

Thermally Self-Regulating Battery Pack for Electric Vehicles

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Abstract

Thermal management plays a vital role in electric vehicle battery systems. It affects system performance, safety, life, and charge rate. This paper presents a study on a self-regulating electric vehicle battery pack that incorporates a novel hybrid thermal management system. It comprises a phase change material (PCM), a liquid coolant system, a temperature measurement system, and a control unit. This innovative system provides a combination of a passive system that utilizes a phase change material to buffer temperatures and an active system that utilizes a water-glycol coolant system to regulate temperatures. A thermal model of the system has been developed to simulate its behavior under various conditions. It considers heat generation, latent heat absorption, and convection heat transfer. This system can be implemented using a microcontroller. The experimental results show that the system can decrease the peak battery temperature by 8-12°C compared to the conventional air-cooled method, while maintaining a cell temperature variation of 2-3°C. The proposed hybrid cooling system can improve the thermal uniformity of the cells, increase the rate of heat dissipation, and maintain the battery at an optimal working range of 25-35°C. In addition, the system can reduce thermal stress, enhance safety, and increase energy efficiency by achieving moderate auxiliary power consumption. In summary, the experimental results prove that the proposed thermally self-regulating battery pack can be an effective, scalable, and energy-efficient solution for advanced thermal management of EV batteries.

Keywords: Electric Vehicles, Battery Thermal Management System (BTMS), Phase Change Materials, Lithium-Ion Battery, Thermal Regulation, Energy Efficiency, Temperature Control.

1. Introduction

The increasing global sales of Electric Vehicles (EVs) led to a significant focus on battery performance. Presently, Lithium-ion (Li-ion) batteries are the preferred option due to their high energy density, greater cycle life, and low mass [2]. However, it has been noticed that the performance of batteries, as well as their reliability and lifespan are heavily dependent on their operating temperature. The loss of storage capacity and decline in battery efficiency due to repeated heating and cooling was observed when the battery was subjected to high current charge–discharge cycles, because of the undesirable thermal runaways [8].

Recently, research on passive and hybrid cooling technologies is rapidly growing, aiming to improve thermal performance while saving energy consumption. Phase change materials (PCMs) is one popular option because of its large latent heat storage capacity and energy efficiency. PCM can absorb excess heat generated in the system during its phase change, thus avoiding heating up the system and the need for energy-intensive systems such as air conditioning [1]. However, the standalone system using PCM alone has its own limitations and drawbacks including low thermal conductivity, which is one of the drawbacks, especially during long periods of high heating or high cooling loads [7].

High-temperature warning and restriction on battery charging are encountered with lithium-ion batteries, due to overheating risks occurring during rapid charge and high-current discharge. Thermal runaway can be initiated due to these factors and lead to battery failure. Therefore, applying a thermal regulation system to lithium-ion batteries has become necessary to meet required performance and safety standards. Because the conventional forced air cooling method is inadequate to meet increasing power demands due to higher battery energy density and the larger dimensions of battery packs, the use of hybrid thermal management schemes that combine phase change materials with active liquid cooling has been proposed [6]. In these schemes, a phase change material is used as a thermal storage material to absorb surge charge currents, while active liquid cooling is employed to continuously remove the heat and ensure uniform temperature of the battery cells [12].

By using the Hybrid Thermal Management System (Hybrid TMS) the overall heat transfer of the battery is significantly improved while the temperature of the battery is kept within certain limits even during high current discharging (high-speed driving) and fast charging processes. A thermally self-regulating battery pack using passive and active cooling concepts can be adapted to changing thermal conditions. The battery module includes hybrid PCM materials and a temperature controlled liquid loop in order to keep the temperature between cells low and to prevent thermal runaways from occurring. The proposed solution reduces the auxiliary power consumption of the battery system compared to fully active cooling concepts. This leads to a higher overall efficiency of the vehicle.

Additionally, a balanced temperature distribution in the battery pack is known to affect electrochemical performance, lifespan, and safety directly [3]. A self-regulating hybrid cooling approach ensures balanced conditions, thereby increasing battery lifespan. This is crucial in developing markets such as India for EVs, considering the high ambient temperature. A hybrid approach is essential in developing markets such as India for EVs, considering the high ambient temperature.

The proposed system is based on structural integrations and scalability for easy application in EVs. The proposed hybrid PCM-liquid cooling system is designed to be modular, ensuring easy integration into existing battery pack structures without significant modification to the battery management system (BMS) architecture. The selection of PCM based on melting temperature, latent heat capacity, and thermal conductivity enhancer ensures efficient heat absorption under transient peak load conditions. At the same time, optimized liquid flow channels enable efficient heat removal from the PCM, returning it to its original phase under low-load operating conditions.

