

INTEGRATED COOLING SOLUTIONS FOR ELECTRIC VEHICLE BATTERY PACKS: A SIMULATION STUDY

Ganesh Shete¹, Gaurav Mali¹, Bhavesh Patil¹, Anurag Mahajan¹, Vaishnavi Ambure¹

¹ School of Mechanical Engineering, MIT Academy of Engineering, Pune-412105, India

Abstract

The simulation study delves into the vital role of thermal management in battery systems, which is critical for battery longevity and efficiency in applications such as electric vehicles and renewable energy storage. The research highlights the significant impact of heat generation on overall battery health and performance under constant charging and discharging cycles. Thermal management, which is critical for minimizing temperature-related difficulties, tries to minimize overheating or severe cold, both of which are known to reduce efficiency and limit operational life. The study analyses the complicated relationship between battery performance and the addition of an air conditioning system using simulation tools such as ANSYS 2023 R2. The planned air-cooling system seeks to maintain an optimal battery temperature range of 20 to 50 °C, with battery cells anticipated to attain a temperature of 55 °C during operation. The goal is to evaluate the feasibility and long-term effectiveness of incorporating air conditioning systems to improve battery thermal performance and potentially extend operating life. This comprehensive technique ensures battery durability and adaptability in our ever-changing electric landscape.

1. Introduction

One of the most significant variables in battery systems is thermal management, which is crucial to the lifespan and effective operation of these energy storage devices. The batteries experience constant cycles of charging and discharging, particularly in applications such as electric vehicles and renewable energy storage. This can result in heat generation that can hurt the batteries' general

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Corresponding author name and email: Ganesh Shete, School of Mechanical Engineering, MIT Academy of Engineering, Pune

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health and performance if it is not well handled. Thermal management is critical because it allows for temperature-related issues, including overheating or excessive cold, which can shorten the operational life of batteries, accelerate degradation, and compromise their efficiency [1]. In addition to maintaining ideal operating conditions, effective thermal management protects against the safety hazards brought on by thermal runaway [2]. The creation of strong heat management strategies is essential to improving the overall performance, safety, and reliability of battery systems as energy demands rise and electricity takes up steam. This will help ensure the sustainability and possibility of a wide range of applications in our electric future. Maintaining the ideal temperature for batteries is like giving them a comfortable space in which to grow. Batteries operate well when they are at the ideal temperature, much like humans do best when it is neither too hot nor too cold. The optimum temperature range of the battery is 20 to 50 °C [3]. This has a significant impact on the lifespan and overall wellness of batteries and goes beyond simple convenience. For a longer and healthier life for our gadgets, electric cars, and the batteries that power them, so if we can control their temperature, that is what we are doing. The major lesson is that keeping batteries at the ideal temperature is essential for both their general well-being and a longer, more dependable life. It is not just about comfort. Investigating the effects of external factors on battery temperature is a crucial step in the effort to advance battery technology. Specifically, the goal of this study is to clarify the complicated connection that exists between battery performance and the installation of an air conditioning system, an external effect. Our goal is to thoroughly investigate and measure how the air conditioning system affects the regulation of battery temperature by using simulation tools like ANSYS 2023 R2. The goal is to assess the cooling system's long-term effects on battery health and lifespan in addition to understanding how it affects sudden temperature variations. This investigation delves further than the obvious to uncover complex relationships between battery systems and heat management techniques. We aim to provide light on the feasibility and long-term viability of incorporating an air conditioning system to improve the thermal performance of batteries through extensive research and simulation. This will contribute to the changing field of battery management systems in a range of applications, from renewable energy storage to electric vehicles. Imke Krueger et al. investigate lithium-ion battery cooling in hybrid vehicles, employing Modelica to integrate thermal models. The study highlights a potential 10% increase in compressor energy demand, emphasizing the impact of refrigerants R134a and R1234yf on passenger comfort and refrigerant cycle efficiency [4]. Brahim Mebarki et al. explore the impact of air-conditioning systems on the power consumption of electric vehicles powered by lithium-ion batteries with MATLAB simulations [5]. Haowen Wu investigates a direct cooling structure in a Battery Thermal Management System (BTMS) for electric vehicles. Using R134a and R1234yf refrigerants, the BTMS effectively controls battery temperatures, demonstrating rapid cooling in high temperatures without changing the system structure. The study concludes that R1234yf is a feasible, cost-effective alternative to R134a in BTMS applications [6]. Y. Lyu et al. optimize electric vehicle battery cooling with a hybrid TEC-liquid-air-air-air system, achieving a notable 43°C temperature reduction (from 55°C to 12°C). Outperforming natural air and liquid methods, this system holds significant promise. [7].

