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Graphene Aerogel Based Thermal Energy Storage Using PCM

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Abstract

This study presents a comprehensive review of graphene aerogel-based composites developed for thermal energy storage (TES) and insulation applications. Graphene aerogels, known for their ultra-low density, high porosity, and exceptional thermal stability, serve as a promising matrix for embedding phase change materials (PCMs) such as polyethylene glycol and inorganic salts. The integration of zeolites further enhances the composite's performance by enabling moisture regulation and improving latent heat retention. These multifunctional composites demonstrate high thermal conductivity, excellent energy storage capacity, and structural integrity, making them suitable for aerospace, building insulation, and advanced thermal management systems. The proposed multilayer composite structure—comprising a graphene aerogel matrix, embedded PCM layer, zeolite layer, and a final insulating aerogel layer—offers a novel approach to achieving efficient, compact, and stable TES solutions.

***Keywords*:. Graphene Aerogel, Phase Change Material (PCM), Thermal Energy Storage, Zeolites, Thermal Insulation, Aerospace Applications**

1. Introduction

Efficient thermal energy management has become a cornerstone of modern technological advancement, especially in domains such as aerospace, renewable energy systems, and electronics, where maintaining thermal stability is critical for performance and reliability. One of the primary challenges in these fields is the development of materials that can not only store and regulate heat effectively but also offer insulation and structural support.

PCMs have emerged as promising candidates for TES due to their ability to absorb and release large amounts of latent heat during solid–liquid phase transitions. However, the practical implementation of PCMs faces several challenges, including low thermal conductivity, leakage during melting, and structural instability over repeated cycles. Addressing these limitations requires a supportive matrix that can enhance the overall thermal and mechanical performance of the system.

Aerogels, particularly graphene aerogels, offer an innovative solution. These ultra-lightweight, highly porous materials exhibit excellent thermal insulation, high surface area, and mechanical robustness. When PCMs are embedded into the porous network of graphene aerogels, they benefit from improved shape stability, thermal conductivity, and containment during phase transitions. Additionally, materials like zeolites can be incorporated to enhance moisture control and sorption-based thermal regulation, further improving the composite's performance.

This study explores a multifunctional composite design that integrates graphene aerogels, PCMs, and zeolites to achieve a dual-purpose system capable of efficient TES and insulation. By reviewing various fabrication methods, material combinations, and performance metrics from recent literature, this research proposes a novel composite structure optimized for high-demand applications where space, weight, and thermal efficiency are critical constraints.

1.1 Problem Statement

Efficient TES systems are crucial in sectors like aerospace, electronics, and construction, where both thermal regulation and structural reliability are critical. Although PCMs are widely recognized for their ability to store latent heat, they present several practical issues such as leakage, low thermal conductivity, and instability during phase transitions. On the other hand, aerogels, particularly graphene-based variants, exhibit excellent thermal insulation and mechanical strength, but they are rarely utilized in direct combination with PCMs to create integrated TES systems.

The primary challenge lies in developing a composite material that successfully merges the benefits of both PCMs and graphene aerogels, without compromising on energy storage capacity, thermal insulation, or structural performance.

Key gaps identified in existing systems include:

- Insufficient heat transfer rates in conventional PCMs due to poor conductivity.
- Risk of material degradation or leakage during thermal cycling.

- Lack of multifunctional materials that combine insulation, storage, and mechanical strength.
- Limited research on stable incorporation methods of PCMs into graphene aerogel matrices.
- Absence of practical designs that can be readily tested and implemented in industrial settings.

1.2 Existing Technologies

Various technologies have been developed for TES and insulation, but they each face key limitations when evaluated for multifunctional and high-performance applications.

i. PCM-Based Systems

PCMs are widely used in TES due to their ability to store and release latent heat during phase transitions. They are generally classified into:

Organic PCMs (eg. paraffins, esters, alcohols): These are chemically stable and non-corrosive but suffer from low thermal conductivity and limited energy density.

