Performance Analysis of Parabolic Trough Solar Collector Using Nanofluids

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Abstract

This paper presents a comprehensive performance analysis of a Parabolic Trough Solar Collector (PTSC) employing Al_2O_3–water nanofluids as the working medium to enhance thermal and exergy performance. The investigation focuses on the influence of nanoparticle concentration on heat transfer characteristics, system efficiency, and overall energy conversion effectiveness. Nanofluid concentrations ranging from 0.05 to 0.30 vol % were experimentally examined under varying Direct Normal Irradiance (DNI) levels between 550 and 900 W/m². The experimental setup was designed to ensure steady-state operation, and the results were validated through comparative analytical modelling based on conventional thermodynamic correlations. The findings revealed a significant improvement in both thermal and exergy efficiencies due to the superior thermal conductivity, specific heat capacity, and convective heat transfer coefficient of the nanofluids. A maximum instantaneous thermal efficiency of 73.4% was achieved at a 0.2% Al_2O_3 concentration, beyond which minor deterioration was observed due to increased viscosity and flow resistance. The study concludes that Al_2O_3–water nanofluids can substantially enhance the heat collection efficiency and sustainability of PTSC systems, making them promising candidates for next-generation solar thermal energy applications and green power technologies.

Keywords

Parabolic Trough, Nanofluids, Solar Collector, Exergy, Heat Transfer, Thermal Efficiency.

1. Introduction

Solar energy is one of the most promising renewable energy sources for achieving sustainable power generation and efficient process heating in various industrial and domestic applications. Among the different solar concentrating technologies, the Parabolic Trough Solar Collector (PTSC) stands out due to its high optical efficiency, simple tracking mechanism, and proven operational reliability in medium- to high-temperature applications. However, the conventional working fluids used in PTSC systems, such as water or synthetic oils, often exhibit limited thermal conductivity, which restricts overall system performance. Recent advancements in nanotechnology have introduced nanofluids—suspensions of nanoparticles in base fluids—as potential alternatives for improving the heat transfer characteristics of solar collectors. The incorporation of nanoparticles such as aluminium oxide (Al_2O_3) into water enhances the thermal conductivity, convective heat transfer coefficient, and stability of the working fluid, thereby improving the energy absorption and conversion efficiency of the collector.

In this context, the present research aims to experimentally investigate and analytically model the thermal and exergy performance of a PTSC using Al_2O_3–water nanofluids at varying particle concentrations. The study focuses on analysing the influence of nanofluid volume fraction, flow rate, and Direct Normal Irradiance (DNI) on the overall performance of the system. The results are expected to provide valuable insights into the feasibility, effectiveness, and optimization potential of nanofluids in solar thermal applications, paving the way for more efficient and sustainable solar energy systems.

2. Literature Review

Several studies have explored the role of nanofluids in solar collectors. Kumar et al. (2022) reported a 12% improvement in PTSC efficiency using Al_2O_3–water nanofluids at a concentration of 0.2%. Mishra et al. (2022) compared hybrid and mono nanofluids, concluding that hybrid nanofluids (Al_2O_3–CuO/water) yield higher performance due to enhanced thermal conductivity. Gao et al. (2022) demonstrated improved exergy efficiency using graphene–water mixtures and highlighted the importance of particle stability in achieving sustained performance.

Similarly, *Rao and Kumar (2021)* studied the thermo-hydraulic behavior of a CuO–water nanofluid-based PTSC and reported a 10.8% increase in collector efficiency under variable mass flow rates. Verma et al. (2023) performed a CFD-based comparative study on different nanoparticle materials (Al_2O_3, TiO_2, and SiO_2) and concluded that Al_2O_3 offers the best trade-off between heat transfer enhancement and pressure drop.

Bhattacharya et al. (2022) examined the effect of nanoparticle size and volume concentration, finding that particles smaller than 50 nm exhibit superior convective heat transfer due to Brownian motion effects. Zhang and Lee (2024) analyzed hybrid nanofluids under transient operating conditions, demonstrating 8–10% improvement in daily energy collection.

Further, *Nasir et al. (2022)* proposed a mathematical correlation for predicting the Nusselt number and friction factor for nanofluid flows in evacuated tube and trough collectors, validating results within ±5% experimental uncertainty. *Kiran et al. (2023)* conducted a field performance study in semi-arid climates, confirming that optical losses dominate performance beyond noon hours and recommending adaptive tracking systems for stability.

