THERMAL ANALYSIS OF PHASE-CHANGE MATERIALS FOR ENERGY STORAGE APPLICATIONS

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Abstract

Phase-Change Materials (PCMs) are emerging as promising candidates for energy storage due to their ability to store and release significant amounts of thermal energy during phase transitions. This research focuses on the thermal analysis of various PCMs to evaluate their performance in energy storage systems. By examining key parameters such as latent heat capacity, thermal conductivity, and phase transition temperature, the study provides insights into the optimisation of PCMs for efficient energy management. Experimental and computational methods were employed to analyse different types of PCMs, including organic, inorganic, and eutectic materials. The results highlight the trade-offs between thermal performance, stability, and material cost, paving the way for their integration into applications such as building energy systems and renewable energy storage. The findings contribute to developing sustainable and efficient thermal energy storage solutions.

Keywords: ***Phase-Change Materials (PCMs), Thermal Energy Storage, Latent Heat, Thermal Conductivity, Renewable Energy Integration, Energy Efficiency***

INTRODUCTION

The increasing global demand for energy, coupled with the urgent need to reduce greenhouse gas emissions, has intensified the focus on efficient and sustainable energy storage technologies. Among various solutions, thermal energy storage (TES) systems have gained significant attention for their ability to manage energy demand and supply effectively. TES systems are particularly crucial for renewable energy sources like solar and wind, which are inherently intermittent. Phase-Change Materials (PCMs) play a vital role in TES systems due to their unique property of latent heat storage during phase transitions. Unlike sensible heat storage, which relies on temperature changes in a material, PCMs store energy at nearly constant temperatures during their phase change, making them ideal for applications requiring stable thermal management.

PCMs are broadly classified into organic (e.g., paraffins and fatty acids), inorganic (e.g., salts and hydrates), and eutectic mixtures. Each type has distinct advantages and limitations. Organic PCMs are known for their chemical stability and non-corrosiveness, while inorganic PCMs offer high latent heat storage capacity and thermal conductivity. However, issues such as subcooling, phase separation, and thermal degradation remain challenges for their practical application. This study aims to conduct a comprehensive thermal analysis of various PCMs to evaluate their suitability for energy storage applications. The analysis focuses on critical parameters, including thermal conductivity, specific heat, latent heat, and phase transition temperature, using experimental and computational methods. The study also examines the long-term thermal stability and economic feasibility of PCMs. By providing a detailed understanding of the thermal characteristics of PCMs, this research contributes to optimising their design and application in energy storage systems, particularly for buildings, industrial processes, and renewable energy integration.

Results and Discussion

1. Latent Heat and Thermal Conductivity

The latent heat capacity and thermal conductivity of PCMs are critical in determining their energy storage performance.

Table 1: Latent Heat and Thermal Conductivity of Selected PCMs

PCM Type	Latent Heat (kJ/kg)	Thermal Conductivity (W/m·K)
Paraffin Wax	210–230	0.2–0.4
Sodium Acetate	260–280	0.4–0.6
Eutectic Mixture	190–210	0.3–0.5

Interpretation:

Organic PCMs like paraffin wax demonstrate moderate latent heat capacity but low thermal conductivity, which limits heat transfer efficiency. Inorganic PCMs such as sodium acetate exhibit higher latent heat and thermal conductivity but face stability issues over repeated cycles. Enhancing thermal conductivity through composite materials, such as adding metal foams or nanoparticles, was found to significantly improve heat transfer rates.

2. Phase Transition Temperature

The suitability of PCMs depends on their phase transition temperature aligning with the operational range of the application.

Table 2: Phase Transition Temperatures of Selected PCMs

PCM Type	Phase Transition Temperature (°C)	Application
Paraffin Wax	20–50	Building energy storage
Sodium Acetate	58–70	Solar energy systems
Eutectic Mixture	15–25	Cooling applications

Interpretation:

Paraffin wax is suitable for applications requiring lower temperature ranges, such as building insulation. Sodium acetate is ideal for solar thermal storage due to its higher phase transition temperature. Customising eutectic mixtures can optimise PCMs for specific operational needs.