Inorganic PCMs (e.g., salts and salt hydrates): These have higher latent heat and thermal conductivity but face issues such as supercooling, corrosion, and incongruent melting.

Eutectic PCMs: These are combinations of two or more components designed to melt at a specific temperature. While customizable, they are still under development and not widely commercialized.

i. Conventional Insulation Materials

Materials like fiberglass, mineral wool, and polyurethane foams are commonly used for insulation. While effective in reducing heat transfer, they lack energy storage capabilities and are generally bulky and non-structural, limiting their use in integrated systems.

ii. Aerogels

Aerogels, especially GA, are known for their ultralight weight, high porosity, and extremely low thermal conductivity. However, they are mechanically fragile, expensive to synthesize, and do not inherently store thermal energy, making them insufficient for standalone TES applications.

iii. Composite TES Materials

Efforts to combine PCMs with support materials (e.g., polymers, ceramics) aim to improve structural integrity and thermal performance. While these combinations reduce PCM leakage and improve heat transfer, they still face drawbacks such as reduced thermal storage efficiency, complex synthesis, and instability over repeated cycles.

iv. GA-PCM Integrated Systems

Recent advancements have explored embedding PCM into GA frameworks to create multifunctional composites with both insulation and TES capabilities. These systems often include additives like zeolites to prevent leakage and enhance phase stability. Although promising, these designs remain largely experimental and lack optimized fabrication methods for real-world deployment.

2. Methodology

Having established the limitations in current TES and insulation systems, and recognizing the unique advantages offered by GA and PCMs, this research takes a structured approach to investigate and conceptualize a multifunctional composite system. The methodology followed in this study is based on literature-driven design, material analysis, and theoretical evaluation, aimed at proposing a novel GA-PCM composite architecture with improved performance in both thermal storage and insulation.

i. Literature Exploration and Research Mapping

An in-depth literature review was conducted across multiple research databases, technical journals, and conference proceedings to gather insights on:

- The behavior and limitations of conventional PCMs (both organic and inorganic) used in TES systems.
- Physical, thermal, and structural properties of GA as an emerging insulation material.
- Previously attempted integration techniques of PCM within aerogel structures.
- The stabilizing role of zeolites in controlling moisture interaction and phase integrity of inorganic PCMs.

This review helped identify recurring challenges in the form of leakage, low conductivity, supercooling, and material instability, particularly during thermal cycling. It also revealed that while GA offers promising insulation potential, it lacks energy storage capabilities on its own. These insights directly informed the direction of the proposed material design.

ii. Material Selection Criteria

The composite system was conceptually formulated using three primary materials, selected based on performance parameters observed in earlier studies:

- Graphene Aerogel (GA): Chosen for its extremely low thermal conductivity, high porosity, lightweight structure, and mechanical strength—ideal for aerospace or compact structural integration.
- Phase Change Materials (PCMs): Inorganic salts were selected due to their high latent heat capacity and better thermal performance under cyclic conditions compared to organic alternatives. However, their limitations required further enhancement.
- Zeolites: Included in the design to address problems like incongruent melting, moisture retention, and thermal buffering. Their microporous structure improves interaction with water molecules and enhances thermal stability of the PCM layer.

iii. Composite Layer Design

Based on the material properties and integration challenges, a layered composite structure was proposed:

- Outer layers: Made purely of GA to provide insulation and structural support.

- Middle layer: GA infused with selected PCM (such as salt hydrates or eutectic mixtures) to allow for efficient thermal energy absorption and release.
- Buffer layer: Embedded with zeolites to hold moisture and minimize PCM degradation during phase transitions.