A thermally self-regulating battery pack concept based on a hybrid structure of Phase Change Materials (PCMs) and liquid cooling for the Electric Vehicles (EVs) is introduced. In comparison with existing solutions, the proposed structure has features of higher safety, lower power consumption, longer lifespan and better temperature management. The performance of the concept is studied by simulation, analysis and comparison. The work highlights the innovative aspect of combining passive thermal buffering with PCMs and active liquid cooling, while enabling adaptive control with lower power consumption and higher temperature homogeneity in comparison with existing solutions.

2. Existing Systems

Battery thermal management systems (BTMS) in EVs play a key role in maintaining the temperature of lithium-ion battery packs, as they are sensitive to temperature changes. These systems help avoid capacity loss and safety risks by using special cooling systems. Air-cooling is a traditional method of battery thermal management in EVs, which makes use of ambient and forced air for battery cooling. It is characterized by its light weight, cost-effectiveness, and ease of maintenance. However, this method is less efficient in battery thermal management systems, as it is based on the low thermal conductivity of air, causing uneven distribution of heat in batteries. Liquid-cooling systems have become highly popular in recent EVs, as they help in improving battery thermal management systems by using liquid-based coolants like water-glycol solutions for efficient battery thermal management. Tesla, Inc., a market leader in EVs, makes use of liquid-cooling systems for efficient battery thermal management systems. Although liquid-cooling systems help in improving battery thermal management systems, they also contribute to increased weight, cost, and energy consumption. Indirect refrigerant-based battery thermal management systems are also used in some vehicles, along with the air conditioning unit [9].

On the other hand, the use of refrigerant-based cooling systems for electric vehicles (EVs) involves the use of specialized cooling plates to cool the batteries. An example of an EV using such a system is the Nissan Leaf. Although the system is effective in cooling the batteries, it is also associated with increased system complexity due to the presence of various system components. Passive cooling systems have been proposed for low-power EVs by using heat sinks. However, the cooling capacity of the passive system is low [8].

Phase Change Materials (PCMs) are employed in some research-based thermal management systems, which use passive thermal buffering by absorbing excessive heat through phase changes in the PCM. This prevents excessive increases in temperature. Nonetheless, such systems are characterized by low thermal conductivity, which slows down the dissipation of heat after the PCM has changed phase. This reduces their capacity to manage high-power operation without the use of other techniques. In most systems, thermal management can be efficiently controlled by the Battery Management System (BMS), which regulates the temperature sensors and the coolants. Although such an electronic system increases safety by preventing overheating, it does not solve the issue of thermal management.

Moreover, the cyclic use of coolants such as pumps, fans, and compressors increases power losses, reducing the efficiency of the vehicle [10].

Overall, it can be concluded that the existing battery thermal management systems in EVs are mostly based on air cooling, liquid cooling, or active cooling technologies. Although these systems ensure battery safety during operation at an acceptable level, they are still facing certain issues related to non-uniform temperatures, energy consumption, complexity in design, etc. This again emphasizes the need to design a sophisticated thermally self-regulating hybrid cooling system that can effectively utilize both passive and active cooling technologies to enhance battery performance.

2.1 Research Gap

Although considerable advancements have been achieved in air cooling, liquid cooling, refrigerant-based cooling, and PCM-based battery cooling technologies for EVs, an apparent research gap exists for the development of an energy-efficient, compact, and self-regulating battery thermal architecture for EVs. In existing battery cooling technologies, active cooling dominates the cooling mechanism, which not only increases power consumption but also complicates the cooling system. In the case of passive cooling technologies based on PCM-based battery cooling, low thermal conductivity and low efficiency for long-term battery cooling are apparent issues. In existing literature, considerable emphasis has been placed on reducing battery temperature peaks rather than considering temperature distribution and adapting to changing battery loads for long-term battery reliability. Limited emphasis has been placed on the integration of hybrid cooling technologies based on PCM and liquid cooling for battery thermal management.

3. Proposed Methodology

The proposed methodology designs a thermally self-regulated EV battery pack by incorporating the hybrid phase change material into the active liquid cooling system within the modular battery architecture. First, an appropriate phase change material is chosen with an optimal phase change temperature of 20°C to 40°C and thermal conductivity enhancers. The phase change material is integrated uniformly around the cylindrical or prismatic lithium-ion battery cells. At the same time, an active liquid cooling system is designed with optimized flow

channels and a compact heat exchanger to remove the built-up heat from the phase change material and the battery cells.

3.1 System Overview

The thermally self-regulating battery pack system will use lithium-ion cells arranged in a modular configuration and will integrate both PCM and liquid cooling channels to create a hybrid cooling architecture. The PCM layer will surround each individual cell or module with a uniform thickness of PCM material to absorb heat that is generated while discharging at high rates and charging rapidly (through the use of latent heat) thus allowing for passive thermal buffering and reducing the rapid increase in temperature as well as thermal gradients between cells.

