresnel Reflector solar thermal system aimed at enhancing thermal performance under high solar irradiance conditions. The work employs advanced numerical simulations combined with multi-objective optimization algorithms to investigate the effects of key design and operational parameters on system efficiency. The ultimate goal is to develop an optimized LFR design that maximizes thermal energy capture, reduces heat losses, and offers a viable solution for renewable energy generation in regions with abundant solar resources and challenging environmental conditions.

2. Literature Review

Several studies have investigated the design and optimization of solar thermal collectors, including Linear Fresnel Reflectors. Kalogirou [1,2] provided comprehensive reviews of solar thermal technologies, emphasizing the potential of CSP systems. Lovegrove and Stein [3] detailed the principles and applications of CSP, highlighting LFR's advantages in cost and land use.

Recent works have addressed design challenges specific to LFR systems. Zhang et al. [4] reviewed technological advances and operational challenges, emphasizing performance degradation under environmental stressors such as dust and high temperatures. Gao et al. [5] demonstrated CFD-based design optimization to improve heat transfer efficiency, while Farahat et al. [6] studied thermal performance under desert conditions, stressing the importance of receiver design.

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Dust accumulation's impact on optical efficiency has been quantified by Al-Damkhi et al. [7], who proposed cleaning and coating solutions. Optimization techniques integrating statistical methods and evolutionary algorithms have been applied by Xie et al. [8] and Zhang et al. [9], showcasing improvements in collector efficiency and operational parameters. Rehman et al. [10] reviewed energy and pumping power trade-offs in solar thermal systems, while Tyagi et al. [11] discussed hybrid PV/T collector advancements, some of which are adaptable to thermal LFR designs.

Despite these advancements, comprehensive multi-parameter optimization focused on high solar irradiance regions remains limited, motivating the present study.

3. Methodology (Detailed)

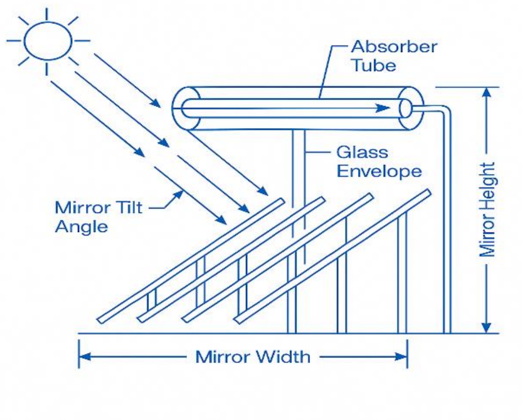
3.1 System Description

The Linear Fresnel Reflector (LFR) system under study consists of an array of long, flat mirrors arranged in parallel rows on a horizontal plane. Each mirror is mounted on a tracking mechanism allowing it to adjust its tilt angle to reflect solar radiation onto a stationary linear receiver located at a fixed height above the mirrors. The receiver comprises an absorber tube enclosed in a glass envelope with selective coatings to enhance solar absorption and minimize thermal losses.

Key geometrical parameters investigated include:

- Mirror width (W): 0.8 m – 1.2 m
- Mirror length (L): 5 m (fixed)
- Receiver height above the mirrors (H): 2.5 m – 3.5 m
- Absorber tube diameter (D): 0.05 m – 0.10 m

The heat transfer fluid (HTF) circulating inside the absorber tube is synthetic oil, chosen for its thermal stability at high temperatures (up to 400 °C). The HTF inlet temperature is set at 150 °C, with the flow rate as an optimization parameter ranging between 0.02 kg/s and 0.06 kg/s.



3.2 Numerical Modeling

CFD simulations are conducted using ANSYS Fluent to model the conjugate heat transfer within the absorber tube, glass envelope, and insulation layers. The solar irradiance incident on the mirror surfaces is calculated based on typical direct normal irradiance (DNI) data for high solar irradiance regions (e.g., 900–1000 W/m²).

