

Experimental Study on Performance Analysis of Evacuated Tube Solar Collector with TiO₂ Nanofluid and Adjustable Parabolic Trough Reflector

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Abstract

This paper presents enhancing the thermal performance of evacuated tube solar collectors (ETSCs) using titanium dioxide (TiO₂) nanofluids combined with reflector and sun-tracking mechanisms. ETSCs are a promising technology in solar thermal energy; however, their efficiency is often limited by the low thermal conductivity of conventional working fluids like water. To address this, TiO₂ nanoparticles were dispersed in water at concentrations of 0.05%, 0.15%, and 0.3% to evaluate their impact on ETSC performance in configurations with reflectors, angle tracking, and combined reflector and sun-tracking systems. Experimental results confirm the superior performance of TiO₂ nanofluids in outlet temperature, efficiency, and heat gain. The storage tank temperature increased from 56.7 °C with plain water to 73.4 °C at 0.05% and 78.2 °C at 0.3%. System efficiency improved from 21.4% to 23%. The highest efficiency was obtained with 0.3% nanofluid combined with reflector and sun-tracking. These results demonstrate a practical pathway to maximize solar energy capture.

Keywords: Evacuated Tube Solar Collector (ETSC); Titanium Dioxide (TiO₂) Nanofluid; Thermal Efficiency; Parabolic Trough Reflector; Solar Tracking; Heat Transfer Enhancement; Renewable Energy.

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NOMENCLATURE

Symbol	Description
A aperture	Aperture area of the evacuated tube
A reflector	Aperture area of the parabolic trough reflector
c_p	Specific heat capacity of the working fluid ($J \cdot kg^{-1} \cdot K^{-1}$)
$c_{p,nf}$	Specific heat capacity of nanofluid ($J \cdot kg^{-1} \cdot K^{-1}$)
ΔT	Temperature difference between inlet and outlet ($^{\circ}C$)
G_n	Normal solar irradiance ($W \cdot m^{-2}$)
G_{tilt}	Solar irradiance on the tilted collector surface
h	Hour angle ($^{\circ}$)
k_{nf}	Thermal conductivity of nanofluid ($W \cdot m^{-1} \cdot K^{-1}$)
$\dot{m}$	Mass flow rate of the working fluid ($kg \cdot s^{-1}$)
Q_u	Useful thermal energy transferred to the working fluid (W)

Greek Symbols

α	Absorptivity of the absorber tube (–)
δ	Solar declination angle ($^{\circ}$)
μ_{nf}	Dynamic viscosity of nanofluid ($Pa \cdot s$)
ϕ	Nanoparticle volume fraction (–)
τ	Transmissivity of the glass envelope (–)
η_{ex}	Exergy efficiency (%)
η_{th}	Thermal efficiency of the collector (%)

Subscript

bf	Base fluid
nf	Nanofluid
np	Nanoparticles

1. Introduction

The escalating global demand for sustainable and environmentally friendly energy solutions has catalyzed significant advancements in renewable energy technologies. Among these, solar energy emerges as a leading contender due to its abundance, accessibility, and potential to mitigate the adverse effects of fossil fuel consumption. Harnessing solar energy not only addresses energy security concerns but also contributes to reducing greenhouse gas emissions, thereby playing a pivotal role in combating climate change [1]. Solar energy can be harnessed

through two primary technologies: photovoltaic (PV) systems and solar thermal systems. PV systems directly convert sunlight into electricity using semiconductor materials, while solar thermal systems capture solar radiation to generate heat for various applications, including water heating, space heating, and electricity generation in concentrating solar power (CSP) systems [2]. Each technology offers unique advantages and challenges, and their integration into energy systems depends on factors such as geographic location, climate conditions, and specific energy requirements.

Solar thermal systems, particularly in regions with high solar irradiance, provide a reliable source of thermal energy for residential, commercial, and industrial applications. These systems typically consist of solar collectors, heat transfer fluids, and storage units. The efficiency of solar thermal systems, however, is influenced by several factors, including the intensity of solar radiation, ambient temperature, collector orientation, and thermal losses through conduction, convection, and radiation [3]. Addressing these challenges is crucial to enhancing the performance and reliability of solar thermal systems under varying environmental conditions. To overcome these limitations and improve the thermal efficiency of solar collectors, researchers have explored various innovative approaches. Three prominent techniques include the use of reflectors, sun-tracking mechanisms, and nanofluids as heat transfer media. Each of these methods targets specific inefficiencies in conventional solar thermal systems and has demonstrated potential in enhancing heat absorption and transfer capabilities [4]. Reflectors, such as parabolic trough collectors (PTCs), are widely employed in CSP applications to concentrate sunlight onto a central absorber tube, thereby increasing the thermal energy captured without expanding the collector area. PTCs are recognized for their mature technology, favorable construction properties, and ability to achieve operating temperatures up to 400 °C, making them suitable for high-temperature applications [5]. Recent studies have enhanced parabolic trough solar collector (PTSC) performance by integrating helical fins into absorber tubes. With Using Cu-Therminol VP-1 nanofluids, in this design improved thermal efficiency by 2.0% and increased the Nusselt number by 55% at $Re = 10^5$, with maintaining moderate pressure losses. These gains result from improved axial and radial flow mixing due to fin geometry and the nanofluid's thermophysical properties, validated by CFD and experiments[6]. These findings underscore the potential of combining geometric modifications with advanced working fluids to achieve significant thermal performance improvements in solar thermal systems. Sun-tracking systems further augment solar energy collection by adjusting the orientation of solar collectors to follow the sun's trajectory across the sky. These systems can be categorized into

single-axis and dual-axis trackers, with the latter offering more precise alignment by adjusting both tilt and azimuth angles. Dual-axis tracking systems have been shown to improve solar energy yield by up to 30% compared to fixed systems, particularly in regions with extended daylight hours [7]. While the incorporation of tracking mechanisms increases system complexity and cost, the resultant efficiency gains often justify their implementation in solar thermal applications.

