

Sustainable and Eco-Friendly Battery Thermal Management System Based on Hybrid Cooling for Electric Vehicles

Akshay P M¹, Drupad R Nair^{1*}, Jyothish Kumar P K¹, Rahul S Arackal¹, P M Suteesh²

¹Department of Mechanical Engineering, Adi Shankara Institute of Engineering and Technology, A P J Abdul Kalam Technological University, India.

²National Institute of Technology Calicut, India

* Corresponding author: 6403drupadmair@gmail.com

doi: <https://doi.org/10.21467/proceedings.7.5.13>

ABSTRACT

Lithium-ion batteries are a crucial component of electric vehicles (EVs), directly impacting their performance, safety, and efficiency. To function optimally, these batteries require precise thermal regulation, maintaining an operating temperature between 15°C and 35°C during both charging and discharging cycles. Keeping the battery within this range extends its lifespan, reduces thermal stress, and minimizes the risk of overheating, which can lead to thermal runaway—a significant safety concern in EV applications. However, existing cooling methods, including air cooling, liquid cooling, phase change materials (PCM), and nanofluid integration, have limitations, especially when exposed to diverse operating conditions and environments. This study introduces an innovative hybrid cooling system that integrates liquid cooling and forced air cooling with evaporative cooling. By utilizing forced air to enhance evaporative cooling, this approach maintains a continuous cooling effect, while liquid cooling efficiently dissipates excess heat to ensure stable temperatures. Beyond improving thermal management, this system helps extend battery life, optimize energy efficiency, and lower the risk of overheating. Its compact design also makes it adaptable for various EV applications, such as passenger vehicles, commercial fleets, public transportation, and stationary energy storage solutions. With its ability to accommodate different thermal demands, this hybrid cooling system presents a highly adaptable and reliable solution for EV technology. By improving battery performance and longevity, it aligns with industry goals to create safer, more durable, and environmentally friendly electric vehicles, ultimately accelerating the transition to sustainable transportation.

Keywords: Battery Thermal Management System, Hybrid Cooling, Simple Air Cooling

1 Introduction

Modern technology relies heavily on lithium batteries, which power everything from consumer electronics to high-demand applications like electric vehicles (EVs) [1]. These batteries are essential to the operation and efficiency of EVs since they serve as their main energy source. However, maintaining a uniform temperature distribution is difficult due to the significant heat generated during the Li battery's charging and discharging cycles. This heat production may result in hotspots and temperature fluctuations inside the battery, causing thermal gradients that compromise safety and performance. These temperature differences might raise the possibility of thermal runaway, a hazardous situation in which a battery overheats and fails due to rapid heat accumulation, possibly resulting in fires or explosions, if they are not controlled [2]. An efficient Battery Thermal Management System (BTMS) is necessary to overcome these problems [3] [4]. In order to improve performance, prolong battery life, and guarantee user safety, a BTMS is made to control the battery pack's internal temperature and maintain it within an ideal range, usually between 15 and 35°C [5]. Because Li-ion batteries are susceptible to temperature extremes, proper temperature control is essential. Low temperatures can lower efficiency and power output, while high temperatures can speed up



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Proceedings DOI: [10.21467/proceedings.7.5](https://doi.org/10.21467/proceedings.7.5); Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-989164-7-1

chemical reactions that damage battery cells. These consequences can be lessened by a well-designed BTMS, which will support the increasing demand for EVs and guarantee the sustainability and dependability of their battery systems. In this study a novel BTMS design that uses wet jute fiber as a cooling agent. An environmentally appropriate substitute for cooling applications, jute is a naturally occurring plant-based material that is inexpensive, readily available, and renewable. It is a promising option for thermal control in Li-ion batteries because of its special qualities, which include being lightweight, biodegradable, and moisture-retaining [6]. Jute is a renewable resource that supports eco-friendly EV technology solutions and the industry's sustainability objectives. This study investigates the potential of jute fiber to enhance temperature management in high-powered battery applications by integrating it into an evaporative cooling system. A 15Ah Lithium Phosphate battery cell combined with the suggested jute-based BTMS underwent extensive experimental testing. A number of cooling methods, including as forced air cooling, evaporative cooling using jute, and natural convection cooling, were assessed. Key thermal performance measures, including the battery's maximum temperature, temperature variations within the cell, and surface temperature uniformity, were the focus of the investigation. Because uneven heating can result in localized stress and accelerate the degradation of battery cells, temperature consistency is very crucial. According to the results, adding jute to the cooling system produces better temperature uniformity across the battery surface by increasing air cooling efficiency. This advantage lessens the possibility of thermal runaway by reducing temperature peaks. Moreover, the lightweight nature of jute offers practical advantages by reducing the overall size and weight of the cooling system, making it more suitable for EV applications where space and weight are critical factors. Unlike traditional cooling methods that rely on complex liquid-cooling or synthetic materials and phase change materials (PCM) [7] [8] [9], the use of jute presents a simplified, cost-effective solution. By leveraging evaporative cooling with jute, this study presents a pioneering approach in BTMS development, highlighting its potential to enhance air-based battery thermal management [10]. This innovative approach has potential implications for the future of EV technology, offering a pathway toward safer and more eco-friendly battery systems. As the demand for EVs continues to grow, the integration of renewable resources like jute in BTMS designs could contribute significantly to the advancement of battery technology, paving the way for enhanced thermal management solutions that support both performance and environmental objectives.

