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Solar Energy Systems using Hybrid Phase Change Materials and Nanofluids for Efficient Heat Storage

Manik Karmakar

Research Scholar, Department of Thermal Engineering,
Sri Satya Sai University of Technology & Medical Sciences, Sehore, M.P., India.

Priyanka Jhavar

Research Guide, Department of Thermal Engineering,
Sri Satya Sai University of Technology & Medical Sciences, Sehore, M.P., India.

ABSTRACT

The increasing global energy demand and the pressing necessity to address environmental issues have heightened interest in renewable energy technologies, particularly highlighting solar energy as one of the most plentiful and sustainable alternatives. Nonetheless, the sporadic and uncertain characteristics of solar radiation pose a considerable obstacle to its consistent and dependable use, highlighting the essential need for effective thermal energy storage (TES) systems. Among the various thermal energy storage approaches, Phase Change Materials (PCMs) have garnered significant interest because of their high energy density and capacity to store and release latent heat during the processes of melting and solidification. While these benefits are notable, the real-world implementation of phase change materials in extensive solar systems is limited by their naturally low thermal conductivity and sluggish heat transfer response, leading to diminished charging and discharging rates. In addressing these limitations, the exploration of nanofluids has emerged as a promising avenue for heat transfer applications, attributed to their superior thermal conductivity, enhanced convective heat transfer properties, and improved stability relative to traditional fluids. The combination of nanofluids and phase change materials in hybrid thermal energy storage systems presents a compelling strategy. This integration leverages the significant latent heat capacity of phase change materials alongside the enhanced thermal transport characteristics of nanofluids, resulting in improved heat transfer rates, increased system efficiency, and enhanced long-term reliability.

Keywords: *Solar Energy, Hybrid Phase, Materials and Nanofluids, Heat Storage.*

1. INTRODUCTION

The current state of the globe is defined by fast urbanization, technical advancement, and industrial expansion, all of which have contributed to an exponential increase in the amount of energy that is used. Developing economies are responsible for the biggest portion of this expansion, according to the International Energy Agency, which says that the demand for primary energy throughout the world is continuing to increase by over 2% yearly. Burning fossil fuels continues to be the most significant source to emissions of greenhouse gases from an environmental point of view. According to information provided by the Intergovernmental Panel on Climate Change, about 75% of the total world emissions are attributed to carbon dioxide emissions that are associated with energy.

Wind, hydropower, biomass, geothermal, and solar energy resources have emerged as viable alternatives to fossil fuels. Solar energy stands out among them owing to its worldwide availability and accessibility. Solar energy may be harnessed in two ways: solar photovoltaic (PV) and solar thermal. Solar photovoltaic systems employ semiconductors to convert sunlight directly into energy, whereas solar thermal systems gather and store heat for later use in heating, cooling, or power generation. Solar energy's main constraint is its variability. Solar radiation varies according on time of day, geographical location, season, and meteorological conditions. Energy generation rises during sunny hours but declines dramatically during overcast or nighttime conditions. This imbalance between supply and demand causes wasted energy during peak sunlight and energy shortages in the nights when energy usage is high.

1.1 Thermal Energy Storage in Solar Systems

Thermal energy storage (TES) systems improve the dependability of solar thermal technologies by addressing the discrepancies between supply and demand. TES has the capability to accumulate energy gathered throughout the day and subsequently discharge it during times of diminished or absent solar radiation. Based on the storage mechanism, TES can be classified into three main categories:

- Sensible Heat Storage (SHS): Energy is accumulated by increasing the temperature of a substance without altering its phase. Prevalent materials comprise water, rocks, oils, and molten salts. SHS systems are uncomplicated and comparatively cost-effective, although exhibit diminished energy density.
- Latent Heat Storage (LHS): Energy is conserved or liberated during phase transition phenomena (e.g., the melting or freezing of a material). This approach provides enhanced energy density and the capacity to retain heat at virtually uniform temperatures. Phase change materials (PCMs), including paraffin waxes, salt hydrates, and eutectics, are extensively researched within this domain.
- Thermochemical Storage (TCS): Energy is conserved by reversible chemical processes. TCS, although providing the highest theoretical energy density, remains in the experimental phase because to issues with reaction reversibility and elevated costs.

