‘Analysis, Simulation on Single Cell of Lithium-Ion Battery’

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ABSTRACT

Lithium-ion (Li-ion) battery performance and safety in electric vehicles (EVs) depend on maintaining ideal temperatures. The hybrid Thermal Management System (TMS) that incorporates a car's cabin air conditioning (VCAC) system is the subject of this study. A simulation examines the amount of heat produced by a single Li-ion cell at different charging and discharging rates and ambient temperatures. The efficiency of VCAC in regulating cell temperature—including cooling efficiency, temperature uniformity, and reaction time during temperature fluctuations—is the main subject of this study. In order to comprehend how VCAC affects overall module temperature control, these single cell results are then interpreted for a larger battery module (44 cells in series or parallel arrangement). The purpose of this study is to demonstrate how VCAC-based hybrid TMS can be used to maximize Li-ion battery temperature regulation in electric vehicles. The work provides important insights for creating battery thermal management systems for next-generation EVs that are more dependable and efficient by examining thermal behavior and extrapolating it to a bigger module.

Key Words: *Battery Thermal Management System, Vehicle Cabin Air Conditioning, Lithium Ion Battery, Electrical Vehicles.*

1. INTRODUCTION -

Lithium-ion (Li-ion) batteries, which power electric vehicles (EVs), must be kept at ideal temperatures for both performance and safety. High energy density, a long lifespan, and the capacity to be recharged are features of lithium-ion batteries that support sustainability. Li-ion batteries, however, can be harmed by very cold temperatures. Extremely high or low temperatures can accelerate degradation and pose safety risks, while cold temperatures might have an impact on power delivery. To solve these issues, battery temperature control requires Thermal Management Systems (TMS). Using specialized liquid or air-cooling systems is a common component of traditional TMS approaches, but it can add weight and complexity to the vehicle. Using hybrid cooling systems, which combine conventional methods with additional heat dissipation sources, is one possible solution. The application of a Vehicle Cabin Air Conditioning (VCAC) system in combination with conventional techniques to cool Li-ion batteries in electric cars (EVs) is the main topic of this study. By adding a VCAC system, the primary objective is to optimize a Thermal Management System (TMS) for Li-ion batteries in EVs. Researchers will investigate how the VCAC system affects a single Li-ion cell's thermal performance under various operating situations by executing simulations. These results will then be applied to a bigger battery module in order to assess how well integrating VCAC controls the battery pack's overall temperature.

2. HEAT GENERATION IN LITHIUM ION BATTERY -

The sensitivity of Li-ion batteries to temperature and the importance of thermal management are crucial for optimizing their performance, safety, and lifespan in electric vehicles. Research has demonstrated that the capacity of Li-ion cells is influenced by temperature. If the temperature falls below the recommended range (typically 15°C to 35°C), the battery's internal resistance will rise, affecting power output and decreasing driving range. On the other hand, excessive high temperatures can speed up lithium plating on the anode, leading to a decrease in usable capacity and a shorter battery lifespan.

Li-ion batteries heat up a bit when you charge them or use them. This happens for three reasons: chemical reactions inside the battery, resistance within the battery itself, and changes in temperature as the battery works. If this heat isn't released properly, the battery can get too hot. A hot battery doesn't work as well, loses power faster, and might even be unsafe. The bad news is, a hot battery can also wear out quicker and hold less charge over time.

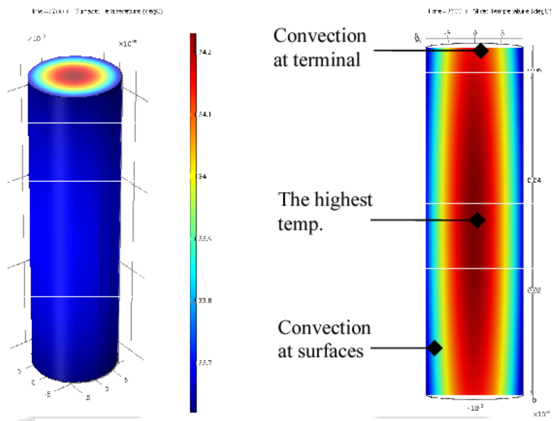

Figure 1: Temperature distribution at 0.5C discharge rate [16]

Research suggests that within a specific range, temperature fluctuations have minimal impact on this phenomenon. However, a more significant threat to battery health and safety arises from excessive heat generation. Thermal runaway, a process characterized by a rapid increase in battery temperature, gas emission, and the potential for explosion, poses a critical safety concern. To mitigate this risk, lithium-ion batteries incorporate various safety mechanisms, including pressure relief vents, thermal fuses, and specialized separators. Additionally, flame-retardant coatings and heat-resistant electrode materials may be employed.

