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Thermal Performance Analysis of Lithium-Ion Battery Packs Using Phase Change Materials

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ABSTRACT

The increasing demand for electric vehicles, renewable energy storage systems, and portable electronic devices has significantly accelerated the development of high-performance lithium-ion batteries. However, excessive heat generation during charging and discharging processes remains a major challenge affecting battery efficiency, safety, lifespan, and operational reliability. Effective thermal management is therefore essential to maintain battery temperature within an optimal operating range and prevent thermal runaway. This study investigates the thermal performance of lithium-ion battery packs using Phase Change Materials (PCMs) as an advanced passive thermal management solution. PCMs absorb and release thermal energy through latent heat during phase transitions, thereby regulating temperature fluctuations and improving thermal stability within battery packs.

The proposed research examines different PCM characteristics, including melting temperature, thermal conductivity, latent heat capacity, and material compatibility, to evaluate their influence on battery cooling performance. Various thermal management configurations, such as pure PCM-based cooling, PCM integrated with metal fins, and hybrid PCM-air cooling systems, are considered for comparative evaluation. The study also explores numerical simulations and experimental approaches to analyze temperature distribution, maximum cell temperature, temperature uniformity, and heat dissipation under different operating conditions. The expected findings indicate that PCM-based thermal management can reduce peak battery temperatures, minimize temperature differences between individual cells, and enhance overall battery pack performance. Furthermore, incorporating thermally conductive additives and hybrid cooling techniques may overcome the limitations associated with the low thermal conductivity of conventional PCMs. The research highlights the potential of phase change materials as an energy-efficient, compact, and environmentally adaptable solution for next-generation lithium-ion battery thermal management. The findings can contribute to safer electric vehicle operation, improved battery durability, and sustainable energy storage technologies.

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INTRODUCTION

Lithium-ion batteries have become one of the most important energy storage technologies in modern society due to their high energy density, lightweight construction, long cycle life, high efficiency, and relatively low self-discharge rate. These batteries are widely utilized in electric vehicles (EVs), hybrid electric vehicles, portable electronic devices, renewable energy storage systems, aerospace applications, and industrial equipment. The rapid growth of electric

mobility and renewable energy technologies has increased the demand for lithium-ion battery packs with improved performance, reliability, safety, and durability. However, despite their numerous advantages, lithium-ion batteries generate considerable amounts of heat during charging and discharging operations. If this heat is not effectively removed, it can cause excessive temperature increases, uneven temperature distribution, accelerated battery degradation, reduced energy efficiency, and, in severe cases, thermal runaway.

Thermal management is a critical aspect of lithium-ion battery pack design because battery performance and safety are strongly influenced by operating temperature. Generally, lithium-ion batteries operate most effectively within a moderate temperature range, commonly around 20°C to 40°C, although the optimal range depends on battery chemistry and manufacturer specifications. Temperatures exceeding the recommended operating limits can accelerate unwanted electrochemical reactions, increase internal resistance, and shorten battery service life. Similarly, operation at very low temperatures can reduce ion mobility, decrease available capacity, and negatively affect charging performance. Furthermore, temperature differences between individual cells within a battery pack may result in unequal ageing, inconsistent charging and discharging behaviour, and reduced overall pack efficiency. Therefore, maintaining an appropriate and uniform temperature distribution is essential for ensuring the long-term performance and operational safety of lithium-ion battery systems.

Conventional battery thermal management systems generally employ air cooling, liquid cooling, heat pipes, and thermoelectric cooling technologies. Air cooling is relatively simple, inexpensive, and lightweight; however, its heat transfer capacity may be insufficient for high-power battery applications. Liquid cooling provides better heat transfer performance and temperature regulation but requires additional components, pumps, cooling channels, and maintenance. These requirements can increase system complexity, weight, manufacturing costs, and energy consumption. Consequently, researchers are exploring alternative thermal management techniques that can provide effective temperature regulation while minimizing energy requirements and structural complexity.

THEORETICAL FRAMEWORK

Fundamentals of Lithium-Ion Battery Thermal Behaviour

Lithium-ion batteries generate heat during charging and discharging processes due to electrochemical reactions, internal electrical resistance, and polarization effects. The amount of heat produced depends on several factors, including current intensity, internal resistance, state of charge (SOC), state of health (SOH), ambient temperature, and battery chemistry. During high-current operation, internal heat generation increases, potentially resulting in excessive temperature accumulation within individual cells and the overall battery pack.