In parallel, the development of nanofluids engineered by dispersing nanoparticles into conventional heat transfer fluids has emerged as a promising strategy for enhancing the thermal performance of solar collectors. Nanofluids exhibit unique properties, including increased thermal conductivity, rapid heat transfer rates, high specific surface area, and improved stability. These characteristics enable more efficient heat absorption and transfer, contributing to overall system efficiency [8]. To maintain fluid stability and prevent issues such as sedimentation and agglomeration, it is generally recommended that nanoparticle sizes do not exceed 100 nm [9]. Experimental studies have demonstrated the effectiveness of various nanofluid formulations in improving the performance of evacuated tube solar collectors (ETSCs). For instance, the application of Al_2O_3 /distilled water nanofluids at volume fractions ranging from 0.03% to 0.06% and flow rates between 20 to 60 liters per hour achieved a maximum thermal efficiency of 57.63% at 0.06% concentration and 60 l/h flow rate [10]. Similarly, research by [11]. indicated that increasing both nanoparticle concentration and mass flow rate positively influenced collector performance, primarily due to enhanced thermal conductivity and improved heat transfer mechanisms. Further advancements in nanofluid technology have explored the integration of advanced nanoparticles, such as single-walled carbon nanotubes (SWCNTs), copper oxide (CuO), silver (Ag), and silicon dioxide (SiO_2). For example, [12] reported that employing 0.2 vol% SWCNT–water nanofluid in an ETSC system increased efficiency from 56.7% (using water) to 66% . CuO/distilled water nanofluids achieved up to a 21.8% efficiency improvement compared to water alone, attributed to their superior optical absorption and thermal conductivity properties [13]. Additionally, SiO_2 nanofluids have shown potential to enhance thermal efficiency by up to 23.5% in flat-plate collectors, owing to their high thermal conductivity and heat transfer coefficients [14]. Maintaining nanofluid stability is critical for sustained performance, as nanoparticle agglomeration can diminish heat transfer effectiveness. The use of surfactants has proven effective in enhancing dispersion stability. For instance,[15]. highlighted the role of surfactants in preventing nanoparticle aggregation, thereby sustaining heat transfer efficiency. In a study by [16],Triton X-100 was used as a surfactant in Al_2O_3 - H_2O nanofluids

for flat-plate solar collectors, where an optimal concentration of 0.021 wt% significantly improved dispersion stability, maintaining homogeneity for up to three days. Therefore, this study presents a comprehensive experimental and numerical investigation into the performance enhancement of evacuated tube solar collectors (ETSCs) through the integration of titanium dioxide (TiO₂) nanofluids, parabolic trough reflectors, and sun-tracking mechanisms. By exploring the combined effects of these techniques, the research aims to provide viable strategies for optimizing solar thermal systems, thereby contributing to the broader adoption of sustainable energy solutions. The nanofluids have been widely used across various fields, including thermal systems and structural materials. The authors showed that in epoxy-silica nanocomposites, the effectiveness of nanoparticle reinforcement depends on particle size, dispersion quality, and filler concentration. Their study showed that 20 nm particles at 5 wt.% achieved the highest strength and stiffness, while 80 nm at 3 wt.% offered better ductility. In contrast, 15 nm particles showed reduced performance due to agglomeration[17]. Recent reviews and comparative studies have expanded understanding of nanofluid applications in solar thermal collectors.[18] the author highlighted environmental benefits, estimating that widespread adoption of nanofluid-based collectors could cut annual CO₂ emissions by several million tons in industrial-scale systems. while [19] provided experimental evidence that nanoparticle-enhanced trough collectors achieved 15–20% higher thermal output under identical solar conditions. [20] conducted a systematic review of PTCs, noting that the integration of nanofluids not only boosts thermal efficiency but also allows for smaller, more compact system designs without sacrificing output.

Although numerous studies have investigated the use of nanofluids, reflectors, and sun-tracking mechanisms individually to enhance solar thermal systems, limited attention has been given to their combined application in evacuated tube solar collectors (ETSCs). This gap highlights the need for a comprehensive approach that evaluates the synergistic effects of these methods under real operating conditions. The innovation of the present study lies in integrating TiO₂ nanofluids with parabolic trough reflectors and dual-axis sun-tracking to achieve higher heat absorption, improved efficiency, and better overall system performance. The research roadmap involves preparing and stabilizing TiO₂ nanofluids, conducting experimental testing of ETSCs with different configurations, comparing the thermal performance of nanofluids and water, and validating the results through numerical analysis. This integrated strategy provides a practical pathway to optimize ETSCs and support the wider adoption of sustainable solar thermal technologies.

2. Methodology

This paper presents a steady-state thermal analysis aimed at evaluating the thermal performance of an evacuated tube thermosiphon system under six distinct operational scenarios. The primary performance metrics considered in the analysis are the heat transfer rate to the working fluid defined as the useful energy gain—and the corresponding thermal efficiency of each configuration. The first set of three scenarios investigates the system using water as the working fluid. In the baseline configuration, the evacuated tube operates without a reflector or solar tracking system. The second scenario introduces a reflective surface to enhance the solar radiation incident on the tube surface. The third scenario further incorporates a solar tracking mechanism to maximize solar energy absorption throughout the day. The remaining three scenarios examine the thermal performance of the system using a titanium dioxide (TiO₂)-based nanofluid as the working fluid at three different volume concentrations: 0.05%, 0.15%, and 0.3%. These cases are designed to evaluate the enhancement in thermal performance due to the improved thermophysical properties of nanofluids under identical environmental conditions. The system consists of a single evacuated tube collector inclined at a fixed angle of 45°, optimized for the geographic location of the test site. The collector absorbs incident solar radiation and transfers the thermal energy to the working fluid through natural convection, initiating a passive circulation loop typical of thermosiphon systems.

2.1 Solar Radiation Model

The total solar radiation incident on the evacuated tube is computed based on incident solar radiation on tilt surface and the geometric orientation of the collector. The model accounts for the Earth-Sun relationship, atmospheric effects, and the inclination of the collector surface to provide an accurate estimation of the absorbed solar energy. The following steps outline the methodology for determining the solar radiation variables to estimate the solar radiation on tilt surface.

2.1.1 Declination Angle (δ)

The declination angle is defined as the angular displacement of the sun's rays from the Earth's equatorial plane. This angle varies periodically throughout the year due to the Earth's axial tilt (approximately 23.45°) and its elliptical orbit around the Sun. The declination angle determines the sun's relative position and influences the duration of daylight and solar intensity received at a given location.

The Cooper equation is widely adopted for estimating the daily declination angle and is given as:

$$\text{Declination angle } (\delta) = 23.45(\sin[360/365 (284 + N)]) \quad (1)$$

Where :

- δ = declination angle ($^{\circ}$),
- N = day of the year (integer from 1 to 365, where $N = 1$ corresponds to January 1st).

This equation accounts for the Earth's annual motion around the Sun and provides an accurate estimation of the sun's position on any given day. The declination angle directly affects the solar zenith angle and thus modifies the incident radiation on a tilted surface.

2.1.2 Hour angle (h)

The hour angle represents the apparent angular displacement of the sun with respect to the local meridian due to the Earth's rotation. It is defined as the angle the Earth rotates in a given time interval, measured from the observer's longitude. The hour angle is computed as:

$$\text{Hour angle (h)} = 15 (\text{Time of day} - 12:00) \quad (2)$$

where:

- h = hour angle ($^{\circ}$),
- T = local solar time (hours), where solar noon ($T = 12$) corresponds to $h = 0^{\circ}$.

