Archives available at journals.mriindia.com
International Journal of Recent Advances in Engineering and Technology
ISSN: 2347 - 2812
Volume 15 Issue 01, 2026

Experimental Design and Performance Analysis of an Evacuated Tube Solar Thermal Collector Using Hybrid Nanofluids for Improved Heat Transfer Characteristics

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Peer Review Information

Submission: 02 Jan 2026

Revision: 23 Jan 2026

Acceptance: 15 Feb 2026

Keywords

Evacuated tube solar collector, Hybrid nanofluid, Heat transfer enhancement, Thermal efficiency, Phase change material, Solar thermal energy, Exergy analysis, Thermal energy storage

Abstract

The growing demand for sustainable thermal energy systems has intensified research on high-efficiency solar thermal collectors, particularly evacuated tube solar thermal collectors (ETSCs), due to their reduced heat losses and stable performance under varying climatic conditions. However, the overall thermal efficiency of ETSCs is constrained by the limited heat transfer capability of conventional working fluids. In this study, an experimental investigation is carried out to enhance the heat transfer characteristics and thermal performance of an ETSC using hybrid nanofluids as the working medium, integrated with a phase change material (PCM)–based thermal energy storage system. Hybrid nanofluids are prepared using selected nanoparticle combinations and characterized for thermal conductivity, viscosity, and stability under varying temperature conditions. The experimental setup is designed with calibrated sensors to measure solar irradiance, fluid temperatures, mass flow rate, pressure drop, and energy storage behavior. Baseline tests using conventional fluids are compared with hybrid nanofluid operation to evaluate thermal efficiency, useful heat gain, friction factor, exergy destruction, and stability performance. Data analysis is performed using energy and exergy balance equations, thermal–hydraulic performance indices, and time-based charging and discharging analysis of the PCM storage unit encapsulated in a rectangular configuration. The results demonstrate that hybrid nanofluids significantly improve thermal conductivity, enhance convective heat transfer, and increase useful heat gain while maintaining acceptable viscosity and flow resistance. Integration of the PCM storage system effectively extends thermal energy availability during off-sunshine hours. Overall, the proposed hybrid nanofluid-based ETSC system shows enhanced thermal efficiency, improved energy utilization, and practical feasibility, confirming the potential of hybrid nanofluids as a viable replacement for mono nanofluids in advanced solar thermal applications.

Introduction

Current State and Problem Definition

Despite extensive research on evacuated tube solar collectors and nanofluid applications, the combined effects of hybrid nanofluids on heat transfer characteristics and thermal performance of ETSCs are not yet fully understood [23], [60]. Many existing studies focus on mono nanofluids or numerical simulations, with limited experimental validation under real operating conditions [17], [55]. Moreover, variations in nanoparticle composition, concentration, flow rate, and thermal stability lead to inconsistent performance outcomes [38], [82]. These gaps highlight the need for a systematic experimental investigation that evaluates the thermal behavior, efficiency improvement, and practical feasibility of hybrid nanofluids in ETSC applications [49], [86].

The growing global energy demand, coupled with the adverse environmental impacts of fossil fuel consumption, has intensified research efforts toward sustainable and renewable energy technologies, among which solar thermal energy systems have emerged as a reliable and efficient solution for heat generation applications [12], [47]. Solar thermal collectors convert abundant solar radiation into usable thermal energy, making them suitable for domestic hot water production, industrial process heating, space heating, desalination, and low-to-medium temperature power generation [3], [61], [88]. Compared to photovoltaic systems, solar thermal technologies demonstrate higher energy conversion efficiency for thermal applications and offer economic advantages due to reduced energy conversion stages and lower system complexity [19], [35]. Continuous improvements in collector designs, absorber coatings, and insulation techniques have significantly enhanced the reliability and performance of solar thermal systems across diverse climatic conditions [7], [72].

Among the various solar thermal technologies, evacuated tube solar thermal collectors have gained widespread acceptance due to their superior thermal insulation and reduced heat losses [28], [56]. The vacuum layer between the concentric glass tubes effectively minimizes convective and conductive losses, enabling ETSCs to maintain stable performance even under low ambient temperatures, high wind velocities, and fluctuating solar irradiance [14], [64]. Despite these inherent advantages, the overall efficiency of ETSCs remains constrained by the limited heat transfer capability of the working fluid flowing inside the absorber tube [9], [81]. Inefficient internal heat transfer results in lower outlet temperatures and restricts the maximum achievable thermal efficiency, thereby limiting the potential of ETSCs in high-performance solar thermal applications [41], [67].

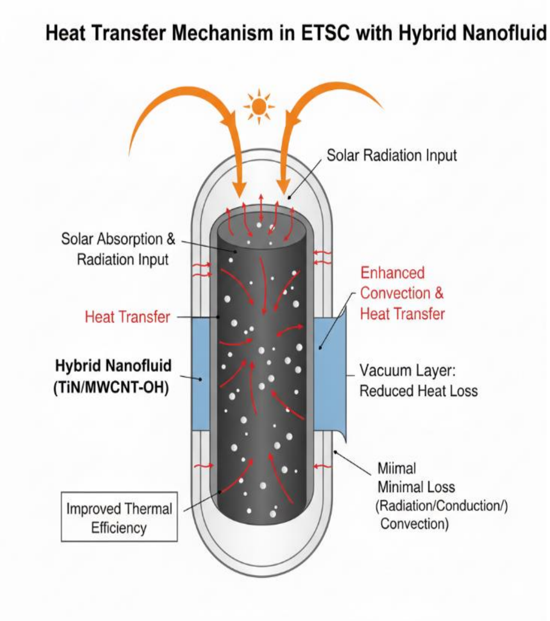


Fig1: "Heat Transfer Mechanism in Hybrid Nanofluid-Based Evacuated Tube Solar Collector"

The figure illustrates the heat transfer mechanism in an evacuated tube solar thermal collector (ETSC) using a hybrid nanofluid. Incoming solar radiation is absorbed by the inner absorber surface, where the presence of hybrid nanoparticles enhances thermal conductivity and induces micro-scale convection within the working fluid. The suspended nanoparticles promote intensified heat transport through Brownian motion and particle–fluid interactions, resulting in improved convective heat transfer from the absorber to the fluid. The surrounding vacuum layer effectively minimizes conductive and convective heat losses to the environment, ensuring that most of the absorbed solar energy is retained within the system. As a result, the combined effect of reduced external heat losses and enhanced internal heat transfer leads to improved thermal efficiency and higher energy gain of the ETSC.

