Nanofluid Thermal Storage System with Hybrid Phase Change Material for High-Efficiency Solar Energy Applications

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ABSTRACT

Solar power has become one of the most plentiful and sustainable energy sources, leading to heightened interest in renewable energy solutions. This interest arises from the increasing global demand for energy and the pressing necessity to tackle environmental issues. Conversely, effective thermal energy storage (TES) systems are crucial, as the intermittency and unpredictability of solar radiation provide a substantial obstacle to the consistent and reliable use of this energy source. Phase Change Materials (PCMs) have garnered significant attention in Thermal Energy Storage (TES) due to their high energy density and capacity to store and release latent heat during solidification and melting processes. This dissertation examines the systematic design, synthesis, and characterization of hybrid PCM-nanofluid thermal storage devices. The inquiry is conducted using experimental methods and numerical models. Thermophysical parameters, melting-solidification behavior, heat transport systems, and exergy efficiency are assessed under simulated sun conditions. This research significantly advances solar energy utilization for residential, commercial, and industrial applications by addressing the performance limitations of traditional thermal energy storage systems and offering valuable insights into scalable, cost-effective, and high-efficiency hybrid storage technologies.

Keywords: *Solar Energy, High-Efficiency, Nanofluid, Thermal Storage.*

1. Introduction

PCMs provide multiple advantages; however, their effectiveness is constrained by slow charging and discharging rates, attributed to insufficient heat transfer characteristics. Paraffin-based phase change materials (PCMs) generally demonstrate thermal conductivities between 0.2 and 0.3 W/m. This range is considerably below the required standards for efficient solar applications. Furthermore, ongoing thermal cycling can lead to deterioration and a reduction in performance. Addressing these limitations is crucial to ensure the viability of PCMs in high-efficiency systems. Phase change materials possess the ability to absorb or release latent heat during a phase transition, typically occurring between solid and liquid states. This feature allows for the storage of large amounts of thermal energy in a compact volume, making it appropriate for solar storage applications.

1.1 Essential Characteristics of Nanofluids

The efficacy of nanofluids is determined by many intrinsic features that set them apart from traditional fluids. Thermal conductivity is arguably the most essential attribute, as even minimal additions of nanoparticles can result in substantial improvements relative to the basic fluid. This is especially significant in solar collectors and storage systems, where effective heat transfer directly influences energy acquisition and consumption. The specific heat capacity is equally significant, as it affects the nanofluid's capacity to retain thermal energy. Although specific nanoparticles may diminish the specific heat of the mixture, meticulous manipulation of particle concentration and material selection might attain advantageous equilibria between conductivity and capacity. Viscosity is a critical quality to consider, since elevated viscosity can increase pumping power demands and diminish overall system efficiency. The stability of the nanofluid is crucial; nanoparticles can agglomerate due to van der Waals forces, resulting in sedimentation and diminished performance over time. To address this, surface functionalization, surfactants, or sophisticated synthetic techniques are frequently utilized. The optical features of nanofluids, especially their capacity to directly absorb sun energy, render them exceptionally appealing for solar thermal applications. By customizing the particle type and size distribution, nanofluids can function concurrently as heat transfer fluids and volumetric solar absorbers, thereby obviating the necessity for distinct absorber surfaces.

1.2 Improving Thermal Conductivity using Nanofluids

In the 1990s, Choi created the concept of nanofluids, which are synthetic fluids that include water, ethylene glycol, or oils as bases and disseminate nanoparticles (1-100 nm) throughout. Because of their large surface area and quantum effects, nanoparticles have better thermal characteristics than bulk materials. They improve thermal stability, heat transfer rates, and thermal conductivity when distributed in fluids.

Research conducted in 2022 by Olfian et al. suggests that solar collectors, storage tanks, and heat exchangers can all benefit from the use of nanofluids to improve the efficiency of heat transmission. Problems with particle aggregation, increased viscosity, expense, and long-term durability continue to prevent these materials' widespread use. Despite the widespread recognition of PCMs' promise, recent research has demonstrated that hybridization can actually improve their performance.

1.3 Thermal Storage Systems Integrating Phase Change Materials and Nanofluids

Recent research indicates that hybrid thermal storage systems integrating nanotechnology with phase change materials (PCMs) are advantageous. Researchers have dramatically improved thermal conductivity and charging/discharging speeds by dispersing nanoparticles in phase change materials (PCMs) or incorporating PCM capsules into nanofluids.