A negative hour angle signifies morning hours (before solar noon), while a positive hour angle represents afternoon hours (after solar noon). The hour angle is essential in calculating the solar altitude and azimuth angles, which define the sun's position in the sky.

2.1.3 Irradiance on normal surface (G_n)

The normal solar irradiance is the intensity of solar radiation received on a plane perpendicular to the sun's rays. It varies slightly throughout the year due to the Earth's elliptical orbit,

which alters the Earth-Sun distance. The normal irradiance is determined using the Duffie and Beckman (2013) formulation [21]:

$$\text{Irradiance on normal surface (G}_n\text{)} = 1,367 \left(1 + 0.033 \left(\cos \left[\frac{360(N)}{365} \right] \right) \right) \quad (3)$$

This equation provides a baseline for computing the solar radiation available before atmospheric interactions such as absorption, scattering, and reflection.

2.1.4 Tilted Surface Radiation (G_{tilt})

The amount of solar radiation intercepted by a tilted collector differs from that on a horizontal plane due to the angular orientation of the surface. The total irradiance received by an inclined collector is determined by applying a geometric correction factor, which accounts for the sun's position relative to the collector's orientation. The tilt correction factor is defined as:

$$\text{Geometric Factor (R}_b\text{)} = \frac{\sin(L - \beta)(\sin(\delta) + \cos(L - \beta)\cos(\delta)\cos(h))}{\sin(L) \sin(\beta)\sin(\delta) + \cos(L)\cos(\beta)\cos(\delta)\cos(h)} \quad (4)$$

The corrected incident solar radiation on the inclined collector is then given by:

$$\text{Irradiance on normal surface (G}_{\text{tilt}}\text{)} = G_n \times R_b \quad (5)$$

Figure 1 shows accurate estimation of the solar radiation intercepted by the inclined evacuated tube, considering the Earth's solar geometry and the collector's orientation. The geometric correction factor ensures that the incident radiation calculation aligns with real-world collector positioning, maximizing the accuracy of thermal performance predictions.

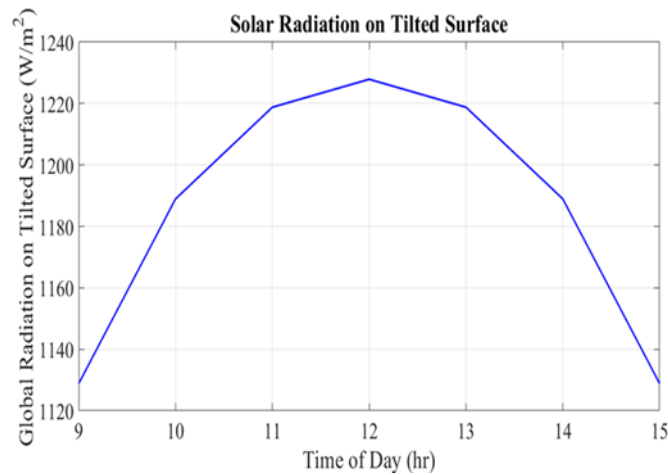


Figure 1:Expected hourly solar radiation in the site

2.2 Thermal Model of the Evacuated Tube

The thermal performance of an evacuated tube solar collector (ETC) is fundamentally determined by its capacity to effectively capture, transfer, and retain thermal energy derived from incident solar radiation. The energy balance governing the ETC accounts for multiple heat exchange mechanisms, including solar absorption, heat transfer to the working fluid, and the various heat losses due to convection, and radiation. This section outlines a comprehensive thermal model of the evacuated tube collector in two configurations, with and without reflector.

2.2.1 Solar Energy Absorption

The total solar energy absorbed by the evacuated tube is determined by the amount of incident solar radiation on the tilted collector surface, the aperture area of the tube, and the optical characteristics of the collector system. The absorbed solar energy is mathematically expressed as [22]:

$$\text{Solar gain by evacuated tube } (Q_{\text{solar gain}}) = G_{\text{tilt}} A_{\text{Apearture}} (\tau \cdot \alpha) \quad (6)$$

Where:

- G_{tilt} is the incident solar radiation on the tilted surface of the collector (W/m^2),

- Aperture: is the aperture area of the evacuated tube (m^2).
- τ : is the transmissivity of the outer glass envelope (Obtained from manufacturer).
- α : is the absorptivity of the inner absorber tube (Obtained from manufacturer).

The product of $\tau \cdot \alpha$ defines the optical efficiency of the system, representing the fraction of incident solar radiation that is transmitted through the outer glass envelope and subsequently absorbed by the absorber tube.

2.2.2 Enhanced Solar Energy Absorption using reflector:

In the presence of a reflector, the total absorbed solar radiation is enhanced by the contribution from the reflected radiation, which is redirected toward the evacuated tube. The total absorbed energy is expressed as:

$$\text{Heat reflected by reflector } (Q_{Ref}) = G_{tilt} A_{reflector} \rho_{ref} (\tau \cdot \alpha)_{ref} \quad (7)$$

Where:

- $A_{reflector}$ is the aperture area of the reflector (m^2).
- ρ_{ref} is the reflectivity of the reflector material (Obtained from manufacturer).

This equation accounts for the enhanced energy absorption due to the additional reflected radiation, contributing to higher thermal performance and outlet temperatures.

2.2.3 Thermal analysis of the ETC:

To evaluate the thermal performance of the ETC, an energy balance approach is employed. The primary quantity of interest is the useful thermal energy transferred to the working fluid, which is calculated using the measured inlet and outlet temperatures obtained during the experimental campaign. The useful energy gain is defined as:

$$Q_u = m \cdot c_p (T_{out} - T_{in}) \quad (8)$$

Where:

- Q_u is the useful energy transferred to the working fluid inside the ETC (W).
- m is mass flow rate of working fluid through ETC (kg/sec).

The thermal efficiency of the ETC, which is a key performance metric, is expressed as the ratio of useful energy to the absorbed solar energy:

$$\eta = \frac{Q_u}{Q_{solar\ gain}} \quad (9)$$

This thermal model enables reliable estimation of both the useful energy and efficiency of the ETC for all considered configurations. By integrating real-time ambient conditions and system-specific parameters, the model predicts the thermal response of the ETC, including variations in outlet temperature under different operating scenarios.

2.3 Experimental Procedures

2.3.1 Material

In this experimental study, TiO₂ nanoparticles, specifically engineered for heat transfer applications, were sourced from a local supplier. The nanoparticles exhibited a purity exceeding 99.5%, an average particle diameter of 20 nm, and a thermal conductivity of 8.4 W/m·K. Owing to their spherical shape and solubility in water, distilled water was selected as the base fluid for preparing the nanofluid.

