ENHANCED THERMAL CONDUCTIVITY AND LATENT HEAT STORAGE CHARACTERISTICS OF PARAFFIN–EXPANDED GRAPHITE COMPOSITE PHASE CHANGE MATERIALS FOR THERMAL ENERGY STORAGE APPLICATIONS

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PROBLEM STATEMENT

Phase Change Materials (PCMs), particularly paraffin wax, have gained significant attention for latent heat thermal energy storage (LHTES) applications due to their high latent heat capacity, chemical stability, non-toxicity, and suitable melting temperature. However, pure paraffin suffers from **very low thermal conductivity (approximately 0.2–0.4 W/m·K)**, which results in slow heat charging and discharging rates, poor heat transfer efficiency, and prolonged thermal response times. These drawbacks limit its practical implementation in solar thermal systems, electronic cooling, waste heat recovery, and building energy management. To overcome these limitations, thermally conductive additives such as expanded graphite (EG) can be incorporated into paraffin to form a composite PCM. Although expanded graphite significantly enhances thermal conductivity, excessive EG content may reduce latent heat storage capacity due to displacement of the PCM. Therefore, there is a need to investigate and optimize the thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composites to achieve an optimal balance between improved heat transfer and sufficient energy storage capacity.

OBJECTIVES

The main objective of this work is to investigate the thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as a phase change material.

The specific objectives are:

1. To prepare paraffin/expanded graphite composite phase change materials with different expanded graphite weight fractions.
2. To evaluate the effect of expanded graphite on the thermal conductivity of paraffin composites.
3. To determine the latent heat storage capacity and phase change temperature of the composite PCM using thermal analysis techniques.
4. To analyze the charging and discharging performance of the composite under thermal cycling conditions.
5. To study the thermal stability and reliability of the composite PCM for repeated heating and cooling cycles.
6. To identify the optimum expanded graphite concentration that provides enhanced thermal conductivity while maintaining high latent heat storage capacity.
7. To assess the suitability of paraffin/expanded graphite composite PCM for thermal energy storage applications such as solar energy systems,

electronic thermal management, and waste heat recovery.

ABSTRACT

Latent Heat Thermal Energy Storage (LHTES) systems using Phase Change Materials (PCMs) have emerged as an efficient solution for improving energy conservation and thermal management in various engineering applications. Paraffin wax is one of the most widely used organic PCMs due to its high latent heat capacity, chemical stability, non-toxicity, and negligible supercooling. However, its practical application is limited by its inherently low thermal conductivity, which results in slow charging and discharging rates. To overcome this limitation, expanded graphite (EG) is incorporated into paraffin to form a composite PCM with enhanced thermal performance. This study investigates the thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite (Paraffin/EG) composites. Composite samples with different EG weight fractions are prepared using a melt blending technique to achieve uniform dispersion of graphite within the paraffin matrix. The thermal conductivity of the composites is evaluated using a transient thermal analysis method, while the phase change behavior, melting temperature, freezing temperature, and latent heat are characterized using Differential Scanning Calorimetry (DSC). The thermal stability and microstructural characteristics of the composites are also examined to assess their suitability for long-term thermal energy storage applications. The experimental results demonstrate that the addition of expanded graphite significantly enhances the thermal conductivity of paraffin, enabling faster heat transfer during melting and solidification processes. Although a slight reduction in latent heat storage capacity is observed with increasing EG content due to the replacement of active PCM volume, the composites retain high energy storage capability while exhibiting improved thermal response. Furthermore, the Paraffin/EG composites show excellent thermal reliability, structural stability, and repeatable phase change performance over multiple thermal cycles. The enhanced thermal conductivity and stable latent heat storage characteristics make Paraffin/Expanded Graphite composites promising materials for thermal energy storage applications, including solar energy systems, electronic device cooling, battery thermal management, waste heat recovery, and building energy conservation. The findings of this study provide valuable insights into the design and optimization of high-performance composite phase change materials for efficient thermal energy storage systems.

INTRODUCTION

Thermal Energy Storage (TES) systems play a significant role in improving energy efficiency and reducing dependence on conventional energy sources. Among various TES technologies, **Latent Heat Thermal Energy Storage (LHTES)** has attracted considerable attention due to its ability to store and release large amounts of thermal energy during the phase transition of a **Phase Change Material (PCM)** at nearly constant temperature. Paraffin wax is one of the most widely used organic PCMs because of its high latent heat capacity, chemical stability, non-corrosive nature, negligible supercooling, and long-term reliability. However, its practical application is limited by its inherently **low thermal conductivity**, which results in slow charging (melting) and discharging (solidification) rates, thereby reducing the overall thermal performance of TES systems.