Despite the wealth of literature, gaps remain in outdoor validation of nanofluid-based PTSCs, long-term stability evaluation, and exergy destruction quantification under variable climatic conditions. Therefore, this study aims to experimentally and analytically assess the PTSC performance using Al_2O_3–water nanofluids under realistic solar conditions.

3. Methodology and Experimental Setup

A prototype Parabolic Trough Solar Collector (PTSC) was designed and fabricated with an aperture width of 1.5 m and a focal length of 2.0 m. The parabolic reflector was constructed using polished aluminium sheets (reflectivity ≈ 0.87) mounted on a mild-steel frame with manual solar tracking capability. The receiver tube, made of stainless steel with an outer diameter of 25 mm, was coated with a selective black paint having an absorptivity of 0.94 and emissivity of 0.12. To minimize convective and radiative heat losses, the receiver tube was enclosed within an evacuated borosilicate glass envelope, maintaining an insulation vacuum of approximately 10^{-3} Pa.

The nanofluid preparation followed a two-step ultrasonication method to ensure uniform particle dispersion and long-term stability. Aluminium oxide (Al_2O_3) nanoparticles with an average diameter of 40 nm were dispersed in deionized water at concentrations ranging from 0.05 to 0.30 vol%. A small amount of surfactant (Sodium Dodecyl Sulphate – SDS, 0.05 wt%) was added to prevent particle agglomeration. The suspension was sonicated for 45 minutes using a high-frequency probe-type ultrasonic processor. The prepared nanofluid exhibited a zeta potential of more than +32 mV, confirming stable suspension characteristics.

The PTSC test setup was instrumented with the following calibrated sensors:

- Temperature measurement: K-type thermocouples (±0.5°C accuracy) placed at inlet and outlet points of the receiver tube.
- Flow rate measurement: Coriolis-type mass flow meter (±0.1% accuracy).
- Solar radiation measurement: Secondary-standard pyranometer (±10 W/m²).
- Ambient and wind speed monitoring: Digital weather station installed adjacent to the collector.

Data were recorded at 30-second intervals during clear-sky conditions between 10:00 AM and 3:00 PM. The useful heat gain (Q_u) and instantaneous thermal efficiency (η_{th}) were calculated using the following standard energy balance relations:

$$Q_u = \dot{m} c_p (T_{out} - T_{in})$$

$$\eta_{th} = \frac{Q_u}{G \times A_{ap}}$$

where

$\dot{m}$= mass flow rate of the working fluid (kg/s),

c_p= specific heat capacity (J/kg·K),

$T_{in}$and T_{out}= inlet and outlet fluid temperatures (°C),

G= direct normal irradiance (W/m²), and

A_{ap}= aperture area of the collector (m²).

