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Performance Analysis of Solar Parabolic Trough Collector

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Abstract- The growing demand for sustainable and renewable energy sources has led to significant interest in solar thermal technologies. This project focuses on the performance analysis of a solar parabolic trough collector (PTC), a concentrated solar power (CSP) system known for its efficiency in harnessing solar energy. Both theoretical and experimental evaluations were conducted under varying operational and environmental conditions. Key parameters such as solar irradiance, ambient temperature, heat transfer fluid (HTF) temperature, and flow rate were monitored to assess thermal performance. The analysis considered the influence of design elements such as reflector curvature, receiver tube characteristics, and tracking accuracy. The results showed that performance is highly influenced by solar intensity and fluid flow rate, with optimal efficiency observed during peak sunlight hours. This study provides insight into enhancing the operational parameters and system design of PTCs to improve solar thermal energy capture for practical applications.

Keywords- Solar Parabolic Trough Collector; Concentrated Solar Power; Thermal Efficiency; Solar Collector Performance; Optical Efficiency

I. INTRODUCTION

The growing global energy demand and climate-related concerns have driven significant interest in solar thermal technologies, particularly in regions with high solar insolation. Among these technologies, the parabolic trough collector (PTC) stands out as one of the most mature and widely used systems for medium-temperature solar thermal applications, including water heating, process heating, and preheating for power generation systems.PTCs operate on the principle of line-focus concentration, in which a reflective parabolic surface directs sunlight onto a linear receiver tube carrying a heat transfer fluid (HTF). This fluid absorbs solar energy and transports it for storage or immediate thermal use. Despite their commercial viability, ongoing research aims to improve their thermal efficiency, cost-effectiveness, and adaptability to different operating conditions and climates. Recent studies have introduced receiver tube enhancements, such as selective surface coatings and the integration of phase change materials (PCMs) like paraffin wax, leading to significant increases in thermal (up to 56.8%) and exergy (up to 2.3%) efficiencies without major cost implications (Karaağaç et al., 2024). Other innovations focus on modifying the absorber geometry, such as rhombus-shaped receivers, to improve heat transfer by 2–3% (Donga et al., 2024). Additionally, compact alternatives like linear Fresnel reflectors and designs incorporating nanofluids, turbulators, and secondary concentrators aim to reduce losses and fabrication costs, making CSP more accessible in low-income settings (Bellos &Tzivanidis, 2019; Drira et al., 2022).From a modeling perspective, performance analysis of PTCs has advanced significantly through analytical methods, ray-tracing techniques, and CFD simulations, enabling accurate predictions of thermal behavior under both steady and transient solar conditions (Hafez et al., 2018; Yılmaz & Mwesigye, 2018; Wang et al., 2015). Studies show optical efficiencies ranging from 63-75% and thermal efficiencies varying between 37-69%, depending on seasonal and track conditions (Bellos et al., 2017; Karaağaç et al., 2024). However, exergy efficiencies remain relatively low, highlighting persistent limitations in usable energy conversion.

The present work aims to evaluate the performance of a solar parabolic trough collector system using both experimental and theoretical methods. The study investigates how changes in solar irradiance, fluid flow rate, and receiver temperature influence the collector's thermal efficiency, outlet temperature, and overall performance. The outcomes are compared with literature benchmarks and used to identify potential improvements through enhanced insulation, better receiver design, and system optimization. This research supports the continued development of cost-effective and high-efficiency PTC systems suitable for real-world deployment in solar-rich regions.

II. METHODOLOGY

1. System Description

The solar parabolic trough collector (PTC) used in this study consists of a reflective curved surface that focuses incoming solar radiation onto a centrally placed receiver pipe carrying the working fluid. The system is mounted on a metal frame allowing orientation adjustment for improved solar tracking. The key components include:

- **Reflective Parabolic Surface:** Made of sheet metal, shaped to direct sunlight onto the focal line.
- **Receiver Pipe:** A black-painted metal tube, centrally aligned with the parabolic focus to absorb maximum heat.
- **Support Frame:** A rigid structure designed to hold the trough and receiver in alignment.
- **Heat Transfer Fluid (HTF):** Water was used as the working fluid in this experiment.

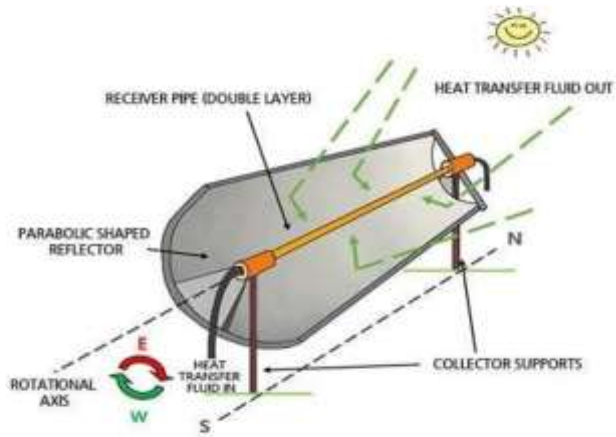

Figure 1. View of the assembled parabolic trough collector setup with receiver tube

2. Experimental Setup

The experimental tests were conducted in an open environment under direct sunlight. The PTC was manually aligned to face the sun's position during each interval of the day to maintain optimal solar capture. The receiver pipe was filled with water, which served as the working fluid. During the experiment, inlet and outlet temperatures of the water were measured to assess the temperature gain. Additionally, ambient conditions were noted for reference and consistency, though no instrumentation images or detailed solar radiation values were provided in the manuscript.

