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Passive Cooling of EV Batteries Using Phase Change Material: A Simulation Study

Anant Sidhappa Kurhade[1]*, Gulab Dattrao Siraskar[2], Sagar Arjun Dalvi[3], Pallavi Vishnu Kharat[4], Nilesh Ambaji Jadhav[5], Varsharani Dilip Shelkande[6], Govindarajan Murali[7], Shital Yashwant Waware[1] and Rahul Shivaji Yadav[8]

[1]Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Sant Tukaram Nagar, Pimpri, Pune - 411018, Maharashtra, India; a.kurhade@gmail.com
[2]Department of Mechanical Engineering, PCET's Pimpri Chinchwad College of Engineering and Research, Ravet, Pune - 412101, Maharashtra, India
[3]Department of Mechanical Engineering, Abhinav Education Society's College of Engineering and Technology (Degree), Wadwadi, Satara - 412801, Maharashtra, India
[4]Civil Engineering Department, Ajeenkya D Y Patil School of Engineering, via Lohegaon, Charoli Budruk. Pune - 412105, Maharashtra, India
[5]Department of Mechanical Engineering, Anantrao Pawar College of Engineering and Research, Parvati, Pune - 411009, Maharashtra, India
[6]Department of Electronics and Telecommunication Engineering, Dr D. Y. Patil Institute of Technology, Pimpri, Pune - 411018, Maharashtra, India
[7]Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation Green Fields, Vaddeswaram, Guntur (Dt) - 522502, Andhra Pradesh, India
[8]Department of Mechanical Engineering, Marathwada Mitramandal's College of Engineering, Karvenagar - 411052, Maharashtra, India

Abstract

The escalating global concerns regarding environmental degradation and climate change are accelerating the shift towards renewable energy sources. Traditional gas-powered vehicles, significant contributors to air pollution and global warming are being increasingly replaced by Electric Vehicles (EVs) as a more sustainable transportation solution. However, one significant challenge associated with EVs is the thermal management of their batteries. To address this issue, this study employed computer simulations to evaluate a passive cooling system for EV batteries, utilising a special material known as a Phase Change Material (PCM). The system's performance was assessed under three different power discharge rates. The results demonstrated that the PCM-based cooling system effectively reduced the maximum temperature increase in the battery by 1-2% compared to an unprotected battery. This indicates that the system efficiently dissipates heat from the battery, thereby improving its overall performance and lifespan.

Major Findings: *1. Effective Thermal Management: The study demonstrates the effectiveness of a PCM-based cooling system in reducing the maximum temperature rise in lithium-ion battery cells, particularly under high discharge rates. 2. Improved*

**Author for correspondence*

Battery Performance and Lifespan: By effectively dissipating heat, the PCM cooling system contributes to improved battery performance and extended lifespan. 3. Potential of Parallel Cell Configurations: The study suggests that parallel cell configurations may offer superior thermal performance compared to series configurations, although further research is needed to validate this finding.

Keywords: *Battery Lifespan, Battery Performance, Battery Thermal Management, Climate Change, Electric Vehicles, Passive Cooling, Phase Change Material, Renewable Energy, Simulation, Temperature Reduction*

