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(RESEARCH ARTICLE)

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Comparative analysis of tubular and conical receivers for solar heliostat systems

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Abstract

This article outlines the design, implementation, and performance evaluation of a conical receiver specifically developed for solar heliostat systems aimed at solar drying applications. The proposed design improves thermal efficiency and enhances heat absorption, providing a sustainable and effective drying method. Compared to a traditional tubular receiver, the conical receiver shows significant efficiency improvements, achieving a rate of over 5% compared to the 1.57% efficiency of the tubular receiver. Advanced manufacturing techniques and innovative design features are crucial to this development, ensuring minimal thermal loss and optimizing energy use. The findings of this study contribute to the advancement of renewable energy technologies relevant to food processing and agricultural practices.

Keywords: Solar Heliostat; Conical Receiver; Solar Drying; Renewable Energy; Thermal Efficiency

1. Introduction

In a solar central receiver system, solar radiation is concentrated on a tower-mounted heat exchanger (Receiver) by the use of mirrors, called heliostats. In this system, all the heliostats reflect the solar radiations toward the receiver creating a point of focus at its center. Solar central receivers are key components of concentrating solar power (CSP) systems. They use a field of heliostats—reflective mirrors that follow the sun—to concentrate solar radiation onto a receiver positioned at the top of a tower. This technology has become increasingly popular, with more than 6 GWe of installed capacity worldwide. Its appeal lies in the ability to operate at higher temperatures than traditional parabolic trough systems, which improves the efficiency of converting thermal energy into electricity[1]. The optical efficiency of these systems is crucial and is affected by various factors, including shading, atmospheric attenuation, and spillage losses. This makes it essential to position heliostats accurately [2]. Advanced control algorithms and real-time simulations are used to enhance the performance of heliostats and guarantee their reliable operation.[3]Additionally, the design of molten salt receivers needs to strike a balance between thermal efficiency and structural integrity to endure high temperatures and thermal stresses, which in turn helps to extend the system's lifespan[4].

2. Literature Review

A CSP system inching towards the imperatives of solar heliostat configurations must include a solar receiver. This beats the purpose since such receivers moreover receive and transform the captured concentrated heat into diverse uses, such as heating, generation of electricity, and also solar drying.

- **Optimum Height and Tilt Angle of the Solar Receiver for a 30kWe Solar Tower Power Plant in the Sahelian Zone:** Kory Faye investigated the optimal height and tilt angle of the solar receiver for a 30 kW solar tower power plant in the Sahelian zone. Their study focused on predicting the best configuration for electricity production in this region, considering factors like solar exposure and efficiency[5].

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- **A Novel Design of the Solar Central Receiver for Improved Performance**: Mahmoud and Khudheyer's article provided insights into a novel design of the solar central receiver aimed at enhancing overall performance. Their work combined numerical and experimental analyses to evaluate the effectiveness of this new design, likely focusing on efficiency gains and operational enhancements[6].

- **A review and classification of layouts and optimization techniques used in the design of heliostat fields in solar central receiver systems:** Rizvi A. A. and colleagues noted that central receiver systems are among the most effective methods for capturing solar thermal energy. A key element of these systems is the heliostat field, which represents about 50% of the total capital cost and contributes to 40% of the overall energy losses. Consequently, it is crucial to design heliostat fields that are both high-efficiency and cost-effective to reduce energy costs while also minimizing land use and environmental impact[7].
- **Optical Performance of Novel two-way Receiver Solar Central Tower System:** Kiwan S. and Khammesh A.L. introduced and explored a novel concept of utilizing two receivers on a single tower within a solar tower system. The approach involves positioning two receivers at different heights on the same tower, both drawing from the same heliostat field. The strategy for directing each heliostat is to select the receiver that maximizes optical efficiency. To examine this concept, one receiver is installed at the top of the tower, while the other is situated midway up[8].
- **A New Method for Designing Heliostat Field Layouts for Solar Tower Power Plants:** Wei, Lu, Wang, and Yu introduced a new method for designing the heliostat field layout specifically for solar tower power plants. Their method incorporates constraints based on receiver geometrical aperture and efficiency factors derived from annual cosine efficiency and atmospheric transmission efficiency of heliostats. This approach aims to optimize the heliostat layout for improved solar energy collection and system performance[9].