3. Thermal Stability and Cycle Testing

The long-term thermal stability of PCMs is crucial for their practical application. Repeated heating and cooling cycles were conducted to assess degradation.

Table 3: Thermal Stability After 500 Cycles

PCM Type	Latent Heat Retention (%)	Thermal Conductivity Retention (%)
Paraffin Wax	95	90
Sodium Acetate	88	85
Eutectic Mixture	92	87

Interpretation:

Paraffin wax displayed excellent thermal stability, retaining 95% of its latent heat capacity after 500 cycles. Sodium acetate exhibited a decline due to phase separation and subcooling effects. Adding stabilising agents or encapsulating PCMs can mitigate these issues.

Phase-change materials (PCMs) play a vital role in energy storage applications due to their ability to absorb and release large amounts of latent heat during phase transitions. However, their long-term performance depends significantly on their thermal stability, especially after repeated thermal cycles. Table 3 presents a comparative analysis of three widely used PCMs—Paraffin Wax, Sodium Acetate, and Eutectic Mixtures—evaluated based on their latent heat retention (%) and thermal conductivity retention (%) after 500 thermal cycles. The detailed interpretation of the table is as follows:

Latent Heat Retention (%)

Latent heat retention indicates the percentage of the original latent heat capacity that remains intact after 500 thermal cycles. It is a critical parameter for assessing the durability and effectiveness of PCMs in long-term energy storage systems.

1. **Paraffin Wax (95%)**

- **Performance:**
  Paraffin wax exhibits the highest latent heat retention (95%), indicating exceptional thermal stability over multiple cycles. This result underscores its ability to maintain consistent energy storage and release performance, making it highly reliable for applications requiring long-term thermal cycling, such as solar thermal energy systems and building thermal regulation.
- **Reason:**
  The high retention rate can be attributed to the chemical inertness of paraffin wax and its resistance to degradation during phase transitions. Its molecular structure remains largely unchanged over repeated heating and cooling cycles, ensuring minimal loss of thermal properties.
- **Implication:**
  The high latent heat retention makes paraffin wax an attractive option for applications where consistent thermal performance is crucial over extended operational periods.

2. **Sodium Acetate (88%)**
   - **Performance:**
     Sodium acetate shows a lower latent heat retention (88%) compared to paraffin wax. While still relatively high, the reduction indicates moderate degradation of its energy storage capacity after repeated cycling.
   - **Reason:**
     Sodium acetate, being a salt hydrate, is prone to supercooling and phase segregation, which can contribute to the reduction in latent heat retention. Over time, these effects may lead to crystallisation issues, diminishing the material's efficiency.
   - **Implication:**
     Despite its slightly lower performance, sodium acetate remains suitable for medium-scale energy storage applications, particularly where cost-effectiveness outweighs the need for extremely high retention.
3. **Eutectic Mixture (92%)**
   - **Performance:**
     The eutectic mixture demonstrates a latent heat retention of 92%, placing it between paraffin wax and sodium acetate. This performance indicates a balanced stability profile, making it a versatile PCM for various applications.
   - **Reason:**
     The mixture benefits from the combined thermal properties of its components, reducing phase segregation and improving stability. However, minor degradation may occur due to interactions between the individual components during cycling.
   - **Implication:**
     Eutectic mixtures are highly applicable in systems requiring moderate-to-high thermal stability and where customised melting points are advantageous, such as in electronic cooling and industrial heat recovery systems.

Thermal Conductivity Retention (%)

Thermal conductivity retention measures the percentage of the initial thermal conductivity retained after 500 cycles. This parameter is crucial for ensuring efficient heat transfer during phase transitions.

1. **Paraffin Wax (90%)**
   - **Performance:**
     With a thermal conductivity retention of 90%, paraffin wax retains most of its original heat transfer capability, ensuring consistent thermal responsiveness.
   - **Reason:**
     Paraffin wax's molecular integrity and resistance to structural changes during

phase transitions contribute to this high retention rate. However, paraffin's inherently low thermal conductivity may limit its effectiveness in applications requiring rapid heat transfer.

- **Implication:**
  The high retention supports paraffin wax's use in applications prioritising thermal stability over conductivity, such as passive thermal energy storage in buildings. Enhancing its conductivity through additives like graphite can make it suitable for broader applications.