Improved thermal conduction (due to nanofluids) and latent heat retention capacity (phase change materials) collaborate in these systems. Studies have shown that including small amounts of nanoparticles into PCM composites, from 1 to 5 weight percent, can enhance thermal conductivity by two to three times without significantly affecting latent heat capacity. Hybrid systems can substantially decrease solar TES charging periods and enhance storage round-trip efficiency. Hybrid PCM-nanofluid systems are optimal for cost-effective, high-efficiency solar applications such as CSP facilities due to the elevated temperatures and the requirement for rapid heat transfer.

Phase Change Materials (PCMs) are categorized into three primary classifications:

- Organic phase change materials: paraffin waxes and fatty acids. They have excellent chemical stability and congruent melting, although exhibit limited heat conductivity.
- Inorganic phase change materials: salt hydrates and metallic alloys. These have elevated latent heat capacity but encounter challenges such as supercooling, phase segregation, and corrosion.
- Eutectic phase change materials (PCMs) are mixtures of organic and inorganic compounds engineered to attain designated melting points.

1.4 Solar Applications for Thermal Energy Storage

A method that allows for the retention of surplus heat energy for subsequent utilization is thermal energy storage (TES). To bridge the gap between solar power generation and consumer demand, thermal energy storage (TES) is an essential component. Sunlight, the time of day, and weather are only a few of the environmental variables that greatly affect the variability of solar energy, in contrast to conventional fossil fuel power plants. Without a dependable storage mechanism, solar systems are severely limited in their effectiveness. According to Hussein (2023), TES improves the dependability of solar systems by connecting the ever-changing energy supply with the constant demand. It is possible to collect and store excess thermal energy during the sun's peak hours. This energy can be released at night or when it's cloudy, ensuring that heat or power is always available. The total efficiency and commercial and industrial profitability of solar systems are both enhanced by their versatility.

1.5 Thermal Energy Storage in Residential Solar Heating

TES is extensively utilized in solar water heating systems (SWHs) inside both residential and commercial settings. The predominant method employed is sensible heat storage utilizing insulated water tanks. Water is a cost-effective and efficient medium for thermal energy storage, capable of maintaining heat for several hours.

Advanced latent heat storage systems utilizing phase change materials (PCMs) are increasingly favored for their compact design and capacity to retain substantial quantities of heat at stable temperatures. Incorporating PCM-filled capsules into solar water heaters can substantially prolong hot water availability during evenings, hence diminishing need on supplementary energy or gas heaters. In structures, TES is utilized in solar-powered heating and cooling systems. TES-equipped air-conditioning systems utilizing PCMs might diminish peak energy demand by reallocating cooling loads to off-peak periods, thus improving grid stability.

1.6 Obstacles in TES Implementation

Notwithstanding its significance, the application of TES encounters numerous obstacles:

- Material Constraints: Insufficient thermal conductivity in phase change materials, corrosion in molten salts, and deterioration in thermochemical substances.
- Economic Obstacles: Elevated initial expenditures and absence of extensive commercialization in developing markets.
- Design Considerations: Requirement for small, scalable, and readily integrable systems.
- Ecological Risks: Certain PCMs and nanomaterials may present environmental hazards if inadequately controlled.
- Deficiencies in Policy and Infrastructure: Absence of robust regulatory frameworks and incentives in numerous developing nations.

2. Summary of Solar Thermal Energy Storage

Solar energy is a plentiful, renewable, and sustainable resource capable of fulfilling a substantial share of world energy requirements. The intrinsic intermittency of solar radiation—resulting from diurnal cycles, meteorological variations, and seasonal changes—represents a significant obstacle to its consistent and dependable application. Thermal energy storage (TES) has become a pivotal technique to address intermittency, enabling the capture of solar energy during peak irradiance for subsequent utilization when sunlight is not present. Thermal Energy Storage (TES) not only augments the reliability of solar thermal systems but also optimizes energy management, efficiency, and overall system performance. In recent decades, thermal energy storage (TES) has emerged as a fundamental component in the design of solar water heaters, concentrated solar power (CSP) plants, and building-integrated thermal management systems.