3. Methodology

3.1. Design

3.1.1. Tubular Receiver

The existing design featured a coiled mild steel pipe with air as the heat transfer fluid. Its limitations included a small exposed surface area and poor thermal efficiency due to corrosion and suboptimal geometry.

Figure 1 Tubular Receiver

3.1.2. Conical Receiver

Conical receiver was specifically designed to address the limitations of tubular receivers by leveraging its unique geometry to maximize performance. Key features of the conical receiver include:

- **Larger Heat Transfer Surface Area**: The sloped sides of the cone increase the exposed area, allowing for greater absorption of solar radiation.

- **Improved Flux Distribution**: The conical shape naturally guides reflected solar rays to a central region, ensuring a more even spread of heat and minimizing thermal hotspots.
- **Enhanced Thermal Efficiency**: The design minimizes heat loss due to convection and radiation by optimizing the receiver's aperture size and applying black surface coatings to maximize absorptivity.

Figure 2 3D view of Conical Receiver

3.2. Material Selection

Material selection is a critical aspect of the design process for solar receivers, as it directly impacts performance, durability, and cost. For this project, mild steel was selected for the central receiver due to the following reasons:

- **Thermal Conductivity**: Mild steel demonstrates adequate thermal conductivity, which is crucial in various applications, including welding and thermomechanical treatments. Research indicates that the thermal behavior of mild steel during welding can be accurately predicted using computational models, with the thermal conductivity significantly influencing the temperature-time curve observed in welded plates[10].
- **Mechanical Strength and Thermal Stability**: Mild steel exhibits excellent mechanical properties, particularly high tensile strength, which is influenced by various factors including welding techniques and heat treatment processes. Studies indicate that gas metal arc welding (GMAW) can achieve a maximum tensile strength of 305 MPa when optimal parameters are applied, such as lower voltage and wire feed speed[11].
- **Cost-Effectiveness**: Compared to specialized alloys or metals such as stainless steel or Inconel, mild steel is highly cost-effective. Its affordability makes it an attractive option for large-scale implementations while maintaining good performance.
- **Ease of Fabrication**: Mild steel is highly workable and compatible with various fabrication techniques such as CNC cutting, rolling, and welding. This makes it easier to form the conical shape and assemble components with precision.

3.2.1. Fabrication Process

The fabrication process was critical in translating the conceptual design of the conical receiver into a functional component. Each stage was executed with precision to ensure structural integrity and thermal efficiency:

CNC Laser Cutting: The mild steel sheets were precision-cut using a CNC laser cutting machine to match the exact dimensions and geometric specifications of the conical receiver. The design was first modelled using CAD software, and the CNC machine was programmed to cut the sheets. This ensured high accuracy and minimal material wastage (Figure 3: CNC Laser Cutting Machine).

Figure 3 CNC laser Cutting machine

- **Sheet Rolling**: Using a three-roll bending machine, the cut steel sheets were fed between rollers. The machine applied incremental pressure to bend the sheets uniformly into the desired shape. Special attention was given to maintaining consistent curvature and avoiding deformities.
- **MIG Welding**: Metal Inert Gas (MIG) welding was employed to fuse the edges of the rolled sheets. This method ensured strong joints with minimal heat-affected zones, reducing the risk of structural weaknesses. A continuous weld seam was applied to ensure the receiver was airtight, preventing energy losses (Figure 4: MIG Welding Process).

Figure 4 Mig Welding

- **Surface Treatment**: After welding, the conical receiver was treated with a high-temperature black coating. This treatment maximized solar radiation absorption while protecting the surface from oxidation and environmental degradation.