1.0 Introduction

In recent years, the world has witnessed a growing concern over environmental degradation and climate change. As a result, there has been a significant shift towards sustainable practices and technologies. One such area where this shift is particularly evident is the transportation sector. Traditional gas-powered vehicles, long recognised as major contributors to air pollution and global warming, are increasingly being replaced by EVs. While EVs offer a promising solution to reduce carbon emissions, they present unique challenges, one of which is the thermal management of their batteries. Battery temperature plays a crucial role in determining the overall performance and lifespan of an EV. Excessive heat can lead to reduced battery capacity, increased degradation and even safety risks. To mitigate these challenges, this study explores the potential of a passive cooling system utilising PCMs. PCMs are substances that absorb or release heat during phase transitions, such as melting or freezing. By strategically integrating PCMs into an EV's battery pack, it is possible to regulate temperature fluctuations and maintain optimal operating conditions. Numerical simulations were conducted to analyse the impact of flow rate and design on heat transfer and temperature distribution within the battery pack. The results indicate that increasing the flow rate improves cooling efficiency but also increases pressure drop. The design of the fluid path and outlet configuration significantly influences the overall thermal performance of the Battery Thermal Management System (BTMS)[1-2]. PCMs offer advantages such as low parasitic power and uniform temperature distribution. The paper reviews various techniques to enhance the thermal conductivity of PCMs, including the use of conductive particles, cellular foams and encapsulation. Additionally, it analyses the impact of key parameters like cell spacing, PCM mass, thickness, specific heat capacity and thermal conductivity on system performance. The conclusion summarises the findings from previous studies and highlights the potential benefits of PCM-based cooling systems for electric vehicle batteries[3]. Hexagonal and trapezoidal battery pack configurations were studied under different discharge rates (1C, 2C, and 3C) and ambient temperatures (28-32°C). The results showed that the Composite Phase Change Material (CPCM)--based hexagonal battery pack effectively maintained temperatures below 50°C at all discharge rates. Compared to PCM cooling, CPCM cooling reduced peak temperatures by 6.7-9.1 %. The trapezoidal battery pack with CPCM further improved performance, reducing peak temperatures by an additional 14.2% and minimising temperature variations[4]. The CPCM, a combination of paraffin wax and graphite powder, enhances thermal conductivity and improves heat dissipation. The study investigates the battery pack's performance under different discharge rates (1C, 2C and 3C) and ambient temperatures (28-30°C). Results show that the CPCM-based trapezoidal battery pack outperforms a traditional PCM-based pack, achieving more efficient heat transfer and maintaining a consistent temperature distribution below 45°C[5]. The low thermal conductivity of paraffin wax limits its effectiveness as a cooling agent. To improve thermal performance, Graphene Platelet Nanopowder (GPN), Multi-Walled Carbon Nanotubes (MWCNT) and Graphite Synthetic Powder (GSP) were added to the paraffin wax to create Ne-PCMs. Experimental results showed that the battery pack with Ne-PCM effectively maintained temperatures below 50°C at all discharge rates (1C, 2C and 3C) and ensured uniform temperature distribution among cells, outperforming both the uncooled and PCM-only configurations[6]. To improve the thermal conductivity of the PCM, expanded graphite was added to create a composite PCM (CPCM). The CPCM was incorporated into the core region of a hexagonal battery pack to mitigate heat accumulation and maintain uniform temperature distribution.

Experimental results demonstrated that the CPCM-based battery pack effectively managed temperature, keeping it within safe limits, especially at higher discharge rates (1C and 2C)[7]. Three battery pack designs and three BTMS were simulated using Ansys Fluent. The results showed that a specific geometry with ethynyl glycol as the coolant provided the most efficient temperature distribution and lowest maximum temperature. Channel-based BTMS was found to be effective in maintaining a consistent temperature distribution, with the maximum temperature below 307K and the minimum temperature above 293K[8]. This approach significantly enhances thermal conductivity. Alternatively, embedding a copper mesh within the PCM composite provides structural integrity and prevents leakage of the liquid PCM. This research explores thermal management techniques for electronic devices, especially in demanding environments. The studies cover a wide range of topics, including. This involves investigating the impact of substrate thermal conductivity on component temperature, utilizing PCMs for smartphone circuit cooling, employing Computational Fluid Dynamics (CFD) for Integrated Circuit (IC) chip thermal management, and utilising AI-based strategies for efficient IC chip placement[9-15]. This research explores methods like jet impingement, twisted tape inserts and nanofluids to improve heat transfer efficiency in tubular heat exchangers[10-19]. This research examines the thermal performance of electronic components on different substrate materials and the influence of heat transfer on symmetric and asymmetric IC chips mounted on Switch-Mode Power Supply (SMPS) boards, both with and without PCM[20-33]. Researchers emphasise the importance of developing a computational model to analyse a single Li-ion battery cell. This model would gather data on heat generation and temperature rise to design an effective BTMS that utilises phase change materials (PCM). The study aims to create a thermal model for cylindrical Li-ion batteries, calculating temperature distribution and maximum temperatures at different discharge rates. By incorporating PCMs on the battery surface, the system aims to achieve consistent temperature distribution and efficient passive cooling, keeping the battery within the optimal operating range for electric vehicles.