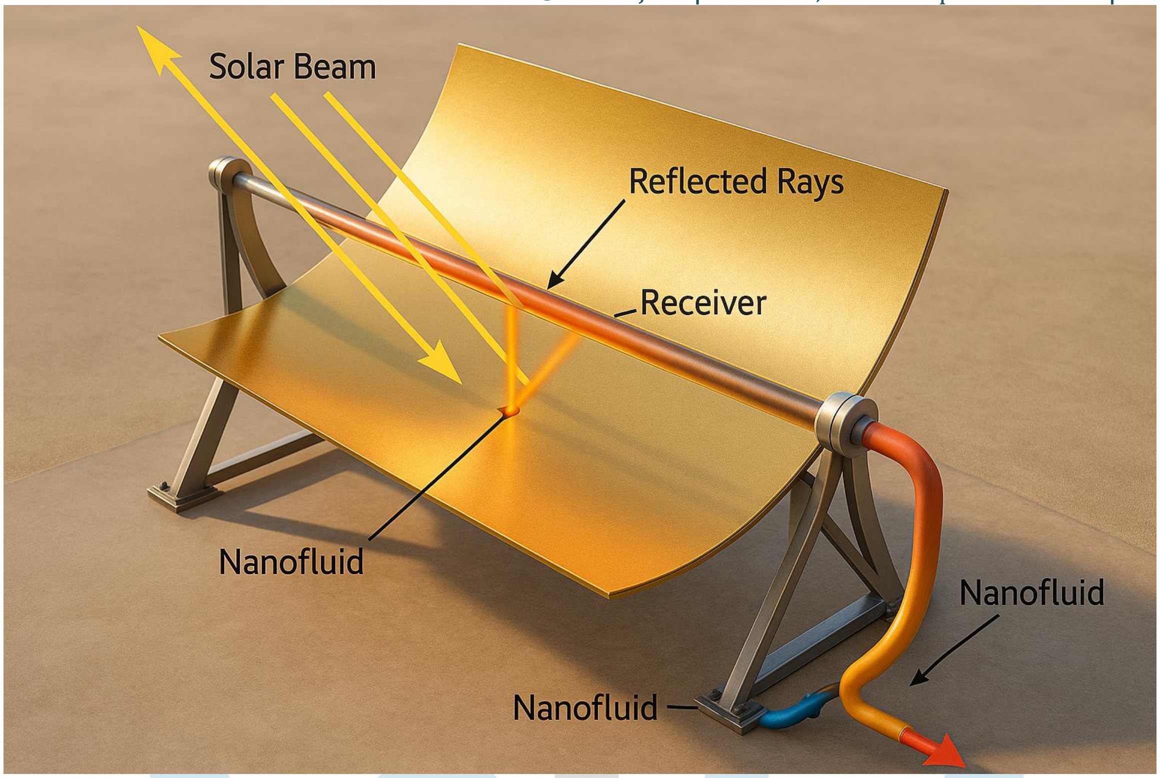
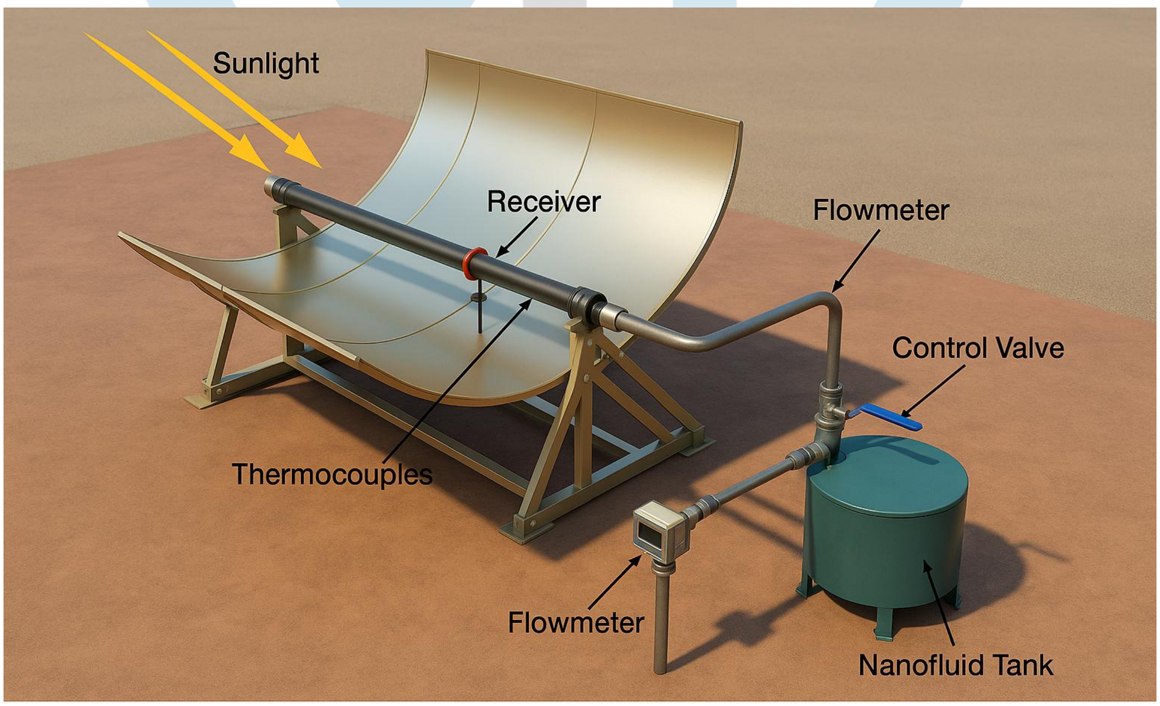


Fig. 1 – Schematic of Parabolic Trough Solar Collector]



Experimental Setup

Fig. 2 – Experimental Setup with Measurement Points

4. Results and Discussion

The experimental and analytical results indicate that increasing the nanoparticle concentration significantly enhances the thermal performance of the Parabolic Trough Solar Collector (PTSC) up to an optimum point. At a nanofluid concentration of 0.2 vol%, the collector achieved its maximum instantaneous thermal efficiency of 73.4%, corresponding to an efficiency improvement of approximately 12% compared to the baseline case using pure water as the heat transfer fluid.