2.3.2 Nanofluid Preparation and Stability

To ensure the long-term stability of nanofluids is essential for their effective application in heat transfer systems. In this study, sodium lauryl sulfate, a surfactant with a density of 1010 kg/m³, was introduced in small quantities (approximately 0.8105 g per batch) to enhance the uniform dispersion of TiO₂ nanoparticles within the base fluid. Stability refers to the sustained suspension of nanoparticles, preventing aggregation and sedimentation caused primarily by van der Waals forces. Aggregation negatively impacts the thermophysical properties of nanofluids, including thermal conductivity, density, and viscosity. The TiO₂ nanoparticles employed exhibit spherical morphology, which aids in maintaining a stable dispersion. To further

improve dispersion, the nanoparticles were initially mixed with distilled water and subjected to mechanical stirring at 1400 RPM using a probe-type stirrer for 1 hour and 15 minutes. This process effectively reduces clustering and ensures uniform nanoparticle distribution, which is vital for optimizing thermal performance as shown in Figure 2.

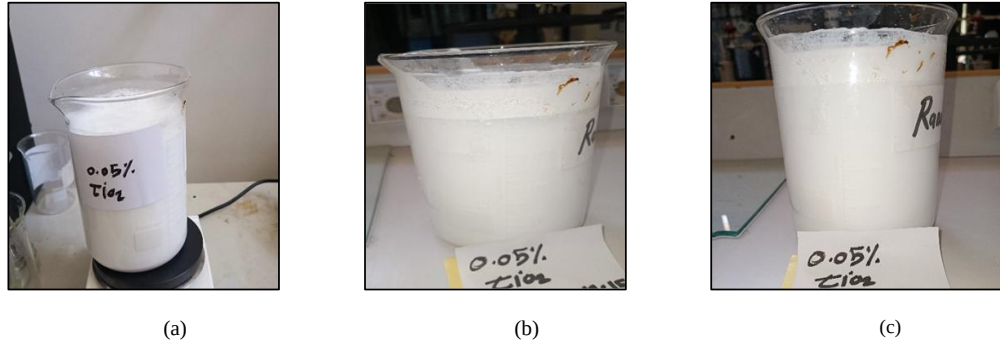


Figure 2: the synthesized 0.05% *TiO2*/water nanofluid using SDS surfactant (a) after 2hr (b) after 12hr (c) after 48hr.

2.4 Characterization of nanofluid

The first step is to determine the thermophysical properties of the nanofluid, which are a function of the volume fraction (ϕ). The volume fraction is defined as the ratio of the nanoparticle volume to the total volume of the nanofluid.

- The nanofluid density is found by the Equation [23]

$$\rho_{nf} = \rho_{np}\phi + (1 - \phi)\rho_{bf} \quad (10)$$

- The nanofluid thermal conductivity is calculated based on the following Equation [24]

$$k_{nf} = k_{bf} \left(\frac{k_{np} + 2k_{bf} + 2\phi(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - \phi(k_{np} - k_{bf})} \right) \quad (11)$$

- The Specific heat of nanofluid can be calculated as follows:

$$c_{p_{nf}} = \frac{c_{p_{np}} \phi \rho_{np} + (1 - \phi) \rho_{bf} c_{p_{bf}}}{\rho_{nf}} \quad (12)$$

- Dynamic Viscosity of nanofluid

$$\mu_{nf} = \mu_{bf} \left(\frac{1}{(1 - \phi)^{2.5}} \right) \quad (13)$$

Based on the above equations and at the different volume fractions of the nanoparticles, the properties of nanofluids are expressed in Table 1

Table 1: Properties of water and nanofluids.

Concentration (wt.%)	Density (kg/m³)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)	Dynamic Viscosity (mPa·s)
0.00 (Base fluid)	997.0	0.607	4182	0.890
0.05	998.6	0.6751	3612.6	1.012
0.15	1001.8	0.8485	2832.7	1.336
0.30	1006.5	1.1784	2139.3	2.171

2.5 Experimental Setup

This study investigates the thermal of an evacuated tube solar collector (ETSC) with parabolic trough reflector, attached to stainless-steel storage tank. The collector assembly is inclined at 45° and oriented southward to maximize solar exposure based on the geographic location of Madaba, Jordan (31.7193° N, 35.7932° E).

The experimental setup comprises a single thermosyphon evacuated tube, a custom-fabricated insulated storage tank, a parabolic trough reflector, a dual-axis sun-tracking mechanism, an anemometer, a nanofluid reservoir, a flowmeter, a pump, and thermocouples. Thermometers equipped with dual K-type thermocouples were positioned throughout the system to measure

temperatures at various points, including the inlet and outlet of the working fluid, the storage tank, and the ambient surroundings. Additionally, an SM206-SOLAR power meter was employed to record global solar irradiance at 10-minute intervals. The specifications and dimensions of the evacuated tube solar collector (ETSC) are detailed in Table 2. A schematic of the experimental setup is presented in Figure 3.

Table 2: Specifications of the collector components

Storage Tank	
Quantity	1
Capacity	8 L
Material Type	Stainless Steel
Evacuated Tube	
Quantity	1
Capacity	2.6 L
Dimensions	Outer Tube Diameter: 0.047 m Inner Tube Diameter: 0.037 m Length: 1.5 m
Material	Borosilicate Glass 3.3
Collector Glazing	Evacuated Tube
Inner Tube Absorptivity	93%
Outer Cover Transmittance	94%



Figure 3: The experimental setup

2.5.1 Testing Method

In this experimental study, preliminary tests were conducted using water as the working fluid to validate the performance and consistency of the setup before introducing nanofluids. Two test runs with water ensured reliable system operation. Once charged, the system operated under solar exposure for six hours, during which fluid temperatures were recorded every 10 minutes using dual K-type thermocouples placed in the storage tank. Simultaneously, a solar power meter measured global solar irradiance at corresponding intervals. After each six-hour cycle, temperature and irradiance data were saved, and the system was drained. To prevent residual nanoparticle sedimentation from affecting subsequent tests, the storage tank and evacuated tubes were thoroughly cleaned before introducing new nanofluid samples. This procedure was repeated for each nanofluid concentration tested.

2.5.1.1 Uncertainties in Measurements

Measurement uncertainties arose from thermocouples, thermometers, an anemometer, an SM206-SOLAR power meter, and swing-arm protractors. Dual K-type thermocouples and thermometers (-50 to $400\text{ }^{\circ}\text{C}$, $\pm 0.1\text{ }^{\circ}\text{C}$) monitored temperatures at the tank inlet, outlet, and ambient point. Global solar irradiance was logged every 10 minutes using the SM206-SOLAR meter (0 – 2000 W/m^2 , $\pm 10\%$ of reading + 2 digits, 0.1 W/m^2 resolution). Wind speed was measured with an anemometer (0 – 30 m/s , $\pm 0.5\%$), while solar angle and orientation were determined using swing-arm protractors (0 – 180° , $\pm 0.1^{\circ}$ to $\pm 0.25^{\circ}$), synchronized with real-time astronomical data (Madaba, Jordan; Lat: 31.7193° N , Long: 35.7932° E).