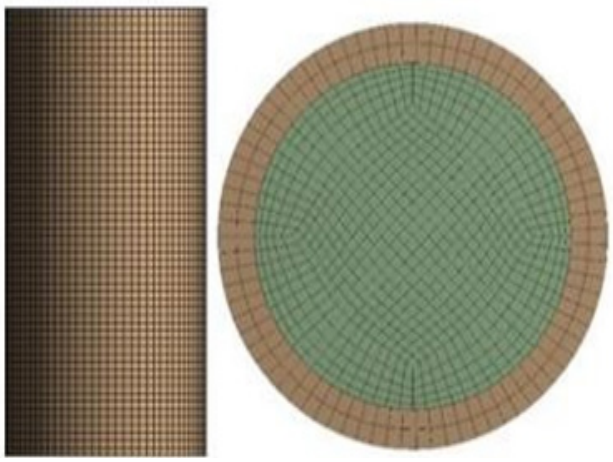


Figure 1. Meshed model with PCM.

2.0 Approach

2.1 Grid Generation

A computer model is prepared to simulate the cooling system for a single cylindrical battery cell. The cell has three main parts: an anode, a cathode and a separator. The model ignores the outer shell of the battery to simplify calculations. The cooling system is designed in Ansys design modeller software. It consists of a solid aluminium coolant container filled with a 1mm thick layer of PCM surrounding the battery cell. As the battery discharges at different rates, the PCM absorbs the heat generated. The researchers performed simulations to find the optimal mesh size for the model by considering temperature rise as a key factor. A mesh size of 1.1mm was chosen, resulting in a total of 436528 elements for the single cell with PCM cooling as shown in Figure 1. Table 1 details the parameters used in the model.

2.2 Battery Characteristics

This study employed a computer simulation model to analyse the discharge behaviour of a lithium-ion battery cell at various discharge rates. The simulation combined two models: dual potential Multi-Scale Multi-Domain (MSMD) and electrochemical Newman Tiedemann, Gu and Kim (NTGK). The NTGK parameters were sourced from previous research, and the battery specifications are outlined in Table 2. The model utilised a pressure-linked equations (SIMPLE) method to simulate the transient behaviour of the battery during constant current discharge. For each simulation, a time step of 30 seconds was used. The boundary conditions for the cell

Table 1. Mesh quality of cell with cooling system

Sr. No	Element	Maximum	Minimum
1	Ortho. Quality	0.988	0.835
2	Skewness	0.476	4.823e-03
3	Aspect Ratio	2.677	1.243
4	Element Quality	0.988	0.723

wall, positive tab, and negative tab were adjusted based on the specific discharge rate. The material properties of the coolant channel and coolant medium are detailed in Table 3.

2.3 Boundary Conditions

The study simulated different boundary conditions for three specific locations on the battery cell (cell wall, positive tab wall and negative tab wall) at various discharge rates. The simulations focused on a single battery cell equipped with a phase change material (PCM) cooling system. For all simulations, consistent initial temperatures were maintained for the cell, the PCM-containing duct and the PCM material, as outlined in Table 4.