2 Equipments Used

List of equipments used for the present experimental set up and their technical specifications are enlisted in Table 1.

Table 1: *List of equipments used*

EQUIPMENTS	SPECIFICATIONS
1. SI-BCDS Battery tester	<ul style="list-style-type: none"> ● Maximum output – 5V 20A ● Number of channels-8
2. Variable power supply	<ul style="list-style-type: none"> ● Maximum output- 32V 5A
3. Thermal chamber	<ul style="list-style-type: none"> ● Volume – 70 Liters
4. K-type thermocouple	<ul style="list-style-type: none"> ● Total count – 8 ● Uncertainty range- 0.5°C
5. LiFePO ₄ cell	<ul style="list-style-type: none"> ● Total count - 8 ● Capacity- 3.2V 15ah
6. DC Exhaust fan	<ul style="list-style-type: none"> ● Total count – 4 ● Power rating – 12V 0.3A

3 Experimental Methodology

3.1 Experimental Setup

Figure 1 represents the layout of the experimental set up. The battery pack is kept inside the thermal chamber to maintain a constant ambient temperature. The tester as well as the thermocouples are connected to all the individual cells. A DC power source is also provided to supply power which is used to run the fans. The data collected from the tester is fed into the computer.

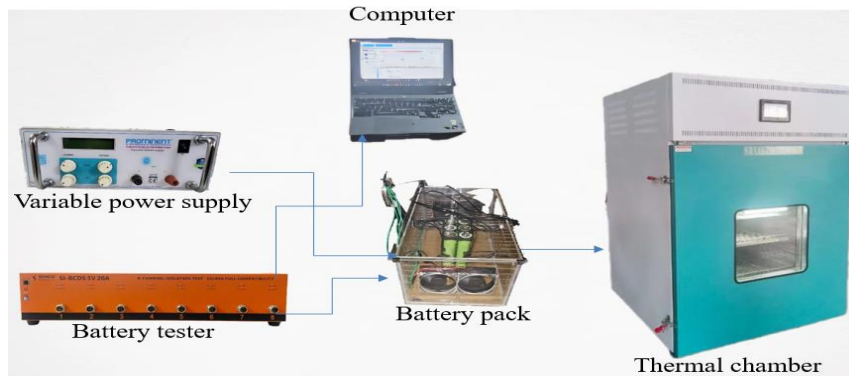


Figure 1: *Layout of the experimental set-up.*

3.2 Experimental Procedure

The initial stage of this experiment focused on testing how effective forced convection cooling is during battery charging. A thermal chamber was used to maintain a consistent temperature, while thermocouples were attached to the battery cells to track any temperature changes. Charging occurred at a rate of 1C (15,000mAh), mimicking real-world scenarios. To disperse heat efficiently, DC fans powered by a variable supply provided controlled airflow—a method commonly referred to as air cooling. Keeping battery temperatures under control is vital for both safety and performance. Temperature data was continuously monitored and saved for analysis. The results highlighted the importance of air cooling, especially for high-power setups, offering valuable insights into optimizing thermal management to improve battery life and reliability. The next phase of the experiment explored how forced convection cooling affected the battery during its discharge cycle. To ensure consistent testing, the setup remained unchanged. The battery cells were discharged at a 1C rate (15,000mAh), mimicking typical usage patterns. The thermal chamber kept the ambient temperature steady, and DC fans continued to provide airflow to prevent overheating. Thermocouples measured temperature changes throughout, while the battery tester software recorded real-time data for detailed analysis. It helped assess the cooling system's effectiveness and identified potential improvements to enhance battery thermal management. In the third phase, a new hybrid cooling method was introduced to improve thermal management during battery charging. This innovative approach combined air cooling with evaporative cooling to enhance heat dissipation and maintain better temperature control, aiming to outperform traditional cooling techniques. The setup included a jute mesh frame, which incorporated a water supply and drainage system. As warm air from the DC fans passed through the damp mesh, the evaporation process cooled the air before it reached the battery cells, helping to reduce heat more effectively. The batteries were charged at a rate of 1C (15,000mAh), with temperatures monitored using thermocouples. The data, recorded in real time, was used to evaluate how well the hybrid cooling system performed compared to standard air cooling. In the final phase, the experiment assessed how well the hybrid cooling system worked during the battery discharging process. The batteries were discharged at a constant 1C rate (15,000mAh) under the same controlled setup. The hybrid cooling mechanism, with its