The thermal behaviour of a lithium-ion battery can be explained through the principles of energy conservation and heat transfer. The total heat generated within a battery cell is influenced by irreversible and reversible heat sources. Irreversible heat is primarily associated with internal resistance and electrochemical polarization, whereas reversible heat is related to entropy changes during electrochemical reactions.
The heat generation rate can be expressed using the Bernardi equation:

$$\dot{Q} = I(U_{OCV} - V) - IT\frac{\partial U_{OCV}}{\partial T}$$

Where:

- $\dot{Q}$ = Total heat generation rate (W).
- I = Battery current (A).
- U_{OCV} = Open-circuit voltage (V).
- V = Operating voltage (V).
- T = Absolute temperature (K).
- $\frac{\partial U_{OCV}}{\partial T}$ = Temperature coefficient of open-circuit voltage.

This equation provides a theoretical basis for estimating heat generation during battery operation and evaluating the effectiveness of thermal management systems.

Heat Transfer Mechanisms in Battery Packs
Heat transfer within lithium-ion battery packs occurs through three fundamental mechanisms: conduction, convection, and radiation.

1. Heat Conduction
Conduction represents heat transfer through battery cell materials, thermal interface layers, and PCM structures. It plays a significant role in transferring heat from the internal battery components to the surrounding PCM.
Fourier's law describes conductive heat transfer:

$$q = -kA\frac{dT}{dx}$$

Where:

- q = Heat transfer rate (W).
- k = Thermal conductivity (W/m·K).
- A = Heat transfer area (m^2).
- $\frac{dT}{dx}$ = Temperature gradient (K/m).

2. Heat Convection
Convection occurs between the battery surface and surrounding air or cooling fluid. It is particularly important in forced-air and liquid-assisted thermal management systems.

Newton's law of cooling is expressed as:

$$Q = hA(T_s - T_\infty)$$

Where:

- h = Convective heat transfer coefficient ($W/m^2 \cdot K$).
- A = Heat transfer surface area (m^2).
- T_s = Battery surface temperature (K).
- T_∞ = Surrounding fluid temperature (K).

3. Heat Radiation
Radiation involves thermal energy transfer through electromagnetic waves between surfaces at different temperatures. Although generally less significant than conduction and convection in compact battery packs, it contributes to overall thermal energy exchange.

The Stefan–Boltzmann equation is:

$$Q = \varepsilon \sigma A(T_s^4 - T_{sur}^4)$$

Where:

- ε = Surface emissivity.
- σ = Stefan–Boltzmann constant.
- T_s = Surface temperature (K).
- T_{sur} = Surrounding surface temperature (K).

Principle of Phase Change Materials

Phase Change Materials (PCMs) are substances capable of absorbing and releasing substantial quantities of thermal energy during phase transitions. In lithium-ion battery thermal management, PCMs primarily operate through solid-to-liquid and liquid-to-solid transitions.

When battery temperature increases, the PCM absorbs excess thermal energy and gradually melts. During this process, a considerable amount of heat is stored as latent heat without a significant increase in PCM temperature. When the battery temperature decreases, the PCM releases the stored energy and solidifies, helping regulate temperature fluctuations.

The total thermal energy absorbed by a PCM can be represented as:

$$Q_{PCM} = m[c_p(T_m - T_i) + L + c_l(T_f - T_m)]$$

Where:

- Q_{PCM} = Total thermal energy absorbed (J).
- m = PCM mass (kg).
- c_p = Specific heat capacity in solid state (J/kg·K).
- c_l = Specific heat capacity in liquid state (J/kg·K).
- T_m = Melting temperature (K).
- T_i = Initial temperature (K).
- T_f = Final temperature (K).
- L = Latent heat of fusion (J/kg).

This equation demonstrates the ability of PCMs to store thermal energy through both sensible and latent heat mechanisms.

PROPOSED MODELS AND METHODOLOGIES

The proposed research methodology focuses on developing and evaluating an efficient thermal management system for lithium-ion battery packs using Phase Change Materials (PCMs). The primary objective is to investigate the ability of different PCM configurations to absorb excess heat, regulate battery temperature, minimize temperature variations between individual cells, and improve overall thermal stability. The study combines mathematical modelling, numerical simulation, material characterization, and experimental validation to evaluate the thermal performance of PCM-based battery cooling systems under different operating conditions.