The implementation of a network of liquid-cooled plates or micro-channels within the modular structure will also provide ongoing cooling for the cells. The elements of the cooling loop, pump, coolant reservoir, and compact heat exchanger will dissipate heat from the cells into the ambient environment achieving uniform temperature distribution through a combination of passive/active means.

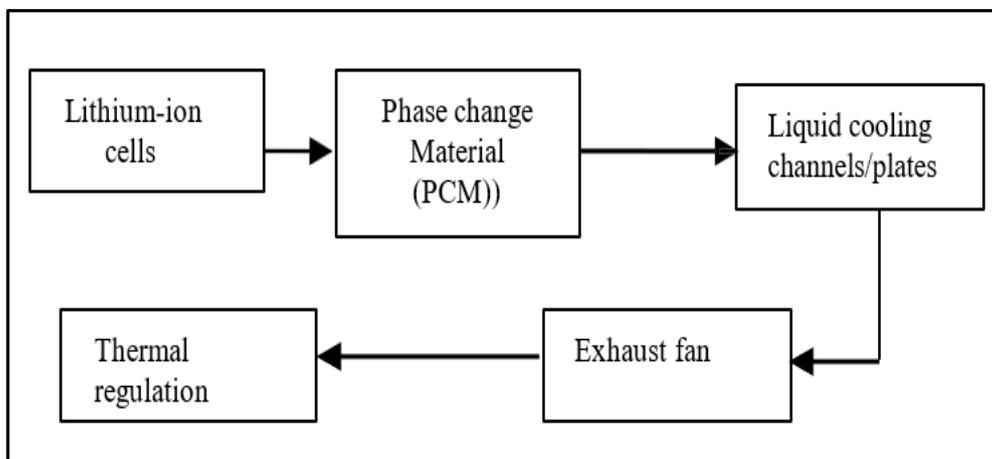


Figure 1. Hybrid PCM-Liquid Cooling Battery Pack Architecture

Lithium-ion cells are the main source of energy for the battery pack of an electric vehicle (EV), as depicted in figure 1, the electrochemical reactions that create electricity while charging and discharging the batteries produce heat. The amount of heat produced is based on how much current is flowing through the battery as well as its internal resistance. Charging and discharging batteries under high-load conditions (for example, when rapidly accelerating or charging quickly) produce significant amounts of thermal energy. If there is inadequate control

over this thermal energy, then performance will decline, cell aging will not be uniform, and there will be a risk to safety. Thus, the heat produced by the cells has to be effectively controlled at the earliest stages of manufacture.

The first level of thermal management can be achieved by the PCM layer that encases the battery cells. In the PCM, the excessive heat can be absorbed by the phase transition of the PCM from a solid to a liquid state at a predetermined melting range. This absorption of latent heat prevents the cells from increasing in temperature too quickly. This phenomenon of absorbing latent heat does not involve any electrical input and thus can be regarded as a passive thermal management system.

The overall thermal resistance of the battery pack is modeled as:

$$R_{\text{total}} = R_{\text{cell}} + R_{\text{pcm}} + R_{\text{coolant}}$$

Minimizing thermal resistance improves heat dissipation and temperature uniformity across battery cells.

3.2 Heat Transfer

The heat transfer in the thermally self-regulating battery pack commences with the conduction of heat from the core of the lithium-ion cell to the outer surface of the cell via conduction. The generation of heat in the cell occurs due to electrochemical reactions and internal resistance of the cell during operation. If the heat is not dissipated, there will be an increase in temperature and non-uniform distribution of heat in the cells. In the next step of the thermally self-regulating battery pack, conduction of heat occurs in the phase-change material (PCM) that covers the cells. In this step, the heat transfer from the outer surface of the cell to the PCM occurs via conduction. When the PCM reaches its melting point, there is a significant absorption of heat in the PCM during the phase change from a solid to a liquid state.

The heat generation inside lithium-ion batteries is calculated using:

$$Q = I^2R + IT \frac{dE}{dT}$$

where Q is heat generation (W), I is current (A), R is internal resistance (Ω), T is temperature (K), and $\frac{dE}{dT}$ represents the entropy coefficient.

This model includes both irreversible (Joule heating) and reversible heat generation, thus enabling the precise prediction of thermal response under different load conditions.

3.3 Communication Protocol

The integrated temperature sensors, fluid pump, and exhaust fan are connected via an embedded control interface controlled by the Battery Management System (BMS). The temperature sensors continually measure the temperature of the battery module and send data in real-time via standard serial communication protocols, including I²C and CAN bus (widely used in automotive electronic systems), to the controller. Based on predetermined thermal thresholds and control logic, the BMS generates control signals that actuate the fluid pump and regulate the flow rate of coolant, as well as control the operation of the exhaust fan based on the amount of required heat dissipation. The control signals from the BMS may include pulse-width modulation (PWM) to allow for varying pump speed or fan speed for thermally-adaptive operation. Through the use of closed-loop communications, the BMS provides efficient thermal management, reduces energy consumption, and maintains stable operating temperatures of the batteries during the dynamic operation of the vehicle or when charging.