jute mesh frame and continuous water flow, remained active throughout. By combining air and evaporative cooling, the system efficiently dissipated heat. Real-time temperature readings from thermocouples were logged and compared with data from traditional cooling tests.

4 Results and Discussion

The readings from the thermocouples were accumulated by the 8-channel isolation tester and the temporal variations of temperature were plotted. The following result analysis shows the advantage of the hybrid cooling method have over the conventional simple air cooling method.

4.1 Cooling performance during charging

4.1.1 Simple air cooling (SAC)

Simple air cooling actively uses DC fans to circulate air around battery packs, providing a more efficient way to dissipate heat compared to passive methods. By maintaining a steady airflow over the battery cells, this technique prevents hotspots and regulates temperature, making it especially useful for high-power applications where excessive heat can harm battery performance and lifespan. In the tests conducted, this cooling method consistently kept temperatures within a tight range. The highest recorded temperature was 32°C, while the lowest was 28.8°C, yielding a minimal difference of 3.2°C. This level of stability demonstrates the effectiveness of forced convection cooling in maintaining battery thermal balance, positioning it as a dependable and economical solution for managing heat in energy storage systems. Figure 2 displays temporal variations of temperature during the charging process with SAC.

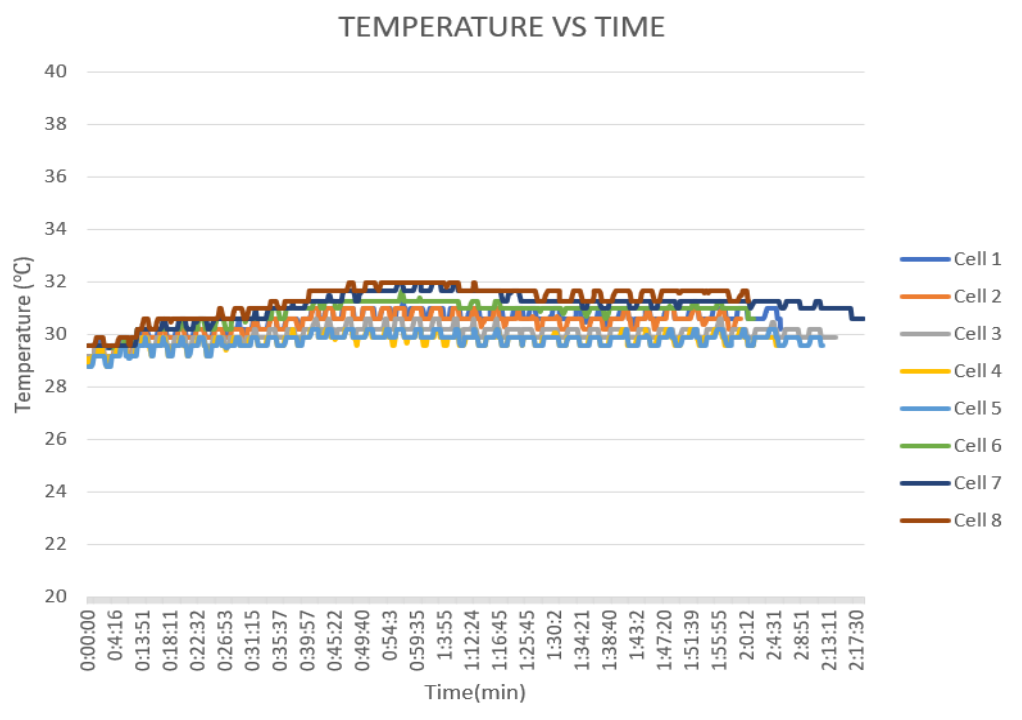


Figure 2: Temporal variation of temperature during charging- SAC

4.1.2. Hybrid Cooling

This cooling approach combines forced air with evaporative cooling to enhance heat dissipation. It uses a moistened jute mesh placed in front of the fan, allowing evaporation to cool the air before it reaches the battery cells. This innovative technique improves efficiency and temperature control. During testing, the system achieved a maximum temperature of 30.6°C and a minimum of 28.5°C, with a temperature

difference of 2.1°C, showcasing its ability to maintain consistent and stable cooling. Figure 3 shows the temporal variations of temperatures on individual cells.