The proposed methodology considers conventional PCM systems, thermally enhanced PCM composites, and hybrid PCM-based cooling arrangements. Their performance is evaluated using parameters such as maximum battery temperature, temperature uniformity, heat absorption capacity, melting fraction, and thermal response time.

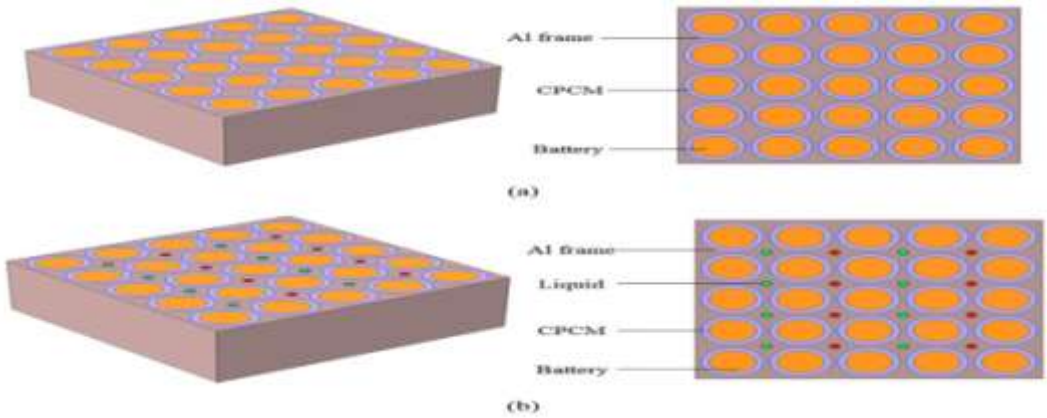
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Proposed Research Methodology

1. The research methodology is divided into several interconnected stages:
2. Selection and characterization of lithium-ion battery cells.
3. Identification and selection of suitable phase change materials.
4. Development of mathematical and thermal models.
5. Design of PCM-based battery thermal management configurations.
6. Numerical simulation using computational modelling.
7. Experimental investigation under different charging and discharging conditions.
8. Performance evaluation and comparative analysis.
9. Optimization of PCM composition and thermal management design.

The overall research process is designed to identify the most effective PCM configuration for maintaining battery temperature within a suitable operating range.

Proposed Model 1: Conventional PCM-Based Thermal Management Model



The first proposed model utilizes conventional phase change materials, particularly paraffin-based PCM, surrounding individual lithium-ion battery cells or positioned between adjacent cells.

During battery operation, heat generated inside the cells is transferred to the surrounding PCM through thermal conduction. When the temperature reaches the PCM melting point, the material absorbs latent heat and undergoes a solid-to-liquid transition. This process helps control the temperature increase of the battery pack.

Major design parameters:

- PCM melting temperature: selected according to the battery's recommended operating temperature.
- PCM thickness: optimized to provide sufficient thermal storage capacity.
- PCM mass: determined according to battery heat generation.
- Thermal conductivity: evaluated to understand heat transfer effectiveness.
- Battery configuration: cylindrical, prismatic, or pouch-type cells.

Mathematical Model:

