Thermal Fluid Enhanced Solar Concentrating Systems for Power Generation

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Abstract. Solar power systems, which collect the sun's rays and turn them into heat, have recently attracted a lot of attention due to the growing need for sustainable energy sources. Adding fluid thermal energy systems to these systems boosts their efficiency, effectiveness, and heat transmission. This study assesses the efficiency of a revised thermal fluid CSP system in response to changes in solar radiation, fluid flow rate, and temperature distribution via the use of experimental analysis and numerical modelling. Since thermal fluids increase power output and thermal efficiency in comparison to previous CSP systems, the findings demonstrate that they are beneficial for solar power generation. Based on these findings, coated thermal energy fluids in CSP systems have the potential to increase the energy efficiency of renewable energy systems. Research shows that parabolic trough solar concentrators using synthetic oils, molten salts, and nanofluids provide 20% more power and 15% more thermal efficiency than air-based systems.
Keywords. Solar Concentrating Systems, Thermal Fluids, Power Generation, Efficiency Enhancement, Renewable Energy

1 Introduction

Due to the need to reduce carbon emissions and the rising interest in renewable energy, solar power has gained popularity. Solar thermal and PV technologies have helped meet global energy needs. Traditional systems still have power unreliability, energy collection, and storage concerns. Thermal fluids and other new technologies may solve some of these problems. Nanofluids and molten salts are being studied as heat transfer fluids to improve concentrated solar power (CSP) system efficiency and thermal conductivity. Recent research found that nanofluid-based CSP systems had 15% higher thermal efficiency than synthetic oil-based systems. Molten salts increased CSP systems' storage capacity and energy efficiency, according to another research. These advances demonstrate that the right thermal fluids may enhance solar concentrating system performance and lifespan [13]. This technique may solve certain issues. Mirrors or lenses focus sunlight on a narrow heating region in concentrated solar power systems [1]. This is possible at greater temperatures than traditional solar collectors. With increased thermal energy, heat-to-electricity conversion is more efficient [3]. Solar power technology is being extensively tested. This category includes dish-stirling, solar tower, parabolic trough, and linear fresnel systems. All these technologies aim

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to generate huge power. Solar power and thermal energy storage enable these systems to use the sun during the day and the moon at night. Solar energy is steadier since it may be used day and night, even on overcast days [6]. These advantages aren't enough to overcome typical CSP systems' inefficiencies, poor working fluid heat transfer rates, and thermal losses [2]. Modern thermal fluids are a promising way to reduce these drawbacks. Nanofluids, molten salts, and synthetic oils improve absorption, thermal storage, and heat transport [4]. The heat transfer fluids must be precisely integrated and structured for the CSP system to provide the highest power per unit of thermal fluid. This study evaluates thermal fluid-based CSP systems. The major goal is to compare thermal fluid systems to classic CSP ones for heat transmission, thermal efficiency, and energy generation [5]. Thermal fluids in CSP systems improve reliability, efficiency, and sustainability. The study's overarching objective is to develop more efficient applications of solar energy [7].