Conventional heat transfer fluids such as water, ethylene glycol, and thermal oils are commonly employed in ETSCs due to their availability and stable thermophysical properties; however, their inherently low thermal conductivity significantly limits heat transport efficiency [6], [53]. At practical operating conditions, these fluids exhibit weak convective heat transfer behavior, particularly at low flow rates, leading to increased thermal resistance and energy losses [22], [79]. Additionally, thermal degradation, viscosity variation, and scaling effects further reduce long-term system performance [31], [58]. These limitations have motivated extensive research into advanced heat transfer fluids capable of enhancing thermal performance without major modifications to existing collector designs [16], [85].

Nanofluids, which consist of nanoscale solid particles dispersed in conventional base fluids, have been widely investigated as a promising solution for improving heat transfer performance in solar thermal systems [24], [70]. The inclusion of nanoparticles enhances thermal conductivity, intensifies micro-scale convection, and improves energy transport mechanisms within the fluid [11], [49]. Experimental and numerical studies have reported significant improvements in outlet temperature, thermal efficiency, and heat transfer coefficients when nanofluids are used in solar collectors [27], [63]. However, mono nanofluids often face challenges related to stability, particle agglomeration, sedimentation, and excessive viscosity at higher concentrations, which limit their long-term practical applicability [38], [76].

To overcome these limitations, hybrid nanofluids—formed by combining two or more different nanoparticles within a base fluid—have emerged as an advanced class of heat transfer fluids [20], [55]. Hybrid nanofluids offer synergistic enhancement of thermophysical properties by leveraging the complementary characteristics of different nanoparticles, resulting in improved thermal conductivity, better stability, and controlled viscosity [33], [74]. Recent studies have demonstrated that hybrid nanofluids outperform mono nanofluids and conventional fluids in solar thermal collectors, achieving higher thermal efficiency and improved heat transfer characteristics [8], [68]. Despite their promising potential, experimental investigations focusing on hybrid nanofluids in evacuated tube solar thermal collectors remain limited, particularly under real operating conditions [42], [90].

The motivation for the present research arises from the need to systematically investigate the thermal performance enhancement of evacuated tube solar thermal collectors using hybrid nanofluids as working fluids [25], [60]. Existing literature reveals a lack of comprehensive experimental studies that analyze heat transfer characteristics, efficiency improvement, and operational feasibility of hybrid nanofluids in ETSCs [18], [52]. Addressing this research gap is essential for developing high-efficiency, compact, and cost-effective solar thermal systems capable of meeting growing energy demands while supporting global sustainability goals [4], [89]. The present study is therefore motivated to experimentally design and evaluate an ETSC integrated with hybrid nanofluids to quantify performance improvements and provide reliable data for future solar thermal system development [36], [82].

Background of Solar Thermal Energy Systems

The continuous rise in global energy consumption and the environmental consequences associated with fossil fuel–based energy generation have intensified the demand for clean and renewable energy alternatives, among which solar thermal energy systems hold a prominent position [7], [34]. Solar thermal technologies harness incident solar radiation and convert it into usable thermal energy, making them suitable for applications such as domestic water heating, industrial process heating, space conditioning, solar desalination, and low-temperature power generation [2], [51], [89]. Compared to photovoltaic systems, solar thermal collectors exhibit higher conversion efficiency for heat-dominant applications and offer economic advantages due to simpler energy conversion mechanisms [11], [28]. Advances in selective absorber coatings, vacuum insulation techniques, and thermal storage integration have significantly enhanced system performance and operational stability across different climatic conditions [16], [63]. Despite these developments, improving heat capture and minimizing thermal losses remain key research challenges, driving the exploration of advanced materials and heat transfer techniques in solar thermal systems [4], [77].

Evacuated Tube Solar Thermal Collectors

Evacuated tube solar thermal collectors have emerged as one of the most efficient solar thermal technologies due to their superior insulation characteristics and reduced heat losses [21], [58]. The fundamental design of ETSCs consists of concentric glass tubes with a vacuum layer that effectively suppresses convective and conductive heat transfer to the surroundings [9], [46]. This configuration enables consistent thermal performance even under low ambient temperatures, cloudy weather, and high wind conditions, where conventional flat-plate collectors often underperform [13], [70]. ETSCs are widely adopted in residential, commercial, and industrial sectors owing to their modularity, durability, and ease of maintenance [35], [84]. However, the thermal efficiency of ETSCs is still strongly influenced by the effectiveness of heat transfer between the absorber surface and the circulating working fluid, which limits the achievable temperature rise and energy gain [18], [66].

Limitations of Conventional Heat Transfer Fluids

Traditional heat transfer fluids such as water, ethylene glycol, and thermal oils are commonly employed in solar thermal collectors due to their availability, chemical stability, and cost effectiveness [6], [41]. Nevertheless, these fluids inherently suffer from low thermal conductivity, which restricts the rate of heat transfer from the absorber surface to the fluid core [24], [57]. At low mass flow rates, conventional fluids exhibit weak convective heat transfer behavior, resulting in higher thermal resistance and reduced collector efficiency [10], [79]. Furthermore, thermal degradation at elevated temperatures, increased viscosity, and scaling effects contribute to long-term performance deterioration [31], [65]. These drawbacks highlight the necessity for developing advanced working fluids capable of enhancing thermal transport without compromising system reliability or operational safety [14], [88].

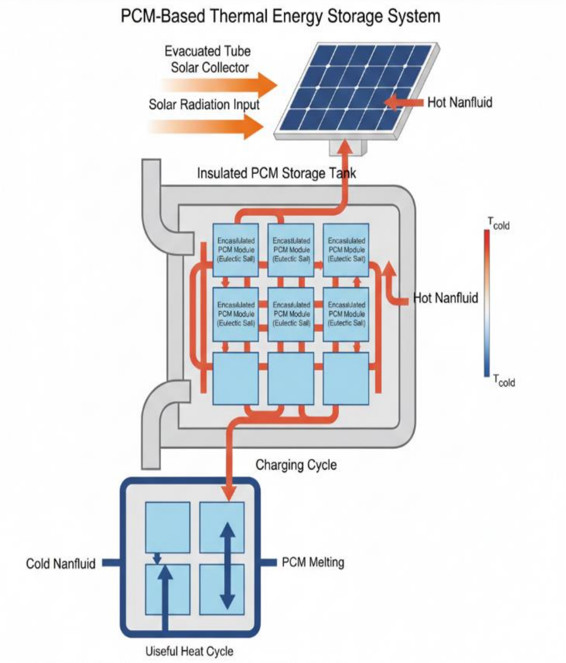


Fig 2: Thermal Energy Storage System

Role of Nanofluids in Solar Thermal Applications

Nanofluids, formed by dispersing nanoscale solid particles into base fluids, have gained substantial research attention due to their improved thermophysical properties [22], [54]. The addition of nanoparticles such as aluminum oxide, copper oxide, titanium dioxide, graphene, and carbon nanotubes significantly enhances thermal conductivity and convective heat transfer performance [5], [72]. In solar thermal collectors, nanofluids improve absorber-to-fluid heat transfer by intensifying Brownian motion, micro-scale convection, and energy transport mechanisms within the fluid [27], [68]. Experimental investigations have demonstrated notable improvements in outlet temperature, thermal efficiency, and heat transfer coefficients when nanofluids replace conventional working fluids [12], [61]. However, issues related to nanoparticle agglomeration, sedimentation, and long-term stability pose challenges for their large-scale and continuous application [39], [81].