4. Hardware Implementation

The hardware implementation of the thermally self-regulating battery pack, as shown in Figure 2, includes the integration of temperature sensors, microcontrollers, PCM units, liquid cooling systems, pumps, and exhaust fans into the structure of the battery pack. These temperature sensors, such as thermistors or digital thermal sensors, are installed at critical points within the battery module to track variations in temperature in real-time.

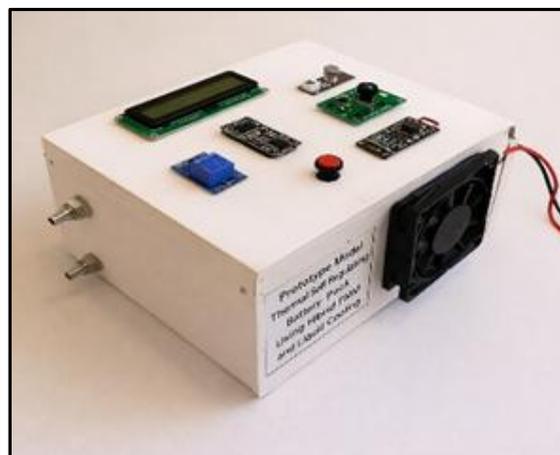


Figure 2. Hardware Prototype

4.1 Microcontroller Unit

Microcontroller Unit is the main processing unit of the thermally self-regulating battery pack system. It receives the real-time temperature data from the sensor inputs and processes the data to ensure the battery temperature is kept within the safe range. It processes the input signals and produces output signals to control the operation of the coolant pump and exhaust fan using PWM signals. In the present work, a low power embedded system controller like Arduino-based microcontroller board may be suitable for the implementation of the system due to its simplicity.

4.2 Sensor Integration

Sensor integration holds a significant position in the thermally self-regulating battery pack by offering the facility of monitoring temperature changes in real time within the battery module. Temperature sensors are integrated in such a manner that they are in proximity to the battery cells, PCM layer, and the cooling channels. These temperature sensors are utilized to monitor the thermal conditions of the system during charging, discharging, and idle conditions.

The system employs precision temperature sensing equipment such as thermistors, digital thermal sensors, or semiconductor-based temperature monitoring chips. High-precision temperature sensing equipment from semiconductor manufacturers such as Texas Instruments can be utilized for reliable thermal detection and signal processing with minimal signal noise. These types of equipment offer improved response time and stability in measurement conditions under dynamic load conditions. The signal from the sensor can be transmitted to the microcontroller or BMS via wired communication media such as I²C, SPI, or analog voltage signals. The signal transmission protocol can vary based on system requirements, signal transmission rates, and signal immunity from noise. Signal conditioning circuits can be implemented to enhance the measurement conditions.

Table 1 outlines the integration of sensors to detect faults and prevent thermal runaway. The control unit activates cooling (pumps and/or exhaust fans) when the temperature exceeds a preset safety limit. By utilizing multiple sensors, engineers can monitor the battery pack temperature evenly throughout the entire assembly. Using a distributed sensing architecture will allow engineers to identify temperature hotspots and temperature imbalances between cells within the battery pack. The thermal issues caused by non-uniform heating of batteries will be

particularly important in high-power EV applications where thermal variation may shorten the life of the battery.

During the hardware setup, calibration of each sensor will be performed to reduce measurement errors and improve the long-term reliability of the sensors. Periodic calibration will help maintain accurate temperatures in the batteries even after exposure to vibration, humidity, and temperature fluctuations. Each sensor will also be securely attached to the battery to ensure that the sensor's readings will not be distorted during vehicle motion. Sensors will be operated using the minimum amount of power possible to reduce the energy consumption of the auxiliary system (electric vehicle). The selection of advanced, low-power sensors will be based on sensitivity, suitable operating temperature range, and viable power efficiency. The performance of the overall EV system will be enhanced by the use of advanced, low-power sensors across the entire battery pack system.

Overall, the sensor integration plays a significant role in increasing the intelligence of the thermal management system in that it allows for adaptive control of the cooling, safety monitoring, and energy efficiency. This is significant in the development of a thermally self-regulating battery pack for use in electric vehicles.

Table 1. Sensors Used and Measured Parameters

Measured Parameter	Sensor Module
DS18B20 Digital Temperature Sensor	Battery cell temperature
ACS712 Current Sensor Module	Current measurement
ZMPT101B Voltage Sensor Module	Pack voltage monitoring
YF-S201 Water Flow Sensor	Flow rate in liquid cooling channel
HFS-4 Heat Flux Sensor	Heat transfer rate
DHT22 Temperature and Humidity Sensor	External humidity
Multiple DS18B20 sensors networked	Distributed temperature monitoring

4.3 BTMS Module

Battery Thermal Management System (BTMS) is a module designed for maintaining the temperature of the EV battery pack within a specific range of safety. It does this by using passive and active cooling systems. It is a compact structure that encloses the battery cells and

includes PCM, liquid channels, sensors, and control systems. The temperature data is collected from DS18B20 Digital Temperature Sensor and is processed by the microcontroller unit. Once it is determined that excessive heat is present, the coolant is circulated by using a pump control and heat dissipation through convective and conductive heat transfer.