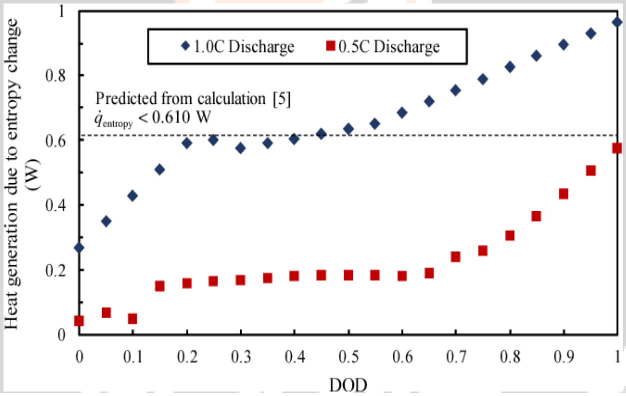

Figure 2: **Heat generation due to entropy change at 0.5C and 1C discharge rates** [9]

The quest for increased range and power in EVs necessitates the use of battery packs with higher energy density and faster charging capabilities. Consequently, these batteries generate a greater amount of heat during operation. Therefore, the implementation of a Battery Thermal Management System (BTMS) becomes paramount in EVs. This system functions by maintaining the battery within a designated temperature range and ensuring uniformity of temperature distribution throughout the pack.

Several approaches exist for EV battery thermal management:

1. Air Cooling: This method represents a simpler and more cost-effective solution. It utilizes airflow to dissipate heat from the battery. While suitable for everyday use, air cooling proves less effective in extreme temperature environments or during demanding driving conditions.
2. Liquid Cooling: This approach offers superior heat transfer capabilities compared to air cooling. A liquid coolant absorbs heat from the battery and transfers it to a heat exchanger for dissipation. While highly effective, liquid cooling systems introduce additional weight and complexity due to the inclusion of pumps, tubing, and radiators.
3. Phase Change Material (PCM) Systems: These systems employ materials with the unique property of absorbing and releasing heat during phase transitions. PCMs offer a passive and localized approach to temperature management but may not be suitable for high-power applications due to limitations in heat transfer capacity.

Research is exploring hybrid TMS approaches that combine different cooling methods. A promising avenue is integrating a Vehicle Cabin Air Conditioning (VCAC) system with a conventional TMS. Studies suggest utilizing the existing VCAC system to supplement battery cooling during hot weather and deactivate it in cold weather to avoid excessive battery cooling. This approach leverages the strengths of both systems, potentially leading to a more efficient and cost-effective solution for Li-ion battery thermal management in EVs.

- Effectiveness of VCAC for EV Battery Thermal Management: Vehicle cabin air conditioning systems (VCACs) can be leveraged for battery thermal management in electric vehicles (EVs). It's a cost-effective solution that utilizes existing components, saving space and weight. However, its effectiveness depends on a careful balance.

- Environmental Impact on VCAC Performance: VCAC effectiveness is heavily influenced by environmental factors. Hot and humid weather taxes the system's ability to remove heat from the battery. Similarly, aggressive driving that generates more heat can overwhelm the VCAC's cooling capabilities. In such scenarios, the battery might experience temperature spikes, reducing performance and potentially impacting lifespan.

- Energy consumption implications of using VCAC for battery cooling: While VCAC leverages existing components, its use for battery cooling adds an extra load on the car's electrical system. The compressor needs to work harder to cool both the cabin and the battery, which can lead to higher energy consumption. This translates to a decrease in driving range, especially during extended periods of battery cooling demand.

Vehicle Cabin air cooling system: The BTMS using air as a medium has been applied to many EVs because it can provide a relatively simple design that can reduce production and maintenance costs. This system can be classified into three type according to the inlet of the air. Obviously, using only the outside air is possible while using the preconditioned cabin air through base VCAC and outside air appropriately in accordance with the situation is another type. Lastly, using the cooled air from an evaporator that is additionally configured to the basic VCAC in certain scenarios where the cooling requirements of the cabin and battery may be different can be considered. Namely, the appropriate type should be selected in consideration of the battery heat generation, the external environment and the driving tendency. However, to air-using BTMS only set the air temperature at the appropriate room temperature without explaining the source of the air. Thus, this paper considers the cabin air cooling system using pre-conditioned air as a medium for battery cooling. The cabin air cooling system can be realized in a way that uses pre-conditioned cabin air through the VCAC of the EV AC system.