Table 3: Specifications of measurement instruments and associated uncertainties.

Instrument	Parameter Measured	Working Range	Accuracy / Resolution	Application
Dual K-type Thermocouples	Temperature	-50 to $400\text{ }^{\circ}\text{C}$	$\pm 0.1\text{ }^{\circ}\text{C}$	Tank inlet, tank outlet, ambient reference
Thermometers (with K-type)	Temperature	-50 to $400\text{ }^{\circ}\text{C}$	$\pm 0.1\text{ }^{\circ}\text{C}$	Cross-check with thermocouples
SM206-SOLAR Power Meter	Global solar irradiance	0 – 2000 W/m^2 (typical)	$\pm (10\% \text{ of reading} + 2 \text{ digits})$, 0.1 W/m^2 resolution	10-minute interval solar radiation logging
Anemometer	Wind speed	0 – 30 m/s (typical handheld type)	$\pm 0.5\%$	Wind speed at collector plane
Swing-arm Protractors	Solar angle/orientation	0 – 180°	$\pm 0.1^{\circ}$ to $\pm 0.25^{\circ}$	Collector tilt and orientation

3. Results & Discussion

3.1 Efficiencies

To determine the optimal nanoparticle concentration and assess the impact of using a parabolic trough reflector and solar tracking system for maximizing the thermal efficiency of the solar collector, several key factors have been identified and will be discussed in this section. Based on the results obtained from both experimental and numerical analyses, it can be observed that increasing the nanoparticle concentration, combined with the use of a parabolic trough reflector and solar tracking system, enhances the thermal efficiency of the collector, as shown in Figure 4. The maximum experimental efficiency of 23% was achieved with 0.3 wt% TiO₂ nanofluid combined with reflector and tracking. This improvement is attributed to two synergistic effects: (i) the enhanced thermal conductivity of TiO₂ nanoparticles, which accelerates heat transfer from the absorber to the working fluid, and (ii) the reflector–tracking system, which increases the solar flux incident on the tube and maintains near-normal incidence throughout the day. Compared to water, which is limited by lower conductivity and higher thermal resistance, nanofluids demonstrate superior heat absorption and transport, resulting in sustained efficiency gains. These findings align with Ghaderian & Sidik [11], who also reported that higher nanoparticle concentration improves collector performance due to improved convective coefficients.

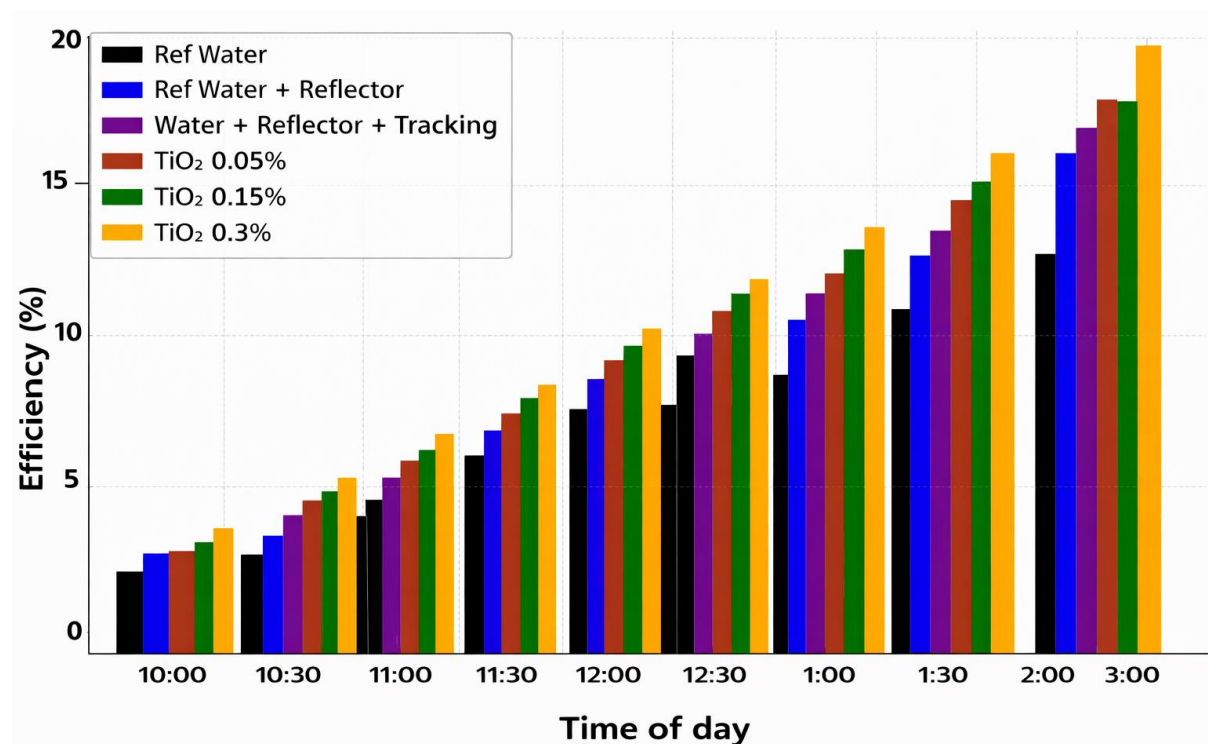


Figure 4: Efficiency comparison over time for different experimental conditions applied to the Setup.

Similarly, the mathematical model Figure 5 confirms that the configuration with 0.3 wt% nanofluid concentration, parabolic trough reflector, and solar tracking yields the highest energy efficiency, reaching over 49%.