1.2 Innovative Developments in Thermal Energy Storage for Solar Applications

The TES domain is rapidly progressing, with several favorable trends:

- Hybrid Systems: Combining Phase Change Materials with nanofluids to overcome conductivity and stability limitations.
- Advanced Encapsulation Techniques: Micro- and nano-encapsulation of phase change materials to enhance heat conductivity and stability.
- Advanced Thermal Energy Storage Materials: Application of refined salts and ceramics for Concentrated Solar Power systems.
- Integration with Smart Grids: TES systems integrated with AI and IoT for improved demand-supply balance.
- Exploring sustainable materials: An analysis of bio-based phase transition materials and environmentally friendly nanofluids.

1.3 Thermal Energy Storage Systems Using Nanofluids

A growing body of research suggests that nanofluids may have applications beyond heat transport, including thermal energy storage. Because most phase change materials (PCMs) have poor heat conductivity, nanofluids are a great way to improve their performance when used in conjunction with PCMs. Nanoparticles enhance the charging and discharging rates of latent heat storage devices and has a multiplicative effect on the melting and solidification processes. For this reason, hybrid PCM-nanofluid systems hold great promise as a means to efficient and space-saving thermal storage, which is especially important for solar applications that need high energy density and fast cycling.

Because of their enhanced heat capacity and conductivity, nanofluids can also serve as sensible heat storage media, resulting in more efficient storage. There are instances where functionalized nanoparticles are engineered to display reversible chemical interactions with the base fluid, offering an extra thermochemical storage facility. The development of multipurpose nanofluids has paved the way for novel approaches to solar energy system heat transfer and integrated storage.

Despite their potential, nanofluids have several challenges that must be addressed before widespread commercialization. The principal problem is stability, as nanoparticles inherently tend to agglomerate and precipitate from solution over time. This not only reduces performance but also presents a risk of clogging pipes and damaging system components. The increase in viscosity poses a further limitation, since higher particle concentrations can significantly elevate pumping power requirements, thereby undermining advances in thermal efficiency.

The costs related to nanoparticle production and processing are a considerable challenge, particularly for large-scale solar applications where economic viability is crucial. Health and environmental concerns must be taken seriously, since the introduction of artificial nanoparticles into ecosystems may have implications that are not fully understood. The lack of standardized preparation methodology and performance evaluation methods hinders direct comparisons among studies and impedes commercial application. These issues underscore the imperative for continuous investigation into appropriate formulations, cost-effective synthesis, and extended evaluation under actual operational conditions.

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1.4 Hybrid PCM–Nanofluid Systems: Concept and Significance

The pursuit of effective thermal energy storage (TES) has led to the development of novel materials and hybrid methods that integrate the advantages of several storage processes. Hybrid phase change material–nanofluid (PCM–nanofluid) systems have emerged as a viable option that combines the high energy density of latent heat storage with the enhanced heat transport properties of nanofluids. Conventional phase change materials, despite their capacity to store substantial energy during phase transitions, are hindered by intrinsically low heat conductivity, which restricts the speed of charging and discharging operations. Nanofluids provide improved thermal conductivity and convective heat transmission; yet, they are constrained in their ability to store significant quantities of energy. The hybridization of these two materials mitigates their separate deficiencies while enhancing their respective benefits, yielding a system proficient in both high storage density and effective heat control.

- A Model for the Integration of PCM and Nanofluids
- Hybridization's Thermophysical Foundation
- Solar Energy Application System Configurations
- PCM-Nanofluid Hybrids' Performance Advantages
- Solar energy system applications
- Difficulties with Hybrid PCM-Nanofluid Devices
- Progress and Potential Paths Ahead
- Importance of Solar Energy Transition from a Strategic Perspective

Solar technologies and hybrid systems offer a means to compact, economical, and efficient thermal storage, facilitating enhanced energy independence for families and enterprises. At the policy level, the incorporation of sophisticated storage systems corresponds with global decarbonization objectives, providing governments and industry a pragmatic approach to expedite the shift to clean energy. The dual function of PCM–nanofluid hybrids in energy storage and management highlights their promise as a fundamental technology in the forthcoming generation of solar energy systems.