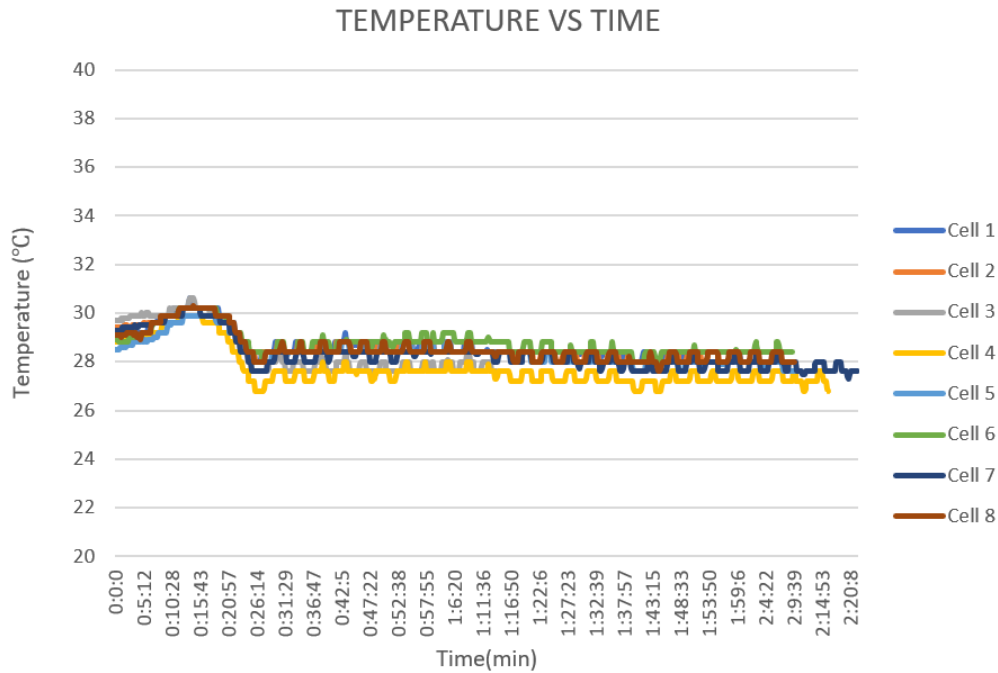


Figure 3: Temporal variation of temperature during charging-HC

The figure 4 displays the bar chart depicting temperature comparison of SAC and HC at initial and final phases of charging. Hybrid cooling stands out for its impressive ability to manage heat. It keeps the peak temperature 1.4°C lower compared to forced convection, because of its moisture-assisted cooling feature. This enhancement comes from evaporative cooling, which efficiently dissipates heat, reduces the risk of overheating, and boosts the system's overall performance.