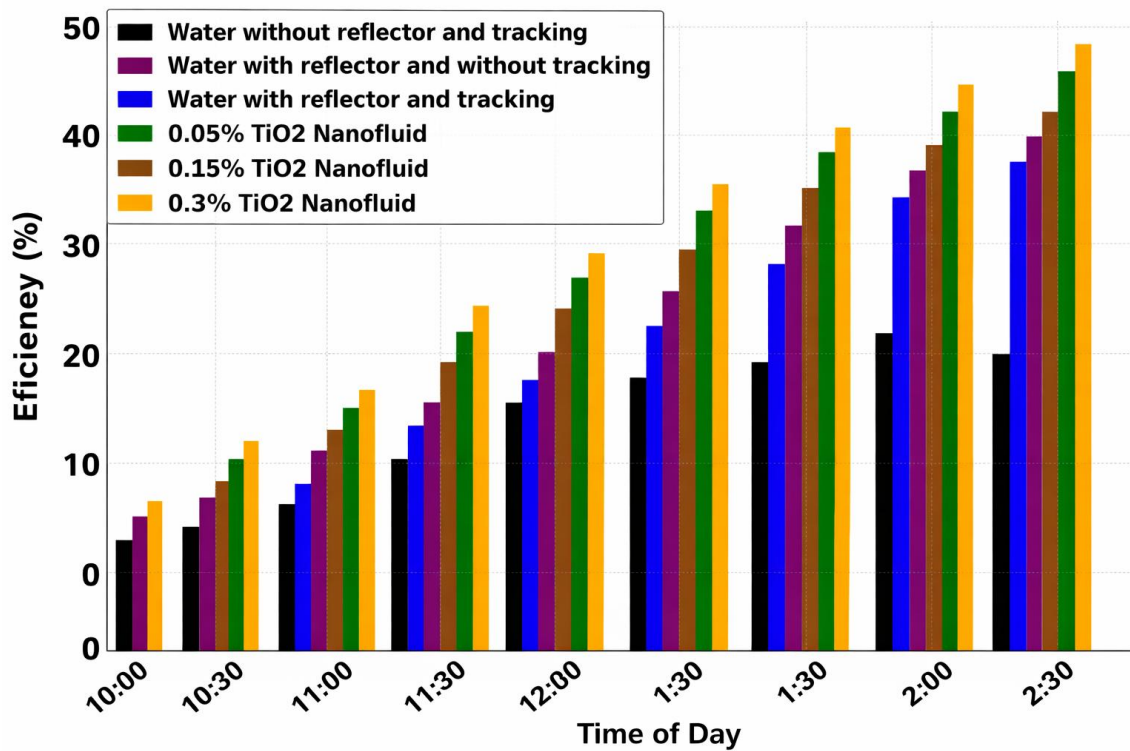


Figure 5: Mathematical model prediction of efficiency variation over time under different experimental configurations applied to the setup.

The inlet/outlet temperature difference of the fluid increases with higher nanoparticle concentration, leading to an improvement in energy efficiency. Due to the high thermal conductivity of nanofluids, the concentration of TiO₂ nanoparticles is directly proportional to the temperature difference. The maximum temperature difference recorded was 78.2 °C for TiO₂ nanofluid at 0.3 wt% as shown in **Figure 6**. This enhancement is attributed to the combination of TiO₂ nanofluids, which improve heat transfer inside the collector, and adjustable reflectors, which increase solar energy collection resulting in a significant temperature boost compared to other configurations. Generally, the enhancement in thermal conductivity leads to an increase in the convective heat transfer coefficient, which, in turn, improves energy efficiency, as observed in the experimental results.

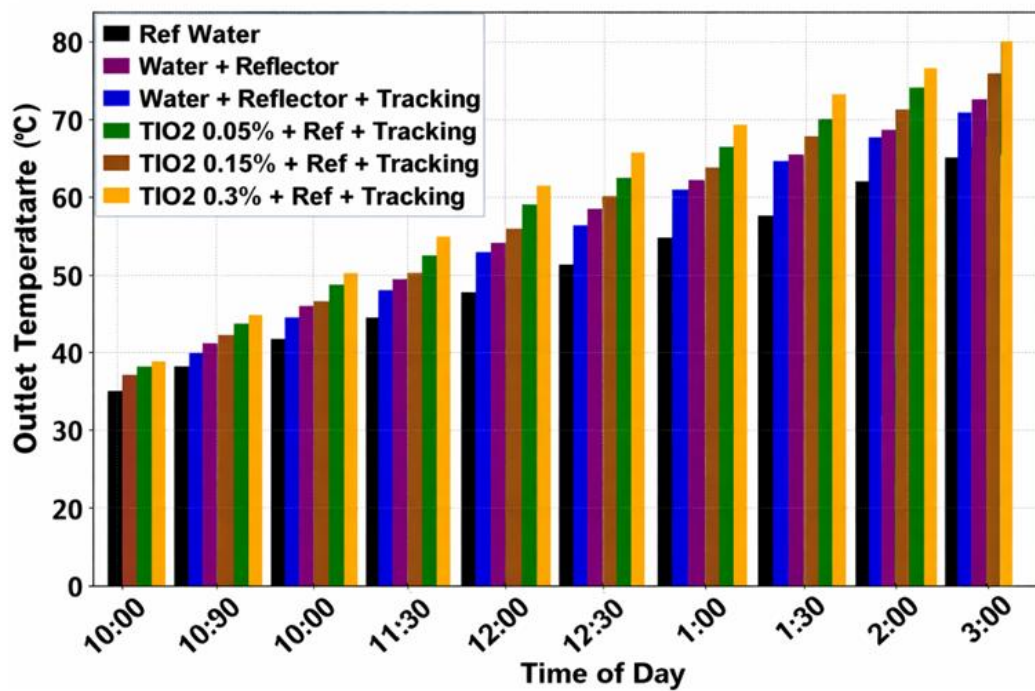


Figure 6: Outlet temperature variation over time for the ETSC under different experimental setups.

3.2 Q Useful

The useful thermal energy was evaluated at 10-minute intervals for each test scenario. Figure 7 and Figure 8 illustrate the superior thermal performance of the evacuated tube collector (ETC in both experimental results and mathematical model predictions when equipped with both a reflector and a solar tracking system. Under this configuration, the useful heat transferred to the working fluid reaches its peak, particularly around solar noon.