As a result, system uses some of the additional components, such as fan ducts and manifolds for blowing direct cabin air into the battery. However, since air has low heat capacity and low thermal conductivity, this system may be less effective at maintaining the temperature uniform inside and between the cells of battery modules, and it is difficult to discharge battery heat compared to the same flow rate of liquid. In other words, this system requires a large amount of air to remove the battery heat, which results in bulky ducts and manifolds where the energy consumption of the fans is high. Furthermore, it is difficult to accumulate a lot of cells in the pack because the gap between the battery cells must be wide. Other drawbacks of this system are that it has noise problems generated by multiple fans or blowers which negatively affects cabin comfort since the cabin air is used directly for BTM. These disadvantages limit the application of the cabin cooling system to an EV's BTMS with increased performance and mileage.

Cabin Air Cooling System is one type of battery thermal management system (BTMS) utilizes air as a cooling medium. This air-based system offers a relatively simple design, potentially reducing production and maintenance costs for EVs. There are three main variations depending on the air source:

- Using Only Outside Air: Preconditioned Cabin Air: This method strategically utilizes both pre-conditioned cabin air from the VCAC and outside air depending on the situation.
- Cooled Air from Evaporator: In certain scenarios where cabin and battery cooling requirements differ, cooled air from an additional evaporator integrated into the VCAC can be employed.
- Pre-Conditioned Cabin Air for Battery Cooling: This system utilizes pre-conditioned cabin air from the VCAC for battery cooling. It requires minimal additional components, such as fan ducts and manifolds to direct the cabin air towards the battery. However, air has limitations as a cooling medium. Compared to liquids, air has lower heat capacity and thermal conductivity. This can make it less effective at maintaining uniform temperatures within and between battery cells, and it becomes challenging to remove significant

amounts of heat. To compensate, a large volume of air would be required, necessitating bulky ducts and manifolds. Additionally, the high energy consumption of fans needed to circulate this large air volume would be a drawback. Furthermore, the need for space between battery cells to allow for airflow would limit packing density within the battery pack. Another disadvantage is noise generation from multiple fans or blowers, which could negatively impact cabin comfort. These limitations may restrict the application of the cabin cooling system to specific EVs where maximizing performance and mileage is less critical.

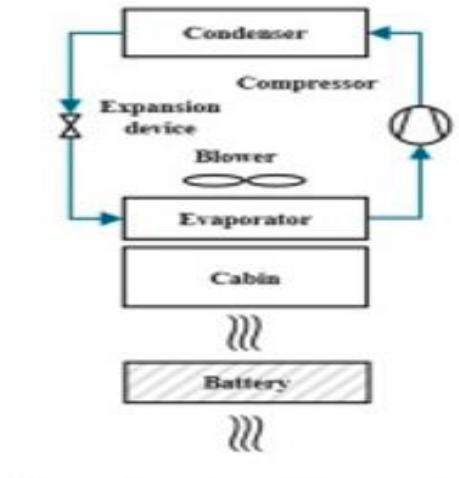

Figure 3: Direct Cabin Air Cooling.[8]

The most suitable option depends on factors such as battery heat generation, the external environment, and driving patterns. Notably, many research studies on air-based BTMS simply set the air temperature to a specific level without considering the air source. This paper explores using pre-conditioned cabin air from the existing VCAC system for battery cooling.

3. METHODOLOGY

Interpreting Single Cell Simulation for Battery Module Thermal Management the simulation of design analyzed the heat generation profile of a single 18650 Li-ion cell under various conditions to understand its thermal behavior:

3.1 Heat Generation Profile:

- Charging/Discharging Rates: The simulation should reveal a higher heat generation rate during faster charging and discharging.
- Ambient Temperatures: Higher ambient temperatures will lead to increased cell temperature due to reduced heat dissipation to the surroundings.

3.2 VCAC System Influence:

The effectiveness of the VCAC system in influencing cell temperature will be analysed through key factors:

- Cooling Effectiveness: The simulation should demonstrate how VCAC integration reduces the peak cell temperature compared to a scenario without cooling. The difference between these peak temperatures will quantify the cooling effectiveness.
- Temperature Distribution Uniformity: Ideally, the VCAC system should promote a uniform temperature distribution across the cell. The simulation results might show temperature variations within the cell, and the analysis should explain how VCAC influences this distribution.
- Response Time During Thermal Transients: This refers to how quickly the VCAC system reacts to changes in cell temperature. Analyzing the time it takes for the VCAC system to stabilize cell temperature after these changes provides insights into its response time.

3.3 Extrapolating to Larger Module:

While the simulation focuses on a single cell, the results can be interpreted for a larger battery module containing 89 cells in series and 24 cells in parallel:

- Series vs. Parallel: In a series configuration, the total voltage of the module is the sum of individual cell voltages, while the current remains the same. Since heat generation is primarily related to current flow, the overall heat generation profile of the module would be similar to the single cell, but at a higher voltage. We have connected 89 cells in series, (3.6 volts each) which adds up the voltage of battery pack to 320 volts. In a parallel configuration, the total voltage remains the same, and the current is the sum of individual cell currents. This would lead to a higher overall heat generation rate in the module compared to the single cell due to the increased current. We have 24 cells in parallel (2.5Ah each) which adds up the total battery pack capacity of 60Ah.