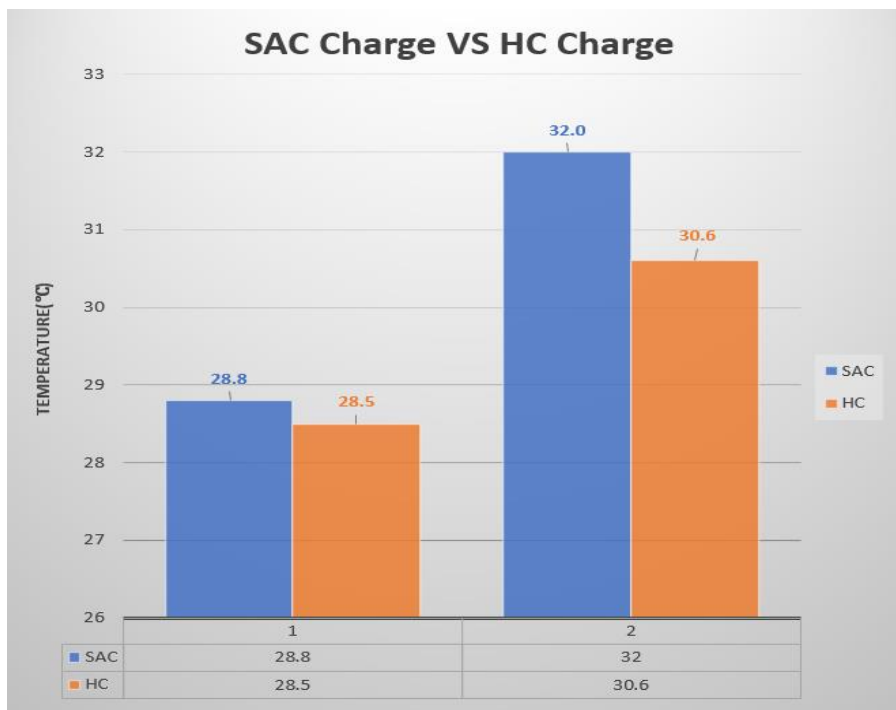


Figure 4: Comparison graph-charging cycle

4.2 Cooling performance during discharging

4.2.1 Simple air cooling

Fig. 5 displays temporal variations of temperature during the discharging process with SAC. It is observed that temperature increases from 29.6°C to 37.2°C, having a difference of 7.6°C. While this method helps manage heat effectively, the notable temperature variation points to uneven cooling across the system. Such inconsistencies can lead to localized hotspots, potentially impacting performance and durability.

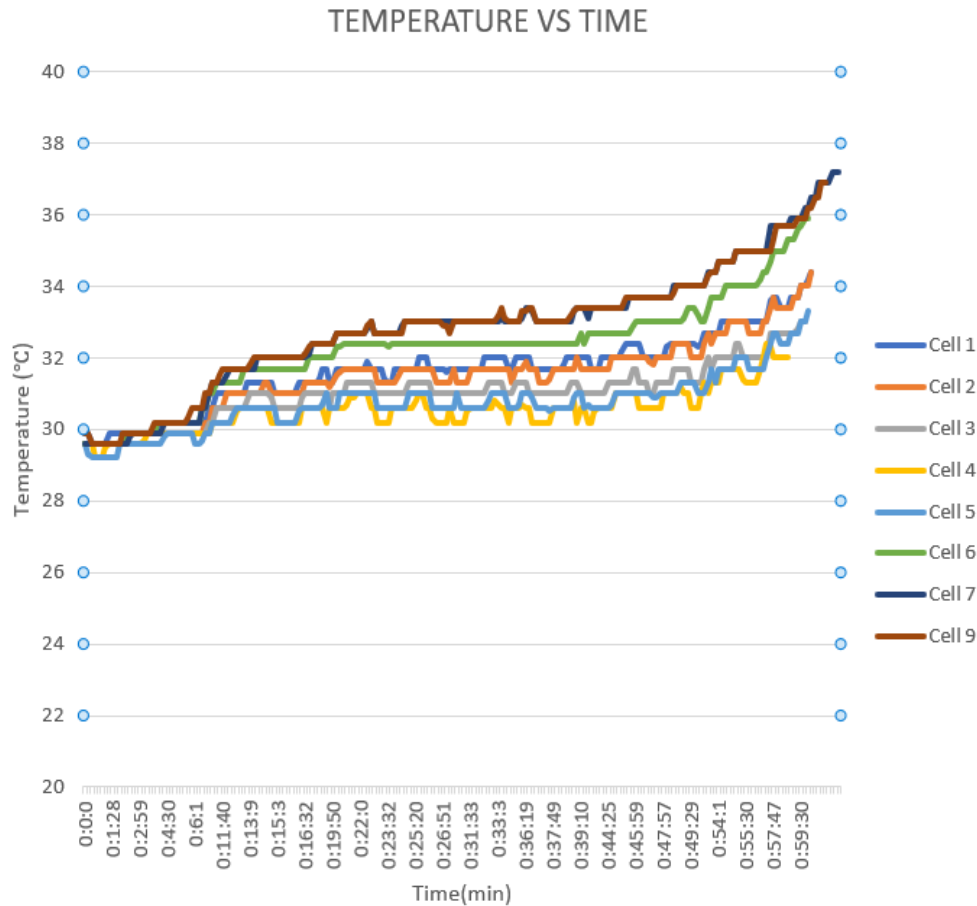


Figure 5: Temporal variation of temperature during discharge-SAC

4.2.2 Hybrid cooling

Fig. 6 shows the temporal variations of temperatures on individual cells. During hybrid cooling in the discharging process, the system maintains a temperature range from 29.6°C at the minimum to 33.6°C at the maximum, resulting in a narrower difference of 4.0°C. This temperature variation highlights the system's ability to achieve more consistent cooling compared to forced convection. By ensuring a uniform thermal distribution, hybrid cooling minimizes hotspots and can enhance performance stability, and reduces thermal stress on components.