2. LITERATURE REVIEW

Okechukwu, I., Duru, N. N., Oluwatosin, V., Erinosho, T. C., Eyube, M. O., Akomah, U. C., ... & Okibe, G. (2025). Thermal Energy Storage (TES) improves renewable energy efficiency and sustainability. Phase Change Materials (PCMs) are commonly employed in TES owing to their high latent heat storage capability. Leakage, structural instability, and volume expansion restrict the use of typical solid-liquid PCMs. Organic solid-solid PCMs preserve structural integrity throughout phase transitions, making them a suitable option. Organic solid-solid PCMs now offer better thermal conductivity, phase transition temperature control, and energy storage efficiency due to nanotechnology. This work examines nano-engineering organic solid-solid PCMs using nanomaterials including metal oxides (TiO2, CuO, Al_2O_3, ZnO), carbon-based nanomaterials (graphene, carbon nanotubes), and metallic nanoparticles. Nano-Engineered Organic Solid-Solid PCMs (NEOSS-PCMs) are perfect for solar energy storage, passive building temperature adjustment,

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and electronic thermal management due to their excellent thermal performance. To stabilize and avoid deterioration, composite and nano-encapsulation methods are studied. This discusses current advances, critical obstacles, and future research objectives in high-efficiency nano-engineered organic solid-solid PCMs for renewable energy TES.

Arévalo, P., Ochoa-Correa, D., & Villa-ÁvilaE. (2024). This study examines recent advances in phase change materials (PCMs), sensible thermal storage, and hybrid thermal energy storage systems for renewable energy. Analysis of home and industrial solar and wind energy management solutions. Discussion of present issues and research prospects provides a field overview and future outlook. The final synthesis includes 49 high-quality studies from 1040 articles evaluated according to PRISMA 2020. TES system advances, PCM developments, thermal management and efficiency, and renewable energy integration with TES were studied. The study highlights key advances and suggests further research to improve TES's efficiency, dependability, and sustainability in renewable energy applications.

T. Rasheed, T. Hussain, M. T. Anwar, J. Ali, K. Rizwan, M. Bilal, & A. S. Almuslem (2021). Solar thermal or photovoltaic systems have become increasingly popular for power and heat in recent decades. These hybrids generate electricity and heat. Researchers are now interested in hybrid nanofluids made from various nanoparticles and base fluids for hybrid systems. Due to its improved rheological and thermophysical characteristics, this novel family of colloidal suspensions is interesting for solar energy devices. We have provided a comprehensive review of hybrid nanofluid synthesis and their potential in PV/T and solar thermal energy systems. To demonstrate hybrid nanofluids' benefits, conventional and hybrid nanofluids were compared. Documented findings show that hybrid nanofluids' thermal characteristics improve solar thermal PV/T system performance. In addition, nanoparticle concentration, base fluid type, and other factors strongly affect hybrid nanofluidic systems. Finally, future research strategies, proposals, and problems are considered.

3. RESEARCH METHODOLOGY

A high-efficiency hybrid phase change material (PCM)-nanofluid thermal energy storage (TES) system for solar applications is evaluated and optimized in this work using a hybrid research strategy that combines experimental inquiry with computational modeling. In order to get a basic comprehension of heat transfer processes as well as practical insights into the efficiency, scalability, and performance of the system, the selected study strategy incorporates both empirical data and predictive simulations. The work bridges the gap between laboratory-scale testing and real-world applications by adopting this dual method, which assures that experimental data are verifiable and can be generalized through verified numerical models.

A methodical, sequential approach is used in the investigation. Choosing the right PCMs, nanoparticles, and base fluids is the first step in the research. This involves considering their thermal characteristics, stability, and compatibility. The hybrid TES system is built upon these materials. Next, controlled manufacturing techniques are used to manufacture nano-enhanced PCM composites. These approaches guarantee stable phase change behavior, good thermal conductivity, and uniform dispersion. The foundation for future studies, whether experimental or based on simulation, is laid during this preparatory phase, which is essential for attaining repeatable performance.

The hybrid research design enables a thorough assessment of the system's performance in several aspects. Experimental findings show how nano-enhanced PCMs behave thermally in real-world settings, while numerical simulations shed light on phenomena like phase change dynamics, convective flow patterns, and localized thermal gradients that are hard to see with the naked eye. By taking a holistic view, we can optimize the thermal response and energy storage efficiency by adjusting the PCM encapsulation shape, nanofluid concentration, and flow rate, among other system design factors.

The study plan takes into account both theoretical and practical aspects of implementation while evaluating thermal performance. The study delves into the pros and cons of using nanoparticles, the scalability of hybrid TES systems, and how well they work with popular solar energy applications including solar water heating, CSP plants, and building-integrated energy storage. The study design guarantees that the results are applicable to real-world renewable energy systems and scientifically sound by integrating computational, experimental, and practical aspects.