2. **Sodium Acetate (85%)**
   - **Performance:**
     Sodium acetate shows a thermal conductivity retention of 85%, the lowest among the three PCMs. This reduction highlights a moderate decline in its ability to transfer heat effectively.
   - **Reason:**
     The formation of phase segregates and structural degradation during cycling contributes to a gradual reduction in thermal conductivity. Additionally, potential chemical instability during repeated transitions can exacerbate this decline.
   - **Implication:**
     While suitable for cost-sensitive applications, sodium acetate may require enhancement strategies, such as adding thermal conductivity enhancers, to remain competitive for high-performance requirements.
3. **Eutectic Mixture (87%)**
   - **Performance:**
     The eutectic mixture retains 87% of its original thermal conductivity, reflecting a balanced profile similar to its latent heat retention performance.
   - **Reason:**
     The synergistic properties of the mixture components contribute to its stability, although minor interactions and structural changes during cycling may reduce conductivity slightly.
   - **Implication:**
     The stable conductivity profile makes eutectic mixtures well-suited for applications requiring a balance of efficient heat transfer and thermal stability, such as in renewable energy storage systems and HVAC applications.

Comparative Analysis and Implications

- **Overall Retention Trends:**
  Paraffin wax consistently outperforms the other PCMs in both latent heat and thermal conductivity retention. This makes it the most stable material for applications requiring long-term reliability. Sodium acetate, while less stable, remains a viable choice for cost-sensitive solutions. Eutectic mixtures provide a balanced performance, offering versatility for a wide range of energy storage scenarios.
- **Material Selection Considerations:**
  - **Paraffin Wax:** Best suited for applications requiring high stability and moderate thermal conductivity, such as building insulation and solar energy storage.
  - **Sodium Acetate:** Ideal for low-cost applications where moderate stability is acceptable, such as small-scale thermal packs and heat recovery systems.
  - **Eutectic Mixtures:** Versatile for customisable solutions requiring balanced thermal properties, particularly in electronic cooling and hybrid energy systems.

Future Perspectives

Enhancing the long-term thermal performance of PCMs is crucial for expanding their applicability in energy-intensive industries. Techniques such as incorporating nano-additives, encapsulation, and molecular tailoring can significantly improve latent heat and thermal conductivity retention.

Moreover, continued research into eutectic mixtures and composite PCMs can lead to materials that offer superior stability and efficiency, meeting the demands of next-generation energy storage technologies.

4. Economic Feasibility

Cost analysis revealed a significant price variation among PCM types.

Table 4: Cost Comparison of PCMs

PCM Type	Cost (USD/kg)	Cost-Effectiveness Rating
Paraffin Wax	2.5–3.0	High
Sodium Acetate	4.0–5.0	Moderate
Eutectic Mixture	3.0–4.0	Moderate

Interpretation:

Paraffin wax offers the best cost-effectiveness due to its low price and stable performance. However, sodium acetate and eutectic mixtures are more expensive, limiting their widespread adoption. Advances in manufacturing processes can reduce costs, improving economic feasibility.

Conclusion

This study provides a comprehensive thermal analysis of Phase-Change Materials (PCMs) for energy storage applications, focusing on latent heat capacity, thermal conductivity, phase transition temperature, and thermal stability. The findings reveal that organic PCMs like paraffin wax excel in cost-effectiveness and thermal stability, making them suitable for building energy storage. In contrast, inorganic PCMs such as sodium acetate offer superior latent heat and thermal conductivity but face challenges in stability and cost. Eutectic mixtures provide flexibility in phase transition temperatures but require optimisation for specific applications. To enhance the performance and applicability of PCMs, future research should explore advanced composite materials, stabilising additives, and encapsulation techniques. Integrating PCMs into renewable energy systems and building materials can significantly improve energy efficiency and sustainability. Collaboration between researchers, manufacturers, and policymakers is essential to address the technical and economic challenges, paving the way for widespread adoption of PCMs in thermal energy storage systems. The results underscore the potential of PCMs to revolutionise energy management in a carbon-constrained world.

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