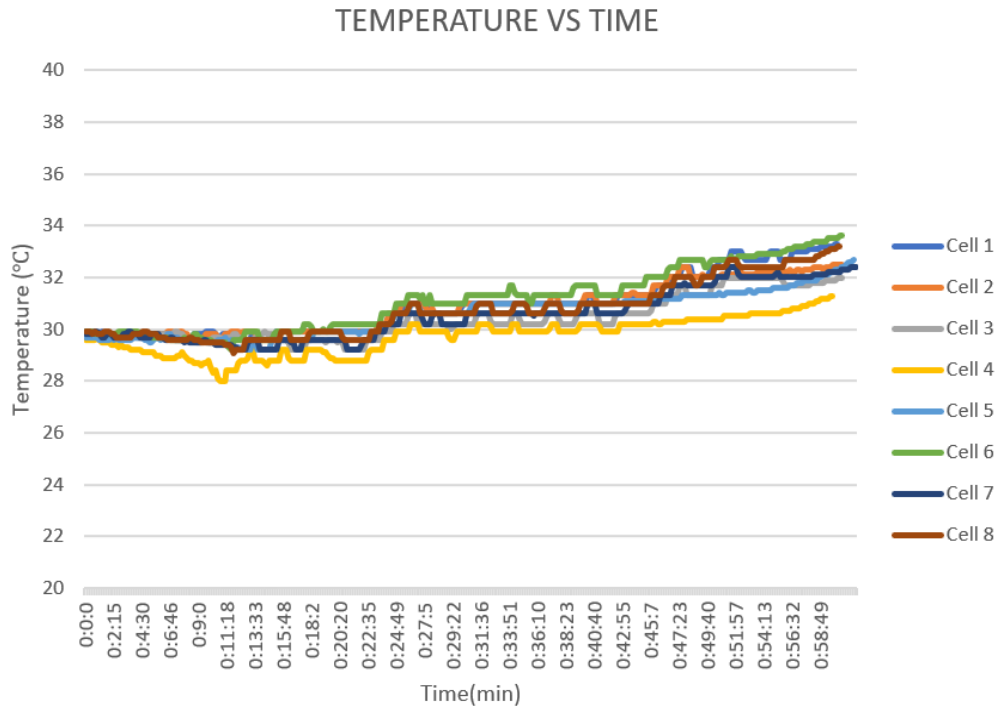


Figure 6: Temporal variation of temperature while discharge-HC

The figure 7 displays the bar chart depicting temperature comparison of SAC and HC at initial and final phases of discharging. At the end of discharging, the hybrid cooling method lowered the peak temperature by 3.6°C compared to forced convection cooling. This reduction is significant, as excessive heat generation during discharge can negatively affect battery lifespan, safety, and overall performance.