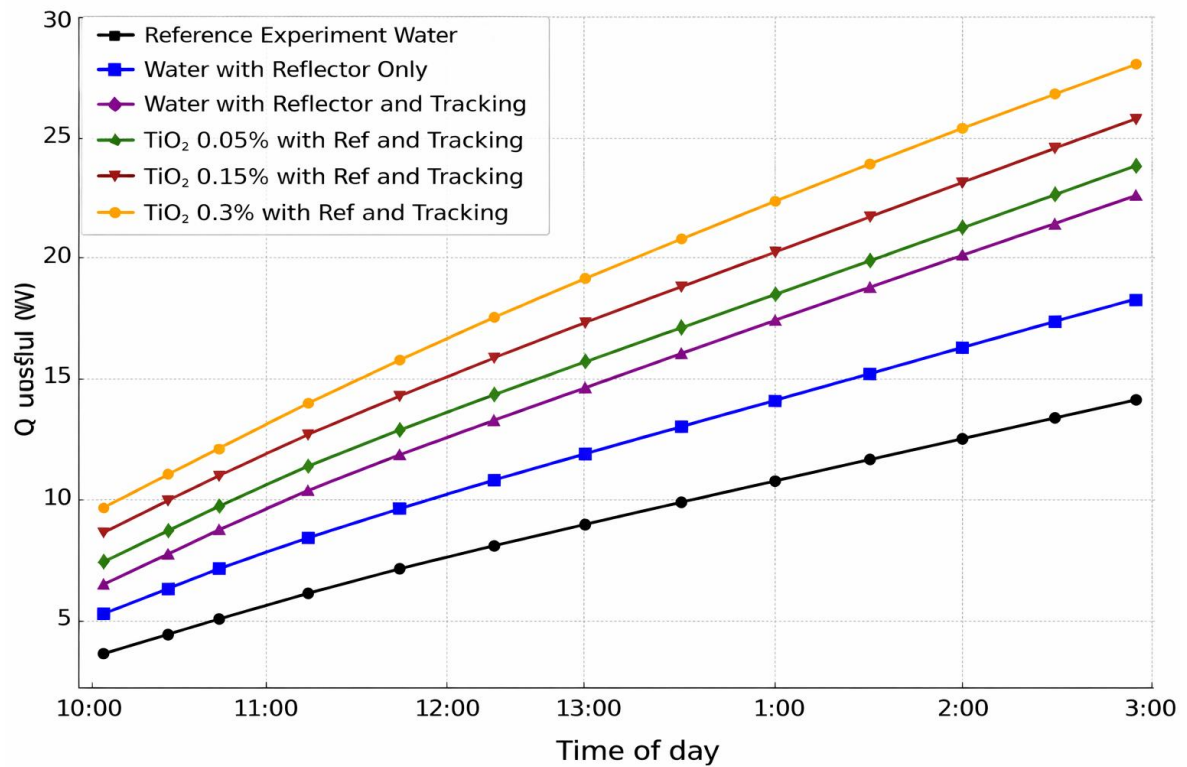


Figure 7: Useful energy transfer to the working fluid under different operational scenarios, based on experimental results.

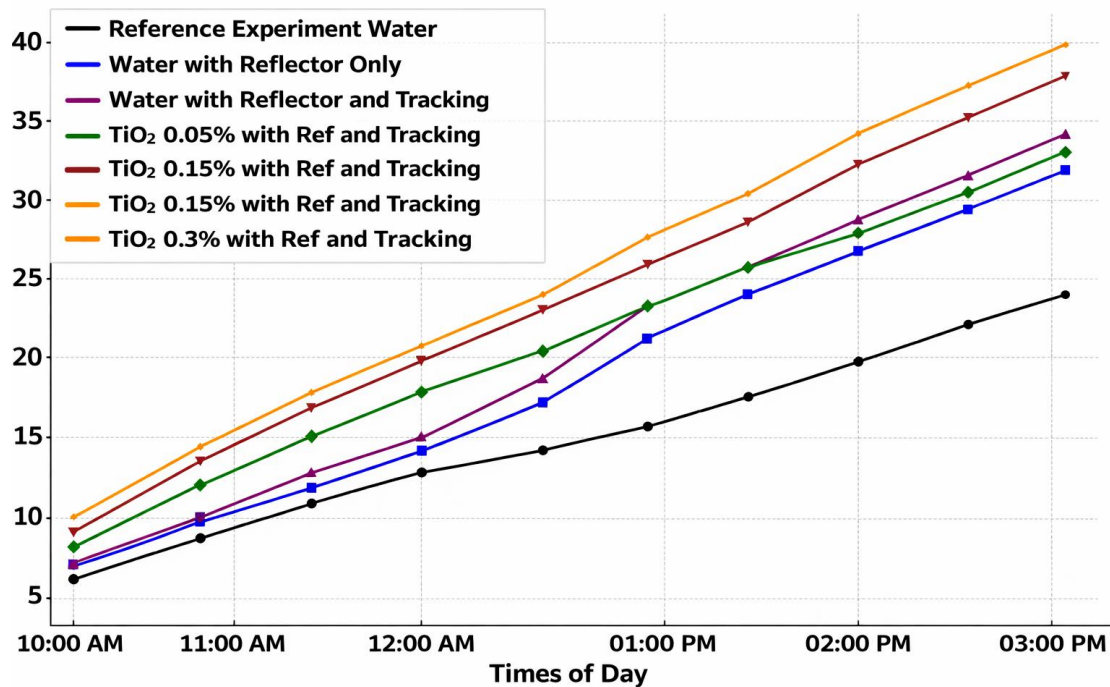


Figure 8: Useful energy transfer to the working fluid under different operational scenarios, based on Mathematical model prediction.

Additionally, the tracking system exhibits enhanced performance during the afternoon period. After trial number 16 (equivalent to 160 minutes from the beginning of the observation period), the useful energy output of the reflector-only and combined reflector-tracking configurations begins to converge. However, beyond this point, the configuration incorporating solar tracking consistently delivers higher useful energy, emphasizing its effectiveness in capturing late-day solar radiation.

4. Conclusions

The performance of a closed-loop evacuated tube solar collector (ETSC) was experimentally investigated using TiO₂ nanofluids in place of distilled water. The analysis was conducted based on the second law of thermodynamics. The following conclusions can be drawn from the results, which evaluate the impact of TiO₂ nanofluids at various particle concentrations, combined with the integration of a parabolic trough reflector and a sun-tracking mechanism within the collector system:

- The results demonstrate a significant enhancement in thermal efficiency when employing the parabolic trough reflector and sun-tracking mechanism with distilled water as the working fluid, achieving an improvement of approximately 20.6%.
- When TiO₂ nanofluid at a concentration of 0.3 wt% was introduced under the same conditions, the thermal efficiency further increased to 23%, a finding corroborated by mathematical model predictions.
- Both experimental and numerical analyses confirm that the application of TiO₂ nanofluids, in conjunction with the parabolic trough reflector and sun-tracking mechanism, boosts the thermal efficiency by approximately 5% compared to standard conditions without these enhancements.
- Pumping power requirements tend to increase with higher nanoparticle concentrations and flow rates. However, this study maintained a relatively low nanofluid concentration, minimizing any significant increase in pumping power.
- The useful thermal energy output was observed to increase with rising nanofluid concentrations and the implementation of the parabolic trough reflector and sun-tracking mechanism.

These findings pave the way for improving the thermal efficiency of solar collectors by substituting conventional fluids with nanofluids. Nevertheless, despite numerous theoretical and experimental investigations in this area, specific challenges remain for the commercial application of nanofluids in heat transfer systems. Issues such as nanoparticle agglomeration, erosion, corrosion, and long-term stability must be addressed. Future research should focus on optimizing the interaction between nanoparticles and base fluids, as well as investigating the influence of temperature on nanofluid performance in operational environments.