Changhao Piao et al. propose an active and passive liquid cooling-based system for electric vehicle (EV) thermal management, addressing limited battery capacity and motor efficiency [8]. Rezvanianani et al. review battery prognostics and health management (PHM) for electric vehicles, comparing physical, data-driven, and fusion approaches [9]. Di Wang and Jinhong Xie design a liquid cooling/heating system for EV battery packages. Experimental results and a validated model reveal that adjusting liquid flow and inlet temperature optimizes battery temperature during cooling, with a notable impact when the flow rate is less than 0.5 L/min; preheating benefits from high flow rates and inlet temperatures, significantly saving time for drivers [10]. Chunyu Zhao et al. examine Li-ion battery thermal management systems (BTMS) for electric vehicles. They categorize existing BTMS, highlighting hybrid methods. Hybrid BTMS, blending passive and active techniques, emerges as a versatile, efficient trend. The paper discusses cost, performance, and criteria, proposing a dimensionless number for assessment. While overcoming basic BTMS limitations, hybrid BTMS introduces complexities and energy consumption considerations. The suggested evaluation approach aims for comprehensive comparisons. The authors anticipate the increasing prominence of hybrid BTMS, especially for extreme conditions beyond electric vehicles. [11].

Katoch et al. explore the environmental benefits of Electric Vehicles (EVs) and emphasize the critical role of efficient Battery Thermal Management Systems (BTMS) in addressing challenges related to lithium-ion batteries. The review identifies opportunities for future research, supporting the growing demand for sustainable electric transportation [12]. Turki et al. focus on designing a coolant-based battery cooling system for electric vehicles, emphasizing the crucial role of battery thermal management. They explore various cooling systems, highlighting the efficiency of liquid cooling, specifically employing ethylene glycol in a copper heat pipe. The selected coolant demonstrates superior heat dissipation, anti-corrosive, and anti-freezing properties, making it suitable for diverse environmental conditions. [13]. Iswanto et al. proposed a novel fluid-based cooling system for electric vehicle batteries, optimizing energy storage by controlling temperature. A sensitivity analysis determined optimal geometries, reducing turbulent flow-related thermal stresses. The innovative design showed a 25% decrease in body temperature, promising high performance for future electric vehicle batteries. [14]. Wazeer et al. delve into battery thermal management using Phase Change Materials (PCMs) for electric and hybrid vehicles. The review emphasizes the superiority of PCMs over traditional methods, ensuring uniform temperature, reduced power consumption, and enhanced thermal uniformity. The exploration of multi-layer PCM configurations and their integration with liquid cooling presents a promising avenue for efficient battery thermal management [15]. This paper by Changhao Piao et al. presents an active and passive liquid cooling-based system for electric vehicle (EV) thermal management. Mathematical models for system components are established using experimental data, demonstrating feasibility and energy efficiency in maintaining battery operating temperatures [16,17]. The paper by Xinghui Zhang et al. discusses lithium-ion battery (LIB) thermal management in electric vehicles (EVs) considering the challenges posed by varying temperatures. It highlights methods such as air, liquid, electric, and phase change material heating/cooling,

emphasizing the need for effective and uniform temperature control. The review concludes with prospects for future research, including adapted temperature maintenance methods, integrated vehicle thermal management, electrolyte modification, and the study of thermal management's impact on battery aging [18,21]. M. B. Domalanta et al. modeled a lithium polymer (LiPo) battery's electrochemical, thermal, and thermal runaway behavior. The Multiphysics model provided insights into electrochemical processes, temperature profiles, and thermal runaway scenarios. Despite discrepancies, it proved valuable for preliminary predictions. Future research should explore extended simulations and sensitivity analyses for optimized battery design and enhanced model reliability [19]. The paper by Po-Hsu Lin explores the electric air conditioning system's impact on electric vehicle comfort. Using a semi-empirical model in MATLAB/Simulink, the study identifies key parameters such as ventilation ratio and blower speed for effective heat removal. The results emphasize the significance of solar load and environmental temperature. This simulation-driven approach aids thermostat controller development and validates A/C system component specifications for adequate refrigeration in electric vehicles [20].