3.0 Results and Discussion

3.1 Single Cell

This study utilised Ansys software to simulate the discharge behaviour of a LiCoO2 26650 lithium-ion

Table 2. Cell specification

Sr. No.	Properties	Value	Unit
01	Cell Size	26650	mm
02	Nominal Voltage	3.6	V
03	Nominal Capacity	3400	mAh
04	Minimum Capacity	3200	mAh
05	Maximum Charge Voltage	4.2	V
06	Minimum Charge Voltage	2.75	V
07	Maximum Discharge Voltage	2.5	V
08	Continuous Discharge Current	3.4	A
09	Pulse Discharge Current	6.8	A (10s max)
10	Charge Current	1.7	A (standard)
11	Internal Resistance	≤ 35	mΩ
12	Operating Temperature Range	-20°C to +55°C	°C
13	Storage Temperature Range	-20°C to +45°C	°C

battery at different C-rates. Without any cooling, the battery's temperature increased with the discharge rate, reaching a maximum of 310.95K at 1.5C. Lower discharge rates resulted in lower peak temperatures (306.95K at 1.0C and 301.45K at 0.5C). To improve thermal management, a phase change material (PCM) cooling system was integrated into the simulation. This system effectively reduced the maximum temperature, especially at higher discharge rates. For example, the maximum temperature at a 1.5C discharge rate decreased to 307.114K with PCM cooling, which is lower than the maximum temperature without cooling at a 1.0C discharge rate. The PCM cooling system also helped maintain a more uniform temperature distribution across the entire battery cell. The minimal temperature difference between the top and the bottom of the cell is crucial for optimal battery performance and longevity.

Table 3. Property of cooling system

Current (A)	2	4	6
Temperature (K)	296	296	295
Cooling Channel Temp.	296	296	295
Solid interface Cell initial Temp (K)	296	296	295

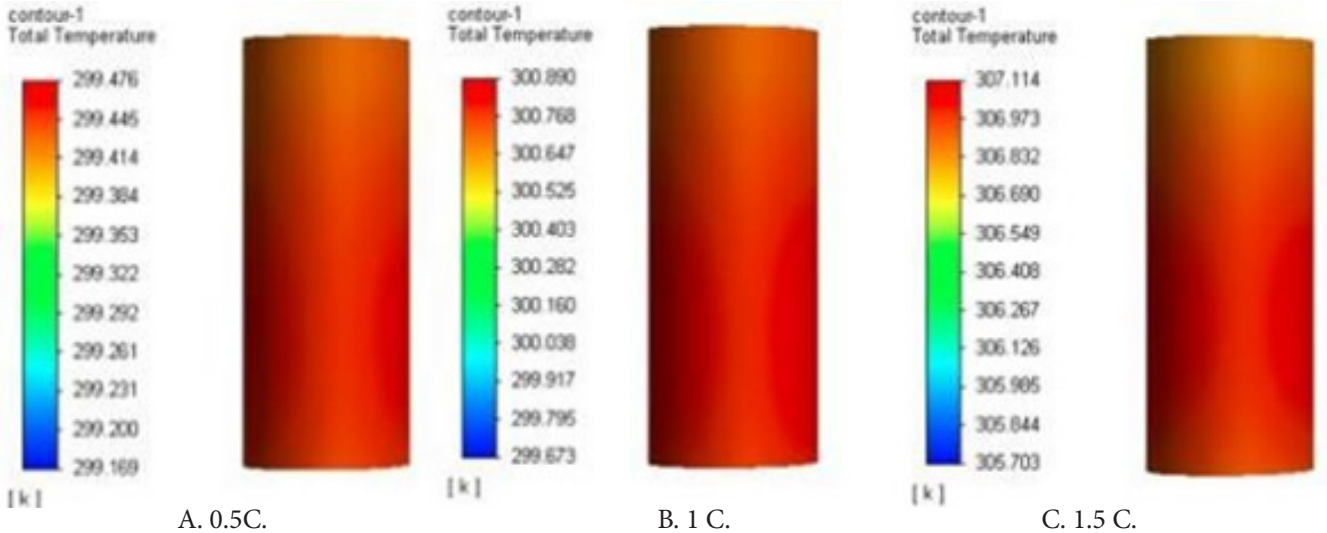
Table 4. Boundary conditions

Sr. No	Property	Channel (Aluminum)
1	Density	2647 (Kg/m3)
2	Specific Heat	861 (J/kg-k)
3	Thermal Conductivity	201.6 (W/m-k)