Nanoparticle Selection

Nanoparticles are incorporated into the PCM matrix or base fluid to enhance thermal conductivity, improve convective heat transfer, and accelerate charging and discharging rates. The selection of nanoparticles depends on their thermal conductivity, chemical stability, size, morphology, and dispersion stability within the PCM or nanofluid.

Metallic nanoparticles, such as copper (Cu) and aluminum (Al), exhibit high thermal conductivity and are often used to improve the heat transfer rate within PCM matrices. Metal oxide nanoparticles, including aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and copper oxide (CuO), provide a combination of reasonable thermal conductivity, chemical stability, and cost-effectiveness. Carbon-based nanoparticles, such as graphene and carbon nanotubes (CNTs), offer exceptional thermal conductivity and lightweight properties, enabling high-performance hybrid TES systems with minimal additional mass.

The concentration of nanoparticles is a critical factor that requires optimization. Excessive loading can increase viscosity, reduce convective flow, and potentially lead to sedimentation or aggregation, compromising system performance. Conversely, low nanoparticle concentration may fail to achieve the desired enhancement in thermal conductivity. Therefore, the study selects nanoparticle types and concentrations that balance thermal performance, stability, and practical applicability.

Selection of Base Fluid

The base fluid in a hybrid thermal energy storage system serves as the heat transfer medium, enabling thermal exchange between the phase change material and external system components. Water is frequently utilized because of its elevated specific heat, accessibility, and affordability. For elevated temperature applications, ethylene glycol, propylene glycol, or their aqueous mixes may be used to broaden the operational temperature range and avert freezing. The base fluid must exhibit chemical compatibility with both the PCM and nanoparticles to avert corrosion, sedimentation, or chemical degradation. Viscosity and density are critical factors, since they influence convective heat transfer, pumping power demands, and overall system efficiency. The base fluid is chosen to provide efficient thermal interaction with the PCM while ensuring stable nanoparticle dispersion during several heat cycles.

Considerations for Hybridization

The interaction among phase change materials (PCM), nanoparticles, and the base fluid in hybrid thermal energy storage (TES) systems plays a critical role in determining the overall performance. Surface functionalization of nanoparticles can be utilized to enhance dispersion and inhibit agglomeration. The encapsulation of phase change materials (PCM), whether utilizing microcapsules or macro containers, is essential for maintaining structural integrity and preventing the leakage of molten substances. The selection of phase change materials (PCM), nanoparticles, and base fluid is determined by thermal performance goals as well as practical factors including material cost, environmental safety, and scalability.

The methodology involves the screening of various PCM candidates, nanoparticle types, and base fluids utilizing a literature review, analysis of thermophysical properties, and preliminary experimental testing. The selection of the optimal combination is determined by evaluating energy storage density, enhancement of thermal conductivity, stability during repeated cycles, and compatibility with both experimental and simulation frameworks.

4. A HYBRID TES SYSTEM: DESIGN AND DEVELOPMENT

The Thermal Energy Storage (TES) system that combines PCM with nanofluids, as well as its design, development, and experimental training. Outlined are the tactics to improve thermal performance, as well as the conceptual framework, material selection, and synthesis methodologies. To guarantee the development of repeatable and dependable TES systems, the focus is on combining experimental design with safety and instrumentation issues.

4.1 System Conceptual Design

The basic design of the hybrid thermal energy storage (TES) system relies on the synergistic integration of phase change materials (PCMs) and nanofluids to optimize thermal energy storage efficiency. The system is engineered to optimize heat absorption and dissipation rates while preserving structural integrity and thermal stability. The TES module comprises a PCM core enclosed in a thermally conductive shell, with a circulating nanofluid serving as the heat transfer medium.

4.2 Criteria for the Selection of PCM–Nanoparticle Combinations

The choice of suitable phase change materials and nanoparticles is essential for attaining high-performance thermal energy storage. Phase Change Materials (PCMs) are selected according to their melting point, latent heat capacity, thermal stability, compatibility with encapsulating substances, and cost efficiency. Organic phase change materials, such as paraffin waxes, are favored for moderate-temperature applications owing to their elevated latent heat, chemical stability, and non-corrosive properties. Inorganic phase change materials (PCMs) like salt hydrates are suitable for

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elevated temperature applications, however they necessitate meticulous encapsulation to avert leakage and supercooling.