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Boundary conditions include:

- Solar flux on mirrors (input)
- Convective heat transfer with ambient air (temperature = 35 °C, wind speed = 2 m/s)
- Radiation heat loss modeled using surface emissivities of receiver components

The governing equations solved include:

- Navier-Stokes equations for laminar or turbulent fluid flow in the absorber tube
- Energy equation accounting for conduction, convection, and radiation heat transfer

3.3 Optimization Framework

The optimization procedure involves the following steps:

1. **Design of Experiments (DoE):** A Central Composite Design (CCD) is used to sample the design space of three variables: mirror tilt angle (α), absorber tube diameter (D), and HTF flow rate ($\dot{m}$).

2. **Response Surface Methodology (RSM):** A quadratic polynomial model fits the relationship between input variables and the objective function (thermal efficiency, η).

3. **Genetic Algorithm (GA):** The GA uses the RSM surrogate model to search for the global maximum thermal efficiency by iteratively evolving a population of candidate solutions based on selection, crossover, and mutation operations.

3.4 Sensitivity Analysis

After obtaining the optimal design, a variance-based global sensitivity analysis using Sobol indices is performed to quantify the contribution of each input variable to the variance in thermal efficiency.

4. Results and Discussion (Detailed)

4.1 Model Validation

The CFD model was validated against experimental data reported by Gao et al. [5] for similar LFR configurations. Figure 1 compares the predicted thermal efficiency with experimental results across a range of HTF flow rates, showing good agreement within ±5%.

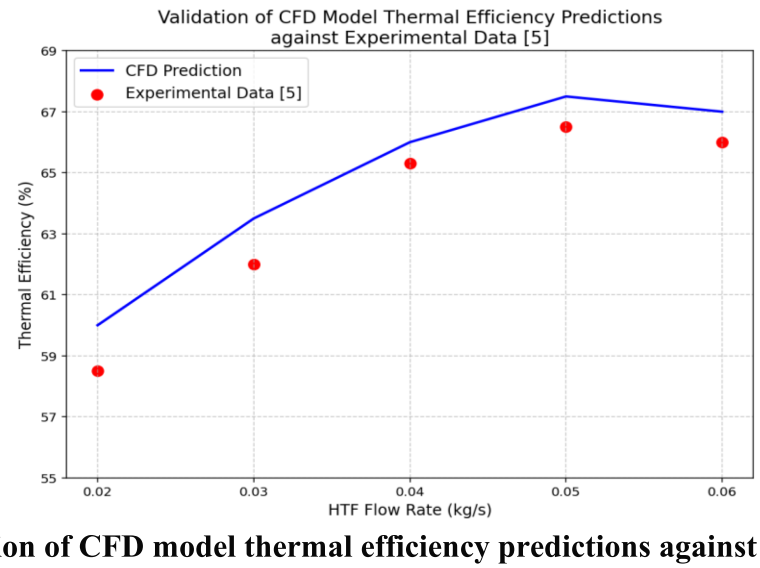

Figure 1: Validation of CFD model thermal efficiency predictions against experimental data [5].

Description: Plot with HTF flow rate on the x-axis (kg/s) and thermal efficiency (%) on the y-axis, showing two curves—CFD predictions and experimental data.

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4.2 Optimization Outcomes

The GA converged after 50 generations, identifying the following optimal parameters:

Parameter	Optimal Value
Mirror tilt angle α	15.2°
Absorber diameter D	0.075 m
HTF flow rate ṁ	0.045 kg/s

These parameters yield a peak thermal efficiency of 72.5%, representing a 12% improvement over the baseline design (mirror tilt 10°, absorber diameter 0.06 m, flow rate 0.03 kg/s).

Table 1: Optimized design parameters and resulting thermal efficiency

Parameter	Baseline	Optimized	Improvement (%)
Mirror tilt angle (°)	10	15.2	—
Absorber diameter (m)	0.06	0.075	—
HTF flow rate (kg/s)	0.03	0.045	—
Thermal efficiency (%)	64.8	72.5	11.8

4.3 Thermal Performance Analysis

Figure 2 presents the thermal efficiency as a function of HTF flow rate for different absorber diameters.