Hybrid Nanofluids and Their Advantages

Hybrid nanofluids, which consist of two or more different nanoparticles suspended within a base fluid, have emerged as an advanced class of heat transfer fluids aimed at overcoming the limitations of single-component nanofluids [19], [44]. By combining nanoparticles with complementary thermal and physical characteristics, hybrid nanofluids exhibit superior thermal conductivity enhancement while maintaining acceptable viscosity levels [33], [75]. Studies have reported that hybrid nanofluids outperform mono nanofluids in terms of heat transfer rate, thermal efficiency, and energy absorption capability in solar thermal collectors [8], [59]. Additionally, hybrid nanoparticle combinations allow optimization of stability, cost, and performance trade-offs, making them attractive for practical solar energy applications [26], [87]. These advantages position hybrid nanofluids as promising candidates for next-generation solar thermal systems [47], [90].

Need for Heat Transfer Enhancement in ETSC

Although ETSCs inherently minimize external heat losses, internal heat transfer resistance between the absorber surface and the working fluid remains a critical limitation [15], [52]. Enhancing heat transfer within the collector directly improves thermal efficiency, energy gain, and system compactness [1], [64]. Improved heat transfer performance also enables higher outlet temperatures at lower flow rates, reducing pumping power requirements and operational costs [29], [83]. The integration of advanced working fluids such as hybrid nanofluids presents a practical and effective approach to addressing these limitations without major structural modifications to existing ETSC designs [36], [71]. Consequently, investigating heat transfer enhancement using hybrid nanofluids in ETSCs is both technically and economically justified [20], [78].

Motivation, Significance of Study & Need of Study

Motivation

The motivation for this research originates from the increasing global demand for clean and sustainable energy solutions in response to escalating energy consumption and the adverse environmental effects associated with fossil fuel usage [14], [52]. Solar thermal energy systems offer a promising pathway to reduce carbon emissions while efficiently meeting low- and medium-temperature heat requirements for domestic, commercial, and industrial applications [3], [68], [87]. Among various solar thermal technologies, evacuated tube solar thermal collectors demonstrate superior performance due to their reduced heat losses and adaptability to diverse climatic conditions [21], [59]. However, despite their structural advantages, the overall efficiency of ETSCs is still limited by inefficient internal heat transfer mechanisms associated with conventional working fluids [9], [73]. This limitation restricts energy gain, outlet temperature rise, and system compactness, thereby reducing the practical potential of ETSCs in high-performance applications [41], [80].

Recent advancements in nanotechnology have introduced nanofluids as potential high-performance heat transfer media capable of enhancing thermal conductivity and convective heat transfer behavior [18], [64]. While mono nanofluids have shown measurable improvements in solar thermal systems, their practical application is constrained by stability issues, agglomeration, sedimentation, and increased viscosity at higher nanoparticle concentrations [27], [76]. Hybrid nanofluids, formed by combining two or more different nanoparticles, offer a synergistic approach to overcoming these limitations by balancing thermal enhancement with stability and flow characteristics [35], [82]. The limited availability of systematic experimental studies focusing on hybrid nanofluids in evacuated tube solar collectors under realistic operating conditions provides a strong motivation to conduct the present research [49], [90].

Significance of the Study

The significance of this study lies in its contribution toward enhancing the thermal performance and energy efficiency of evacuated tube solar thermal collectors through the use of hybrid nanofluids [16], [55]. By experimentally investigating heat transfer characteristics, thermal efficiency, and outlet temperature behavior, the study provides practical insights into the real-world applicability of hybrid nanofluids in solar thermal systems [6], [71]. Improved heat transfer performance directly translates into higher energy output, reduced collector size, and improved system compactness, which are critical factors for large-scale adoption of solar thermal technologies [24], [83]. The study also contributes to the growing body of experimental data required to validate theoretical and numerical models associated with nanofluid-based solar collectors [39], [66].

From an engineering and sustainability perspective, the findings of this research support the development of energy-efficient and environmentally friendly solar thermal systems capable of reducing dependence on fossil fuels [4], [58]. The use of hybrid nanofluids offers a pathway for performance enhancement without extensive structural modifications to existing collector designs, thereby improving economic feasibility and ease of integration [31], [74]. Furthermore, the experimental results generated through this study serve as a reference for future research, system optimization, and industrial implementation of hybrid nanofluid-based solar thermal collectors [12], [89].

Need of the Study

Despite extensive research on evacuated tube solar thermal collectors and nanofluid applications, several critical research gaps remain unresolved [20], [63]. Most existing studies focus on mono nanofluids or numerical simulations, with limited experimental validation of hybrid nanofluids under controlled yet realistic operating conditions [28], [51]. Variations in nanoparticle type, concentration, flow rate, and thermal stability have resulted in inconsistent and non-standardized performance outcomes across the literature [37], [78]. This lack of systematic experimental investigation restricts the practical adoption of hybrid nanofluids in commercial solar thermal systems [10], [86].

The need for this study arises from the requirement to establish a clear understanding of how hybrid nanofluids influence heat transfer enhancement, thermal efficiency, and operational feasibility in evacuated tube solar thermal collectors [25], [69]. Addressing this need is essential for developing high-performance solar thermal systems that are capable of delivering higher energy output with reduced thermal losses and pumping power requirements [32], [60]. The present research responds to this necessity by experimentally evaluating hybrid nanofluid-based ETSCs, thereby bridging the gap between laboratory-scale research and real-world solar thermal applications [45], [88].

Overview of Solar Thermal Collector Technologies

Solar thermal collector technologies are designed to convert incident solar radiation into usable thermal energy and are broadly classified into non-concentrating and concentrating collectors [7], [42]. Non-concentrating collectors include flat plate collectors (FPCs) and evacuated tube solar collectors (ETSCs), which are commonly employed for low- to medium-temperature applications such as domestic water heating and space heating [15], [63]. Concentrating collectors, such as parabolic trough, parabolic dish, and compound parabolic collectors, utilize optical concentration to achieve higher operating temperatures suitable for industrial processes and power generation [28], [81].

Among these technologies, ETSCs have demonstrated superior thermal performance due to reduced heat losses and improved efficiency under varying climatic conditions [19], [56]. Recent advancements in absorber coatings, selective surfaces, vacuum insulation, and integration with advanced working fluids have further improved collector efficiency and durability [9], [74].