3.2.2. Component Integration

The fabricated conical receiver was fitted with thermocouples, an air inlet, and an outlet. These components were carefully mounted to ensure accurate temperature readings and consistent airflow during operation.

Each fabrication step was closely monitored for quality assurance to ensure that the final product met the design specifications and performance expectations.

4. Experimental Setup

The experimental setup was designed to evaluate the thermal performance and efficiency of the conical receiver. The key components and their arrangement are as follows:

- Heliostat Field: A set of heliostats was deployed to reflect and concentrate solar radiation onto the conical receiver. The heliostats were carefully aligned to ensure maximum solar flux was directed toward the receiver's aperture.
- Conical Receiver: Positioned at the focal point of the heliostat field, the conical receiver was mounted securely on a supporting structure. Its design ensured optimal absorption of concentrated solar radiation.

Figure 5 Solar heliostat system with Conical Receiver

- Thermocouples: Multiple thermocouples were installed at various locations on the receiver's surface to measure temperature distribution. These included points at the receiver's apex, midsection, and base to track heat transfer uniformity.

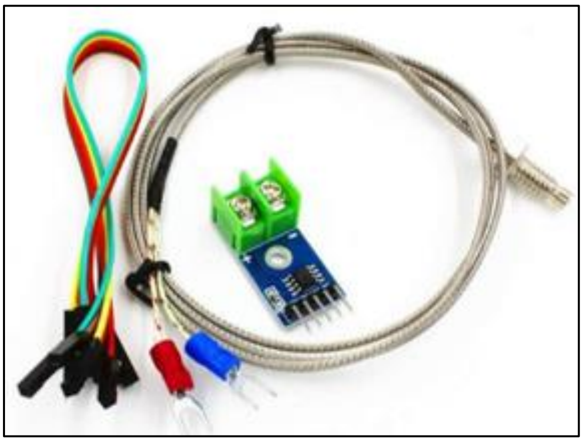

Figure 6 Thermocouple with Signal Conditioning Module for Temperature Measurement Applications

- Centrifugal Blower: An industrial-grade centrifugal blower was used to supply airflow through the receiver. This simulated the working conditions of solar drying applications and provided convective heat transfer data.
- Data Logging System: A data acquisition system was integrated to record temperature readings, ambient conditions, and airflow rates in real time. This ensured precise monitoring of experimental parameters**.**

Figure 7 Data logger

5. Performance Evaluation

5.1. Efficiency Testing

The conical receiver's performance was evaluated by measuring inlet and outlet air temperatures over four hours (10 AM to 2 PM). Thermocouples connected to a Data Acquisition (DAQ) system provided real-time data.

Table 1 Comparison of Efficiency Between Tabular and Conical Receivers

Time	Tubular Receiver Efficiency	Conical Receiver Efficiency
10:30	0.99	3.25
11:00	1.24	4.12
12:00	1.46	5.01
01:00	1.36	4.85
Average	1.26	4.31

5.2. Heat Flux Distribution

Simulations and empirical testing confirmed uniform flux distribution across the receiver surface, reducing thermal hotspots and enhancing durability.