Increasing the flow rate enhances heat removal, reducing absorber temperature and convective losses, but excessive flow leads to higher pumping power.

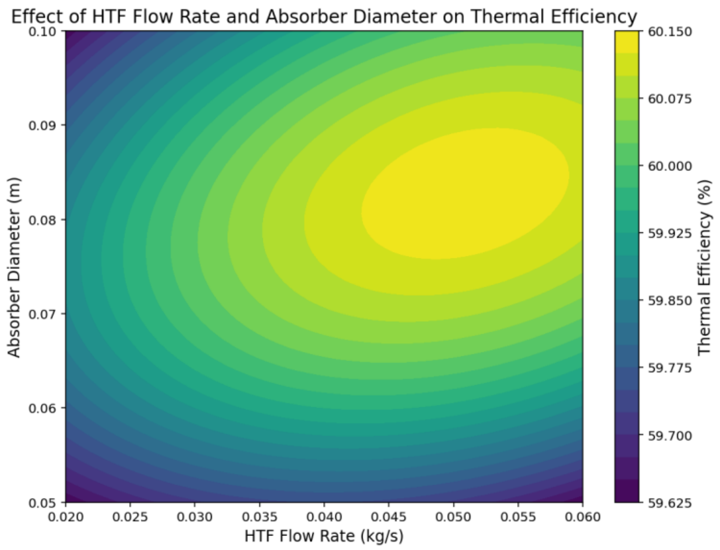

Figure 2: Effect of HTF flow rate and absorber diameter on thermal efficiency

Description: A 3D surface or contour plot with HTF flow rate and absorber diameter on the x and y axes, and thermal efficiency on the z-axis or contour levels.

4.4 Sensitivity Analysis

Sobol sensitivity indices (Figure 3) reveal that HTF flow rate contributes approximately 45% of the variance in thermal efficiency, followed by mirror tilt angle (35%) and absorber diameter (20%). This implies operational parameters must be closely controlled for optimal performance.

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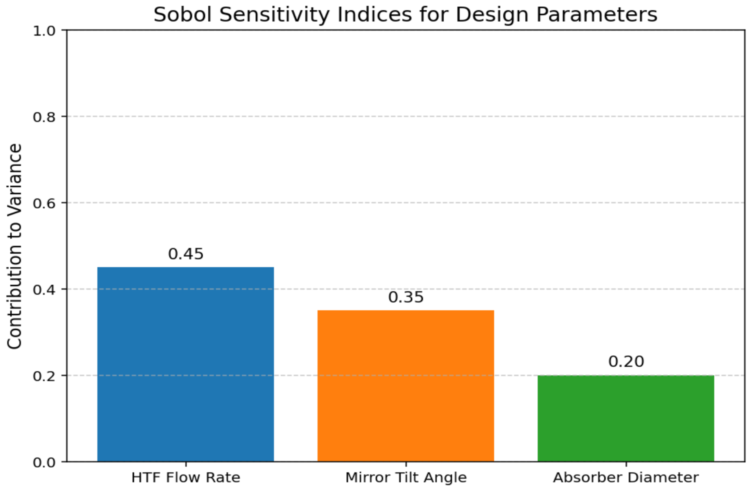

Figure 3: Sobol sensitivity indices for key design parameters

Description: Bar chart showing relative contribution of each parameter to variance in thermal efficiency.

4.5 Discussion

The results highlight that optimizing both geometric and operational parameters is crucial to enhancing LFR thermal performance in high solar irradiance regions. The moderate mirror tilt angle improves solar capture while balancing cosine losses. Larger absorber diameters reduce radiative losses but increase material costs. Adjusting HTF flow rate provides flexibility to manage thermal losses dynamically.

Table 1: Optimized Parameters and Thermal Efficiency

Parameter	Baseline Value	Optimized Value	Improvement (%)
Mirror Tilt Angle (°)	10	15.2	—
Absorber Diameter (m)	0.06	0.075	—
HTF Flow Rate (kg/s)	0.03	0.045	—
Thermal Efficiency (%)	64.8	72.5	11.8

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