The literature survey includes the importance of BTMS for the smooth functioning of batteries, along with this, it also includes various ways and methods of battery thermal management. This study helped to decide the topic for investigation as a comparative study of air conditioning cool air and ambient air used to cool the battery down for smooth functioning. This investigation has some objectives as to create a thermal management system to keep battery pack temperatures within the ideal range (20 °C to 50 °C) while in operation, to compare the two methods for BTMS like ambient air as a medium for cooling and air conditioning system's cool air, to implement methods to ensure that batteries operate reliably within the temperature limitations indicated, to increase overall lifespan and durability, and to integrate techniques into the thermal management system to reduce heat-related stress, improving the battery's overall lifespan and durability.

2. Materials and Methods

The research methodology is structured to systematically address the thermal management challenges in batteries through the introduction of an air conditioning system. The primary objectives include the thermal management of the battery, ensuring its operation within the optimum temperature range, and enhancing the lifespan and working ability of the battery. This study adopts an analytical approach, employing CATIA software for the design of the battery pack and ANSYS 2023 R2 software with Fluent mode and the k-epsilon equation for simulation analysis. The battery pack is meticulously designed using CATIA, with dimensions of 92×65×92 mm. The design incorporates provisions for air inlet and outlet, facilitating the flow of cool air through the battery pack at a speed of 0.2 m/s. The inlet provision, located at the upper surface along the vertical axis, has dimensions represented by the equation: Inlet Dimensions = 15 mm × 2 mm + Bulge (2 mm). The outlet provision is situated at the bottom of the opposite side with identical dimensions. Individual battery cells within the pack are characterized by a diameter of

18 mm and a height of 65 mm, each possessing a voltage of 3.2 V and a capacity of 6000 mAh. Considering the heat generated during battery operation, the temperature of each cell is assumed to be 55°C, exceeding the optimum temperature range. To represent this, the equation for the assumed cell temperature is given by: $T_{cell} = 55^{\circ}\text{C}$. To mitigate this excess heat, an air conditioning system is introduced. This system circulates cool air generated by an AC system through the battery pack. The flow of cool air is represented by the equation: Cool Air Flow rate of 0.2 m/s. The simulation analysis is conducted using ANSYS 2023 R2 software, implementing Fluent mode and the k-epsilon equation. The simulation accounts for the thermal behavior of the battery pack, assessing heat dissipation and temperature distribution. The methodology ensures precision in representing the physical dimensions and properties of the battery pack, inlet and outlet provisions, and individual cells.

3. Materials and Methods

Indoor air quality (IAQ) is crucial for human health and well-being, causing respiratory problems, headaches, and chronic illnesses. An IoT-based indoor air quality monitoring system can be developed using an ESP32 microcontroller, a gas sensor, a smoke sensor, a CO₂ sensor, a relay module, a cooling fan, a power supply, and the Blynk app. The system monitors harmful gases, smoke, and carbon dioxide levels in indoor environments, activates a cooling fan if necessary, and sends real-time data to the Blynk app. The system aims to provide real-time insights, enabling timely interventions for healthier living and working environments.

3.1. Architecture

It shows the overall architecture of the HVAC system. This block diagram indicates both occupancy-based light & fan automation systems and Indoor Air Quality (IAQ) monitoring and controlling systems by atomizing ventilation and Air conditioning systems. In this work dust sensor GP2Y1010AU0F to measure PM2.5 [1], a LM35 temperature sensor, and an MHZ14-A sensor to measure carbon dioxide are integrated, and it is utilized for specific purposes.