4.4 Power Supply and Interfacing

A stable DC power supply is necessary for ensuring proper and stable operation of the thermal management control circuit. Voltage regulation is done by using linear and switching regulators, such as the "LM7805 Voltage Regulator." It provides a constant 5V DC supply for low-voltage electronic components. High-quality voltage regulators in integrated circuit form from companies like "STMicroelectronics" are used for better efficiency and less electrical noise in the control circuit. Processing boards from "Raspberry Pi Foundation" and similar embedded systems can be used for signal processing and actuator control. Grounding, shielding, and filtering techniques are used for minimizing electromagnetic interference and ensuring stable performance.

4.5 Enclosure and Physical Integration

The thermally self-regulating battery pack casing is designed for mechanical strength, thermal conductivity, and protection from environmental factors. The battery cells, PCM layer, and electronic control modules are accommodated in a casing made of a lightweight material such as an aluminium alloy and high-strength polymer composite material. The design is in accordance with safety and mechanical reliability requirements for automotive applications. The physical integration of components is achieved by arranging the battery cells, sensors, and cooling components in a compact modular structure for efficient heat transfer and minimizing system size. The components' accurate mounting, component-cell spacing, and optimized routing of the coolant pipeline enable efficient thermal regulation.

5. Software Implementation

The software development for the system (shown in Figure 3) was done using embedded programming techniques so that there could be reliable communications among the temperature sensors, controller unit and actuators (e.g., pump, exhaust fan). The controller program is written within the development environment of the Arduino or compatible embedded software package. This software is responsible for initialising the sensor interfaces,

defining the input/output ports, and establishing communications between the battery temperature sensors and the controller unit to monitor actual thermal conditions inside of the battery during operation in real-time. The developed thermal model for the battery temperature can be validated using finite element simulation tools such as ANSYS or COMSOL Multiphysics. It is important to include the following in the simulation results: temperature contour plots, transient thermal response, and a comparison between the predicted and experimentally measured data during operation.

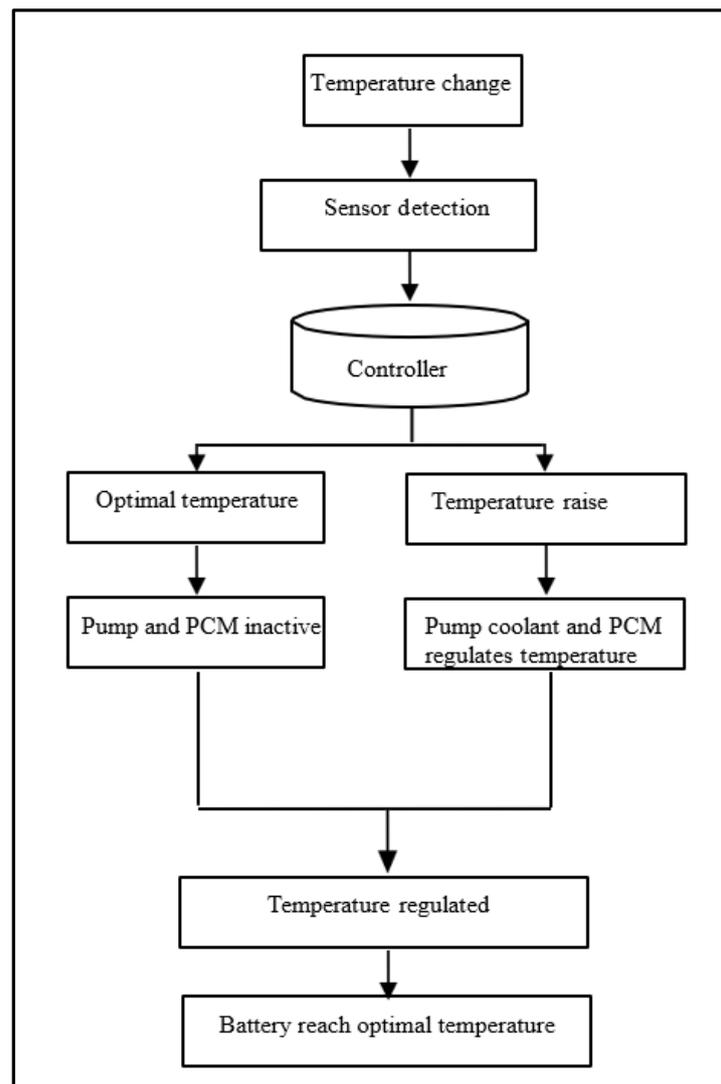


Figure 3. Thermal Regulation Process of the Proposed System

5.1 Firmware Implementation

The sensor module constantly keeps track of the battery's temperature and sends digital signals to the microcontroller using I²C or UART serial communication. The microcontroller