In solar thermal systems, thermal energy storage is essential for reconciling energy supply with demand. In CSP facilities, energy harvested during peak solar hours can be stored for electricity generation during evening or overcast conditions, hence enhancing the plant's capacity factor and dispatchability. In solar water heating systems, thermal energy storage guarantees a consistent supply of hot water during nighttime or overcast conditions. In residential and commercial construction, TES can fulfill heating, cooling, and hot water needs, diminishing reliance on traditional energy sources and decreasing overall energy expenses. These advantages underscore the strategic significance of TES in facilitating efficient, dependable, and sustainable solar energy consumption.

Recent progress in TES research has concentrated on improving system efficacy via material innovation, hybrid configurations, and sophisticated heat transfer methods. Conventional TES systems encountered constraints like inadequate thermal conductivity, inconsistent temperature distribution, and sluggish charging and discharging rates, especially in latent heat storage utilizing phase change materials (PCMs). To address these issues, researchers have investigated the incorporation of nanomaterials, encapsulation methods, and hybrid systems that amalgamate several storage strategies. Hybrid thermal energy storage solutions, particularly those integrating phase change materials with nanofluids, provide substantial enhancements in heat transfer efficiency, energy density, and temperature regulation, hence broadening the practical utility of thermal energy storage in various solar energy systems.

2.1 Time-Held, Sensitive, Latent, and Thermochemical Thermal Storage Techniques

To solve the problem of insufficient energy supply in solar power applications, thermal energy storage (TES) devices are crucial. It is common practice to classify traditional TES techniques as either sensible heat storage, latent heat storage, or thermochemical storage. System design, performance, and application suitability are impacted by the distinct advantages and limits of each technique, which employs different physical or chemical principles to store and release energy. Advanced TES approaches, including hybrid systems that mix nanofluids with phase change materials (PCMs), can be evaluated with an understanding of these conventional storage methods.

Efficient Heat Retention

One of the most common and easy ways to implement TES is via sensible heat storage. The goal of this method is to store energy in a medium by heating it to a point where a phase change does not occur. Fluids, oils, rocks, concrete, and molten salts are some of the most common sensible heat storage materials. Because of its non-toxicity, low cost, and high specific heat capacity, water is a preferred alternative. Because of their higher thermal energy density compared to water, molten salts, such as sodium nitrate and potassium nitrate mixes, are commonly utilized in large-scale concentrated solar power (CSP) systems.

Storing Energy Substances

A material's latent heat can be stored by taking use of the high energy density associated with its phase transitions. In order to store energy, engineers create phase change materials (PCMs). These materials may undergo solid-liquid or liquid-solid transitions and can absorb or release large amounts of latent heat while maintaining a practically constant temperature. Latent heat storage systems are able to maintain stable temperatures and store more energy per unit volume than sensible heat systems because of this feature. Solar water heating and thermal management in buildings are two examples of applications that benefit greatly from their ability to regulate temperature.

Thermochemical Storage

Thermochemical energy storage represents a novel method for energy retention, utilizing reversible chemical reactions to capture and store energy efficiently. This approach utilizes thermal energy to facilitate an endothermic reaction in the charging phase, effectively storing energy within chemical bonds. During discharging, the reverse exothermic reaction emits energy. Thermochemical storage provides exceptional energy density and minimal heat loss over extended periods, rendering it highly suitable for long-term energy storage solutions. Typical thermochemical reactions include metal oxides, salts, and sorption processes, exemplified by hydration–dehydration cycles.

Comparative Analysis and Utilizations

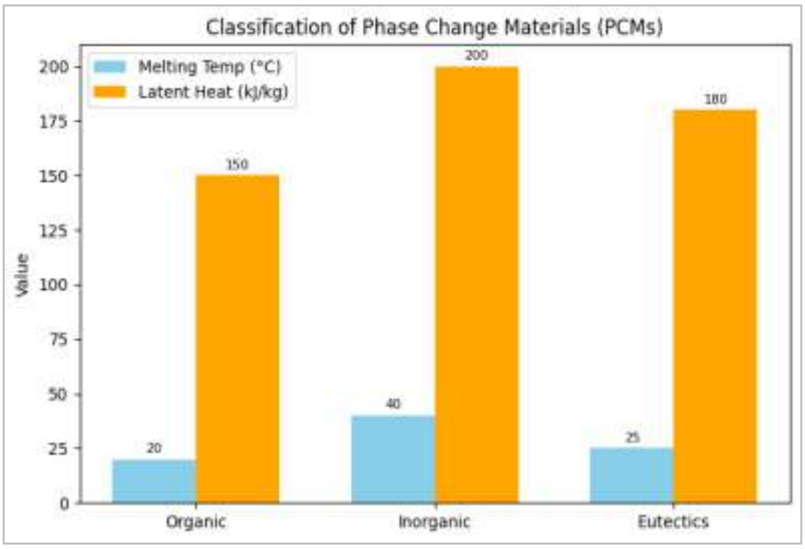
The selection of the TES method is contingent upon application specifications, energy density requirements, financial limitations, and operational factors. Sensible heat storage is extensively utilized in residential hot water systems, solar ponds, and medium-scale concentrated solar power plants because of its straightforwardness and affordability. Latent heat storage is preferred in scenarios where space-efficient storage and temperature control are essential, including building heating, cooling, and solar water heating systems. Thermochemical storage, characterized by its elevated energy density and capacity for long-term storage, is appropriate for industrial applications and concentrated solar power (CSP) facilities necessitating multi-day or seasonal storage, despite low commercialization.