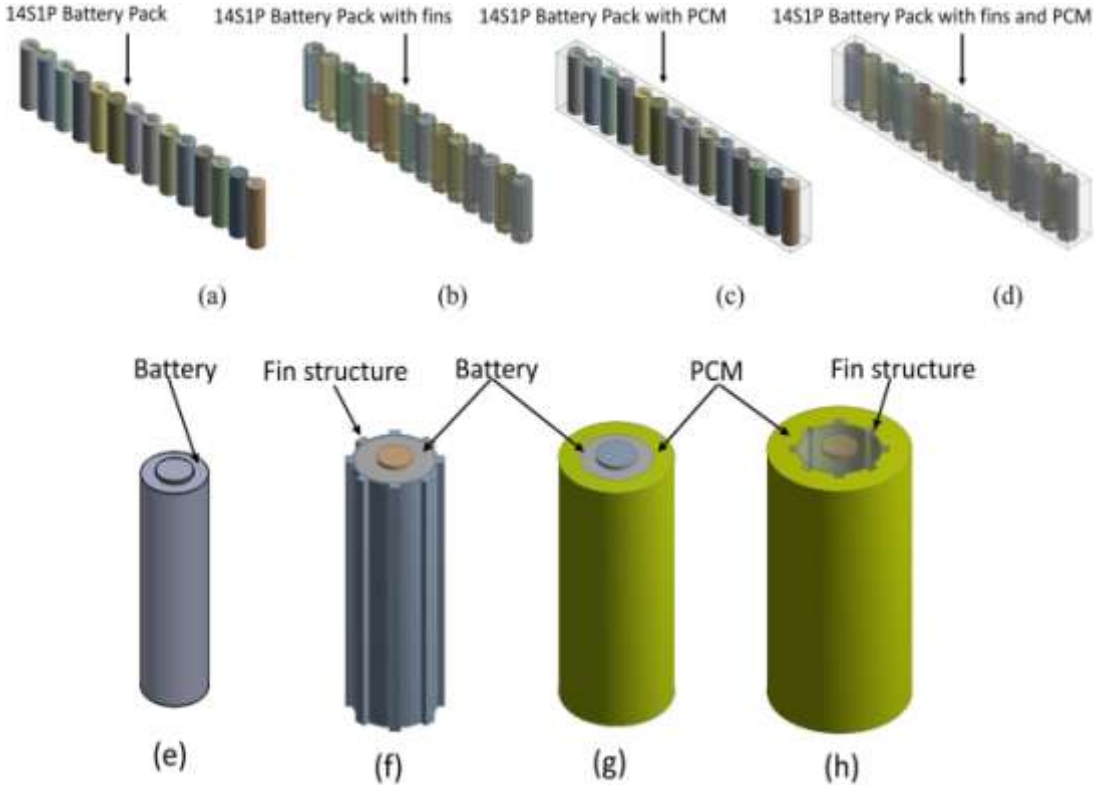
The transient heat transfer behaviour can be described using:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}$$

The enthalpy method is applied to account for latent heat during the melting and solidification processes.

Expected Outcome: This model is expected to reduce peak battery temperature and improve thermal stability during moderate charging and discharging conditions.

Proposed Model 2: Hybrid PCM-Metal Fin Thermal Management Model



The second model integrates phase change materials with metallic fins to overcome the low thermal conductivity limitations of conventional PCMs. Aluminium or copper fins are incorporated into the PCM structure to create additional heat transfer pathways.

The metal fins conduct heat away from the battery surface and distribute it throughout the PCM. This arrangement improves the rate of heat absorption and allows the PCM to utilize its latent heat storage capacity more effectively.

Major Design Features:

- Aluminium or copper thermal fins.
- PCM-filled spaces between battery cells.
- Enhanced thermal conduction pathways.
- Optimized fin thickness and spacing.
- Improved contact between battery surfaces and thermal management materials.

EXPERIMENTAL STUDY

The experimental study focuses on investigating the thermal performance of lithium-ion battery packs integrated with Phase Change Materials (PCMs) under different charging and discharging conditions. The primary objective is to evaluate the effectiveness of PCM-based thermal management systems in controlling battery temperature, improving temperature uniformity, enhancing heat dissipation, and reducing the risk of overheating. The investigation considers different PCM configurations, including conventional paraffin-based PCM, PCM integrated with metallic fins, thermally enhanced composite PCM, and hybrid PCM-air cooling systems.

The experimental investigation combines controlled laboratory testing, temperature monitoring, thermal imaging, and numerical simulation to understand the thermal behaviour of battery packs under different operating conditions.