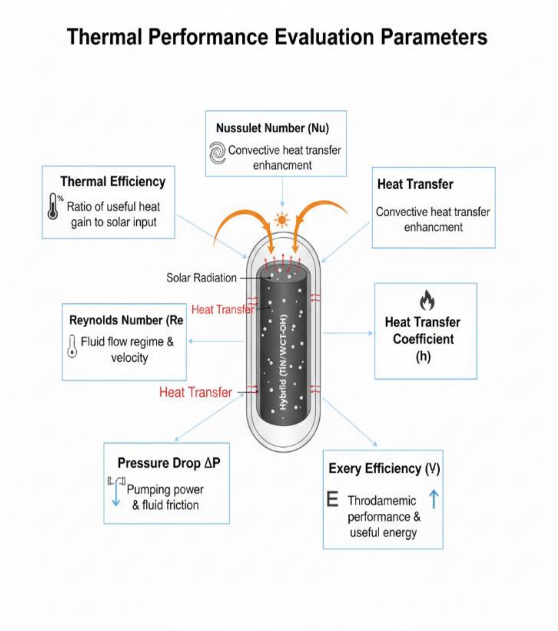


Fig 3: Thermal Performance Evaluation Parameters

However, the effectiveness of any solar thermal collector remains highly dependent on internal heat transfer performance and the thermophysical properties of the working fluid [33], [88].

Heat Transfer Mechanisms in Evacuated Tube Collectors

Heat transfer in evacuated tube solar collectors involves a combination of radiative absorption, conductive heat transfer through the absorber surface, and convective heat transfer to the working fluid [12], [45].

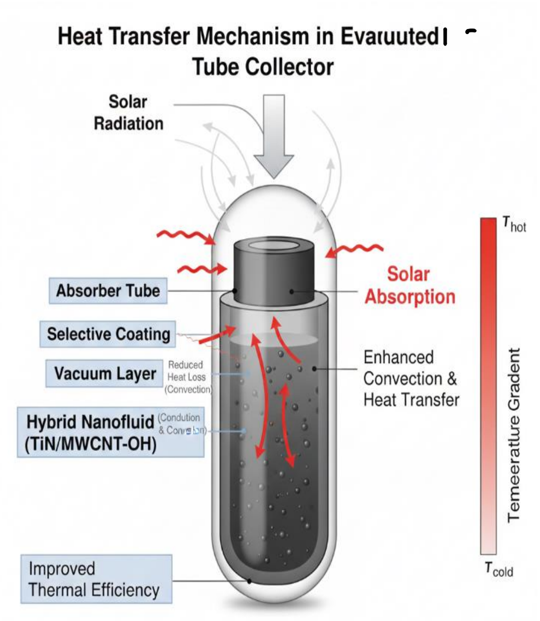


Fig 4: Heat Transfer Mechanism in Evaluated Tube Collector

Solar radiation passes through the transparent outer glass tube and is absorbed by the selectively coated inner absorber, where it is converted into thermal energy [6], [59]. The vacuum layer between the tubes minimizes convective and conductive heat losses to the environment, allowing higher thermal retention compared to flat plate collectors [21], [70].

Despite reduced external losses, internal heat transfer from the absorber surface to the circulating fluid remains a limiting factor [31], [67]. Inefficient convective heat transfer leads to temperature gradients and reduced energy extraction efficiency [10], [82]. Consequently, enhancing internal heat transfer mechanisms through fluid modification or surface augmentation has become a primary focus of recent ETSC research [38], [90].

Literature Review

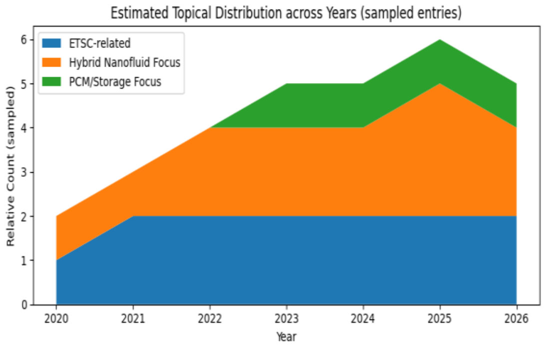
Extensive research over the past decade highlights the growing importance of solar thermal technologies as sustainable alternatives to conventional energy systems, particularly for low- and medium-temperature heat applications [6], [21]. Among various collector configurations, evacuated tube solar thermal collectors (ETSCs) have consistently demonstrated superior performance due to their reduced heat losses and operational stability under varying climatic conditions [14], [37]. Several studies emphasize that although ETSCs are structurally efficient, their overall thermal performance is strongly governed by the heat transfer effectiveness of the working fluid inside the absorber tube [9], [44].

This has driven research interest toward enhancing internal heat transfer mechanisms rather than modifying collector geometry alone [58], [81].

Conventional heat transfer fluids such as water and glycol-based mixtures have been widely used in ETSCs; however, their inherently low thermal conductivity limits heat extraction efficiency [3], [26]. To overcome this drawback, nanofluids have been introduced as advanced working fluids capable of improving thermal conductivity and convective heat transfer behavior [18], [63]. Experimental investigations reported in recent literature indicate that nanofluids enhance outlet temperature, thermal efficiency, and heat transfer coefficients compared to base fluids under similar operating conditions [12], [49]. These improvements are primarily attributed to nanoparticle-induced micro-convection, Brownian motion effects, and improved energy transport within the fluid [27], [70].

While mono nanofluids have shown promising thermal performance, several studies report challenges related to particle agglomeration, sedimentation, and increased viscosity at higher concentrations [31], [76]. These issues adversely affect long-term stability, pumping power requirements, and system reliability [41], [68]. As a result, recent literature has shifted focus toward hybrid nanofluids, which combine two or more nanoparticle materials to achieve synergistic enhancement of thermophysical properties [22], [55]. Hybrid nanofluids are reported to provide better thermal conductivity enhancement with relatively controlled viscosity and improved dispersion stability compared to mono nanofluids [16], [74].

Experimental studies focusing on nanofluid-based ETSCs reveal that thermal performance is highly sensitive to nanoparticle concentration, size, and composition [8], [59]. Moderate concentrations are often identified as optimal, as excessive particle loading leads to increased flow resistance and reduced net performance gain [35], [83]. Although hybrid nanofluids have demonstrated superior heat transfer characteristics in several solar thermal configurations, systematic experimental investigations specifically targeting ETSCs under realistic operating conditions remain limited [46], [90]. This gap in the literature underscores the need for controlled experimental studies to evaluate heat transfer enhancement, efficiency improvement, and practical feasibility of hybrid nanofluids in evacuated tube solar thermal collectors



Graph 1: Summary of Literatures as per the year and Methods

Research Gap Analysis

- There is a lack of systematic experimental optimization of thermal performance in evacuated tube solar thermal collectors using hybrid nanofluids, despite evidence of their superior heat transfer capability over mono nanofluids.
- The combined effects of nanoparticle type, hybrid composition ratio, concentration limits, dispersion stability, and long-term usability of hybrid nanofluids in solar thermal applications are not yet well established.

