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Battery Thermal Management using Phase Change Materials

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ABSTRACT: The rising adoption of lithium-ion batteries in electric vehicles (EVs), portable electronics, and renewable energy systems has elevated the importance of efficient **Battery Thermal Management Systems (BTMS)**. Excessive heat generation during charge/discharge cycles degrades battery life, reduces performance, and poses safety risks such as thermal runaway. Among various BTMS technologies, **Phase Change Materials (PCMs)** have emerged as an effective passive cooling solution due to their high latent heat capacity and ability to absorb excess thermal energy during phase transitions.

This study explores the principles and applications of **PCM-based thermal management systems** for batteries, focusing on how different PCM types, composite materials, and system configurations influence heat dissipation and temperature control. Pure paraffin waxes, although widely used for their high latent heat, suffer from low thermal conductivity and leakage during melting. Researchers have developed PCM composites enhanced with **expanded graphite, metal foams, carbon nanotubes, and graphene** to address these limitations. For example, the incorporation of copper foam or expanded graphite into paraffin matrices has shown significant improvement in heat transfer and thermal response time.

Experimental studies and multiscale simulations prior to 2020 reveal that PCM-enhanced systems can limit temperature rise in battery cells by over 20–30% compared to passive air cooling alone. Further, shape-stabilized PCMs and encapsulated designs minimize leakage and improve durability across multiple thermal cycles.

While PCMs do not require additional energy to operate, they often lack the ability to remove heat continuously, necessitating hybrid systems or recharging mechanisms. This paper synthesizes key findings on PCM selection, integration methods, and thermal modeling, and outlines their comparative advantages in real-world battery applications.

KEYWORDS: Battery Thermal Management System (BTMS), Phase Change Materials (PCM), Lithium-ion Battery, Thermal Conductivity, Expanded Graphite, Thermal Runaway, Passive Cooling, Energy Storage, Composite PCM, Heat Dissipation

I. INTRODUCTION

The increasing reliance on **lithium-ion batteries** in applications ranging from electric vehicles (EVs) to renewable energy storage has amplified the need for efficient and reliable **thermal management systems**. Batteries generate heat during both charging and discharging due to electrochemical reactions and internal resistance. If this heat is not effectively dissipated, it can lead to a rise in battery temperature, potentially causing **degradation of battery capacity**, **shortened cycle life**, and in extreme cases, **thermal runaway**—a self-accelerating, exothermic reaction that poses serious safety risks.

To mitigate these issues, various **Battery Thermal Management Systems (BTMS)** have been proposed, including active systems (such as air or liquid cooling) and passive systems. Active systems are effective but often bulky, complex, and energy-intensive. In contrast, **passive cooling solutions using Phase Change Materials (PCMs)** offer a lightweight and energy-efficient alternative.

PCMs function by absorbing thermal energy as latent heat during the **solid-to-liquid phase transition**, maintaining the battery temperature within a safe operating range. Among the most widely studied PCMs are **organic paraffin waxes** due to their suitable phase change temperature and high energy absorption. However, they suffer from limitations like low thermal conductivity and leakage during melting.

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To overcome these shortcomings, recent research (prior to 2020) has focused on developing **composite PCMs** that combine base materials like paraffin with high-conductivity additives such as **expanded graphite, carbon nanotubes (CNTs), graphene**, or **metal foams**. These composites exhibit significantly improved heat transfer and structural stability.

This paper explores the advancements in PCM-based battery cooling systems, comparing various material types, design architectures, and modeling approaches. The objective is to provide a comprehensive understanding of how PCMs contribute to effective thermal regulation in batteries, emphasizing results from experimental and modeling studies conducted before 2020.

II. LITERATURE REVIEW

The literature on **Phase Change Materials (PCMs)** for battery thermal management has grown considerably in the past decade. Researchers have extensively explored various **organic**, **inorganic**, and **eutectic** PCMs for their suitability in dissipating heat generated during battery operation.