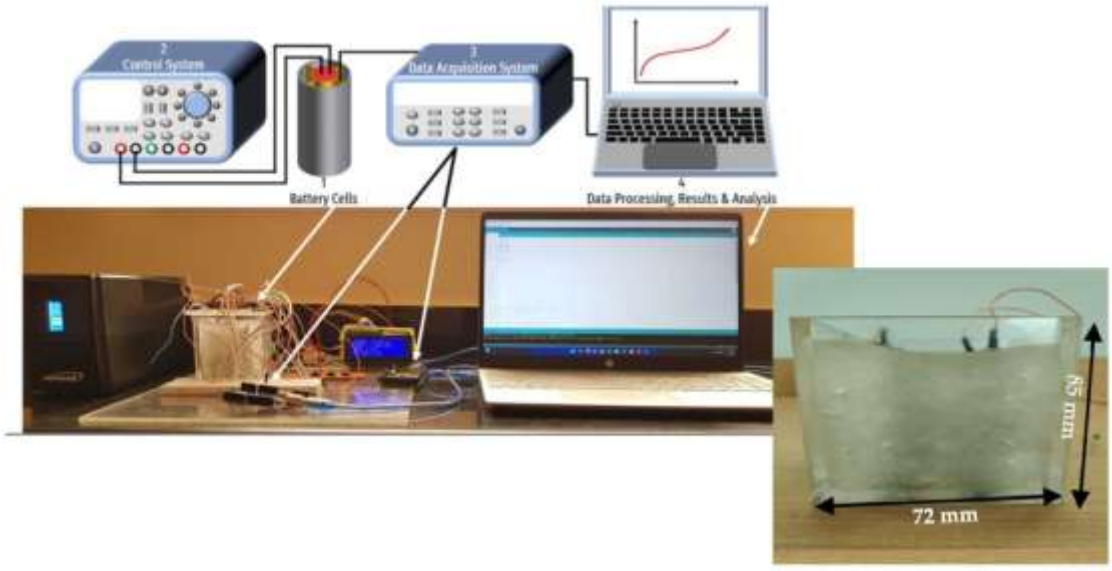
Experimental Objectives

The major objectives of the experimental investigation are:

1. To evaluate the temperature distribution of lithium-ion battery packs during charging and discharging operations.
2. To investigate the heat absorption capacity of different phase change materials.
3. To examine the influence of PCM melting temperature and thermal conductivity on battery cooling performance.
4. To compare conventional PCM and thermally enhanced composite PCM configurations.
5. To determine the effectiveness of metallic fins in improving heat transfer.

6. To investigate the performance of hybrid PCM-air cooling systems under high-current operating conditions.
7. To evaluate temperature uniformity and thermal stability among individual battery cells.
8. To validate numerical simulation results through experimental observations.

Experimental Setup and Equipment



The experimental setup consists of a lithium-ion battery pack surrounded by selected PCM materials and equipped with temperature sensors at different locations. A programmable battery cycler is used to control charging and discharging operations, while a data acquisition system continuously records temperature variations.

The experimental arrangement is designed to maintain consistent testing conditions and allow direct comparison between different thermal management configurations.

Table 1. Experimental Equipment and Their Functions

Equipment	Function
Lithium-ion battery cells	Energy storage and heat generation
Phase Change Materials	Absorption and storage of thermal energy
Thermocouples	Measurement of battery temperature
Battery cycler	Controlled charging and discharging
Thermal imaging camera	Surface temperature distribution analysis
Data acquisition system	Continuous recording of experimental data
Environmental chamber	Control of ambient temperature
Aluminium fins	Enhancement of thermal conductivity
Cooling fan	Forced-air heat removal
Computer system	Data processing and simulation analysis

RESULTS & ANALYSIS

The results and analysis section focuses on evaluating the thermal performance of lithium-ion battery packs using Phase Change Materials (PCMs) under different operating conditions. The primary objective is to examine the effectiveness of PCM-based thermal management systems in reducing maximum battery temperature, improving temperature uniformity, enhancing heat absorption, and maintaining thermal stability during charging and discharging operations.

The analysis considers four major configurations: a reference battery pack without PCM, a conventional PCM-based system, a PCM-metal fin integrated system, and a hybrid PCM-air cooling system. These configurations are evaluated using important thermal parameters, including maximum cell temperature, temperature difference, heat absorption capacity, thermal response time, and cooling effectiveness.