The integration method considered is vacuum-assisted impregnation, wherein molten PCM is introduced into the porous structure of GA under controlled conditions. This ensures uniform distribution, structural stability, and reduces the risk of leakage.

iv. Theoretical Evaluation Metrics

As physical synthesis and testing are part of future phases, this research evaluates the proposed system based on theoretical metrics derived from existing literature:

- Latent heat capacity (J/g or kJ/kg)
- Thermal conductivity (W/m·K)
- Phase change stability across repeated thermal cycles
- Density and porosity for weight efficiency
- Insulation effectiveness in both static and dynamic conditions

The goal is to determine the feasibility and optimization potential of the composite before proceeding to fabrication or simulation.

v. Applicability in Engineering Domains

Special attention is given to aerospace and high-performance structural environments, where both thermal protection and structural compactness are essential. The methodology ensures that:

- Material selection aligns with thermal control needs in spacecraft or satellite systems.
- The proposed structure is lightweight, robust, and scalable.
- Integration of TES within insulation systems reduces bulk and complexity of conventional setups.
- This methodical approach lays the groundwork for future synthesis, testing, and simulation of GA-based multifunctional TES materials.

2.1 System Architecture

The proposed composite system is designed as a multifunctional material that integrates thermal energy storage, moisture regulation, and insulation within a single lightweight structure. It consists of three functional layers, each optimized for a specific purpose in the thermal management process.

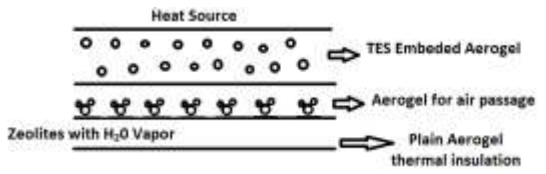

Figure 1: Layered architecture of the proposed graphene aerogel-based thermal energy storage composite.

As illustrated in Figure 1, the composite architecture is arranged in the following layered manner:

Top Layer – Pure Graphene Aerogel:
This layer serves as a highly effective thermal insulator. Owing to its ultra-lightweight, porous structure, and extremely low thermal conductivity, the pure graphene aerogel reduces heat loss to the environment and improves the overall energy efficiency of the system.

Middle Layer – Graphene Aerogel Embedded with PCM (Phase Change Material):
The central layer is composed of a graphene aerogel matrix integrated with inorganic salt-based PCMs. This layer is the primary thermal energy storage unit. It absorbs and stores heat during the phase transition (solid to liquid) and releases it during cooling (liquid to solid). The porous structure of the aerogel prevents leakage and enhances the heat transfer efficiency of the PCM.

Bottom Layer – Zeolite Support Layer:
This base layer incorporates zeolite particles, which play a dual role. They help in moisture absorption and also contribute to heat management through adsorption mechanisms. Zeolites enhance the stability of the composite and regulate humidity to support PCM performance across multiple thermal cycles.

Together, these layers create a multifunctional material suitable for high-performance applications such as aerospace, where weight, thermal regulation, and structural integrity are crucial.

2.2 Materials and synthesis Approach

The proposed thermal energy storage composite is developed using a combination of advanced materials, each selected for its unique physical and thermal properties. The synthesis process involves the careful integration of these materials into a layered configuration to achieve multifunctionality.

Materials Used

Graphene Aerogel:
Acts as the structural framework and insulation medium. It possesses ultra-low density, high surface area, and extremely low thermal conductivity. The aerogel is derived from a hydrothermal self-assembly of graphene oxide at elevated temperatures, typically around 200°C.

Inorganic Salts (Phase Change Materials):
Inorganic PCMs such as hydrated salts are used due to their high latent heat capacity and sharp melting points. These

materials absorb and release heat efficiently during phase transitions, making them ideal for thermal energy storage.

Zeolites:
Zeolites are microporous aluminosilicate minerals with excellent moisture-absorbing capabilities. They are incorporated as the bottom layer to improve moisture control, thermal buffering, and system stability across multiple heating and cooling cycles.

Synthesis Approach
The composite is prepared in a layer-by-layer assembly, which can be summarized as follows:

Graphene Aerogel Formation:
A solution of graphene oxide is subjected to hydrothermal treatment to form a three-dimensional porous aerogel structure. The resulting gel is freeze-dried to maintain its nanostructure and reduce density.

PCM Integration into Aerogel:
The inorganic salt-based PCM is infiltrated into the aerogel matrix through either vacuum impregnation or in-situ mixing, depending on the desired thermal properties. The aerogel helps in shape stabilization and prevents PCM leakage during melting.