3.2 Comparison of Performance of Single Cell

Figures 4, 5 and 6 illustrate the temperature fluctuations of a single-cell battery with and without a PCM cooling system during discharge cycles of 1.5C, 1.0C and 0.5C, respectively. The PCM, directly applied to the battery surface, effectively mitigates temperature rise, extending battery life and preventing thermal runaway. Initially, the battery's temperature starts around 296-298 Kelvin. Without cooling, the peak temperature reached by the battery varies with the discharge rate, with higher rates resulting in higher peak temperatures before complete discharge.

This study compared the thermal performance of a lithium-ion battery cell with and without a PCM cooling system. The results demonstrated a significant reduction in the maximum temperature of the cell when cooled with the PCM. At a discharge rate of 1.5C, the maximum temperature decreased from approximately 314K to 307K, representing a reduction of 2-1 % across different discharge rates. This confirms the effectiveness



A. 0.5C. B. 1 C. C. 1.5 C.

Figure 2. Temperature contour.

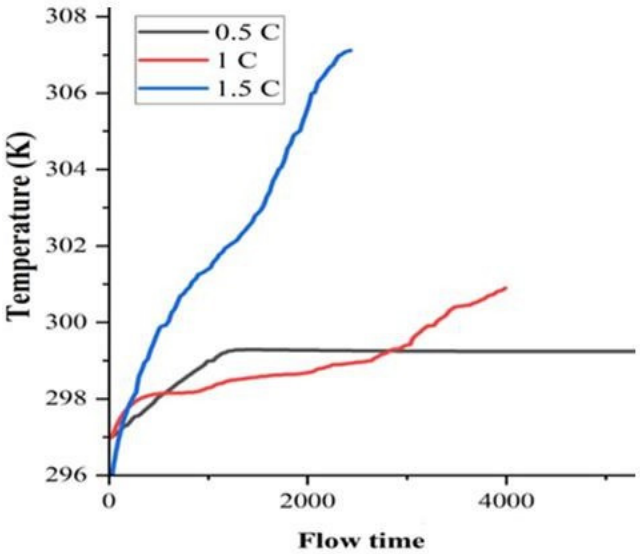


Figure 3. Temperature curve.

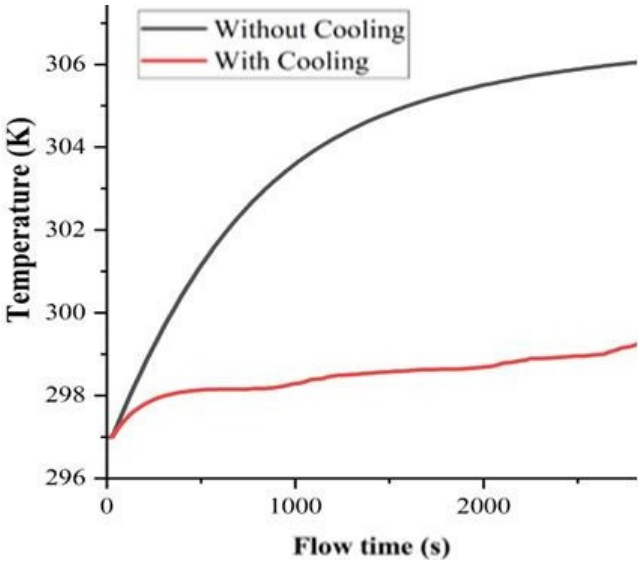


Figure 5. Comparison at 1C.