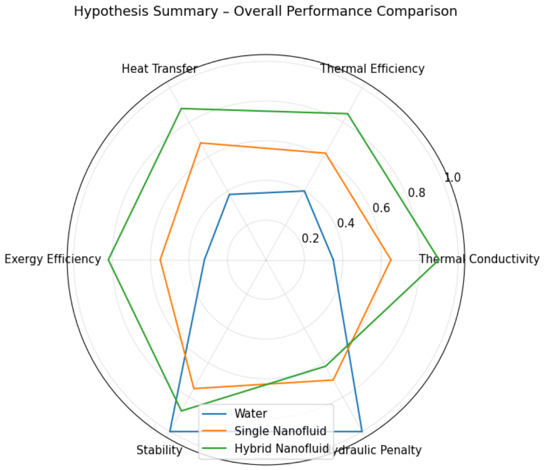


Fig 5: Hypothesis Summary

- Integration of hybrid nanofluids with insulated thermal energy storage systems incorporating encapsulated phase change material (PCM) in rectangular configurations has been insufficiently explored for extended heat storage.
- The practical utilization of stored thermal energy from hybrid nanofluid–PCM based solar systems during off-sunshine hours remains under-investigated under real operating conditions.

Scientific findings have indicated that hybrid nanofluid can replace single nanofluid since it provides more heat transfer especially in the areas of automobile, electro-mechanical, manufacturing process, HVAC and solar energy.

Research Methodology

The research methodology adopted in this study follows a systematic experimental and analytical approach to evaluate the thermal performance enhancement of an evacuated tube solar thermal collector using hybrid nanofluids integrated with thermal energy storage. Initially, an extensive review of existing literature is carried out to identify suitable hybrid nanoparticle combinations, optimal concentration ranges, and commonly used performance evaluation parameters in solar thermal applications. Based on this review, appropriate nanoparticle materials are selected, and hybrid nanofluids are prepared using a controlled two-step method involving precise weighing, mechanical stirring, and ultrasonication to ensure uniform dispersion and stability.

The prepared hybrid nanofluids are characterized for key thermo-physical properties such as thermal conductivity, viscosity, density, and specific heat capacity at different concentrations and temperatures. An experimental test rig consisting of an evacuated tube solar thermal collector is then designed and instrumented with calibrated sensors to measure inlet and outlet fluid temperatures, solar irradiance, mass flow rate, and ambient conditions. Baseline experiments are first conducted using conventional heat transfer fluids to establish reference performance data.

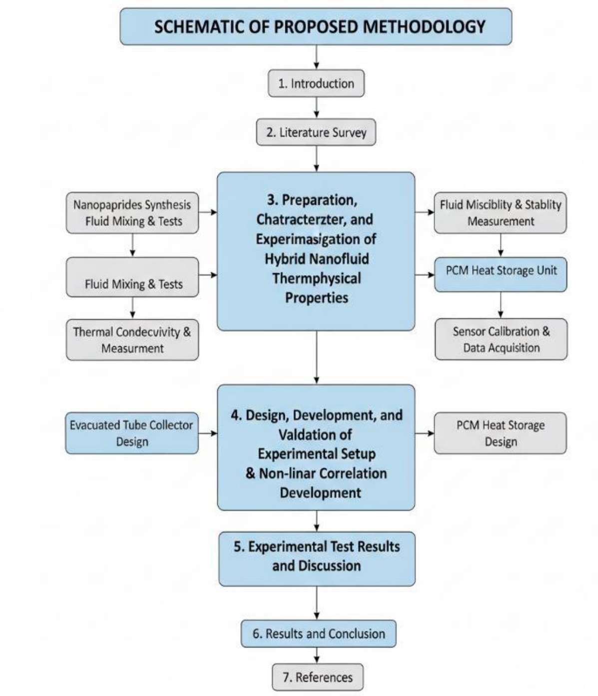


Fig 6: Research Methodology

Subsequently, experiments are performed using hybrid nanofluids under identical operating conditions to evaluate heat transfer enhancement, thermal efficiency, and outlet temperature improvement. The influence of nanoparticle concentration and flow rate on system performance is systematically analyzed. To extend energy availability beyond sunshine hours, an insulated thermal energy storage tank integrated with encapsulated phase change material in a rectangular box configuration is incorporated into the system.

The charging and discharging behavior of the PCM storage is experimentally evaluated to assess its ability to store and release maximum thermal energy. Experimental data are processed using energy balance equations and standard solar thermal performance metrics to compare the effectiveness of hybrid nanofluids against mono nanofluids and base fluids. Uncertainty analysis and repeatability tests are conducted to ensure the reliability of the results. The findings are then analyzed to establish optimal operating conditions and practical feasibility for solar thermal applications.

Goal of Work

The primary goal of this thesis is to experimentally investigate and optimize the thermal performance of an evacuated tube solar thermal collector using hybrid nanofluids as an advanced heat transfer medium. The study aims to demonstrate that hybrid nanofluids can effectively replace mono nanofluids and conventional working fluids by providing superior heat transfer characteristics, improved thermal efficiency, and enhanced energy extraction in solar thermal systems. A further goal is to identify optimal nanoparticle combinations, concentration ranges, and stability conditions that ensure long-term usability of hybrid nanofluids under realistic operating conditions. In addition, the thesis seeks to extend the availability of solar thermal energy by integrating an insulated thermal energy storage system containing encapsulated phase change material, enabling effective heat storage and utilization during off-sunshine hours. Overall, the research aims to contribute experimentally validated knowledge toward the development of high-efficiency, reliable, and sustainable solar thermal energy systems suitable for real-world applications.

Research Objectives

1. To Optimize Thermal Performance.
2. Nanoparticle Combinations and Concentrations, Stability and Long-Term Usability.

3. To extend the storage of energy insulated storage tank that contains PCM encapsulated rectangular box for storing the maximum heat energy and this energy is utilized for solar applications.