processes the data received from the sensors using thermal threshold algorithms that include filtering and data validation to ensure accurate data. Depending on the data received from the sensors related to battery temperatures, the system sends commands to operate the cooling system. If the temperatures are too high, it activates the coolant pump to circulate coolant through the cooling system. If temperatures increase further, it activates the exhaust fan to increase cooling. It uses Pulse Width Modulation (PWM) to increase the speed of the coolant pump and exhaust fan depending on the temperatures in the battery module, which reduces power consumption and prevents any drastic change in temperatures in the battery module. It also includes safety delays to avoid unnecessary operation of mechanical systems.

5.2 Controller Working

The controller can be designed using an embedded platform like Arduino, which can be considered a central processing unit of the thermal management system. It can receive data related to temperatures from various sensors and compare it with certain threshold limits to ensure proper battery operation. The data received can be processed to generate a control signal to operate the cooling systems. The pump configuration can be used to circulate coolant fluid through the liquid cooling system to remove excess heat generated in the battery pack. The exhaust fan configuration can be used to enhance heat dissipation from the heat exchanger to the surroundings. This can be achieved by circulating air around the battery enclosure. The fan can operate based on PWM or digital switching signals depending on certain temperature conditions.

The thermal control system operates based on threshold-based feedback logic:

- If $T < 30^{\circ}C \rightarrow$ Cooling OFF
- If $30^{\circ}C \leq T < 40^{\circ}C \rightarrow$ Pump ON (low speed)
- If $T \geq 40^{\circ}C \rightarrow$ Pump + Fan ON (high speed)

This adaptive control reduces energy consumption while maintaining safe thermal limits.

5.3 Working of Phase Change Material

The PCM is also utilized in battery thermal management systems for storing and releasing heat through phase change material transitions. In most cases, paraffin wax and salt hydrates are considered suitable materials for use in thermal management systems owing to

their latent heat storage capacity and stability. However, the choice of a suitable PCM material is determined by its melting point, thermal conductivity, and energy absorption properties corresponding to EV battery operation conditions. In thermal management systems, the PCM stores latent heat during situations of increased battery temperature, resulting in phase change from solid to liquid states and effectively managing thermal stress on EV batteries. However, during situations of reduced temperature, the PCM releases heat during solidification, thus maintaining thermal balance in EV batteries. The use of paraffin wax and composite material is considered highly efficient owing to its maximum heat storage capacity and suitable melting points for managing heat during varying temperature conditions [11].

The heat absorbed by PCM during phase transition is given by:

$$Q_{pcm} = m \cdot L$$

where m is the mass of PCM (kg) and L is the latent heat of fusion (kJ/kg). The transient heat conduction in PCM is governed by:

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T$$

This equation models temperature distribution and phase transition behavior within the PCM layer.

5.4 Coolant Temperature Management

The coolant used in the system is a mixture of water and glycol. This coolant mixture is mostly used in electric vehicle thermal management systems because of its high capacity to absorb heat, low freezing point, and high thermal stability [5]. The coolant circulates through micro-channel liquid cooling plates to dissipate excess heat generated in battery cells and layers of PCM. The capacity of the proposed system to manage heat can be used to keep the battery cells in a range of optimal temperatures between 20°C to 40°C under varying loads. The proposed system combines both passive and active cooling systems to ensure proper temperature uniformity in battery packs.

The convective heat transfer rate in the liquid cooling system is expressed as:

$$Q = hA(T_s - T_f)$$

where h is the convective heat transfer coefficient, A is surface area, T_s is surface temperature, and T_f is fluid temperature.

The coolant heat removal capacity is calculated as:

$$Q = \dot{m}c_p(T_{\text{out}} - T_{\text{in}})$$

where \dot{m} is mass flow rate (kg/s).

6. Results and Discussion

The testing setup for the thermally self-regulating battery pack was implemented in a laboratory-scale prototype for the battery cells, PCM enclosure, liquid cooling channels, sensors, microcontroller unit, pump, and exhaust fan assembly. Testing for the battery pack was implemented in a controlled environment for simulating various operating conditions such as normal discharge, high discharge, and fast charging conditions. Real-time temperature variation inside the battery module was implemented for temperature sensors such as DS18B20 Digital Temperature Sensor. The controller platform for the battery management system implemented Arduino for controlling the battery pack.