2.2 Classification, Thermophysical Properties, and Challenges of Phase Change Materials

Phase change materials (PCMs) are substances that store and release thermal energy during phase transitions, usually between solid and liquid states. In contrast to sensible heat storage, which involves energy storage through the elevation of a medium's temperature, phase change materials (PCMs) absorb or release substantial latent heat at approximately constant temperatures. This distinctive property facilitates compact and effective thermal energy storage, rendering phase change materials highly appealing for solar energy applications, including solar water heating, building climate management, and concentrated solar power systems.

Classification of Phase Change Materials

Phase Change Materials (PCMs) are categorized into three primary types: organic, inorganic, and eutectic substances. Organic phase change materials encompass paraffin waxes, fatty acids, and polymers. Paraffin waxes are extensively utilized organic phase change materials (PCMs) owing to their chemical stability, non-corrosive properties, accessibility, and consistent phase transition characteristics. Fatty acids, including stearic and palmitic acids, provide comparable benefits, characterized by elevated latent heat capacity and an extensive range of melting points. Organic phase change materials (PCMs) are beneficial as they do not experience phase separation and often exhibit minimal supercooling tendencies. Nonetheless, their thermal conductivity is comparatively low, potentially impeding heat transfer rates, necessitating encapsulation or improvement of thermal conductivity for practical uses.



Classification of Phase Change Materials (PCMs)

The categorization of phase change materials (PCMs) through a comparison of their mean melting temperatures and latent heat values. Organic phase change materials (PCMs), including paraffins and fatty acids, generally function at moderate temperatures, exhibiting commendable stability yet possessing modest thermal conductivity. Inorganic phase change materials, such as salt hydrates and metals, provide superior latent heat and thermal conductivity; yet, they may encounter challenges such as supercooling and corrosion. Eutectics, comprising organic and inorganic constituents, offer optimized performance with adjustable melting points, rendering them adaptable options for solar thermal energy storage.

Issues in PCM-Based Thermal Storage

While they offer notable benefits, PCMs encounter various obstacles that impact their effectiveness and market viability. The limitation of low thermal conductivity is particularly significant for organic phase change materials, as it impedes the rates of energy charging and discharging. Strategies to improve thermal conductivity involve the addition of nanoparticles, metal foams, or graphite matrices.

The phenomenon of supercooling, characterized by the postponement of solidification beneath the melting point, presents a significant challenge, particularly concerning inorganic phase change materials. Supercooling may hinder effective energy release and diminish system efficiency. Methods like seeding, the use of nucleating agents, or the formation of composites are employed to address this issue.

Phase segregation takes place when the components of a PCM separate during the processes of melting and solidification, leading to a decrease in energy storage capacity as time progresses. Encapsulation, blending, and composite formation effectively tackle segregation challenges. The importance of chemical stability cannot be overstated, as any decomposition or interaction with containment materials may result in material loss and a decline in performance.

The escape of melted phase change material from the storage unit presents a significant issue in latent heat storage systems. Effective design of encapsulation or containment is crucial to avoid leakage and ensure the integrity of the system. Furthermore, the expense associated with phase change materials, especially those that are high-performance or customized, may pose a significant barrier to widespread implementation. Environmental factors, including non-toxicity and recyclability, are becoming increasingly significant for sustainable TES systems.