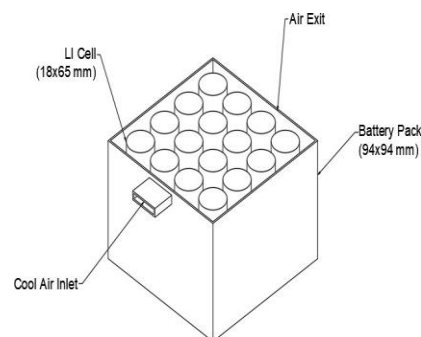


Figure 1. Battery pack model

Table 1: Grid Independence Study

Sr. No	Meshing Size (mm)	Nodes	Elements	Temperature (K)
1	12	49105	39334	325.884
2	8	49128	39356	326.195
3	6	49197	39466	327.150
4	5	49128	39400	327.124
5	4	49220	39488	327.115

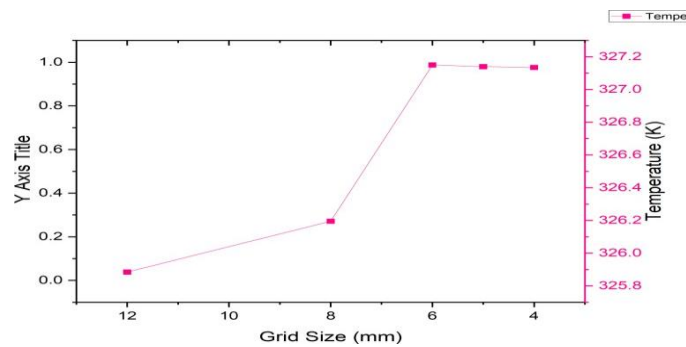
**Figure 2.** Grid Independence Study Graph

Figure 2 illustrates the results of the grid independence study, which evaluated several mesh sizes for the analysis. The results show that a mesh size of 4 mm is appropriate for the investigation, as the resulting values roughly match those obtained at mesh sizes of 6 mm and 5 mm. This implies that a mesh size of 4 mm is regarded as sufficient for the analysis in terms of accuracy and calculating performance, indicating its fit for the study's specific objectives

4. Design and Modeling

The simulation results shed light on how the battery pack performs under various scenarios

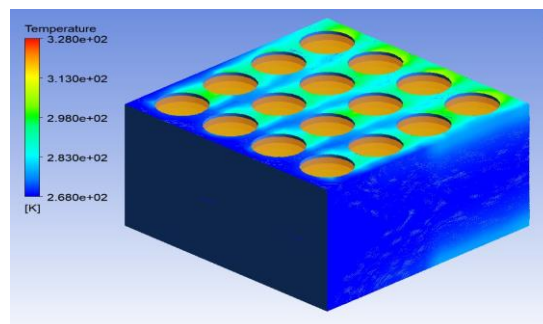
**Figure 3.** Temperature distribution result (AC)

Figure 3 provides important information about the temperature fluctuations within individual cells, which is an essential element of our research. The air conditioning system, which is critical to this research, constantly maintains temperatures between 20 and 50 degrees Celsius, perfectly corresponding with our operational targets. The data shown demonstrates the system's success in obtaining and maintaining temperature stability, with the highest recorded temperature in any cell being 321.7 K, well within the operational boundaries. Notably, these results were obtained with incoming air that was initially 268 Kelvin and had an entry velocity of 0.125 m/s. This information emphasizes the air conditioning system's strong performance by emphasizing its capacity to properly manage cell temperatures under a variety of conditions. Figure 4 shows how individual cells respond to cooling by ambient air, which is an important component of our research focused on maintaining ideal battery temperatures. Surprisingly, the data shows that the peak temperature within the battery reaches 327 K, which is slightly higher than our desired range. This unanticipated outcome necessitates a thorough assessment of the cooling strategies and their connection with our operating goals. These results were obtained with ambient air flowing through the battery at a temperature of 303 Kelvin and an entry velocity of 0.125 m/s.