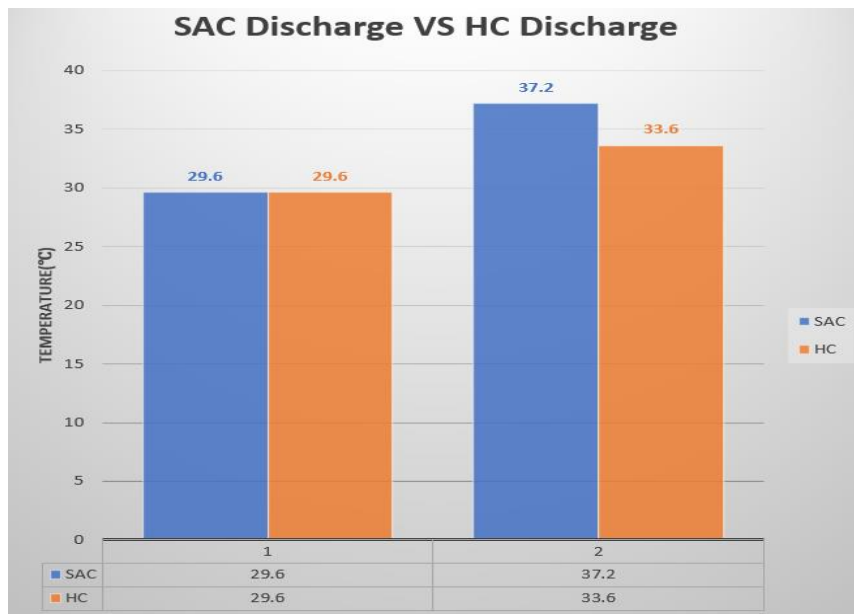


Figure 7: Comparison graph-discharge cycle

4.3 Average cooling performance

4.3.1 Charging

Figure 8 shows the comparison of maximum and minimum temperatures of battery pack in charging condition during simple air cooling and hybrid cooling. The simple air cooling maintains temperatures between 29.33°C and 31.08°C, resulting in a variation of 1.75°C. While this demonstrates stable cooling, hybrid cooling achieves even better consistency. With temperatures ranging from 29.11°C to 30.23°C, hybrid cooling shows a variation of just 1.12°C as shown in Fig.8 . This highlights its superior ability to regulate temperature more uniformly, reducing fluctuations and improving thermal stability. The improved control offered by hybrid cooling makes it a more effective solution for maintaining consistent performance.

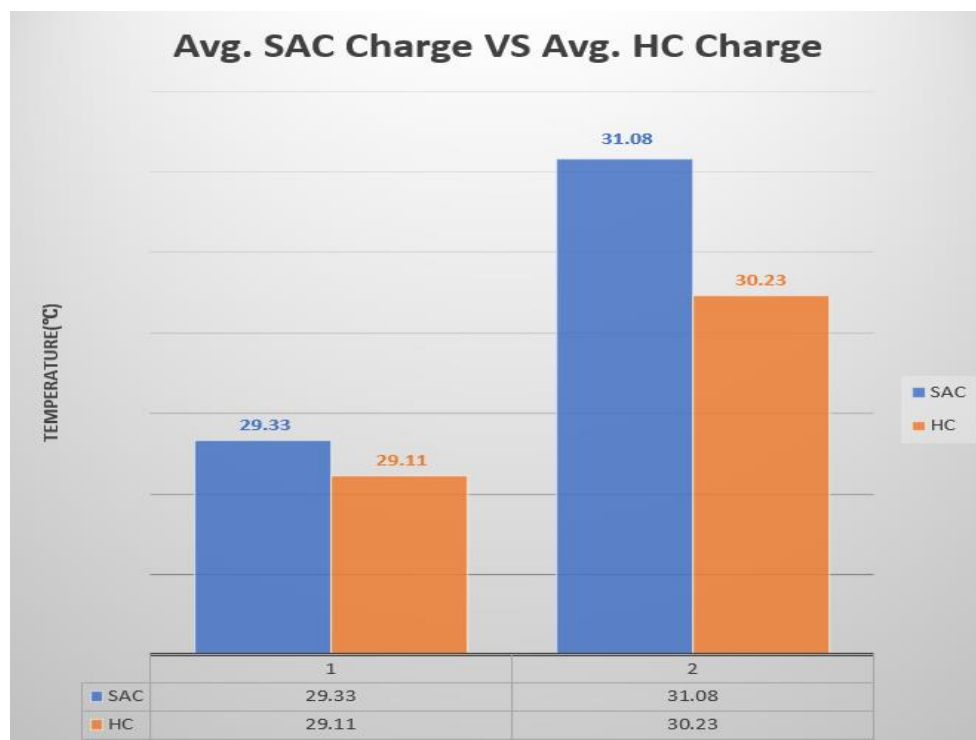


Figure 8: Maximum and minimum temperature in charging-SAC and HC

4.3.2 Discharge

Fig. 9 shows mean maximum and mean minimum temperatures of battery pack in discharging condition. With simple air cooling, temperatures range from 29.67°C to 34.68°C, showing a difference of 5.01°C. This indicates that while the system controls heat, it allows for noticeable temperature variations. On the other hand, hybrid cooling keeps the range tighter, from 29.78°C to 32.66°C, with a comparatively smaller difference of 2.88°C. This demonstrates hybrid cooling's ability to maintain a more consistent temperature, enhancing thermal stability and reducing the likelihood of overheating, making it a more efficient solution overall.