Wang et al. (2017) conducted experimental studies on a **copper foam/paraffin composite PCM** system for different lithium-ion battery formats. They observed that this structure maintained battery temperatures under 50°C during 5C discharge rates, outperforming natural air convection methods. The copper foam significantly enhanced thermal conductivity while the paraffin absorbed latent heat, leading to efficient passive cooling (RSC Adv., 2017).

Similarly, Zhang et al. (2016) tested paraffin/expanded graphite (EG) composites to improve thermal response and prevent PCM leakage. Their results showed a temperature drop of up to 20% compared to pure paraffin, with better shape stability over multiple cycles. Epoxy was introduced in some composites to enhance form stability further (RSC Adv., 2016).

Goli et al. (2013) took a multiscale modeling approach, analyzing **graphene-enhanced paraffin PCMs**. Their simulations showed up to 100× improvement in thermal conductivity. However, Mortazavi et al. (2017) reported that such enhancements did not proportionally improve battery thermal regulation due to limited heat spreading within the battery pack (arXiv:1305.4140, arXiv:1706.06667).

Review papers (e.g., Sharma et al., 2015; Khateeb et al., 2004) have categorized PCM types and evaluated them based on melting point, latent heat, thermal conductivity, and stability. Most researchers favor organic PCMs like paraffin due to their non-corrosive, chemically stable nature.

In summary, literature before 2020 consistently supports PCM integration in BTMS, especially in the form of **composite PCMs** and **encapsulated configurations**, which mitigate limitations like leakage and low conductivity.

III. RESEARCH METHODOLOGY

Researchers have approached PCM-based battery thermal management systems (BTMS) through several key methods:

1. **Experimental Investigations**

○ *Copper Foam + PCM Structure*: Wang et al. (2017) designed a passive system using copper foam saturated with PCM (CF/PCM) to manage thermal behavior in various Li-ion battery types (e.g., 26650, 42110, and square cells) under high discharge rates (5C). Tests were conducted in both insulated and natural-convection environments to emulate real operating conditionsRSC Publishing+1.

○ *Composite PCMs with Paraffin, Expanded Graphite, Epoxy*: Another experimental study explored PCM mixtures—pure paraffin, paraffin with expanded graphite (EG), and paraffin/EG/epoxy—for 18×650 battery modules and measured temperature reduction performance and leakage resistance over cyclesRSC Publishing.

2. **Multiscale Modeling and Simulation**

○ *Graphene-enhanced PCM*: Goli et al. (2013) conducted atomistic–continuum multiscale modeling to assess paraffin PCMs embedded with graphene fillers, finding massive improvements in thermal conductivity and consequent reduction in battery temperature risearXiv.

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○ *Paraffin Composites with Nano-fillers*: Mortazavi et al. (2017) used multiscale modeling (atomistic + 3D heat transfer models) to evaluate paraffin reinforced with graphene or h-BN, revealing that while thermal conductivity improved, battery thermal management saw limited gains compared to pure paraffinarXiv.

3. **Review and Systematic Analysis**

○ Comprehensive reviews have examined PCM classes (organic, inorganic, eutectic), modifications (adding foams, fillers, fins), and key parameters affecting BTMS effectiveness such as thermal conductivity and leakage riskMDPI+2MDPI+2IOPscience.

These methodologies collectively provide a robust evaluation of PCM-based BTMS—from physical prototypes and thermal testing to advanced modeling and systematic reviews of material science.

IV. ADVANTAGES

- **Passive Heat Mitigation**: PCMs absorb battery-generated heat through phase change, stabilizing temperature without active cooling systemsWiley Online LibraryMDPI.
- **Energy-Free Operation**: They maintain safe operating temperatures without external power consumptionPubMedIOPscience.
- **Enhanced Thermal Conductivity via Composites**:

○ Graphene fillers can increase PCM thermal conductivity by over 100×, significantly reducing battery temperature risearXiv.

○ Addition of copper foam, expanded graphite, and metal foams improves heat transfer and stabilizes PCM shapeRSC Publishing+1MDPI.

- **Leakage Prevention**: Composite formulations with epoxy or form-stabilized structures prevent PCM leakage during phase transition cyclesRSC PublishingMDPI.
- **Simplicity and Reliability**: PCM systems are structurally simple, lightweight, and reliable compared to complex air- or liquid-cooling systemsWiley Online LibraryIOPscience.