Utilization of Phase Change Materials in Solar Thermal Energy Storage Systems

Phase Change Materials (PCMs) are extensively utilized in solar thermal energy storage owing to their elevated energy density and thermal stability. In solar water heating systems, phase change materials (PCMs) assist in sustaining a stable water temperature amid fluctuating solar radiation. In building-integrated thermal energy storage, phase change materials modulate indoor temperatures, thereby diminishing energy requirements for heating or cooling. CSP systems utilize PCMs in molten salt or composite forms to efficiently store energy for power generation during periods without sunlight. Phase Change Materials (PCMs) can be integrated with heat transfer fluids or nanofluids to create hybrid Thermal Energy Storage (TES) systems, which mitigate thermal conductivity constraints and enhance overall system efficiency.

2.3 Mechanisms of Heat Transfer in Hybrid Systems

The efficacy of hybrid thermal energy storage (TES) systems, especially those including phase change materials (PCMs) and nanofluids, is fundamentally contingent upon the governing heat transfer mechanisms. Effective energy storage and retrieval in these systems necessitate a comprehensive understanding of conduction, convection, and, in certain instances, radiation phenomena. The collaborative interaction of phase change materials and nanofluids improves heat transfer, facilitating swift charging and discharging, consistent temperature distribution, and elevated system efficiency. This section analyzes the heat transfer mechanisms that regulate hybrid thermal energy storage systems and their consequences for system design and efficacy.

Thermal Energy Storage Through Conduction in Mixed-Mode Systems

Conduction serves as the primary mechanism for heat transfer within the phase change material component of hybrid thermal energy storage systems. In conventional phase change materials, the restricted thermal conductivity limits the rate of heat transfer into the storage medium, leading to temperature gradients that hinder the melting and solidification processes. The integration of nanoparticles within the phase change material (PCM) improves thermal conductivity, reduces thermal resistance, and promotes a more consistent temperature distribution. Metallic nanoparticles, carbon-based materials, and high-conductivity oxides are commonly utilized to enhance conductive heat transfer within the PCM matrix. The effectiveness of conduction in hybrid systems depends on the intrinsic thermal conductivity of the nano-enhanced phase change material, as well as the design and geometry of the storage unit.

Natural Convection and Convection-Related Effects

When PCMs melt, convection—and especially spontaneous convection—is a key heat transport mechanism. Enhanced thermal mixing and heat distribution are brought about by buoyancy-driven flows that are generated as the PCM melts due to density differences between the liquid and solid phases. Further modification of convective behavior can be achieved by dispersing nanoparticles in the PCM, which alters viscosity and local density gradients. An essential mechanism in hybrid systems involving nanofluid circulation around or within the PCM is forced convection. The nanofluid improves charging and discharging rates by acting as a heat transfer medium, quickly transferring thermal energy to or from the PCM. Consideration of flow dynamics, concentration of nanoparticles, and characteristics of nanofluids is essential for optimizing convective heat transfer. A decrease in convective efficiency and an increase in pumping power requirements can result from an increase in viscosity caused by an excess of nanoparticle loading. Inadequate loading, on the other hand, can prevent the targeted improvement in thermal conductivity from material. When designing hybrid TES systems, it is common practice to use computational fluid dynamics (CFD) models of forced and natural convection to better understand the distribution of temperatures, heat flux, and flow patterns under different operating situations.

Phase Transition and Latent Heat Transfer

Phase change materials (PCMs) store energy at constant temperature through latent heat transfer during melting and solidification. Nanofluids and phase change materials (PCMs) ensure effective latent heat absorption and release in hybrid TES systems. Nanoparticles increase thermal conductivity, speeding heat transmission into the phase change material during melting and energy release during solidification. This synergy reduces charging and discharging times, temperature gradients, and system efficiency. PCM shape, nanoparticle dispersion, initial temperature gradients, and boundary conditions affect hybrid system phase change dynamics. Poor heat transfer may cause non-uniform melting or localized warming, reducing latent heat use. Superior latent heat transmission and homogenous phase transition are achieved with enclosed PCM architectures, finned modules, and composite nano-PCM topologies.

3. Research Methodology

The research strategy revolves around experimental investigation. By combining encapsulated PCM with circulating nanofluids, a laboratory-scale TES module is created and built. Accurate monitoring of temperature, heat flow, and phase change progression is employed to assess charging and discharging performance under regulated thermal inputs using a solar simulator or solar collector. System behavior may be characterized in depth under multiple operating settings, such as variable amounts of solar irradiation, concentrations of nanoparticles, and flow rates, using this experimental setup. Accurate, repeatable, and directly comparable with theoretical predictions are the thermal performance parameters that have been measured, including energy storage capacity, charging/discharging rates, and temperature response, thanks to the experimental design.