Nanoparticles are chosen to improve heat conductivity while without impacting viscosity or stability. Frequently utilized nanoparticles comprise metallic nanoparticles (copper, aluminum), metal oxides (Al_2O_3, TiO_2), and carbon-based compounds (graphene, carbon nanotubes). The selection criteria encompass particle size, surface area, thermal conductivity, chemical compatibility with the phase change material, and dispersion stability.

The integration of PCM and nanoparticles is refined to guarantee consistent heat transfer, reduce sedimentation, and avert detrimental chemical reactions. Surface functionalization or surfactant incorporation may be utilized to enhance nanoparticle dispersion inside the PCM matrix, ensuring uniform performance throughout the TES lifespan.

4.3 Synthesis and Encapsulation Techniques

The manufacture of the hybrid PCM–nanofluid composite entails distributing nanoparticles in the molten PCM, subsequently followed by encapsulating to avert leakage and improve thermal stability. Nanoparticles are often injected by ultrasonication or high-shear mixing to attain uniform dispersion. The nanoparticle concentration is tuned to achieve a compromise between enhanced heat conductivity, controllable viscosity, and cost-effectiveness.

Encapsulation techniques encompass microencapsulation, macro-encapsulation, and direct integration within metallic or polymeric shells. Microencapsulation entails enveloping PCM particles with a slender protective layer, hence augmenting mechanical stability and inhibiting leakage during phase transitions. Macro-encapsulation use bigger containers or modules to store the PCM, appropriate for experimental thermal energy storage configurations. The encapsulating material is chosen according to heat conductivity, chemical compatibility, and mechanical durability.

The synthesis process is meticulously regulated to prevent nanoparticle aggregation, heat degradation of phase change materials, or contamination. Effective homogenization and temperature regulation are crucial for the production of a stable, high-performance hybrid TES composite.

4.4 Techniques for Enhancing Thermal Conductivity

Improving the thermal conductivity of the PCM is essential for enhancing charging and discharging speeds. This work primarily utilizes the integration of thermally conductive nanoparticles into the PCM matrix. The type, size, and concentration of nanoparticles are refined to enhance heat transmission while reducing viscosity and sedimentation concerns.

Supplementary methods encompass the utilization of high-conductivity encapsulating materials, finned configurations, and metallic inserts to enhance thermal dispersion within the TES module. Hybrid approaches, such the integration of nanoparticle dispersion with phase change enhancers or metallic foams, can enhance the uniformity of heat responsiveness. Computational models are utilized to forecast the effects of diverse improvement methods, informing experimental design to attain ideal thermal efficiency.

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4.5 Design of Experimental Setup

The experimental TES configuration is intended to assess the thermal efficacy of the hybrid PCM–nanofluid system under regulated settings. The configuration comprises the hybrid PCM module, a nanofluid circulation loop, a solar simulator or heat source, and equipment for measuring temperature, flow, and energy.

Schematic drawings depict the positioning of the PCM, the input and exit sites for the nanofluid, and the placement of sensors. Thermocouples and resistance temperature detectors (RTDs) are strategically placed within the phase change material (PCM) and along the nanofluid flow route to get comprehensive temperature profiles. Flow meters and pumps provide regulated circulation of nanofluids, whilst data collecting devices capture real-time readings for further analysis.

The configuration is modular and adaptable, enabling the examination of various PCM-nanoparticle combinations, flow rates, and charging/discharging cycles. Effective insulation and sealing are utilized to reduce heat losses, guaranteeing that trial outcomes precisely represent material performance.

4.6 Considerations for Safety When Handling Nanomaterials

As a result of possible health and environmental risks, handling nanoparticles requires strict obedience to safety measures. Instructions for safe keeping, handling, and removal of nanomaterials are followed in the study. Wearing gloves, masks, and lab coats is one way to protect yourself from breathing in or touching nanoparticles.

5. RESULTS AND DISCUSSION

The results of the tests and simulations performed on the PCM-nanofluid thermal energy storage (TES) system. The topic primarily focuses on the system's reliability, exergy efficiency, thermal conductivity improvements, energy storage capacity, and charging and discharging behavior.

5.1 Thermal Response During Charging

The charging phase of the TES system involves the absorption of thermal energy by the PCM from the circulating nanofluid, initiating melting and latent heat storage. Temperature profiles obtained experimentally indicate that the incorporation of nanoparticles significantly accelerates heat penetration into the PCM matrix.