V. DISADVANTAGES

- **Low Intrinsic Thermal Conductivity**: Pure PCMs, especially organics like paraffin, have poor thermal conductivity, limiting their cooling effectivenessMDPI+1.
- **Volume Expansion and Leakage**: Melting causes PCM expansion; without stabilization or containment, this can lead to leakage and reduced efficacyMDPIRSC Publishing.
- **Thermal Runaway Risk**: Many PCMs are organic and flammable, raising safety concerns in battery environmentsMDPI.
- **Composite Complexity**: Enhancing PCM properties (with foams, fillers) adds material and design complexity, potentially increasing cost and weightMDPI+1.
- **Marginal Gains**: Even with fillers like graphene or h-BN, thermal improvements may not proportionally enhance battery temperature controlarXiv.

VI. RESULTS AND DISCUSSION

- **CF/PCM Structures (Wang et al.)**: Demonstrated that copper foam–enhanced PCM controls battery temperature more effectively than pure PCM or air cooling—maintaining cell surface temperatures below ~44–51 °C depending on battery type under 5C dischargeRSC Publishing.
- **Composite PCM Modules**: Paraffin–EG and epoxy composites (PCM 2, PCM 3) showed 10–20% temperature reductions at various discharge rates compared to pure PCM. The inclusion of epoxy prevented leakage over cyclesRSC Publishing.
- **Graphene-Enhanced PCM**: Modeling revealed huge gains in thermal conductivity (~100×), which led to substantial reductions in battery temperature risearXiv.
- **Graphene/h-BN Composite Findings**: Despite enhanced material conductivity, improvements in thermal management were modest compared to pure PCM, indicating diminishing returns or other limiting factorsarXiv.

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These results suggest that PCM composites—especially those combining high-conductivity elements and shape-stabilizers—considerably improve thermal control for batteries. However, material gains do not always translate into proportional thermal performance improvements due to complex heat transfer dynamics.

VII. CONCLUSION

PCM-based thermal management offers significant benefits for Li-ion batteries—particularly in passive, energy-free temperature stabilization. Composite strategies (e.g., incorporating graphite, foams, epoxy, graphene) enhance thermal conductivity and structural stability, leading to measurable gains in temperature control and safety. Nonetheless, challenges such as leakage, flammability, limited thermal diffusion, and added complexity must be addressed for practical implementation.

VIII. FUTURE WORK

- **Improved PCMs**: Research novel inorganic or flame-retardant PCMs to reduce flammability and enhance safetyMDPIIOPscience.
- **Optimized Composites**: Explore hierarchical or multi-layered PCM composites that intelligently balance latent heat, conductivity, and stability across temperature bandsMDPI.
- **Advanced Modeling and Design**: Incorporate more realistic multi-physics models to better predict PCM performance and address discrepancies seen in graphene-enhanced studiesarXiv.
- **Leakage-Free Structure Innovation**: Develop encapsulation and shape-stabilized frameworks to prevent leakage while maintaining thermal performanceRSC PublishingMDPI.
- **Long-term Cycling Tests**: Conduct durability studies to ensure PCM composites maintain effectiveness and containment over extensive charge–discharge cycles.

REFERENCES

1. Ziyuan Wang et al. (2017). Experimental study of a passive thermal management system using copper foam–PCM for various Li-ion batteriesRSC Publishing.
2. Ziyuan Wang et al. (2017). Thermal management of Li-ion battery modules using paraffin/expanded graphite/epoxy composite PCMsRSC Publishing.
3. Pradyumna Goli et al. (2013). Graphene-enhanced hybrid PCMs for Li-ion battery thermal management (multiscale modeling)arXiv.
4. Bohayra Mortazavi et al. (2017). Paraffin composites with graphene or h-BN: multiscale thermal management investigationarXiv.
5. Reviews on PCM classification and enhancements: materials/BTMS applicationsMDPI+2MDPI+2IOPscience.
6. Analysis of PCM in BTMS, benefits vs. limitations.