

Thermal Management of Electric Vehicle Battery Using Phase Change Material: A Case Study

Honey Dehariya

Student, Department of Mechanical Engineering, Technocrats Institute of Technology and Science (TIT Main), Bhopal, Madhya Pradesh, India

Abstract

Electric vehicles (EVs) rely heavily on lithium-ion batteries, whose temperature strongly affects performance, ageing, efficiency and safety. Heat is generated during battery charging and discharging, and excessive temperature rise can accelerate degradation and increase safety risks. This research presents a case study of battery thermal management using Phase Change Material (PCM). PCM absorbs thermal energy as latent heat during its phase transition and can therefore limit battery temperature rise without continuous mechanical cooling. An illustrative numerical case study compares a representative lithium-ion battery module with and without a paraffin-based PCM layer. Under the selected operating condition, the maximum temperature after 60 minutes is reduced from 55.1 °C without PCM to 41.5 °C with PCM, a reduction of 13.6 °C. The study indicates that PCM can be an effective passive thermal-management approach for transient high-heat-load conditions. However, its low thermal conductivity and finite heat-storage capacity can limit long-duration performance. Hybrid PCM-active cooling and thermally enhanced PCM are therefore promising directions for future EV battery systems.

Keywords: Electric Vehicle, Lithium-Ion Battery, Battery Thermal Management System, Phase Change Material, PCM, Latent Heat, Battery Cooling, Thermal Management, Thermal Runaway, Electric Vehicle Battery.

Introduction

Electric vehicles are increasingly being adopted as an alternative to conventional vehicles because of environmental concerns, energy efficiency and the need to reduce dependence on fossil fuels. The battery is one of the most important components of an EV because it determines vehicle range, power capability, charging behaviour and a significant part of the vehicle cost.

Lithium-ion batteries are widely used because of their high energy density, high power capability and relatively long cycle life. During charging and discharging, however, electrochemical reactions and internal resistance generate heat. If this heat is not effectively controlled, battery temperature can rise and temperature differences can develop between cells.

High temperature can accelerate battery ageing and, under severe conditions, contribute to thermal runaway. Very low temperature can also reduce power and charging performance. Consequently, an effective Battery Thermal Management System (BTMS) is necessary to maintain a suitable temperature range and improve temperature uniformity.

Air cooling, liquid cooling, heat pipes and refrigerant cooling are commonly used BTMS technologies. Phase Change Material offers a passive alternative. When PCM reaches its phase-change temperature, it absorbs heat as latent heat while its temperature changes comparatively slowly. Placing PCM around battery cells can therefore delay temperature rise and reduce peak temperature.

In this study, the thermal response of a representative EV battery is compared for two conditions: without PCM and with PCM. A numerical illustration is provided to demonstrate the expected temperature-control effect.

Literature Review

Pesaran investigated battery thermal management requirements for electric and hybrid vehicles and emphasized the importance of controlling battery temperature. Al-Hallaj and Selman studied thermal behaviour of lithium-based batteries and highlighted the role of thermal control in EV applications.

Khateeb et al. investigated a lithium-ion battery thermal management system using PCM for an electric scooter and demonstrated the potential of latent heat storage to limit battery temperature rise. Mills and Al-Hallaj examined passive thermal management of lithium-ion battery packs and reported the usefulness of PCM-based cooling.

Rao and Wang reviewed power-battery thermal energy management methods, including air cooling, liquid cooling and PCM-based systems. Ling et al. reviewed PCM thermal management for lithium-ion batteries and identified melting temperature, latent heat and thermal conductivity as important design parameters.

Bandhauer et al. discussed thermal issues in lithium-ion batteries and identified heat generation and temperature control as important factors in battery design. Previous research therefore supports PCM as a promising passive thermal-management technology, while also identifying low thermal conductivity and finite heat-storage capacity as important limitations.

Problem Statement

Heat generation during EV battery operation can increase cell temperature and create thermal non-uniformity. Conventional active cooling systems can remove heat effectively but may require pumps, fans, heat exchangers and additional energy. The problem addressed in this case study is to evaluate whether Phase Change Material can reduce battery temperature rise through passive latent-heat absorption.

For the numerical illustration, a representative 48 V, 40 Ah lithium-ion battery module is considered. The initial and ambient temperatures are 25 °C, the representative discharge rate is 2C, and a paraffin-based PCM with a melting temperature of 38 °C, latent heat of 180 kJ/kg and mass of 1.5 kg is considered.

Figure 1 shows the basic thermal-management concept: heat generated in the battery is transferred to the PCM, where part of the thermal energy is absorbed as sensible and latent heat.