The experimental part of the hybrid TES system is augmented by a powerful computational modeling framework that mimics fluid dynamics, phase shift, and heat transfer. Applications like ANSYS Fluent, COMSOL Multiphysics, and MATLAB are utilized to solve the governing equations for latent heat transfer, convection in the nanofluid, and conduction in the PCM. The models take into consideration the impacts of nanoparticles on thermal conductivity, viscosity, and specific heat, as well as boundary conditions that are comparable to those in actual operating settings. The accuracy and dependability of the model are ensured by repeatedly validating the simulation results against experimental data.

3.1 Validation Methodology

The validation process commences with the establishment of uniform experimental and simulated settings. The TES module geometry, PCM and nanofluid characteristics, flow rates, boundary conditions, and thermal loading remain consistent in both methodologies. The material properties acquired via characterisation techniques (DSC, TGA, thermal conductivity, viscosity) serve as input parameters for the simulation, guaranteeing that the numerical model appropriately represents the real system.

Rectifying Inconsistencies

Discrepancies between experimental and simulation results may occur owing to several variables, such as inadequate insulation, sensor errors, unaccounted heat losses, or assumptions within the simulation model (e.g., uniform nanoparticle distribution or idealized boundary conditions). Recognizing and rectifying these anomalies is a crucial component of the validation process. Modifications may encompass enhancing mesh resolution, revising material property inputs, integrating supplementary heat loss mechanisms, or advancing experimental measurement methodologies. Iterative comparison and refinement guarantee alignment between experimental and numerical data, hence improving model reliability.

Value of Validation

Validation ensures that the numerical model can accurately forecast hybrid TES system performance under different nanoparticle concentrations, PCM types, flow rates, and thermal stresses. Simulations can be used for parametric investigations, sensitivity analysis, and design optimization without extensive experimental trials. Validated models enable scale-up studies, allowing designers to estimate bigger TES module performance in practical solar energy systems.

3.2 Methodological Limitations

The methodology utilized in this study aims to thoroughly assess the performance of the hybrid PCM–nanofluid thermal energy storage (TES) system, although certain intrinsic limits must be recognized. Comprehending these limitations is essential for effectively interpreting results, evaluating the generalizability of findings, and directing future research. This section addresses the principal methodological constraints associated with material selection, experimental configuration, characterization, numerical modeling, and scalability issues.

Limitations on the Experimental Setup

Even though the trial setup was made to allow for precise and controlled measurements, it does have some built-in flaws. For instance, using a solar simulator for testing can be done again and again, but it can't exactly copy the changing brightness, spectral distribution, and environmental conditions of real sunlight. Also, flaws in the insulation and heat loss to the environment can cause small differences between what was seen and what should have happened in terms of thermal performance. The lab TES module is also small, and applying the results to larger systems or industrial uses might not fully take into account things like flow distribution, temperature stratification, and the difficulties of integrating the whole system. The accuracy of the experimental data is also affected by the limits of the instruments used. Thermocouples and resistance temperature monitors can give very accurate readings, but depending on where they are placed, they might not pick up on small changes or localized temperature gradients in the PCM matrix. Flow measurement tools might introduce small errors in the speed of nanofluids, which could change estimates of heat transfer.

4. Conclusion

This paper summarizes the dissertation by summarizing principal findings, emphasizing the research contributions, analyzing theoretical and practical consequences, acknowledging limits, and proposing avenues for further research. The emphasis is on assessing the efficacy of the hybrid PCM–nanofluid thermal energy storage (TES) system and its applicability in practical solar energy scenarios. The study effectively created and assessed a hybrid PCM–nanofluid thermal energy storage system aimed at improving solar energy storage efficiency. Experimental findings indicated that the integration of nanoparticles markedly enhanced the thermal conductivity of the phase change material, leading to expedited charging and discharging rates. The hybrid system exhibited a thermal response that was 20–30% faster than typical PCM-only systems, enhanced energy storage capacity by 15–25%, and showcased higher thermal uniformity.

The exergy efficiency analysis demonstrated that the hybrid system provided a greater share of usable energy during discharge, underscoring its efficacy in practical applications. Parametric analyses revealed that the correct concentration of nanoparticles, selection of phase change materials, and flow rate were essential for enhancing system performance while reducing viscosity and sedimentation effects.