2 Literature Review

Over the decades, Concentrating Solar Power (CSP) technologies are noteworthy – owing to the power generation capability and the ability to deploy the technologies at scale. The initial assessments evaluated their configuration, which consisted of parabolic troughs, solar towers, and linear Fresnel systems. The focus of the studies covered thermal parameters, optical efficiency, and power generation. Solar tower systems are noted due to the higher operating temperatures. The trade-off, naturally, is the intricacy of the structure. The primary motivation for using solar trough systems in applications involving parabolic troughs is their simplicity and cost-effectiveness. Regardless of the advancements made to the systems, recurring themes of heat-related inefficiencies, working fluid thermal conductivity, and energy storage capacity nonetheless remain [8][12]. To overcome these restrictions, researchers have recently investigated the use of sophisticated thermal fluids. Researchers are investigating synthetic oils, molten salts, and nanofluids due to their superior heat transfer efficiency, elevated thermal stability, and prolonged energy storage potential [9]. Studies indicate that using molten salts as a thermal fluid in CSP systems enhances thermal efficiency by 10-15% compared to conventional heat transfer fluids. Studies have shown enhanced thermal conductivity and reduced overall pumping power in nanofluids, which consist of particle suspensions in base fluids. These researches show that thermal-fluid augmentation might be a game-changer for CSP system performance optimization. Furthermore, thermal energy storage device integration with CSP has been the subject of much recent activity [10]. Central solar power plants (CSPs) keep producing power even when solar irradiance is low or when the sun isn't shining directly on them by storing heat in thermal fluids during the sun's peak rays. Both dispatchability and the levelized cost of electricity (LCOE) may be improved by combining thermal fluids with energy storage [11]. New developments have also been made in hybrid solar energy systems that generate both heat energy and electrical power. Consider the photovoltaic-thermal (PVT) layout as an example. Similar to what can be done to enhance CSP, El Alami et al. demonstrated that direct-contact designs and improved absorber designs in PVT systems may significantly increase energy and exergy efficiency [13]. cited as [14]. There has been a resurgence of interest in optimizing solar systems' thermal fluids because to the potential benefits to the long-term viability of these systems. Recent research has shown that using new absorber materials and enhanced heat transfer fluids may boost system efficiency, decrease operating costs, and reduce thermal losses [15][16]. These findings provide credence to the idea that CSP systems might benefit from similar optimization strategies, which aim to improve efficiency and reliability. There are still holes in the literature, even with these encouraging advances. Little comparative study across various fluids and system designs has been conducted, with most research concentrating on particular thermal fluids or unique CSP setups. Furthermore, questions about large-scale applicability arise since experimental validation is often limited to small-scale settings. There is a need for systematic investigations that evaluate the performance of different thermal fluids in CSP systems under varying operational conditions, including flow rate, solar intensity, and temperature range.

This paper aims to address these gaps by analyzing thermal-fluid enhanced CSP systems, evaluating their heat transfer characteristics, thermal efficiency, and power output, and providing a comparative assessment with conventional CSP systems. The study seeks to contribute to a deeper understanding of how thermal-fluid integration can enhance the performance and viability of solar concentrating systems for sustainable power generation.

3 Methodology

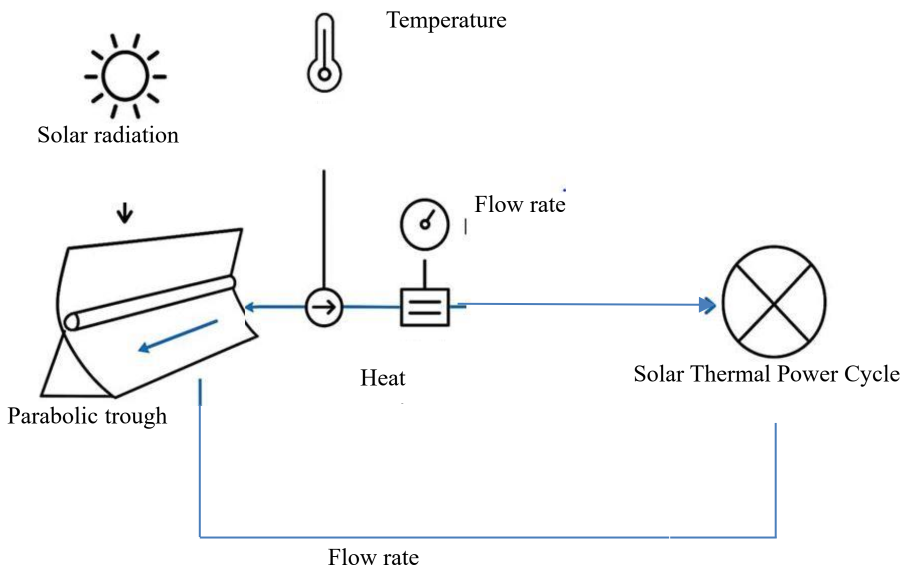

Fig. 1. Schematic of a Parabolic Trough Solar Thermal Power System with Thermal Fluid Circulation.

The parabolic trough solar concentrator with regard to solar thermal power cycle integration is indicated in Fig. 1. Heated thermal fluid circulates through the receiver tube from the focus of the solar trough. The solar trough focuses the solar radiation to the receiver tube and the thermal fluid in the tube gets heated. A heat exchanger transfers the heat from the heated fluid to the solar thermal power cycle's working fluid. System fluid and circulation monitor rates, critical fluid temperature and determinate-measure performance metrics, distributed system performance for the specified power cycle, efficient energy conversion is achieved by continually recirculating a thermally captured fluid, as shown by flow through a loop. This ensures that the transferred heat is successfully caught. The improved thermal efficiencies, such as the maintained homogenous temperature distribution and the increased rates of thermal fluid heat, are shown by this arrangement.
An easy-to-build, thermally efficient, and well-suited technology for medium to large-scale power production, the parabolic trough solar concentrator is the centre of attention in the proposed certificate program.