The system performance is evaluated using:

Temperature uniformity:

$$\Delta T = T_{\text{max}} - T_{\text{min}}$$

Thermal efficiency:

$$\eta = \frac{Q_{\text{removed}}}{Q_{\text{generated}}} \times 100$$

Cooling effectiveness:

$$\epsilon = \frac{T_{\text{in}} - T_{\text{out}}}{T_{\text{in}} - T_{\text{ambient}}}$$

These metrics quantify thermal stability and cooling performance.

The experimental results, as shown in Fig 4 and 5, verified that the hybrid PCM-liquid cooling system could keep the battery temperature within a safe range. The proposed hybrid

cooling system could reduce the battery maximum temperature and improve temperature uniformity compared to conventional passive cooling. The water-glycol coolant circulation system showed efficient heat removal capacity, verifying the performance of the proposed hybrid cooling system. The testing result verifies that the proposed hybrid cooling system improves thermal safety, energy efficiency, and reliability for EV battery packs.

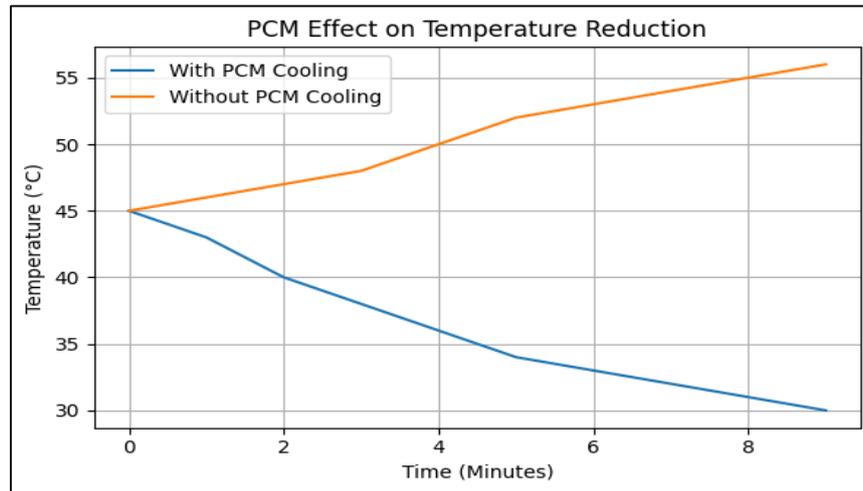


Figure 4. Effect of PCM on Battery Temperature

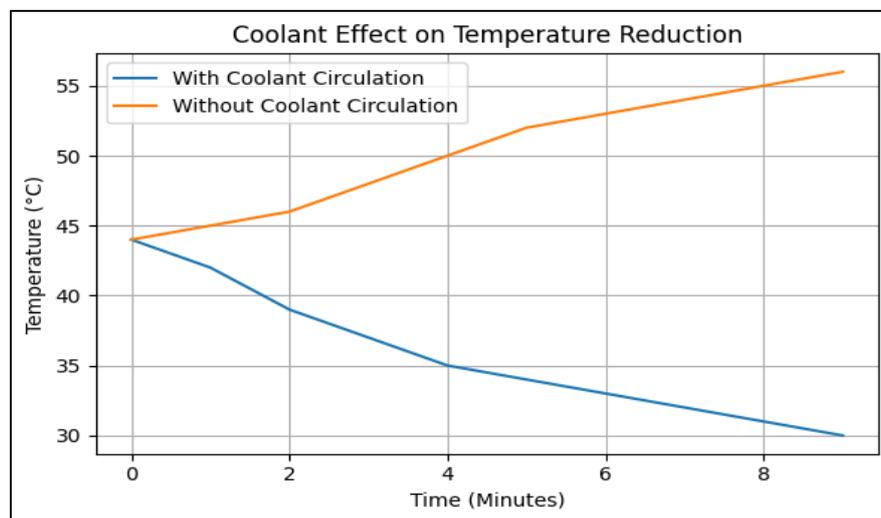


Figure 5. Effect of Coolant Flow on Battery Temperature

The experimental results of the proposed hybrid PCM and liquid cooling battery thermal management system showed significant improvements in terms of temperature control and uniformity. In terms of high charge/discharge cycles, the proposed system reduced the maximum battery temperature by 8-12°C compared to conventional air-cooling systems, while maintaining the cell temperature variations at 2-3°C. In addition, the phase-change material was effective in absorbing the peak thermal load during high rates of heating, while the liquid

coolant was effective in removing the stored thermal energy, thus maintaining the stable operation within the optimal range of 25-35°C. This confirms the effectiveness of the thermally self-regulating system.

Table 2. Comparative Performance Analysis

Parameter	Air Cooling	PCM	Hybrid PCM + Liquid
Peak Temperature	High	Medium	Low
Uniformity	Poor	Moderate	High
Energy Consumption	Low	Very Low	Moderate
Efficiency	Low	Medium	High

The table 2 provides a comparative evaluation of various battery thermal management techniques based on their performance characteristics. In air cooling, the peak temperature and non-uniform temperature are high due to low heat transfer capacity. In the PCM-based cooling system, the temperature can be controlled by the latent heat absorption capacity of the PCM material. However, the heat dissipation capacity is low. In the proposed cooling system, the performance characteristics are high with low peak temperature, high temperature uniformity, and high thermal efficiency with moderate energy consumption.