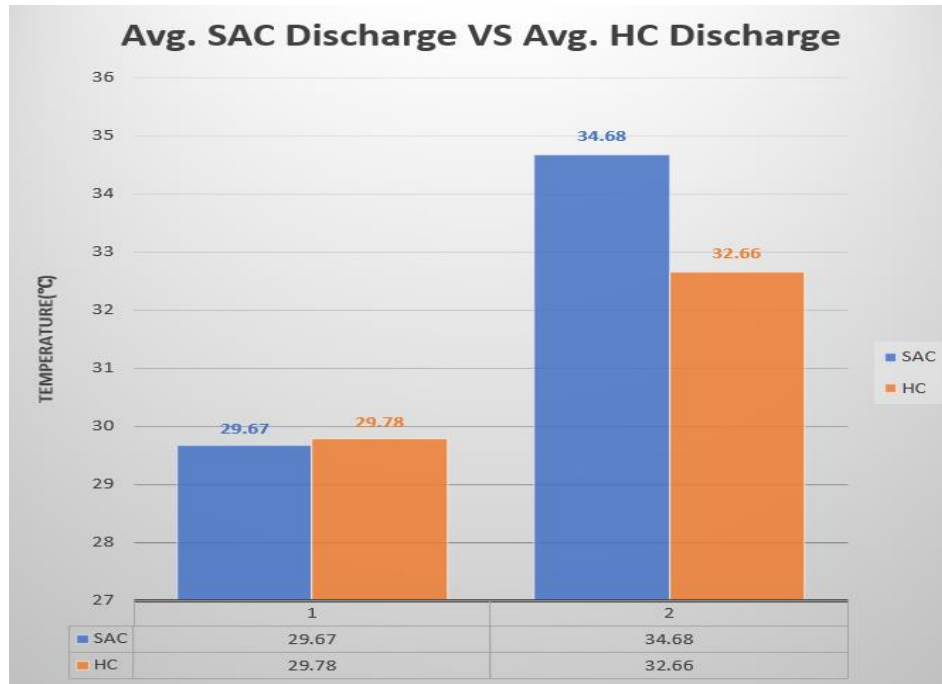


Figure 9: Avg. max and min temperature in discharging-SAC and HC

5 Conclusions

The results obtained clearly shows that hybrid cooling provides a noticeable improvement in temperature control. It is clear that the moisture-assisted cooling mechanism is essential to improving heat dissipation because the hybrid cooling system's peak temperature is 1.4°C lower than that of the forced convection arrangement. During the discharging phase, the hybrid cooling method lowered the peak temperature by 3.6°C compared to forced convection cooling. This reduction is significant, as excessive heat generation during discharge can negatively affect battery lifespan, safety, and overall performance. The experimental findings highlight that moisture-saturated jute plays a key role in improving temperature regulation. By absorbing excess heat through evaporative cooling, the jute mesh effectively lowers maximum battery temperatures while ensuring greater uniformity in heat distribution. One of the most notable advantages of this cooling method is that it achieves temperature reduction without requiring additional energy input. The jute mesh passively regulates temperature through evaporation. This means that not only does the system help in reducing overheating, but it also contributes to energy savings, making it a highly efficient solution for battery thermal management since eco-conscious thermal management play a vital role in green tech, supporting electric mobility, renewable energy storage, and smart grid solutions [11]. Future work could focus on optimizing airflow design and assessing jute's long-term durability in thermal management systems. The future work of this study also includes the study of optimum fiber diameter, airflow velocity, fiber location, study on cell arrangement for maximum heat dissipation etc.

6. Declarations

6.1 Competing Interests

All authors declare that they have no competing interests.

6.2 Acknowledgements

The authors would like to express their sincere gratitude to National Institute of Technology Calicut and Adi Shankara Institute of Engineering and Technology for providing the necessary facilities and resources for the successful completion of this project. The authors acknowledge the support of peers and family for their encouragement throughout the research.

6.3 Study Limitations

The study was limited to a small scale battery pack of eight 15Ah, 3.2V LiFePO₄ cells because of the unavailability of facilities for charging and discharging larger battery packs. While conducting the experiment, humidity inside the battery pack may increase. To rectify this issue dehumidifier needs to be introduced inside the battery pack.

6.4 Warning for Hazard

The proximity of water-saturated jute mesh to electrical components introduces a risk of leakage-induced short circuits. All electrical connections were carefully insulated, and the acrylic case was sealed to prevent water ingress. Continuous temperature monitoring using K-type thermocouples and battery testing software was implemented to detect early anomalies. Fire extinguishing equipment was kept accessible throughout the procedure. Safe handling practices, including the use of heat-resistant gloves and safety goggles, were strictly followed during battery installation, connection and testing operation.

6.5 Publisher's Note

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How to Cite

Akshay *et al.*, "Sustainable and Eco-Friendly Battery Thermal Management System Based on Hybrid Cooling for Electric Vehicles", *AIJR Proc.*, vol. 7, no. 5, pp. 100-110, Sep. 2025. doi: <https://doi.org/10.21467/proceedings.7.5.13>

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