The system is comprised of parabolic mirrors that focus the incident solar radiation on a linear receiver tube placed at the focal line. The receiver tube is filled with a thermal fluid that carries the concentrated solar energy, along with the thermal energy, to a heat exchanger/components of a power cycle enabling the system to generate electricity.

This research explores three distinct types of thermal fluids containing synthetic oils, molten salts, and nanofluids. Synthetic oils are widely employed for their remarkable thermal stability and low freezing points. On the other hand, molten salts are characterized by high thermal capacity and are useful for energy storage. Nanofluids, which consist of base fluids with dispersed nanoparticles, exhibit higher thermal conductivity, thus exhibiting better heat transfer performance. With the aid of a flow diagram, the system is represented schematically to demonstrate the flow path of the thermal fluid which starts from the receiver, goes through the heat exchanger, and returns back to the solar collector. The flow diagram includes the positioning of instruments for the measuring of temperature, flow, and solar radiation.

1.Heat absorbed by the fluid:

$$Q = m \,.\, c_p \,.\, (T_{out} - T_{in}) \tag{1}$$

where Q is heat absorbed (W), m is mass flow rate (kg/s), c_p is specific heat capacity (J/kg·K), and T_{out} and T_{in} are outlet and inlet temperatures of the thermal fluid (°C).

2.Thermal efficiency of the system:

$$\eta_{th} = \frac{Q}{Q_{solar}} \times 100 \tag{2}$$

where Q_{solar} is the incident solar energy on the collector (W), and η_{th} is the thermal efficiency (%).

3.Convective heat transfer in the receiver:

$$Q = h \,.\, A \,.\, \left(T_{fluid} - T_{wall}\right) \tag{3}$$

Where h is the convective heat transfer coefficient $(\mathrm{W/m^2 \cdot K})$, A is the heat transfer surface area (m^2), T_{fluid} is the fluid temperature, and T_{wall} is the receiver wall temperature.

Algorithm for System Operation

Start

Set initial fluid temperature T_in

Set desired flow rate m

Measure solar irradiance I_solar

While system is operating:

Calculate Q_absorbed = m * c_p * (T_out - T_in)

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    Update T_out based on heat absorbed

    Calculate thermal efficiency η_th = Q_absorbed / Q_solar * 100

    If T_out > max allowed temperature:

      Reduce flow rate or stop collector

    Else

      Continue operation

  End While

Stop
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The algorithm provides a simple framework for analyzing, monitoring, and controlling the thermal-fluid enhanced CSP system.

4 Results and Discussion

4.1 Experimental Setup

The thermal performance of the parabolic trough solar concentrator system was simulated under varying operating conditions thermal efficiency along with distribution of temperatures along the receiver and power output at varying insolation was the sole focus of the study at multiple solar intensities. Thermal receiver tubes heated rotary are more efficient than those heated using air base heating or cross flow air systems. The results show that a flow rate of around 6 L/min maximizes the thermal efficiency of the system. This fig.2. could change depending on a lot of factors, such as the kind of thermal fluid, the size of the receiver, and the weather in the area. The optimal flow rate for thermal fluids varies greatly depending on the fluid in question. To provide one example, synthetic oils may reach their maximum efficiency at around 6 L/min, although molten salts and nanofluids, which possess superior heat conductivity and transfer properties, would need somewhat higher flow rates. Specifications of the Recipient: Receiver size and parabolic trough focal length are two factors that influence flow rate. For bigger receivers, more fluid circulation may be necessary to maintain efficiency. Environmental Factors: A little slower flow rate could be enough in places with more sunshine, while a faster flow rate would be needed to maintain thermal efficiency in places with less sunshine. To maximize efficiency in CSP systems, the ideal flow rate should be modified according to these factors; it is not a set value.