7. Conclusion and Future Scope

The proposed thermally self-regulating battery pack design, incorporating hybrid phase change materials and liquid cooling, is successful in enhancing the thermal stability, safety, and efficiency of the battery systems in electric vehicles. Experimental validation of the proposed battery cooling system is conducted, showing the reduction in peak temperature and efficient heat dissipation. This is in accordance with the thermal safety guidelines for automotive applications. A promising battery cooling system for the next generation of electric vehicle battery systems is developed. Thermal runaway is avoided, and battery lifespan is maximized for sustainable electric mobility. The future scope of this research is to incorporate smart control for battery cooling using AI and IoT for predictive control. New advanced materials for high conductivity phase change materials and optimized designs for micro-channel cooling can be developed for efficient heat transfer. This battery cooling system can be implemented for high-capacity battery packs for electric vehicles for safety, performance, and sustainable mobility. Research can be conducted for advanced battery cooling technologies

such as solid-state battery cooling and airflow optimization. This battery cooling system can be integrated with advanced battery management systems for efficient battery cooling and reliability.

References

- [1] Awasthi, Anchal, Neelkanth Nirmalkar, and Anurag Kumar Tiwari. "A Review of PCM Based Hybrid Battery Thermal Management Systems for the Prismatic Lithium-Ion Batteries of the Electric Vehicle." *Future Batteries* 5 (2025): 100035.
- [2] Hwang, Foo Shen, Thomas Confrey, Colin Reidy, Dorel Picovici, Dean Callaghan, David Culliton, and Cathal Nolan. "Review of Battery Thermal Management Systems in Electric Vehicles." *Renewable and Sustainable Energy Reviews* 192 (2024): 114171.
- [3] Liu, Hongkai, Chentong Shi, Chenghao Liu, and Wei Chang. "A Review of Lithium-Ion Battery Thermal Management Based on Liquid Cooling and Its Evaluation Method." *Energies* 18, no. 17 (2025): 4569.
- [4] Wazeer, Adil, Apurba Das, Chamil Abeykoon, and Arijit Sinha. "Phase Change Materials Employment for Battery Thermal Management System in Electric and Hybrid Vehicles: A Review." Available at SSRN 4134185 (2022).
- [5] Garud, Kunal Sandip, Le Duc Tai, Seong-Guk Hwang, Nghia-Huu Nguyen, and Moo-Yeon Lee. "A Review of Advanced Cooling Strategies for Battery Thermal Management Systems in Electric Vehicles." *Symmetry* 15, no. 7 (2023): 1322.
- [6] Hyun, Su Woong, Jae Hyuk Kim, and Dong Ho Shin. "Hybrid PCM–Liquid Cooling System with Optimized Channel Design for Enhanced Thermal Management of Lithium–Ion Batteries." *Energies* 18, no. 18 (2025): 4996.
- [7] Chen, Huafu, Gaosheng Wei, Li Xu, and Xiaoze Du. "Performance Study on a Novel Hybrid Thermal Management System for Cylindrical Lithium-Ion Battery Pack Based on Liquid Cooling and PCM." *Applied Thermal Engineering* 271 (2025): 126392.
- [8] Akkus, Ferhat, and Mehmet Zerrakki Isik. "A Review of Thermal Management Systems of Lithium-Ion Batteries Used in Electric Vehicles." *Journal of Traffic and Transportation Engineering (English Edition)* (2025).

- [9] Fu, Ping, Lan Zhao, Xuguang Wang, Jian Sun, and Zhicheng Xin. "A Review of Cooling Technologies in Lithium-Ion Power Battery Thermal Management Systems for New Energy Vehicles." *Processes* 11, no. 12 (2023): 3450.
- [10] Ashwin Ramanathan, Y., G. Anuradha, Harish Rajan, and R. Lakshmi Sriman. "Battery Thermal Management System Using Nano Enhanced Phase Change Materials." In *IOP Conference Series: Earth and Environmental Science*, vol. 850, no. 1, IOP Publishing, 2021, 012031.
- [11] Zhao, Yanqi, Boyang Zou, Tongtong Zhang, Zhu Jiang, Jianning Ding, and Yulong Ding. "A Comprehensive Review of Composite Phase Change Material Based Thermal Management System for Lithium-Ion Batteries." *Renewable and Sustainable Energy Reviews* 167 (2022): 112667.
- [12] Lyu, Zhipeng, Jinrong Su, Zhe Li, Xiang Li, Hanghang Yan, and Lei Chen. "A Compact Hybrid Battery Thermal Management System for Enhanced Cooling." *arXiv preprint arXiv:2412.00999* (2024).