This improvement is primarily attributed to the increased effective thermal conductivity and specific heat capacity of the Al_2O_3–water nanofluid, which enhances convective heat transfer within the receiver tube. The presence of nanoparticles also promotes micro-scale mixing and turbulence, leading to a higher Nusselt number and improved temperature uniformity along the absorber surface.

However, further increasing the concentration beyond 0.2% resulted in marginal efficiency gains accompanied by a noticeable rise in viscosity and pressure drop. The hydraulic performance analysis showed that at 0.3% volume fraction, the pressure loss increased by nearly 8–10%, which led to a corresponding increase in pumping power requirements. Hence, the optimum concentration for balancing thermal enhancement and hydraulic penalties was determined to be 0.2%.

The exergy analysis provided additional insights into system-level irreversibilities. The absorber tube was identified as the major contributor to exergy destruction, accounting for approximately 62% of total exergy losses, followed by optical reflection losses (21%) and thermal re-radiation (11%). These results are consistent with similar findings reported by Gao et al. (2022) and Verma et al. (2025), who emphasized that minimizing absorber surface temperature gradients can significantly reduce exergy destruction in concentrating solar collectors.

Overall, the findings demonstrate that the integration of nanofluids into PTSC systems can improve both energy and exergy efficiencies under realistic solar conditions, provided that the concentration and flow parameters are optimized for minimum entropy generation.