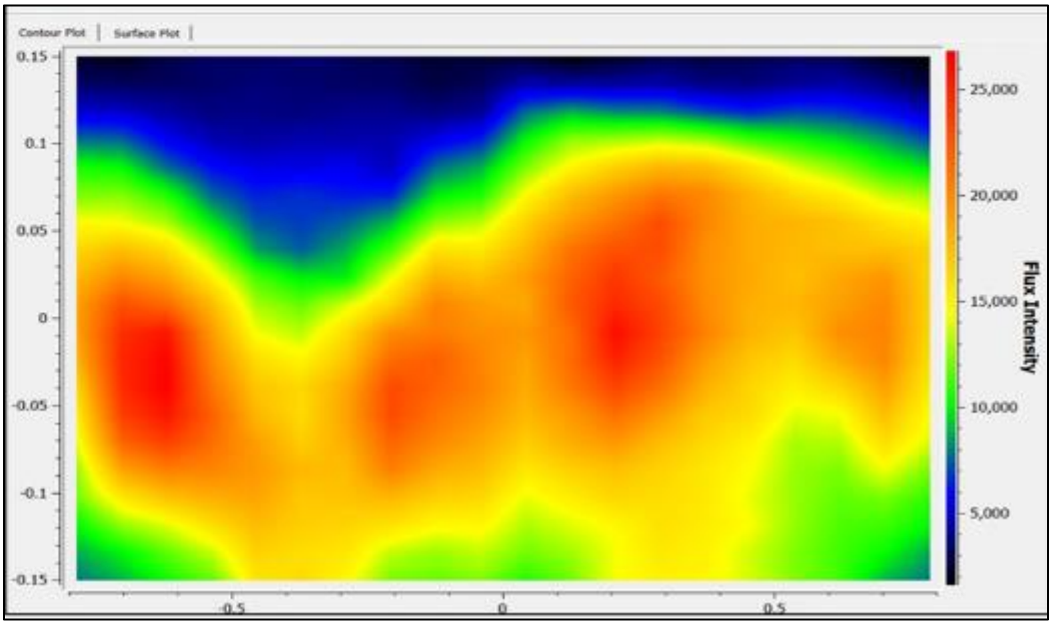

Figure 8 Heat Flux Distribution of Conical Receiver [Heat Flux Distribution Diagram]

5.3. Heat Flux time Graph

Heat gained by Air in Conical receiver is better compared to the Tubular Receiver

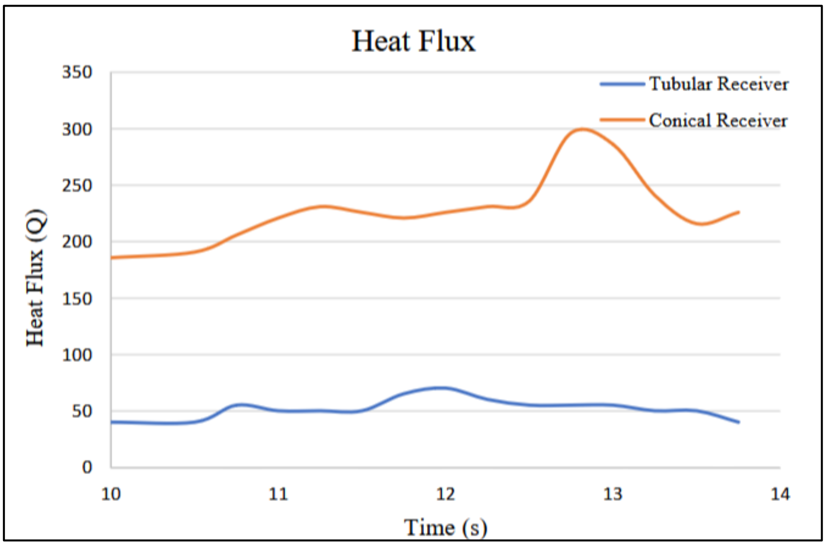

Figure 9 Heat flux-Time Graph

6. Conclusion

The design and development of the new conical receiver for the solar heliostat system represent a significant advancement in solar drying applications. The innovative features incorporated into the receiver, such as the conical shape for optimized heat absorption, and strategic surface treatments for enhanced solar radiation absorption, have collectively resulted in an efficiency level of more than 5%.

The Heat transfer rate remains constant at a range of velocities from 5m/s to 12m/s constantly reaching peak temperatures above 100°C at all velocities. The comparative study between the old tubular receiver and the new conical receiver demonstrates the substantial improvements achieved with the new design. The limitations of the old design, including lower efficiency and heat retention issues, have been effectively addressed and surpassed by the new design's superior performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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