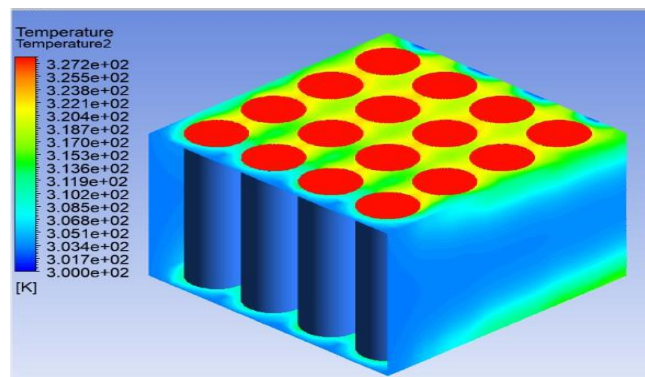


Figure 4. Temp. distribution result (Ambient Air)

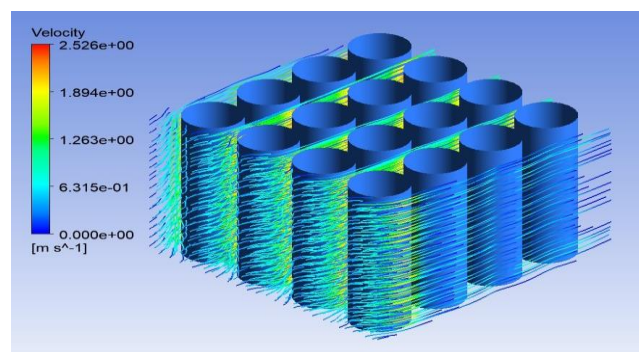


Figure 5. Velocity distribution of cool air

The simulation results provide clarity regarding the velocity distribution within the battery pack under various operational conditions. Individual cell velocity profiles are shown in Figure 5, emphasizing the necessity of the air conditioning system in achieving consistent velocity. Surprisingly, the maximum velocity seen in any individual cell is 2.5 m/s, demonstrating the system's efficient airflow management. A continuous pattern can be seen in Figure 6, which also illustrates individual cell velocity profiles. Notably, the maximum velocity reported in any one cell is 2.48 m/s, proving the system's capacity to maintain efficient airflow management. These findings highlight the air-cooling system's dependable performance in maintaining uniform velocity profiles within the battery pack under varying operational situations.

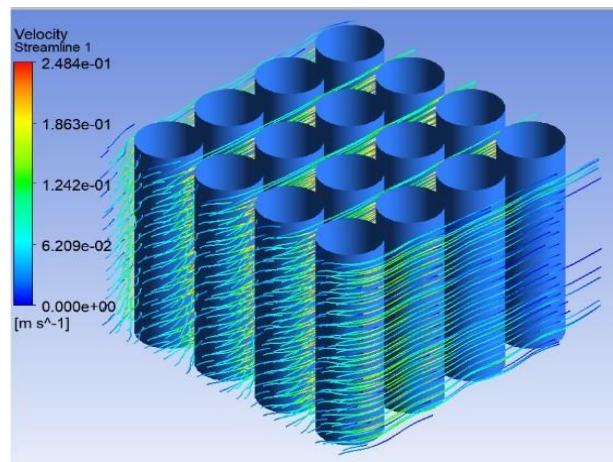


Figure 6: Velocity distribution of ambient air

5. Conclusions

The meshing size is taken as 4 mm because it gives accurate and precise results, refer the Table 1. The research underscores the critical role of thermal management in optimizing the performance and lifespan of battery systems, particularly within the temperature range of 20 to 50 °C. The impact of air conditioning (AC) systems on ambient air on battery temperature regulation was the focus of our inquiry. The simulation results, shown in Figures 2 and 3, demonstrate the AC system's efficacy in keeping temperatures within its target range, with the maximum measured temperature of 321.7 K (47°C) achieving operational targets. In Figure 3, however, the use of ambient air for cooling results in a somewhat higher maximum temperature of 327 K (54°C), demanding more investigation into its usefulness. The velocity distribution, as seen in Figures 4 and 5, emphasizes the AC system's efficacy in managing airflow even more. The findings indicate that the air conditioning system is more suited to maintaining appropriate battery temperatures, resulting in improved performance, safety, and longevity. In the move towards an electric future, these findings have important implications for the integration of effective thermal management

systems, particularly those that favor the use of air conditioning, across a variety of applications ranging from renewable energy storage to electric vehicles.

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