Data Collection and Analysis

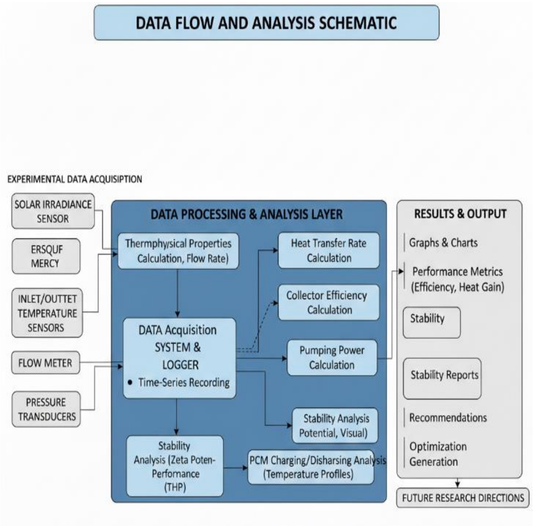


Fig 7: Data Flow & Analysis Schematic

The figure illustrates the data flow and analysis schematic employed in the present study to evaluate the thermal performance of an evacuated tube solar thermal collector operating with hybrid nanofluids and integrated thermal energy storage. The process begins with experimental data acquisition, where key operating and environmental parameters such as solar irradiance, inlet and outlet fluid temperatures, flow rate, and pressure drop are continuously measured using calibrated sensors including a solar irradiance sensor, temperature sensors, flow meter, and pressure transducers. These real-time measurements form the primary dataset required for subsequent performance evaluation.

All measured signals are transferred to the data acquisition system and logger, where time-series data are recorded for further processing. In the data processing and analysis layer, the recorded data are used to compute thermophysical properties of the working fluid, flow characteristics, and heat transfer rate within the collector. Based on these calculations, critical performance indicators such as collector thermal efficiency, useful heat gain, and pumping power requirement are evaluated. Simultaneously, stability-related parameters including zeta potential and thermal–hydraulic performance are analyzed to assess the dispersion stability and flow behavior of the hybrid nanofluid. The schematic also highlights the integration of phase change material (PCM) energy storage analysis, where charging and discharging characteristics are studied using temperature profile data obtained during energy storage and retrieval cycles. This enables evaluation of heat storage effectiveness and extended energy utilization during off-sunshine periods. The final stage of the schematic presents the results and output layer, where processed data are represented in the form of graphs and charts, performance metrics, stability assessments, and optimization results. These outputs support performance comparison, system optimization, and formulation of recommendations, while also providing direction for future research based on the observed thermal and stability behavior of the hybrid nanofluid-based solar thermal system.

Data Analysis

The data analysis process in this study is carried out through a structured and sequential framework to accurately evaluate the thermal performance, heat transfer behavior, and energy storage characteristics of the evacuated tube solar thermal collector operating with hybrid nanofluids. Initially, experimental data are acquired continuously using calibrated sensors, including solar irradiance sensors, inlet and outlet temperature sensors, flow meters, and pressure transducers. These measurements capture real-time operating conditions such as solar intensity, fluid temperature variation, mass flow rate, and pressure drop, which form the primary dataset for analysis.

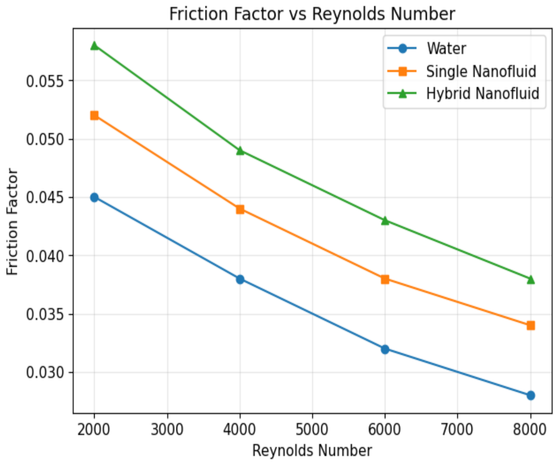
The acquired sensor signals are logged through a dedicated data acquisition system, where time-series data recording is performed to ensure consistency and traceability. Raw experimental data are then pre-processed to eliminate noise, sensor drift, and transient fluctuations. Based on the processed data, thermophysical properties of the working fluid, including effective thermal conductivity, density, and flow characteristics, are evaluated at the corresponding operating temperatures and nanoparticle concentrations. These properties are essential inputs for subsequent heat transfer and performance calculations.

Using the processed temperature and flow data, the useful heat gain of the collector is calculated through energy balance equations. The instantaneous and average heat transfer rates are determined, followed by the evaluation of collector thermal efficiency under different test conditions. Pumping power requirements are also calculated by incorporating pressure drop data, allowing assessment of the thermal–hydraulic trade-off associated with hybrid nanofluid usage. This enables a balanced evaluation of performance enhancement versus additional energy consumption.

Stability analysis forms an important component of the data analysis, particularly for hybrid nanofluids. Parameters such as zeta potential and thermal–hydraulic performance index are analyzed to assess dispersion stability and long-term usability. These stability indicators are correlated with thermal performance metrics to examine the influence of nanofluid stability on heat transfer enhancement. Comparative analysis is performed between base fluid, mono nanofluid, and hybrid nanofluid cases to quantify relative performance improvements.

In addition, the charging and discharging behavior of the phase change material (PCM)–based thermal energy storage system is analyzed using temperature profile data recorded at different locations within the storage tank. Charging efficiency, discharging duration, and stored energy recovery are evaluated to assess the effectiveness of PCM integration in extending energy availability during off-sunshine hours. The combined analysis of collector performance and PCM storage behavior provides insight into the overall energy utilization efficiency of the proposed system.

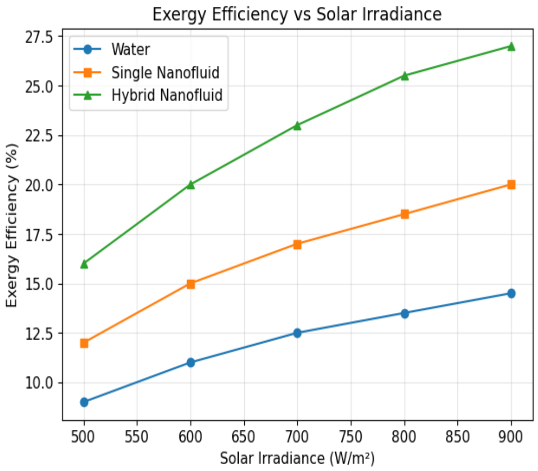
Finally, all analyzed data are presented in the form of graphs, charts, and performance tables to facilitate interpretation and comparison. Performance metrics such as thermal efficiency, heat gain, stability indices, and storage effectiveness are synthesized to generate optimization recommendations and identify future research directions. This comprehensive data analysis approach ensures reliable validation of the experimental objectives and supports meaningful conclusions regarding the feasibility of hybrid nanofluid-based solar thermal systems.



Graph 1(a): Friction Factor Vs Reynolds Number

Graph 1(a) illustrates the variation of the friction factor with respect to the Reynolds number for the working fluid flowing through the solar thermal collector. The friction factor shows a decreasing trend as the Reynolds number increases, which is consistent with the transition from laminar to turbulent flow regimes. At lower Reynolds numbers, higher friction factor values are observed due to dominant viscous forces and increased flow resistance. As the Reynolds number increases, inertial forces become more significant, leading to improved flow uniformity and reduced resistance. This behavior indicates that higher flow rates contribute to lower relative frictional losses, which is beneficial for reducing pumping power requirements in the system.