To overcome this limitation, researchers have focused on enhancing the thermal conductivity of paraffin by incorporating highly conductive additives. **Expanded Graphite (EG)** has emerged as one of the most promising thermal conductivity enhancers due to its lightweight structure, porous network, excellent thermal conductivity, high surface area, chemical inertness, and compatibility with paraffin. The porous structure of expanded graphite effectively absorbs molten paraffin through capillary action, preventing leakage during phase transition while simultaneously creating continuous heat transfer pathways within the composite material.

The **Paraffin/Expanded Graphite (Paraffin/EG) composite PCM** combines the excellent latent heat storage capability of paraffin with the superior thermal conductivity of expanded graphite. This synergistic combination significantly enhances the heat transfer rate, shortens melting and solidification times, and improves the thermal response of the storage system without causing a substantial reduction in latent heat capacity. Consequently, Paraffin/EG composites are considered suitable for applications such as solar thermal energy storage, building thermal management, waste heat recovery, battery thermal management, electronic cooling, and industrial heat storage systems.

The thermal performance of a Paraffin/Expanded Graphite composite depends on several factors, including the weight fraction of expanded graphite, composite preparation method, porosity, density, and the interaction between paraffin and graphite. Increasing the EG content generally enhances thermal conductivity, but excessive graphite loading may reduce the latent heat storage capacity because part of the PCM volume is replaced by the conductive filler. Therefore, an optimal balance between thermal conductivity enhancement and latent heat retention is essential for achieving maximum TES performance.

This study investigates the **thermal conductivity and latent heat thermal energy storage characteristics of Paraffin/Expanded Graphite composite phase change materials**. The research focuses on evaluating the influence of expanded graphite concentration on thermal conductivity, melting and freezing behavior, latent heat storage capacity, thermal cycling stability, and overall energy storage performance. The findings provide valuable insights into the development of high-performance composite PCMs for efficient thermal energy storage applications, contributing to sustainable energy utilization and improved thermal management technologies.

LITERATURE REVIEW

Phase Change Materials (PCMs) have gained significant attention as efficient thermal energy storage (TES) materials due to their ability to store and release large amounts of latent heat during phase transition. Among the available PCMs, paraffin wax is one of the most widely used because of its high latent heat, chemical stability, non-corrosive nature, and low cost. However, its practical application is limited by its inherently low thermal conductivity (approximately 0.2–0.4 W/m·K), which results in slow charging and discharging rates. To overcome this limitation, researchers have incorporated highly conductive materials such as expanded graphite (EG) into paraffin to improve heat transfer performance while maintaining high energy storage capacity.

Zhang et al. (2019) investigated paraffin/expanded graphite composite PCMs prepared through vacuum impregnation. Their study demonstrated that the addition of expanded graphite significantly increased the thermal conductivity of paraffin by several times without causing substantial reduction in latent heat. The porous structure of expanded graphite effectively absorbed molten paraffin and prevented leakage during phase transition, making the composite suitable for practical thermal energy storage applications.

Li et al. (2020) evaluated the influence of different expanded graphite weight fractions on the thermal performance of paraffin composites. The experimental results showed that thermal conductivity increased almost linearly with increasing EG content, whereas latent heat slightly decreased due to the reduced proportion of paraffin. The study concluded that an optimum EG concentration provides a balance between enhanced heat transfer and sufficient energy storage capacity.

Huang et al. (2021) investigated the thermal cycling stability of paraffin/expanded graphite composites over hundreds of heating and cooling cycles. The composite PCM exhibited excellent structural stability with negligible degradation in latent heat and phase change temperature after repeated thermal cycling. These findings confirmed that expanded graphite not only improves thermal conductivity but also enhances the long-term reliability of composite PCMs.

Chen et al. (2022) explored the microstructural characteristics of paraffin/expanded graphite composites using Scanning Electron Microscopy (SEM) and Differential Scanning Calorimetry (DSC). Their analysis revealed that the interconnected porous network of expanded graphite provided efficient heat conduction pathways while securely retaining paraffin within its pores. The composite exhibited faster melting and solidification rates compared to pure paraffin, making it highly suitable for rapid thermal energy storage systems.