PCM-Based EV Battery Thermal Management

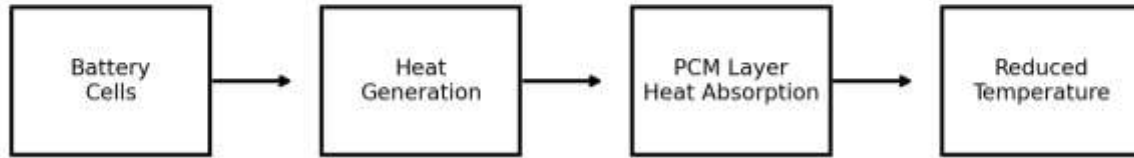


Figure 1. Schematic representation of PCM-based EV battery thermal management.

Results and Discussion

The following values represent an illustrative numerical case study under the assumptions described in Section 6. They are included to demonstrate the research analysis and should be replaced by validated simulation or experimental measurements before being presented as measured research results.

Time (min)	Without PCM (°C)	With PCM (°C)	Temperature Reduction (°C)
0	25.0	25.0	0.0
10	31.2	29.0	2.2
20	37.8	33.1	4.7
30	43.1	36.0	7.1
40	48.0	38.4	9.6
50	52.0	40.2	11.8
60	55.1	41.5	13.6

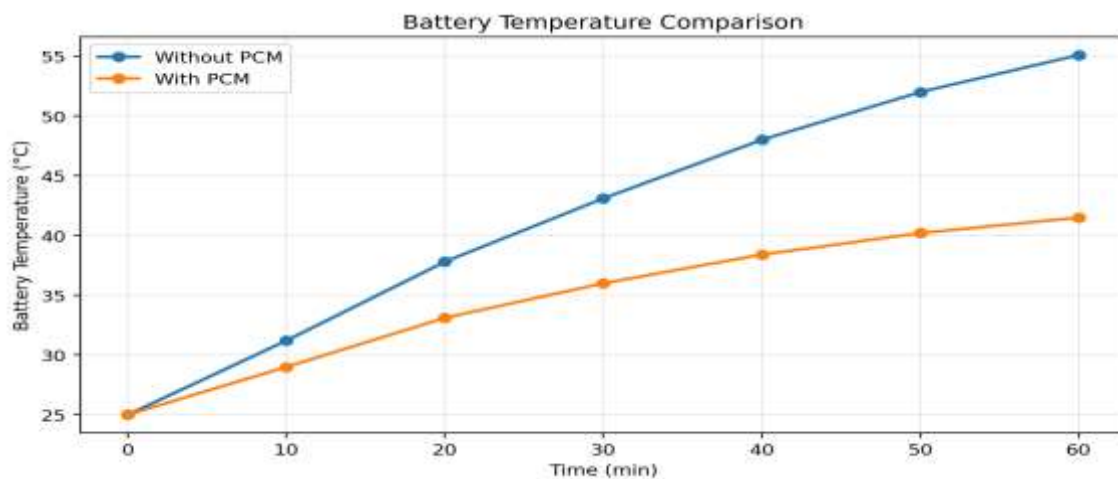


Figure 2. Illustrative battery temperature comparison with and without PCM.

Without PCM, the illustrative battery temperature increases from 25.0 °C to 55.1 °C over 60 minutes. With PCM, the temperature increases from 25.0 °C to 41.5 °C. The difference at 60 minutes is 13.6 °C. The corresponding reduction relative to the no-PCM final temperature is approximately 24.7%. The reduction becomes more noticeable as the PCM approaches its melting temperature. Once phase change begins, a significant portion of the generated heat is stored as latent heat, which slows the battery temperature rise. This behaviour demonstrates the principal advantage of PCM-based passive cooling.

PCM performance depends on melting temperature, latent heat, thermal conductivity and mass. A PCM with an unsuitable melting temperature may not control the battery temperature effectively. Similarly, conventional paraffin PCM has relatively low thermal conductivity, which can limit the rate of heat spreading. Thermally conductive additives such as expanded graphite can improve heat transfer.

At prolonged high-power operation, PCM can eventually become fully melted and its temperature-control capability can decrease. Therefore, PCM is particularly attractive for transient or intermittent high-heat-load conditions, while hybrid PCM-liquid or PCM-air cooling can be considered for continuous high-power operation.

Future Scope

1. Experimental validation of the PCM-based battery thermal model.
2. Investigation of nano-enhanced PCM and expanded-graphite PCM.
3. Optimization of PCM mass, thickness and melting temperature.
4. Development of hybrid PCM-liquid cooling systems for high-power EV batteries.
5. Investigation of fast-charging and high-current operating conditions.
6. Study of PCM performance under different ambient temperatures.
7. Long-term analysis of repeated melting and solidification cycles.
8. Application of artificial intelligence for predictive battery thermal management.
9. Life-cycle, weight and economic assessment of PCM-based battery thermal management systems.

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