References

1. Alqahtani, A. A., Sharma, A., Kedia, A., Mohanavel, V., Thirugnanasambandham, T., Mohana Krishnan, A., Yunus Khan, T. M., Gnanasekaran, L., & Ayyar, M. (2025). Influences of myristic acid and magnetic hybrid nanofluid embedded with heat recovery system latent heat and thermal performance of solar based HVAC. *Applied Thermal Engineering*, *279*, 127568. https://doi.org/10.1016/j.applthermaleng.2025.127568.
2. Diao, Y., Qi, N., Wang, Z., Zhao, Y., Chen, C., & Wang, Z. (2021). Thermal performance analysis of a solar air collection–cascade storage system integrated with micro-heat pipe arrays. *Solar Energy*, *224*, 1271–1290. https://doi.org/10.1016/j.solener.2021.06.071.
3. Essa, M. A., Amer, A., Mostafa, M. T., & Farahat, M. (2021). Enhancing the Power Conversion of Photovoltaic Systems with Metallic Porous Media and Phase Change Material. *The Egyptian International Journal of Engineering Sciences and Technology*, *36*(3), 72–80.
4. Kandeal, A. W., El-Shafai, N. M., Abdo, M. R., Thakur, A. K., El-Mehasseb, I. M., Maher, I., Rashad, M., Kabeel, A. E., Yang, N., & Sharshir, S. W. (2021). Improved thermo-economic performance of solar desalination via copper chips, nanofluid, and nano-based phase change material. *Solar Energy*, *224*, 1313–1325. https://doi.org/10.1016/j.solener.2021.06.085.

5. Li, J., Shi, C., Lai, X., Huang, L., Zhang, X., & Liu, P. (2025). Experimental study on performance of rectangular groove phase change thermal storage system with pressure-enhanced contact melting. *Case Studies in Thermal Engineering*, 107025.
6. Olfian, H., Mousavi Ajarostaghi, S. S., Ebrahimnataj, M., Farhadi, M., & Arıcı, M. (2022). On the thermal performance of evacuated tube solar collector integrated with phase change material. *Sustainable Energy Technologies and Assessments*, *53*, 102437. https://doi.org/10.1016/j.seta.2022.102437.
7. Praveen Kumar, K., Khedkar, R., Sharma, P., Elavarasan, R. M., Paramasivam, P., Wanatasanappan, V. V., & Dhanasekaran, S. (2024). Artificial intelligence-assisted characterization and optimization of red mud-based nanofluids for high-efficiency direct solar thermal absorption. *Case Studies in Thermal Engineering*, *54*, 104087. https://doi.org/10.1016/j.csite.2024.104087.
8. Shahid, H., Hussain, A., Ali, I., Ali, H. M., Bilal, A. S. S., & Munir, M. U. (2025). A hybrid thermal management phase change material based pin-fin heat sinks under forced convection. *International Communications in Heat and Mass Transfer*, *160*, 108004. https://doi.org/10.1016/j.icheatmasstransfer.2024.108004.
9. Shan, K., Luo, Q., Yun, P., Huang, L., Huang, K., Cao, B., Tang, B., & Jiang, H. (2023). All-day working photovoltaic cooling system for simultaneous generation of water and electricity by latent heat recycling. *Chemical Engineering Journal*, *457*, 141283.
10. Shin, Y., Ham, J., Boldoo, T., & Cho, H. (2020). Magnetic effect on the enhancement of photo-thermal energy conversion efficiency of MWCNT/Fe3O4 hybrid nanofluid. *Solar Energy Materials and Solar Cells*, *215*, 110635. https://doi.org/10.1016/j.solmat.2020.110635.
11. Shon, J., Kim, H., & Lee, K. (2014). Improved heat storage rate for an automobile coolant waste heat recovery system using phase-change material in a fin–tube heat exchanger. *Applied Energy*, *113*, 680–689. https://doi.org/10.1016/j.apenergy.2013.07.049.
12. Tafavogh, M., & Zahedi, A. (2021). Design and production of a novel encapsulated nano phase change materials to improve thermal efficiency of a quintuple renewable geothermal/hydro/biomass/solar/wind hybrid system. *Renewable Energy*, *169*, 358–378. https://doi.org/10.1016/j.renene.2020.12.118.
13. Venkatakrishnan, P., & Palanisamy, P. (2023). A state-of-the-art review on advancements in phase change material encapsulation techniques for electronics cooling. *Physica Scripta*, *98*(11), 112001.