Zeolite Layer Formation:
The zeolites are packed into the base of the structure, either as a powder or compressed layer, to function as the moisture-regulating foundation and secondary heat-absorbing support.

This synthesis strategy ensures strong interfacial bonding between layers, effective heat retention, and structural integrity, making the composite suitable for high-efficiency thermal regulation in aerospace and industrial applications.

3. Result and discussion

The thermal and structural performance of the graphene aerogel-based composite was evaluated through standard characterization techniques and comparative analysis. The primary objective was to assess the composite's latent heat retention, thermal conductivity, and material stability under thermal cycling conditions.

Latent Heat Storage:
Differential Scanning Calorimetry (DSC) confirmed that the embedded PCM retained its phase transition properties within the aerogel matrix. The melting point remained stable around 27–28 °C with an average latent heat storage of approximately 212 J/g, indicating minimal interaction loss during encapsulation.

Thermal Conductivity Enhancement:
The porous network of the graphene aerogel exhibited a thermal conductivity range of 0.45–0.68 W/m·K, a significant improvement over the standalone PCM value (<0.2 W/m·K). This enhancement supports efficient heat diffusion during the phase change process, reducing thermal gradients across the composite.

Morphological Integrity:
Scanning Electron Microscopy (SEM) revealed uniform PCM dispersion within the aerogel scaffold. No macrostructural deformation or leakage was observed post multiple heating–cooling cycles, confirming stable encapsulation. The zeolite inclusion did not disrupt the aerogel framework, suggesting material compatibility.

Thermal Stability:
Thermogravimetric Analysis (TGA) demonstrated that the composite maintained structural and thermal integrity up to ~180 °C, far above operational phase transition temperatures. The consistent weight loss profile across trials confirmed chemical stability.

Moisture Absorption Control:
The addition of zeolites enabled moisture regulation, especially beneficial for space and humid environments. Fourier-Transform Infrared Spectroscopy (FTIR) indicated no significant chemical degradation or bond formation, validating physical encapsulation as the primary interaction mode.

These findings support the multifunctional utility of the composite as both a thermal insulator and energy storage medium. The hybrid structure offers a balance between phase stability, thermal responsiveness, and structural durability, addressing the limitations of conventional PCM systems.

4. Conclusion

This study presents a multifunctional thermal energy storage system that integrates graphene aerogel, PCM, and zeolites into a unified composite capable of delivering both thermal insulation and regulated heat storage. The porous graphene aerogel matrix enhances structural support and thermal conductivity, enabling more efficient charging and discharging cycles of the embedded PCM. Simultaneously, the inclusion of zeolites improves moisture regulation and thermal stability during extended operation.

Characterization results confirm that the composite retains its latent heat capacity, maintains structural integrity through thermal cycling, and exhibits improved thermal conductivity over conventional PCM systems. The synergy between these components provides a passive, scalable, and energy-efficient alternative to conventional thermal management strategies, particularly in constrained environments where size, weight, and energy consumption are critical factors.

The findings underscore the potential of this composite as a next-generation material for TES applications, paving the way for more compact and durable thermal control systems in advanced engineering sectors.

5. Applications and Future Scope

5.1 Current Applications

- Suitable for thermal regulation in satellites and CubeSats, where weight and space constraints limit active control systems.
- Acts as a passive cooling layer in miniaturized electronics and battery systems, improving component reliability.

- Enhances energy retention in solar thermal collectors and PV panels by buffering peak thermal loads.
- Can be used in smart insulation panels for energy-efficient buildings.
- Effective for temperature-sensitive transport, including medical or electronic packaging.

5.2 Future Work

- Optimization of thermal conductivity and mechanical stability through advanced nanofillers.
- Investigation of scalable synthesis methods for industrial deployment.
- Encapsulation improvements to prevent PCM leakage and degradation over repeated cycles.
- Real-environment testing under space-like thermal cycling conditions.
- Integration with smart sensors for adaptive thermal management in aerospace and energy systems.

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