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References

- [1] G. G. Njema, J. K. Kibet, and S. M. Ngari, “Advancements in the photovoltaic optimization of a high performance perovskite solar cell based on graphene oxide (GO) hole transport layer,” *Res.*, vol. 1, no. 2, p. 100055, Dec. 2024, doi: 10.1016/j.nexres.2024.100055.
- [2] E. C. Okonkwo, E. A. Essien, E. Akhayere, M. Abid, D. Kavaz, and T. A. H. Ratlamwala, “Thermal performance analysis of a parabolic trough collector using water-based green-synthesized nanofluids,” *Sol. Energy*, vol. 170, pp. 658–670, Aug. 2018, doi: 10.1016/j.solener.2018.06.012.
- [3] S. A. Kalogirou, “Solar thermal collectors and applications,” *Prog. Energy Combust. Sci.*, vol. 30, no. 3, pp. 231–295, 2004, doi: 10.1016/j.pecs.2004.02.001.
- [4] J. A. Bocanegra, A. Marchitto, and M. Misale, “Nanofluids in solar collectors: a comprehensive review focused on its sedimentation,” *Clean Technol. Environ. Policy*, vol. 27, no. 4, pp. 1753–1784, Apr. 2025, doi: 10.1007/s10098-024-02964-2.
- [5] S. A. Kalogirou, “Solar thermal collectors and applications,” *Prog. Energy Combust. Sci.*, vol. 30, no. 3, pp. 231–295, 2004, doi: 10.1016/j.pecs.2004.02.001.
- [6] G. Hou *et al.*, “Thermal performance improvement for parabolic trough solar collectors integrated with twisted fin and nanofluid: Modeling and validation,” *Case Stud. Therm. Eng.*, vol. 60, p. 104763, Aug. 2024, doi: 10.1016/j.csite.2024.104763.
- [7] J. M. González-Sopeña, V. Pakrashi, and B. Ghosh, “An overview of performance evaluation metrics for short-term statistical wind power forecasting,” *Renew. Sustain. Energy Rev.*, vol. 138, p. 110515, Mar. 2021, doi: 10.1016/j.rser.2020.110515.
- [8] R. Saidur, K. Y. Leong, and H. A. Mohammed, “A review on applications and challenges of nanofluids,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1646–1668, Apr. 2011, doi: 10.1016/j.rser.2010.11.035.
- [9] Z. Liu, V. Bode, P. Hadayati, H. Onay, and E. J. R. Sudhölter, “Understanding the stability mechanism of silica nanoparticles: The effect of cations and EOR chemicals,” *Fuel*, vol. 280, p. 118650, Nov. 2020, doi: 10.1016/j.fuel.2020.118650.

- [10] Y. Xuan and W. Roetzel, "Conceptions for heat transfer correlation of nanofluids," *Int. J. Heat Mass Transf.*, vol. 43, no. 19, pp. 3701–3707, Oct. 2000, doi: 10.1016/S0017-9310(99)00369-5.
- [11] J. Ghaderian and N. A. C. Sidik, "An experimental investigation on the effect of Al₂O₃/distilled water nanofluid on the energy efficiency of evacuated tube solar collector," *Int. J. Heat Mass Transf.*, vol. 108, pp. 972–987, May 2017, doi: 10.1016/j.ijheatmasstransfer.2016.12.101.
- [12] I. M. Mahbubul, M. M. A. Khan, N. I. Ibrahim, H. M. Ali, F. A. Al-Sulaiman, and R. Saidur, "Carbon nanotube nanofluid in enhancing the efficiency of evacuated tube solar collector," *Renew. Energy*, vol. 121, pp. 36–44, June 2018, doi: 10.1016/j.renene.2018.01.006.
- [13] A. J. Moghadam, M. Farzane-Gord, M. Sajadi, and M. Hoseyn-Zadeh, "Effects of CuO/water nanofluid on the efficiency of a flat-plate solar collector," *Exp. Therm. Fluid Sci.*, vol. 58, pp. 9–14, Oct. 2014, doi: 10.1016/j.expthermflusci.2014.06.014.
- [14] O. Mahian, A. Kianifar, S. A. Kalogirou, I. Pop, and S. Wongwises, "A review of the applications of nanofluids in solar energy," *Int. J. Heat Mass Transf.*, vol. 57, no. 2, pp. 582–594, Feb. 2013, doi: 10.1016/j.ijheatmasstransfer.2012.10.037.
- [15] N. Goel, R. A. Taylor, and T. Otanicar, "A review of nanofluid-based direct absorption solar collectors: Design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors," *Renew. Energy*, vol. 145, pp. 903–913, Jan. 2020, doi: 10.1016/j.renene.2019.06.097.
- [16] T. Yousefi, F. Veysi, E. Shojaeizadeh, and S. Zinadini, "An experimental investigation on the effect of Al₂O₃–H₂O nanofluid on the efficiency of flat-plate solar collectors," *Renew. Energy*, vol. 39, no. 1, pp. 293–298, Mar. 2012, doi: 10.1016/j.renene.2011.08.056.
- [17] R. Masoodi, P. Heydar, and S. Islam, "The Effect of SiO₂ Nanoparticle on the Mechanical Properties of Silica-Epoxy Nanocomposites-An Experimental Study," vol. 1, no. 1, 2025.

- [18] S. P. Tembhare, D. P. Barai, and B. A. Bhanvase, “Performance evaluation of nanofluids in solar thermal and solar photovoltaic systems: A comprehensive review,” *Renew. Sustain. Energy Rev.*, vol. 153, p. 111738, Jan. 2022, doi: 10.1016/j.rser.2021.111738.
- [19] G. Hou *et al.*, “Thermal performance improvement for parabolic trough solar collectors integrated with twisted fin and nanofluid: Modeling and validation,” *Case Stud. Therm. Eng.*, vol. 60, p. 104763, Aug. 2024, doi: 10.1016/j.csite.2024.104763.
- [20] V. K. Jebasingh and G. M. J. Herbert, “A review of solar parabolic trough collector,” *Renew. Sustain. Energy Rev.*, vol. 54, pp. 1085–1091, Feb. 2016, doi: 10.1016/j.rser.2015.10.043.
- [21] “Solar Engineering of Thermal Processes, 4th Edition John A. Duffie, William A. Beckman. (1).pdf.”
- [22] M. J. Muhammad, I. A. Muhammad, N. A. Che Sidik, and M. N. A. W. Muhammad Yazid, “Thermal performance enhancement of flat-plate and evacuated tube solar collectors using nanofluid: A review,” *Int. Commun. Heat Mass Transf.*, vol. 76, pp. 6–15, Aug. 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.009.
- [23] X. Zhang, H. Gu, and M. Fujii, “Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles,” *Exp. Therm. Fluid Sci.*, vol. 31, no. 6, pp. 593–599, May 2007, doi: 10.1016/j.expthermflusci.2006.06.009.
- [24] S.-Q. Zhou and R. Ni, “Measurement of the specific heat capacity of water-based Al₂O₃ nanofluid,” *Appl. Phys. Lett.*, vol. 92, no. 9, p. 093123, Mar. 2008, doi: 10.1063/1.2890431.

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