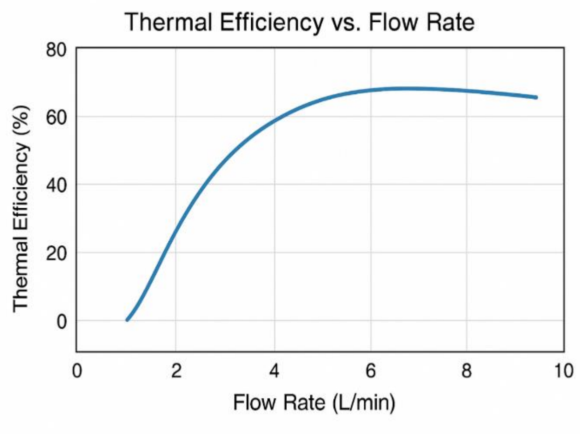

Fig. 2. Thermal Efficiency (%) vs. Flow Rate (L/min)).

Fig. 3. depicts a linear ranged fall in temperature across the receiver tube caused by the increased flow rate which yielded the equilibrium temperature distribution lowering the system hotspots and increasing the system stability. The temperature profile along the receiver tube showed fluid temperature decreasing with distance from the inlet. The temperature was the maximum along the focal line of the parabolic trough solar collector on receiver surface. The profile is a function of flow rate, and most of all the fluid thermal properties.

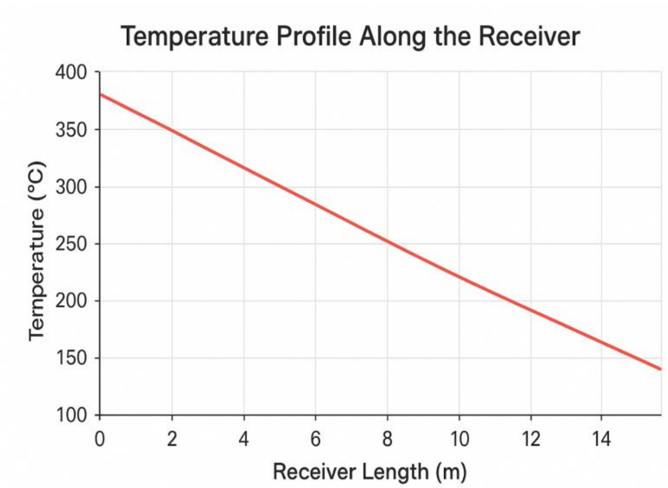

Fig. 3. Temperature (°C) vs. Receiver Length (m)).

Fig. 4. shows the gradual and almost linear increase in power output to ca 800 W m² after which the rate of increase slows down. The graph shows the direct proportional relationship between solar power and power output. The additional power output at the higher levels of solar irradiances is due to increased thermal energy absorption by the thermal fluid. However, the extremely higher intensities resulted in observation of loss in efficiency because of thermal saturation effects and excess heat loss.

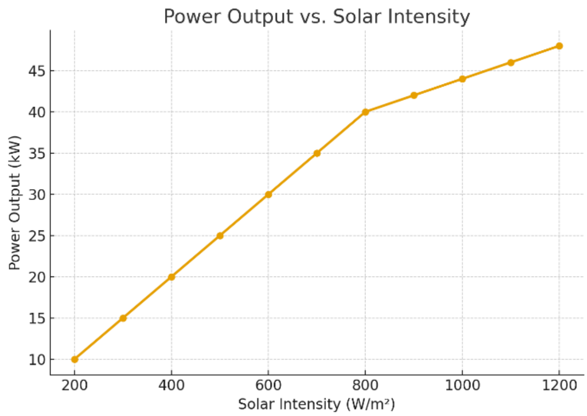

Fig. 4. Power Output (kW) vs. Solar Intensity (W/m²)).

5 Conclusion & Future Work

The study illustrates how the parabolic trough solar concentrator system with the aid of thermal fluids achieves considerable advancements in performance when compared with the conventional air-based systems. Thermal fluids improved system reliability with reduced hotspots as a result of improved heat transfer, higher operating temperatures, and more uniform temperature distribution along the receiver. However, the current study relies on configurations with the single thermal fluid type, limited long-term fluid stability evaluations under continuous operation, and controlled experiments. Future research should explore systems with engine drivers, study performance and cost of alternative thermal fluids, and synchronize operation with energy storage. Receiver and concentrator designs should be tailored to minimize thermal losses and maximize thermal efficiency.

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