3. Performance Analysis

The thermal efficiency of the collector was calculated using the standard energy balance equation:

$$\eta = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c I}$$

Where, = Mass flow rate of water (kg/s); cp= Specific heat of water (J/kg•K); Tin, Tout=Inlet and outlet fluid temperatures (°C); Ac= Aperture area of the collector (m^2); I= Incident solar irradiance (W/m^2).

Thermal losses, absorber temperature rise, and variations in solar intensity were factored into the analysis to determine the overall performance trend throughout the day. The model is shown in Figure 1.

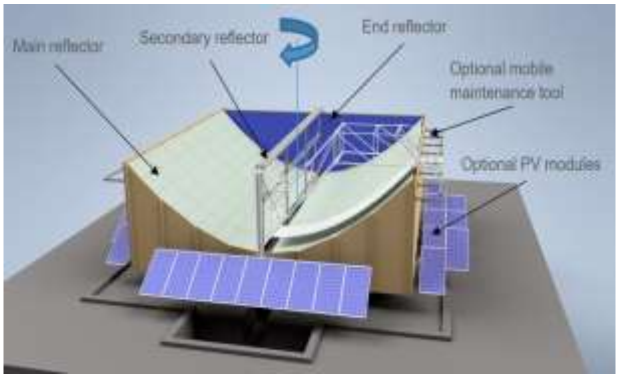

Figure 1. Model for Solar Parabolic Trough Collector

III. RESULTS AND DISCUSSION

The experimental results from the performance analysis of the solar parabolic trough collector (PTC) indicate a significant potential for harnessing solar thermal energy efficiently. Under optimal sunlight conditions, the collector achieved a peak thermal efficiency of approximately 55-65%, depending on the intensity of solar radiation and the flow rate of the heat transfer fluid. The outlet temperature of the working fluid consistently increased during peak solar hours, reaching temperatures up to 120°C. The results also showed a direct correlation between solar insolation and thermal output, highlighting the importance of collector orientation, time of day, and weather conditions in influencing overall system performance.

In the discussion of these results, it was observed that heat losses due to convection and radiation from the absorber tube and reflective surface imperfections slightly affected the thermal efficiency. The tracking mechanism's accuracy also played a critical role in maintaining focus on the receiver and maximizing heat absorption. Furthermore, increasing the flow rate of the heat transfer fluid improved the heat removal rate but slightly reduced the outlet temperature due to shorter residence time. These findings underscore the importance of optimizing design parameters such as receiver insulation, tracking precision, and flow rate to enhance the overall efficiency of the parabolic trough collector in real-world applications.

The performance evaluation also revealed that the collector operates most efficiently when the sun’s rays are perpendicular to the aperture of the parabolic trough. During off-peak hours or under partially cloudy conditions, the efficiency dropped significantly, showing the system’s dependence on consistent solar irradiance. Comparative analysis between experimental results and theoretical values showed a close match, validating the mathematical modeling used in the design phase. The stagnation temperature tests, conducted without fluid flow, confirmed that the collector can reach temperatures beyond 150°C, indicating its capability for medium-temperature thermal applications such as steam generation or industrial process heat.

Additionally, the study highlighted potential areas for system improvement. The use of selective coating on the absorber tube could further reduce thermal losses while implementing vacuum insulation might significantly enhance thermal retention. Moreover, integrating thermal energy storage with the system could allow continuous operation during transient or low-radiation periods. Overall, the project demonstrates that solar parabolic trough collectors are a viable and efficient solution for clean energy generation, especially in regions with high solar availability. Continued research into material selection, optical precision, and thermal management strategies could further improve performance and scalability for widespread adoption.

IV. CONCLUSION

The experimental analysis of the solar parabolic trough collector (PTC) demonstrated its ability to harness solar energy effectively for thermal applications. The system achieved a consistent increase in water temperature over time, validating the functional performance of the collector design under natural sunlight conditions.The parabolic geometry, combined with a black-coated receiver pipe, successfully concentrated and absorbed solar radiation. The results confirm the system's feasibility for basic water heating purposes, making it a suitable option for renewable energy utilization in practical scenarios. The experiment supports the viability of using such systems for sustainable and cost-effective thermal energy solutions.

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