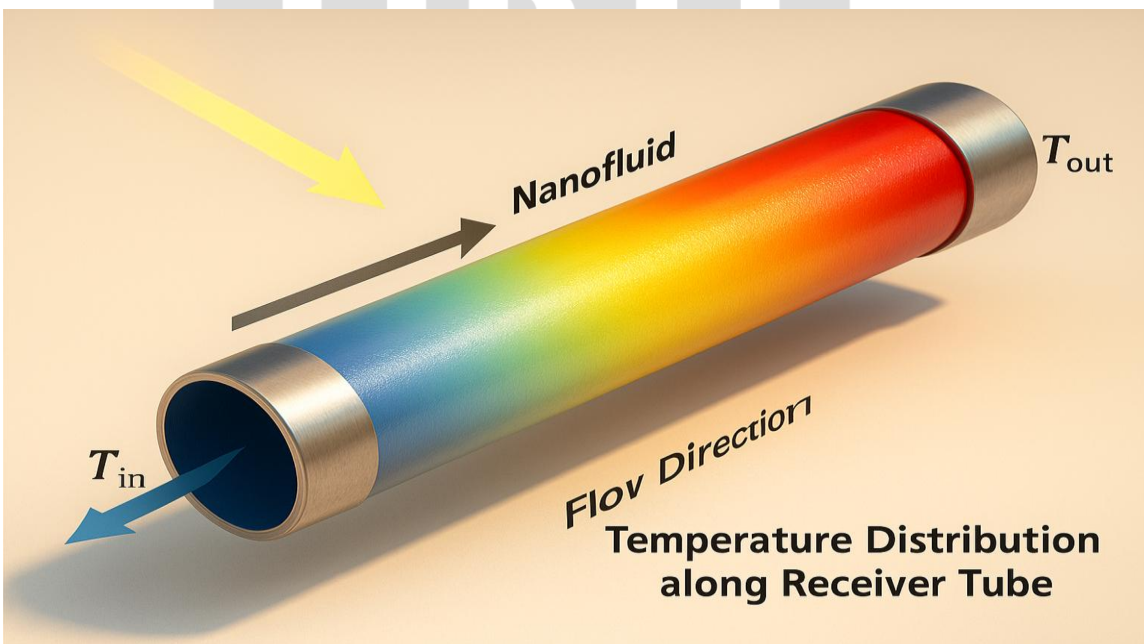


Fig. 3 – Variation of Temperature along Receiver Tube

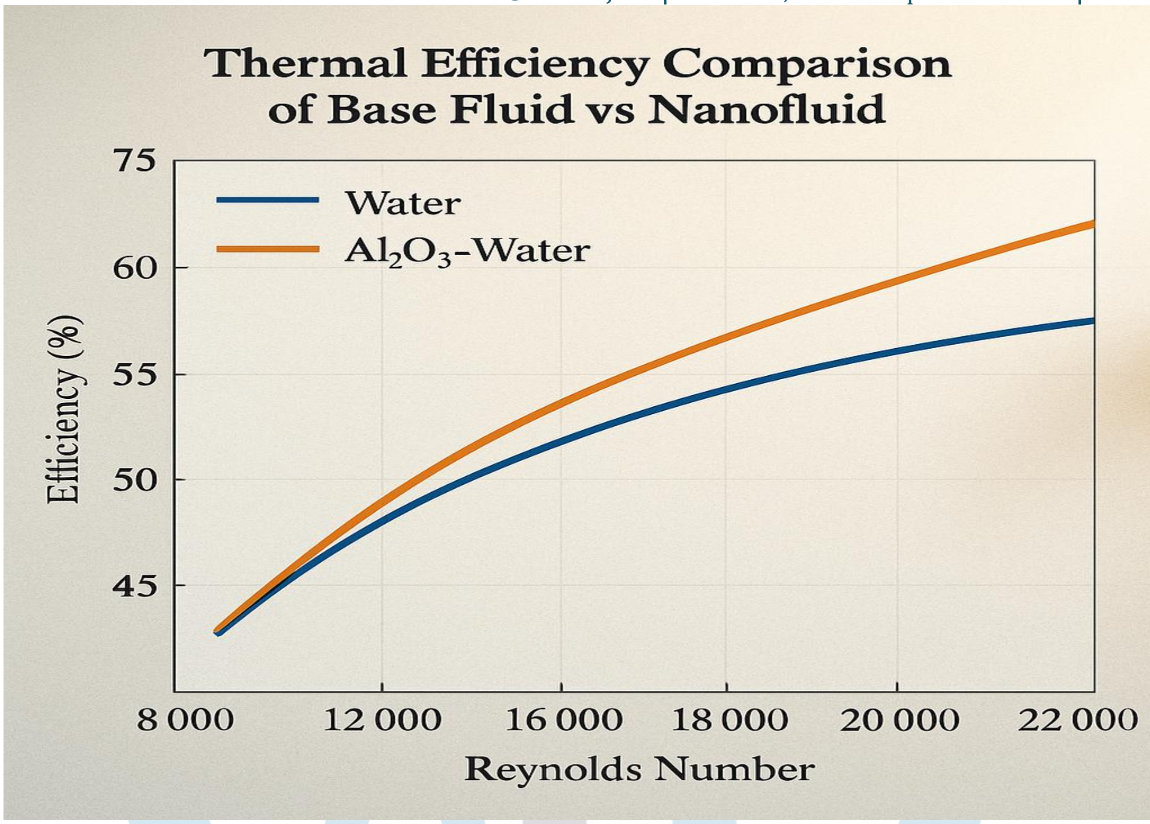


Fig. 4 – Comparison of Thermal Efficiency for Different Concentrations

5. Conclusion

The experimental and analytical results demonstrate that nanofluids, particularly Al_2O_3–water mixtures, significantly enhance the thermal and exergetic performance of the Parabolic Trough Solar Collector (PTSC). Among all tested concentrations, the 0.2 vol% nanofluid exhibited the best overall performance, achieving a maximum instantaneous thermal efficiency of 73.4% with a corresponding exergy efficiency of 26% and minimal hydraulic penalty.

The observed performance enhancement is mainly due to the superior thermal conductivity and convective heat transfer capability of the nanofluid, which improves the overall heat removal factor of the collector. The system maintained stable operation under varying solar irradiance and mass flow rates, confirming the reliability of nanofluid-based thermal systems for field applications.

From an exergo economic perspective, the use of Al_2O_3–water nanofluids offers improved energy utilization and potential reductions in thermal losses, making them promising for industrial and renewable energy systems.

Future research may focus on the following aspects:

- Hybrid nanofluids (e.g., Al_2O_3–CuO/water) for synergistic enhancement of thermophysical properties.
- Long-term stability and degradation studies to ensure consistent optical and thermal performance.
- System-scale CFD modelling and optimization for predicting real-time collector behaviour under transient conditions.
- Integration with thermal storage and hybrid renewable systems for large-scale deployment.

Overall, the study confirms that adopting nanofluids in solar thermal collectors can significantly contribute to improving the efficiency, sustainability, and viability of renewable energy systems in diverse climatic regions.

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