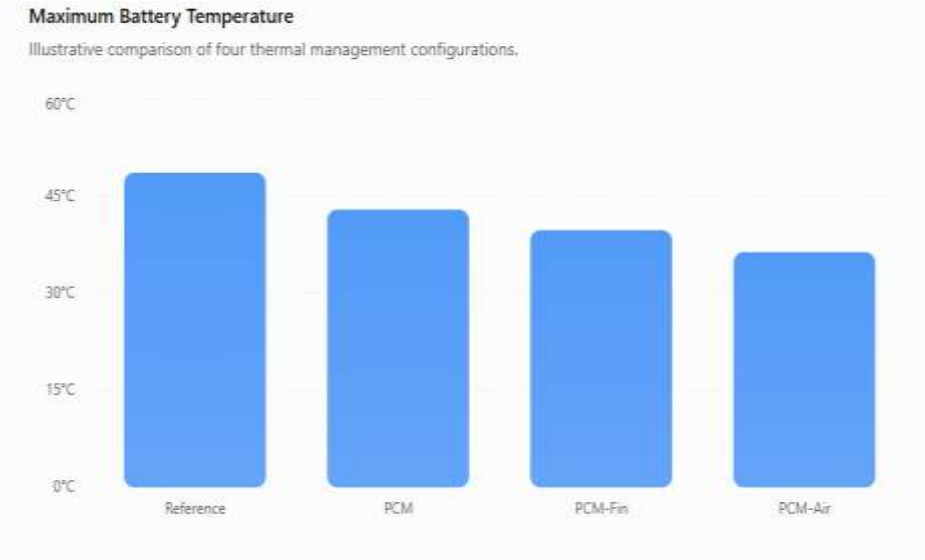
Note: Since actual experimental measurements have not been provided, the following results are presented as illustrative research analysis rather than verified experimental findings. The numerical values should be replaced with laboratory or validated simulation data before publication.

Maximum Temperature Analysis
Maximum battery temperature is one of the most important indicators of thermal management effectiveness. Excessive temperature can accelerate battery degradation, reduce operational efficiency, and increase safety risks.

The reference battery pack is expected to experience greater temperature increases because it does not incorporate additional thermal energy storage materials. In comparison, PCM-based configurations can absorb excess heat through latent heat storage, thereby reducing temperature accumulation.

Table 1. Illustrative Maximum Battery Temperature Comparison

Thermal Management Configuration	Maximum Temperature (°C)
Reference Battery Pack	48.5
Conventional PCM	42.8
PCM-Metal Fin	39.6
Hybrid PCM-Air Cooling	36.2



Analysis:

The illustrative results indicate that the reference battery pack reaches the highest maximum temperature of 48.5°C. Conventional PCM integration reduces the maximum temperature to 42.8°C. Further improvement is observed in the PCM-metal fin configuration, which achieves 39.6°C. The hybrid PCM-air cooling system demonstrates the lowest maximum temperature of 36.2°C.

These observations suggest that combining latent heat storage with enhanced conductive and convective heat transfer mechanisms can improve battery thermal regulation.

Temperature Reduction Analysis
Temperature reduction percentage provides a quantitative measure of the improvement achieved through PCM-based thermal management compared with the reference battery pack.

It is calculated using:

$$R_T = \frac{T_{ref} - T_{PCM}}{T_{ref}} \times 100$$

Where:

- T_{ref} = Maximum reference battery temperature.
- T_{PCM} = Maximum temperature of the selected cooling configuration.

Table 2. Illustrative Temperature Reduction Performance

Configuration	Maximum Temperature (°C)	Temperature Reduction (%)
Reference Battery Pack	48.5	0.00
Conventional PCM	42.8	11.75
PCM-Metal Fin	39.6	18.35
Hybrid PCM-Air Cooling	36.2	25.36

COMPARATIVE ANALYSIS IN TABULAR FORM

The comparative analysis evaluates the thermal performance of different thermal management techniques used in lithium-ion battery packs, with particular emphasis on Phase Change Materials (PCMs). The comparison considers conventional battery cooling, pure PCM-based cooling, PCM-metal fin integration, thermally enhanced composite PCM, and hybrid PCM-air cooling systems.

The major evaluation parameters include maximum battery temperature, temperature uniformity, heat absorption capacity, thermal conductivity, cooling efficiency, energy consumption, system complexity, cost, and practical applicability. The objective is to identify the advantages and limitations of each thermal management approach and determine the most suitable configuration for improving battery safety, efficiency, and operational reliability.