Wang et al. (2023) compared paraffin/expanded graphite composites with other carbon-based additives such as graphene nanoplatelets and carbon nanotubes. Although graphene demonstrated higher intrinsic thermal conductivity, expanded graphite offered a more economical and scalable solution with excellent compatibility and leakage resistance. The study highlighted that EG-based composites provide an optimal balance between cost, manufacturability, and thermal performance.

Recent research has also focused on optimizing fabrication techniques, including vacuum impregnation, melt blending, and compression molding, to improve the uniform dispersion of expanded graphite within paraffin. These manufacturing approaches enhance the composite's mechanical stability and thermal reliability while minimizing void formation and paraffin leakage. Furthermore, numerical simulations using finite element methods have been employed to predict heat transfer behavior and optimize composite structures for applications in solar thermal energy storage, building energy management, electronic cooling, and battery thermal management.

Overall, the existing literature demonstrates that paraffin/expanded graphite composite PCMs significantly outperform pure paraffin in terms of thermal conductivity, charging/discharging rate, leakage resistance, and thermal reliability. Although the incorporation of expanded graphite slightly reduces latent heat storage due to dilution of the PCM content, the improvement in heat transfer efficiency greatly enhances the overall performance of latent heat thermal energy storage systems. Consequently, paraffin/expanded graphite composites have emerged as promising materials for next-generation thermal energy storage applications requiring high efficiency, long service life, and reliable thermal performance.

EXISTING SYSTEM

The conventional phase change materials (PCMs), such as pure paraffin wax, are widely used for latent heat thermal energy storage because of their high energy storage capacity, chemical stability, and non-toxicity. However, pure paraffin exhibits very low thermal conductivity (approximately 0.2–0.3 W/m·K), resulting in slow heat absorption and release rates. This limitation increases the charging and discharging time of thermal energy storage systems and reduces their overall efficiency. Additionally, repeated melting and solidification cycles may lead to leakage and poor structural stability, limiting long-term practical applications.

Disadvantages of the Existing System

- Very low thermal conductivity causes slow heat transfer.
- Longer charging and discharging times reduce system efficiency.
- Leakage of molten paraffin during phase transition.
- Poor structural stability after repeated thermal cycles.
- Limited heat transfer performance restricts large-scale thermal energy storage applications.

PROPOSED SYSTEM

The proposed system utilizes a **Paraffin/Expanded Graphite (EG) Composite Phase Change Material (PCM)** to enhance thermal energy storage performance. Expanded graphite forms a highly conductive three-dimensional network within the paraffin matrix, significantly improving thermal conductivity while maintaining a high latent heat storage capacity. The composite PCM ensures faster melting and solidification, minimizes leakage, improves thermal stability, and enhances cyclic reliability. As a result, the Paraffin/EG composite provides efficient and reliable thermal energy storage for applications such as solar thermal systems, electronic cooling, battery thermal management, and building energy conservation.

Advantages of the Proposed System

- Significantly improved thermal conductivity due to expanded graphite.
- Faster charging and discharging of thermal energy.
- High latent heat storage capacity is retained.
- Reduced paraffin leakage during melting.
- Enhanced thermal and mechanical stability over repeated thermal cycles.
- Improved heat transfer efficiency and overall system performance.
- Longer service life with excellent cyclic durability.

IMPLEMENTATION

The implementation of the **"Thermal Conductivity and Latent Heat Thermal Energy Storage Characteristics of Paraffin/Expanded Graphite Composite as Phase Change Material"** involves the preparation of a paraffin-expanded graphite (EG) composite, characterization of its thermal properties, and evaluation of its thermal energy storage performance. The complete implementation is described below.

Step 1: Material Selection

The primary materials used in this work are:

- **Paraffin Wax** – Serves as the Phase Change Material (PCM) due to its high latent heat, chemical stability, non-toxicity, and suitable melting temperature.
- **Expanded Graphite (EG)** – Acts as a highly conductive porous matrix that enhances the thermal conductivity of paraffin and prevents leakage during phase transition.

Step 2: Composite Preparation

1. Paraffin wax is heated to a temperature of **70–80°C** until it melts completely.
2. Expanded graphite is dried to eliminate moisture before mixing.
3. The molten paraffin is gradually added to the expanded graphite while stirring continuously.
4. Different weight percentages of expanded graphite (e.g., **5%, 10%, 15%, and 20%**) are prepared to determine the optimum composition.
5. The mixture is stirred uniformly to ensure homogeneous distribution of paraffin within the graphite pores.
6. The composite is poured into molds and cooled naturally to room temperature.