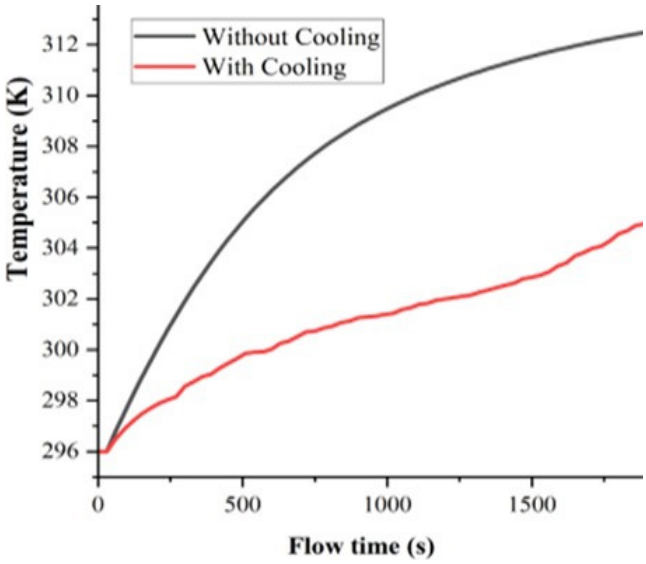


Figure 4. Comparison at 1.5C.

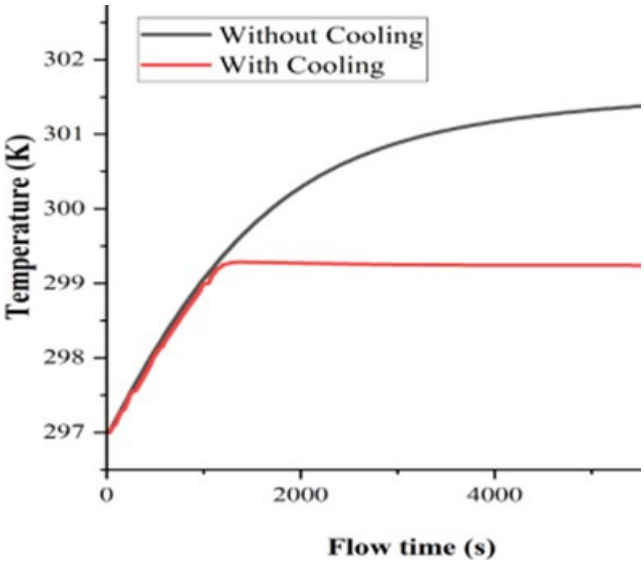


Figure 6. Comparison at 0.5C.

of the PCM-based cooling system in regulating battery temperature and potentially extending its lifespan. While this research focused on a single cell, the principles can be applied to entire battery packs in future studies. Additionally, the thermal conductivity of the PCM could be further enhanced to improve heat transfer efficiency. Finally, experimental validation of the simulation results would provide valuable insights into the real-world performance of the PCM cooling system.

4.0 Conclusions

This study successfully employed CFD simulations to analyse the thermal behaviour of a lithium-ion battery cell under various discharge rates. By incorporating a PCM as a direct cooling mechanism, the simulations demonstrated a significant reduction in the maximum temperature rise compared to an uncooled cell. The effectiveness of the PCM cooling system was evident, with a temperature reduction ranging from 2% to 1% depending on the discharge rate.

Furthermore, the study explored the impact of battery cell arrangement on thermal management. Initial findings suggest that parallel cell configurations may offer superior thermal performance compared to series configurations. However, further in-depth analysis is required to validate these preliminary results. Overall, this research provides valuable insights into the thermal management of lithium-ion battery cells, highlighting the potential of PCM-based cooling systems to enhance battery performance and safety. Future studies may delve deeper into optimising PCM properties, exploring advanced cooling techniques and investigating the long-term effects of thermal cycling on battery degradation.

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