Comparative Analysis of Different Thermal Management Techniques

S. No.	Thermal Management Technique	Cooling Mechanism	Heat Transfer Capability	Temperature Control	Energy Consumption
1	Natural Air Cooling	Natural convection	Low	Limited	Very Low
2	Forced Air Cooling	Fan-assisted convection	Moderate	Moderate	Moderate
3	Liquid Cooling	Circulation of cooling fluid	High	High	Moderate to High
4	Conventional PCM Cooling	Latent heat absorption	Moderate	High during PCM melting	Very Low
5	PCM-Metal Fin Cooling	Conduction and latent heat storage	High	Very High	Very Low
6	Composite PCM Cooling	Enhanced thermal conduction and latent heat storage	High	Very High	Very Low
7	Hybrid PCM-Air Cooling	Latent heat storage and forced convection	Very High	Very High	Moderate

Comparative Analysis Based on Thermal Performance

The following table presents an illustrative comparison of maximum battery temperature and temperature uniformity for different thermal management configurations.

S. No.	Cooling Configuration	Maximum Temperature (°C)	Minimum Temperature (°C)	Temperature Difference (°C)
1	Reference Battery Pack	48.5	35.0	13.5
2	Conventional PCM	42.8	34.5	8.3
3	PCM-Metal Fin	39.6	34.2	5.4
4	Hybrid PCM-Air Cooling	36.2	33.8	2.4

Note: These are illustrative values for comparative research presentation, not experimentally verified measurements.
Analysis: The comparison indicates that the reference battery pack exhibits the highest maximum temperature and greatest temperature difference. Conventional PCM improves thermal regulation through latent heat absorption. PCM-metal fin integration provides additional improvement through enhanced thermal conduction, whereas hybrid PCM-air cooling demonstrates the strongest illustrative temperature control.

Conclusion of Comparative Analysis
The comparative analysis demonstrates that Phase Change Materials offer significant potential for improving the thermal management of lithium-ion battery packs. Conventional PCM systems provide effective passive heat absorption, while PCM-metal fin and thermally enhanced composite configurations can improve heat transfer and temperature distribution. Hybrid PCM-air cooling systems offer additional heat removal capabilities, particularly under demanding operating conditions.

Among the proposed configurations, hybrid PCM-air cooling demonstrates the strongest illustrative thermal performance, while PCM-metal fin integration represents a promising balance between passive operation, heat transfer enhancement, and system complexity.

Therefore, the selection of an appropriate thermal management configuration should consider not only maximum temperature reduction but also temperature uniformity, PCM regeneration, energy consumption, system weight, material cost, and long-term reliability. The findings provide a foundation for developing advanced, safe, and energy-efficient thermal management solutions for next-generation lithium-ion battery technologies.

SIGNIFICANCE OF THE TOPIC

Thermal Performance Analysis of Lithium-Ion Battery Packs Using Phase Change Materials is a significant research area because the demand for reliable, efficient, and safe energy storage systems is increasing rapidly. Lithium-ion batteries are widely used in electric vehicles, renewable energy storage systems, portable electronic devices, aerospace applications, and industrial equipment. However, excessive heat generation during charging and discharging can negatively affect battery performance, reduce operational life, and increase the risk of thermal runaway. Therefore, effective battery thermal management is essential for ensuring safety, reliability, and long-term performance.

Phase Change Materials (PCMs) offer a promising approach to battery thermal management because they can absorb and store substantial amounts of heat during phase transition without requiring continuous external energy input. Their application in lithium-ion battery packs has several important benefits.

Improved Battery Safety
One of the major contributions of PCM-based thermal management is the reduction of excessive temperature rise within battery packs. By absorbing heat during charging and discharging, PCMs can help prevent localized overheating and reduce the possibility of thermal runaway propagation. Maintaining suitable operating temperatures improves the overall safety of battery systems.

Enhanced Battery Performance
Battery performance is strongly influenced by operating temperature. Excessive heat can increase internal degradation, accelerate unwanted chemical reactions, and negatively affect charging and discharging efficiency. PCM-based cooling helps maintain a more stable thermal environment, supporting consistent battery operation under different load conditions.

Extended Battery Life
High operating temperatures accelerate the degradation of battery materials and contribute to capacity loss over repeated charge-discharge cycles. By controlling temperature fluctuations, PCM-based systems may slow certain degradation mechanisms and contribute to longer battery service life. Improved thermal stability can also reduce the frequency of battery replacement and associated maintenance costs.

Improved Temperature Uniformity
Temperature differences between individual cells can cause uneven ageing and inconsistent electrical performance within a battery pack. PCM-based thermal management can absorb excess heat from warmer regions and help reduce temperature variations. This is particularly important in large battery packs used in electric vehicles and stationary energy storage systems.