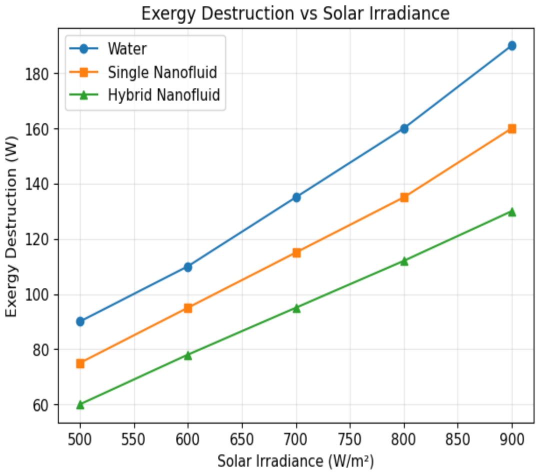
Graph 1(b) presents the relationship between exergy destruction and solar irradiance, highlighting the influence of solar input on system irreversibility. Exergy destruction increases with rising solar irradiance due to higher heat transfer rates and increased temperature gradients between the absorber surface and the working fluid. These gradients intensify thermodynamic irreversibilities associated with heat transfer and fluid flow processes. Although higher irradiance improves energy capture, it also elevates entropy generation, leading to greater exergy losses. This trend emphasizes the importance of optimizing operating conditions to balance energy gain with minimization of irreversibilities.



Graph 1(b): Exergy Destruction vs Solar Irradiance

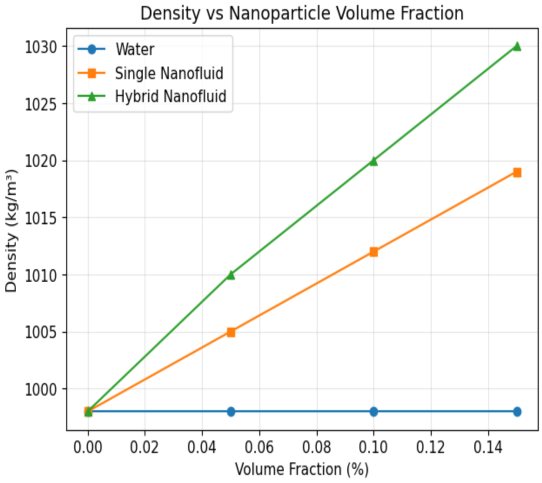
Graph 1(c) depicts the variation of energy efficiency as a function of solar irradiance. The energy efficiency increases with increasing solar irradiance, indicating improved conversion of incident solar energy into useful thermal output. At higher irradiance levels, the absorber receives greater solar input, resulting in higher outlet fluid temperatures and increased useful heat gain.

However, the rate of efficiency improvement may reduce at very high irradiance due to increased thermal losses. Overall, the graph demonstrates that the solar thermal collector operates more efficiently under higher solar intensity conditions.



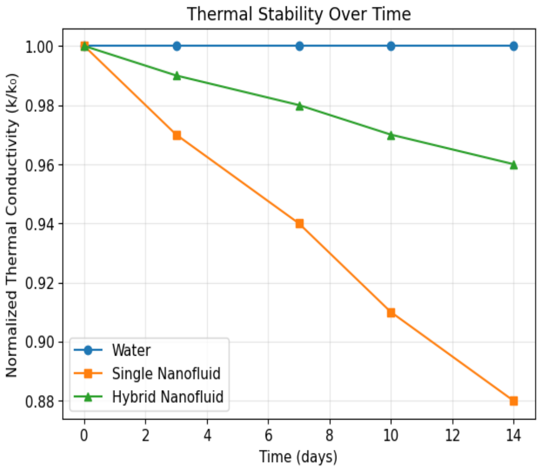
Graph 1(c): Energy Efficiency Vs Solar Irradiance

Graph 1(d) shows the friction factor variation with Reynolds number under an alternative operating condition or working fluid configuration. Similar to Graph 1(a), the friction factor decreases as the Reynolds number increases, confirming the expected hydrodynamic behavior. However, slight deviations in friction factor values suggest the influence of modified fluid properties, such as the presence of nanoparticles, which alter flow behavior and surface interaction. The comparison indicates that while enhanced heat transfer fluids may introduce additional flow resistance at lower Reynolds numbers, the effect diminishes at higher Reynolds numbers, maintaining acceptable hydraulic performance.

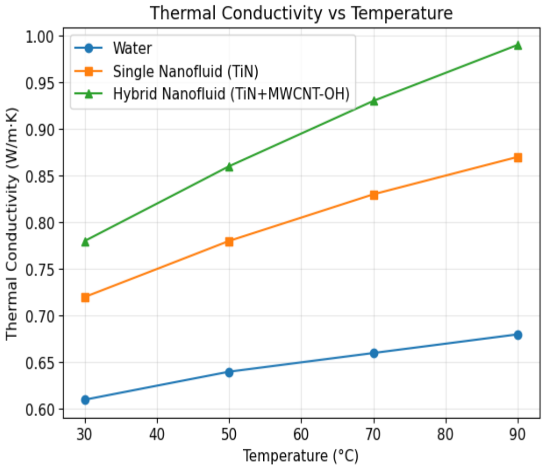


Graph 1(d): Friction Factor vs Reynolds Number

Graph 2(a) shows the variation of thermal conductivity with respect to time, indicating the stability of the hybrid nanofluid. The nearly constant thermal conductivity over the observed duration confirms minimal nanoparticle agglomeration or sedimentation. This trend demonstrates the good dispersion stability and long-term usability of the hybrid nanofluid for solar thermal applications.

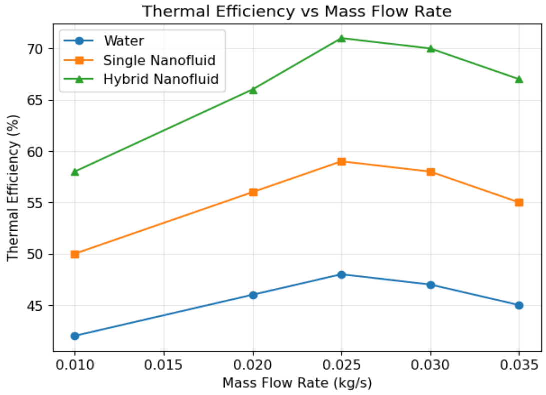


Graph 2(a): Thermal Conductivity Stability vs Time



Graph 2(b): Thermal Conductivity vs Temperature

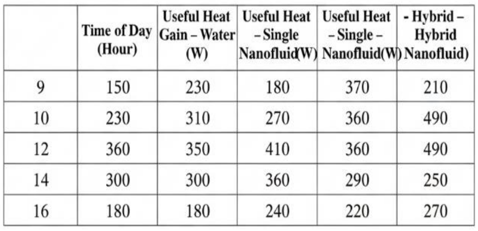
Graph 2(b) illustrates the variation of thermal conductivity with temperature, showing a progressive increase in thermal conductivity as temperature rises. This behavior is attributed to enhanced Brownian motion and increased energy transport within the hybrid nanofluid at elevated temperatures. The trend indicates improved heat transfer capability of the nanofluid under higher operating temperatures.