Step 3: Sample Fabrication

- Composite specimens are prepared in standard dimensions suitable for thermal conductivity and thermal energy storage testing.
- The prepared samples are sealed to prevent contamination and maintain dimensional stability.

Step 4: Thermal Conductivity Measurement

The thermal conductivity of the prepared composites is measured using:

- Transient Plane Source (TPS) Method, or
- Hot Disk Thermal Conductivity Analyzer.

The measured values are compared with those of pure paraffin to evaluate the enhancement achieved by adding expanded graphite.

Step 5: Latent Heat Analysis

Differential Scanning Calorimetry (DSC) is employed to determine:

- Melting temperature
- Solidification temperature
- Latent heat of fusion
- Specific heat capacity

The DSC results are analyzed to verify that the addition of expanded graphite improves heat transfer while maintaining acceptable latent heat storage capacity.

Step 6: Thermal Energy Storage Performance

The charging and discharging behavior of the composite PCM is evaluated by:

- Heating the samples using a controlled heat source.
- Recording the temperature variation using thermocouples connected to a data acquisition system.
- Measuring charging time, discharging time, and thermal response.
- Comparing the performance of pure paraffin with paraffin/expanded graphite composites.

Step 7: Leakage and Stability Test

- The composite samples are heated above the melting temperature.
- Leakage observations are recorded.
- Repeated thermal cycling (100–500 cycles) is performed to evaluate thermal reliability and structural stability.

Step 8: Data Analysis

The experimental data are analyzed using statistical and graphical methods:

- Thermal conductivity vs. Expanded Graphite percentage.
- Latent heat vs. Expanded Graphite percentage.
- Charging and discharging curves.
- Energy storage efficiency.
- Thermal cycling stability.

System Flow

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Material Selection
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        ▼
Preparation of Paraffin
        |
        ▼
Preparation of Expanded Graphite
        |
        ▼
Mixing & Composite Fabrication
        |
        ▼
Sample Preparation
        |
        ▼
Thermal Conductivity Testing
        |
        ▼
DSC Latent Heat Analysis
        |
        ▼
Charging & Discharging Tests
        |
        ▼
Leakage & Thermal Cycling Tests
        |
        ▼
Performance Evaluation
        |
        ▼
Result Analysis & Comparison
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Expected Outcomes

- Significant enhancement in thermal conductivity compared to pure paraffin.
- Faster charging and discharging rates due to improved heat transfer.
- High latent heat storage capacity with minimal reduction after adding expanded graphite.
- Improved shape stability and leakage resistance.
- Enhanced thermal reliability after repeated heating and cooling cycles.
- Better suitability for thermal energy storage applications such as solar energy systems, waste heat recovery, battery thermal management, and building energy conservation.

Conclusion

The investigation of **paraffin/expanded graphite (EG) composite phase change materials (PCMs)** demonstrates that incorporating expanded graphite significantly enhances the thermal performance of paraffin for latent heat thermal energy storage (LHTES) applications. The addition of EG creates a highly conductive thermal network within the paraffin matrix, substantially increasing its thermal conductivity and reducing the charging and discharging times. Although the latent heat storage capacity decreases slightly with increasing EG content due to the replacement of paraffin by graphite, the composite retains a high energy storage density while exhibiting much faster heat transfer characteristics.

The paraffin/EG composite also shows excellent thermal stability, improved shape stability during phase transition, and good cyclic reliability, making it suitable for repeated thermal energy storage operations. The enhanced thermal conductivity minimizes temperature gradients within the PCM, resulting in more efficient and uniform melting and solidification processes. These characteristics overcome the inherent limitations of pure paraffin, particularly its low thermal conductivity, without significantly compromising its latent heat storage capability.

Overall, the paraffin/expanded graphite composite is a promising phase change material for medium-temperature thermal energy storage systems. Its improved heat transfer performance, reliable phase change behavior, and long-term stability make it an attractive candidate for applications such as solar thermal energy storage, waste heat recovery, electronic cooling, building energy management, and industrial thermal regulation. Future research may focus on optimizing the expanded graphite content, enhancing mechanical strength, and investigating large-scale manufacturing techniques to further improve the commercial viability of these composite PCMs.

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