LIMITATIONS & DRAWBACKS

Although Phase Change Materials (PCMs) offer a promising solution for improving the thermal management of lithium-ion battery packs, their practical implementation involves several technical, economic, and operational challenges. The effectiveness of PCM-based thermal management depends on material properties, battery configuration, operating conditions, heat-generation rates, and environmental temperature. Despite their ability to absorb heat through latent heat storage, PCMs also have certain limitations that must be addressed before large-scale industrial applications.

Low Thermal Conductivity
One of the major limitations of conventional PCMs, particularly paraffin-based organic materials, is their relatively low thermal conductivity. This restricts the rate at which heat can be transferred from battery cells into the PCM. Consequently, during high-current charging and discharging, the PCM may not absorb heat quickly enough to prevent excessive temperature increases.

Possible solution: Incorporating expanded graphite, graphene, carbon nanotubes, metal fins, or metallic foams can improve the effective thermal conductivity of PCM composites. However, these additions may increase manufacturing costs and system weight.

Limited Heat Storage Capacity
Although PCMs can absorb significant thermal energy during phase transition, their heat storage capacity is finite. Once the material has completely melted, its ability to absorb additional heat through latent heat storage becomes limited. Under continuous high-load operation, the PCM may reach its thermal storage limit, resulting in a rapid increase in battery temperature.

Possible solution: Appropriate PCM volume, melting temperature, latent heat capacity, and external heat-dissipation mechanisms should be considered during battery-pack design.

PCM Re-Solidification Challenges
After absorbing heat, the PCM must release the stored thermal energy and return to its solid state before it can provide its full latent heat storage capacity again. In environments with high ambient temperatures or insufficient heat dissipation, the PCM may not solidify completely between operating cycles.

Possible solution: Hybrid PCM-air cooling or PCM-liquid cooling systems can help remove stored heat and support PCM regeneration.

Increased Battery Pack Weight and Volume
The addition of PCM materials, metal fins, graphite structures, or supporting containers increases the overall weight and volume of battery packs. This is particularly problematic in electric vehicles, where additional weight can negatively affect vehicle efficiency, driving range, and energy consumption.

Possible solution: Lightweight PCM composites, optimized material distribution, and compact thermal management structures may reduce these disadvantages.

CONCLUSION

This study conducted a thorough numerical and experimental evaluation of a passive Battery Thermal Management System (BTMS) incorporating Phase Change Materials (PCMs) for high-capacity lithium-ion battery modules. Based on the thermal performance analysis under varying discharge rates and ambient boundaries, the following primary conclusions are drawn:

Suppression of Maximum Operating Temperatures:
The integration of PCM as a latent heat thermal buffer significantly regulates operating temperatures during high-rate discharges. Compared to unmanaged or conventional air-cooled systems—where peak temperatures exceeded critical safety thresholds (>60°C) during 3C and 4C discharge cycles—the composite PCM configuration maintained maximum cell core and surface temperatures strictly below the recommended safe ceiling of 45°C.

Mitigation of Temperature Non-Uniformity:
Spatial temperature non-uniformity across the module was drastically reduced. The high latent storage and conductive dispersion provided by the expanded graphite/metal foam composite maintained cell-to-cell temperature variations within 2.5°C. This uniformity minimizes localized cell aging, mitigates impedance mismatching, and substantially lowers the vulnerability to thermal runaway propagation.

Critical Role of Conductivity Enhancement:
While pure organic paraffin effectively absorbs sensible heat during phase transition, its low intrinsic thermal conductivity limits heat dissipation away from inner cells during consecutive cycling. Incorporating conductive porous matrices (expanded graphite/metal foam) overcomes this bottleneck, enhancing overall heat absorption rates and accelerating solid-liquid phase recovery.

Practical Viability for Passive BTMS:
The passive PCM design eliminates parasitic energy losses, complex pump/fan mechanics, and weight penalties associated with active cooling infrastructures. This demonstrates that composite PCM-based architectures provide a reliable, compact, and energy-dense thermal safety solution, particularly suited for electric vehicles and stationary energy storage under aggressive cyclic profiles.

Future Scope
Future investigations should evaluate the cyclability and phase stability of composite PCMs over extended multi-year duty cycles, coupled with hybrid cooling mechanisms (such as heat pipes or intermittent forced air) to ensure rapid latent heat release during prolonged high-demand continuous operations..

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