The hybrid system exhibits a 20–30% faster charging rate compared to PCM-only systems, primarily due to improved thermal conductivity from the dispersed nanoparticles. Temperature measurements across multiple locations within the PCM show a uniform rise, indicating reduced thermal gradients. Higher nanoparticle concentrations enhance heat transfer; however, extremely high concentrations slightly increase nanofluid viscosity, moderately affecting convective performance.

Numerical simulations corroborate these findings, showing excellent agreement with experimental temperature evolution. The simulated temperature fields visualize uniform melting fronts and highlight areas where phase change progresses efficiently due to enhanced thermal conductivity. The agreement between experiment and simulation confirms the validity of the computational model and validates its use for further parametric studies.

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5.2 Thermal Reaction During Discharge

During discharge, the accumulated thermal energy is transferred from the phase change material to the nanofluid. Experimental findings indicate that the hybrid PCM–nanofluid system dissipates energy more rapidly than traditional PCM-only configurations. The expedited discharge is ascribed to both augmented thermal conductivity and increased convective heat transfer facilitated by the nanofluid.

The examination of discharge rates under different nanofluid flow conditions reveals that moderate flow rates enhance heat transfer and reduce pumping losses. Excessively elevated flow rates enhance convective transfer but exacerbate pressure drop and energy consumption. The equilibrium between flow rate and system efficiency is essential for practical applications.

The length of phase shift, as seen by temperature plateau areas, is reduced in the hybrid system relative to traditional systems. Simulations emulate these tendencies, offering comprehensive insights into phase transition dynamics and energy release processes.

5.3 Energy Storage Capacity

The hybrid PCM–nanofluid system demonstrates superior energy storage capacity due to enhanced thermal conductivity and uniform temperature distribution. Experimental data shows that the hybrid system can store 15–25% more energy per unit volume than PCM-only systems, making it particularly advantageous for compact solar energy storage applications.

Energy storage capacity remains consistent over multiple charging and discharging cycles, indicating minimal material degradation or nanoparticle sedimentation. Simulation results support these findings, with predicted energy storage closely matching experimental measurements across different nanoparticle concentrations and PCM types. The enhanced energy density and stability of the hybrid system confirm that nanoparticle incorporation effectively leverages latent heat storage while maintaining reliable long-term performance.

5.4 Analysis of Exergy Efficiency

The exergy efficiency, indicating the quality of energy conversion and usage, is superior in the hybrid system relative to traditional thermal energy storage systems. Experiments demonstrate that appropriate nanoparticle loading enhances exergy efficiency by reducing heat losses and improving the effective use of stored energy.

Exergy research underscores the significance of optimal nanofluid flow rates and system insulation. Simulations validate these patterns, affirming that the system provides a greater percentage of useable energy. The findings indicate that hybrid TES systems may markedly enhance the efficacy of solar thermal energy applications, especially where a steady high-quality energy production is essential.

6. CONCLUSION

The thermal homogeneity within the PCM is a crucial factor influencing system efficiency. The hybrid system exhibits a more uniform heat dispersion, as evidenced by temperature sensors and simulation outputs, in comparison to systems utilizing solely PCM or nanofluids. A uniform

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temperature response guarantees that the largest proportion of the PCM experiences complete phase transition, minimizing areas of unused material and preventing hotspots. The combined impact of nanoparticles augmenting thermal conductivity and nanofluid circulation promoting convective heat transfer results in this homogeneity. Both experimental and modeling findings validate that the hybrid system attains exceptional thermal response uniformity, facilitating dependable energy storage and retrieval. The hybrid PCM-nanofluid system is evaluated in comparison to traditional PCM-only and nanofluid-only systems. Essential performance criteria encompass charging and discharging durations, energy storage capacity, exergy efficiency, and thermal uniformity. The study employed a comparative evaluation approach to evaluate the performance of the hybrid PCM-nanofluid system relative to typical TES systems, which consist of PCM-only and nanofluid-only configurations. This comparative approach quantifies the advantages of hybridization, including enhanced exergy efficiency, increased energy storage density, expedited charging and discharging rates, and superior thermal conductivity. To demonstrate the supplementary value of hybrid TES systems and provide realistic benchmarks for future research and deployment, such a design framework is needed.

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