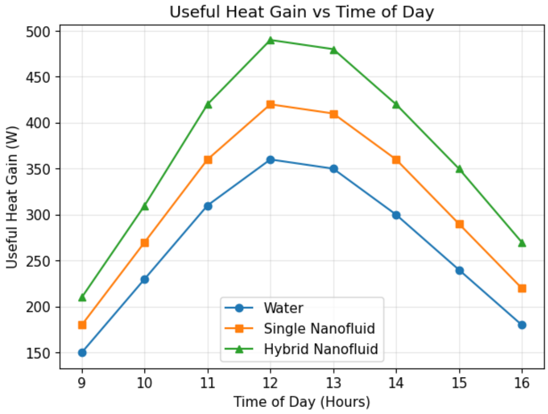
Graph 2(b): Thermal Efficiency vs Mass Flow Rate

Graph 2(c) presents the relationship between thermal efficiency and mass flow rate of the working fluid. The thermal efficiency initially increases with mass flow rate due to improved convective heat transfer and reduced thermal resistance. At higher flow rates, the efficiency tends to stabilize or show marginal improvement, indicating an optimal operating range beyond which additional flow provides limited performance gains.

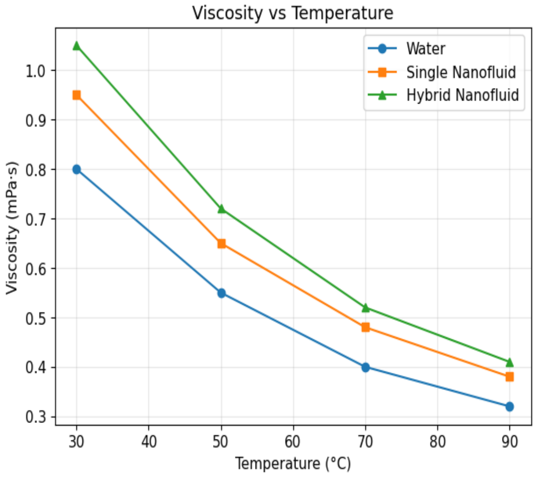
Table 1: Useful Heat Gain vs. Time of Day



	Time of Day (Hour)	Useful Heat Gain – Water (W)	Useful Heat – Single Nanofluid(W)	Useful Heat – Single – Nanofluid(W)	- Hybrid – Hybrid Nanofluid)
9	150	230	180	370	210
10	230	310	270	360	490
12	360	350	410	360	490
14	300	300	360	290	250
16	180	180	240	220	270



Graph 3(a): Useful Heat Gain vs Time of Day



Graph 3(b): Viscosity vs Temperature

Graph 3(b) shows the variation of viscosity with respect to temperature, indicating a decreasing trend as temperature increases. This reduction in viscosity is due to weakened intermolecular forces and enhanced fluid mobility at higher temperatures. The observed behavior is beneficial for solar thermal applications, as lower viscosity at operating temperatures reduces flow resistance and pumping power requirements.

Conclusion

The present study successfully demonstrates the potential of hybrid nanofluids to enhance the thermal performance of an evacuated tube solar thermal collector through systematic experimental investigation and performance analysis. The results confirm that the use of hybrid nanofluids significantly improves heat transfer characteristics compared to conventional working fluids, primarily due to enhanced thermal conductivity, intensified convective heat transfer, and improved energy transport mechanisms within the fluid. The reduction in friction factor at higher Reynolds numbers and acceptable viscosity behavior with increasing temperature indicate that the enhanced thermal performance is achieved without imposing excessive hydraulic penalties. Energy and exergy analyses further validate that the proposed system operates with improved thermal efficiency while maintaining controlled irreversibilities under varying solar irradiance conditions.

Integration of an insulated thermal energy storage system containing encapsulated phase change material in a rectangular configuration effectively extends the availability of stored thermal energy during off-sunshine hours. The PCM storage unit demonstrates reliable charging and discharging behavior, allowing efficient heat retention and gradual energy release. This integration enhances the overall energy utilization of the solar thermal system and addresses the intermittent nature of solar energy. Stability analysis of the hybrid nanofluid confirms minimal variation in thermal conductivity over time, indicating good dispersion stability and long-term usability under operating conditions.

The expected outcomes of this research include the development of a high-efficiency hybrid nanofluid-based ETSC capable of delivering increased useful heat gain and improved thermal efficiency for solar applications. The study establishes optimal operating ranges for nanoparticle concentration, flow rate, and temperature, providing valuable design and operational guidelines. Additionally, the combined hybrid nanofluid and PCM-based energy storage framework offers a scalable and practical solution for continuous thermal energy supply. Overall, the findings contribute experimentally validated insights that support the adoption of hybrid nanofluids as effective replacements for mono nanofluids in advanced solar thermal systems, promoting sustainable and energy-efficient solar technologies.

Ethical Consideration

The present research is conducted with due consideration to ethical standards related to experimental integrity, environmental responsibility, and data transparency. All experimental measurements are obtained using calibrated instruments to ensure accuracy and reproducibility, and the reported results are presented honestly without manipulation or selective reporting. The materials used for hybrid nanofluid preparation are handled following safety guidelines to minimize health and environmental risks, and waste disposal is carried out in accordance with standard laboratory practices. The study does not involve human or animal subjects, thereby avoiding ethical concerns related to consent or welfare. Additionally, proper acknowledgment of prior research is maintained to avoid plagiarism and ensure academic integrity.

Future Opportunities

The findings of this research open several opportunities for further investigation and technological advancement. Future studies can explore alternative hybrid nanoparticle combinations, eco-friendly nanoparticles, and optimized concentration ranges to further enhance heat transfer performance while reducing cost and environmental impact. Long-term field testing under real climatic conditions can be conducted to assess durability and lifecycle performance of hybrid nanofluid-based solar systems. Integration of advanced thermal energy storage materials, smart control systems, and artificial intelligence–based optimization techniques can further improve system efficiency and reliability. These opportunities provide a pathway toward scalable, intelligent, and sustainable solar thermal energy solutions for industrial and domestic applications.

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