- Temperature Management Challenges: The simulation results can highlight potential challenges in managing temperature uniformity across all cells in the module. As the distance from the VCAC cooling source increases within the module, some cells might experience slightly higher temperatures. This can be addressed by strategically placing VCAC vents or incorporating additional heat transfer elements within the module design based on the simulation insights.

- Validation and Limitations: It's important to acknowledge the limitations of extrapolating single cell data. The actual heat generation and temperature distribution within a module can be influenced by factors like cell-to-cell variations, module packaging materials, and placement of internal components. Real-world testing of a prototype module with temperature sensors can validate the simulation's predictions and identify any discrepancies.

By analysing the single cell simulation and considering the configuration of the larger module, you can gain valuable insights into the effectiveness of the VCAC-based hybrid TMS for managing the overall battery pack temperature. The limitations of single cell extrapolation should be acknowledged, and the research can pave the way for further investigation and optimization through real-world testing.

4. RESULT AND DISCUSSION

Thermal Behavior of a Li-ion Cell with VCAC Integration:

4.1 Heat Generation Profile: The simulation should reveal a clear link between charging/discharging rates and heat generation within the cell. Because of the higher internal resistance and Joule heating caused by the faster ion flow, higher rates result in a more notable heat generation profile. The findings need to measure this correlation and demonstrate the quantity of heat produced at various current rates. Analysis of the effects of ambient temperature is also necessary. Even under moderate charging/discharging conditions, the temperature of the cell may rise because higher ambient temperatures generally cause the cell to lose heat more slowly to the surrounding environment. The difference in peak cell temperature at different ambient temperatures should be quantified by the simulation.

4.2 VCAC System Influence:
The effectiveness of the VCAC system will be evaluated based on key factors:
Cooling Effectiveness**:** This is the difference in peak cell temperature between conditions where a VCAC operates and those where it does not, at the same charging/discharging rates and outside temperature. Its cooling effectiveness is measured by a notable drop in peak cell temperature upon VCAC activation.

- Temperature Distribution Uniformity**:** The VCAC system should ideally encourage a consistent temperature distribution throughout the cell. However, because of uneven airflow or the location of the VCAC vent, the simulation results may vary slightly. Examine these variations and talk about how the placement or design of VCACs could be improved for a more even distribution.

4.3 Extrapolating to Larger Module: While the simulation focuses on a single cell, the results can be interpreted for a larger battery module containing 44 cells (series and parallel configuration):

- Series vs. Parallel: In a series configuration, the current stays constant per cell but the total module voltage is the sum of the individual cell voltages. The overall heat generation profile of the module would be similar to the single cell, but at a higher voltage, because heat generation is primarily related to current flow. In a parallel configuration, the current is the total of the currents in each individual cell, but the overall voltage stays constant. Because of the increased current, this would cause the module's overall heat generation rate to be higher than that of the single cell.

- Temperature Management Challenges: The simulation results can highlight potential challenges in managing temperature uniformity across all cells in the module. Cells further away from the VCAC cooling source might experience slightly higher temperatures. This can be addressed by strategically placing VCAC vents or incorporating additional heat transfer elements (e.g., heat pipes) within the module design based on the simulation insights.
- Validation and Limitations: It's important to recognize the limits of extrapolating data from a single cell. Cell-to-cell differences, the materials used in the packing of the module, and the arrangement of internal components can all have an impact on the actual heat generation and temperature distribution within the module. A prototype module equipped with temperature sensors can be tested in real life to verify the simulation's predictions and spot any anomalies.

This study focuses on the efficiency of the VCAC-based hybrid TMS for controlling the overall battery pack temperature by examining the simulated heat generation profile, the impact of the VCAC system, and the constraints of single cell extrapolation. The results can direct future research and development as well as cooling system optimisation for useful uses in electric vehicles.

5 CONCLUSIONS

To sum up, this study has shown that a VCAC-based hybrid TMS is a promising method for enhancing Li-ion battery temperature control in plug-in hybrid automobiles. The simulation results showed opportunities for additional optimisation, such as establishing uniform temperature distribution and enhancing response time during thermal transients, and offered insightful information about how well VCAC reduces peak cell temperatures. Although the study concentrated on VCAC integration, further research might look into tailoring VCAC operation to battery cooling requirements or even consider adding other cooling techniques like Phase Change Materials (PCM) for better thermal buffering and enhanced battery pack performance and safety.

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