Effect of Cooling Velocity on Battery Temperature

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HIGHLIGHTS

- Developed a mathematical model and conducted simulations in ANSYS to study the effect of cooling velocity on battery temperature.
- Identified the optimal cooling velocity that enhances heat dissipation while minimizing energy consumption.
- Analyzed data to observe temperature reduction trends across different cooling velocities with clear graphical and numerical results.
- Provided practical insights for improving battery thermal management systems in electric vehicles and energy storage applications.

ABSTRACT

Critical to achieving performance, safety, and life in the battery for such high-demand applications, such as electric vehicles or energy storage, is proper thermal management. In this project, cooling velocity effects on battery temperature are explored with the intention of optimizing BTMS for enhanced heat dissipation and energy efficiency. Thus, following the development of a mathematical model and simulations within ANSYS involving varying cooling velocities, the thermal behavior of the batteries is thereby analyzed. The graph shows that enhancing the cooling velocity has a corresponding significant level of reduction in temperature for the batteries, but at some point, the returns diminish. Thus, an optimum cooling velocity is found, wherein minimal energy consumption achieves effective dissipation of heat. These findings can therefore be used to design BTMS that are more efficient in terms of battery performance and longevity.

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1. Introduction

With the rapid adoption of lithium-ion batteries in energy storage systems and electric vehicles, ensuring their safety, efficiency, and longevity has become a critical concern. One of the key challenges faced by these systems is managing the heat generated during battery operation. Excessive heat can lead to degraded battery performance, reduced lifespan, and, in extreme cases, thermal runaway, which poses significant safety risks. Therefore, the development of an efficient Battery Thermal Management System (BTMS) has been a pressing area of research and innovation in modern energy systems.

Lithium-ion cells, characterized by their high energy density and energy-to-weight ratio, primarily due to low density and high pair-specific energy, produce heat in charging and discharging from electrochemical reactions and resistive losses. It is a standard fact that an accumulation of hotness might lead to asymmetrical temperature across the pack, thus to some potential hotspot that may compromise the overall performance of the system. BTMS is used to regulate the temperature of battery cells with uniformity, so they may be maintained within an optimal operating range (usually 20–40°C).

- Heat Conduction $\boldsymbol{q = -k\, dT/dx}$
- Convective heat transfer: $\mathbf{q=hA(T_{surface}-T_{ambient})}$

BTMS Classification:

BTMS can be generally classified according to the cooling method used:

1) Air-Cooling Systems:
   - It dissolves heat from the battery cells by circulating air
   - Relatively inexpensive and light weight but have lower efficiency for handling large thermal loads.
2) Liquid-Cooling Systems:
   - These systems use fluid coolant to absorb and transfer heat away from the battery cells.
   - They are highly efficient for high performance systems but more complex and expensive.
3) Phase Change Material (PCM)-Based Systems:
   - Use phase-changing materials, such as solid-liquid phase changers, to absorb heat when in operation.
   - Use passive cooling but require an integration approach with active systems for large-scale applications.
4) Hybrid Systems
   - Combine two or more cooling methods, such as air and liquid, to enhance performance.
   - Achieve balance between efficiency, cost, and complexity.

Among these, air-cooling systems are most widely used for low to moderate energy applications because they are very simple and easy to implement. However, their performance is highly dependent on the airflow configuration, velocity, and the spacing between battery cells. This project will be aimed at finding an optimum performance of an air-cooled BTMS by determining the effect of cooling velocity on battery temperature.

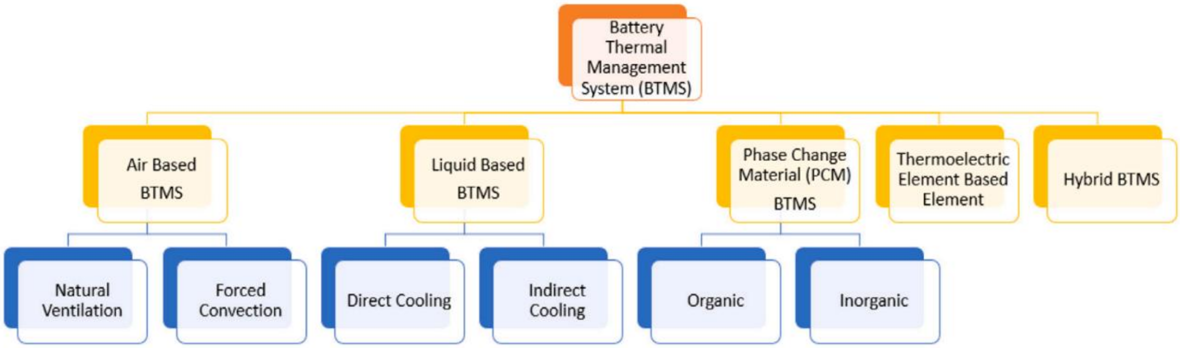


fig 1 Overview of Battery Thermal Management System (BTMS) highlighting different cooling methods (air cooling, liquid cooling, and phase change materials)

Project Overview

The primary aim of this project is to explore the effects of airflow velocity on the thermal performance of a lithium-ion battery pack. Computations in ANSYS are carried out at three air velocities, namely 2 m/s, 5 m/s, and 10 m/s, to evaluate the effectiveness of these air velocities in reducing temperatures of the battery and achieving uniform cooling. A comprehensive thermal analysis is conducted regarding temperature distribution, cooling efficiency, and the trade-off that can occur between energy cost and thermal management performance.

This project investigates the thermal performance of a lithium-ion battery pack under varying airflow velocities by analyzing the heat generation within the cells and its dissipation through air cooling. Lithium-ion batteries generate heat during charging and discharging due to electrochemical reactions and resistive losses. The generated heat can be expressed using the following equation:

$$Q_{\text{total}} = I^2 R + I \frac{\partial V}{\partial T}$$

Significance of Study

Effective thermal management is critical for the safety and durability of lithium-ion battery systems. This study contributes to the growing body of research by providing insights into the design and optimization of air-cooled BTMS. The findings will aid in improving the reliability and performance of battery packs in applications like electric vehicles, renewable energy systems, and portable electronics.

The results of this study not only highlight the importance of cooling velocity in thermal management but also serve as a basis for future advancements in BTMS. Additionally, the insights from this research can guide the development of hybrid and advanced cooling techniques for high-power battery systems.

2. Problem Statement

With the increasing use of batteries in electrical vehicles, portable electronics and renewable energy systems, maintaining optimal battery temperature has become a critical challenge. High temperature generation during charging and discharging cycles can lead to reduced battery efficiency, shortened lifespan, as well as possible safety risks like thermal runaway.

Battery Thermal Management Systems (BTMS) are developed to overcome these problems through temperature regulation by various cooling mechanisms. However, the cooling velocity of the medium, either air or liquid, significantly affects the productiveness of the systems. A low cooling velocity may lead to overheating of battery, thereby leading to degradation of performance. Conversely, a very high cooling velocity increases energy consumption, which can reduce the system's overall efficiency without a proportional gain in thermal regulation.

The problem this project addresses is finding the optimal cooling velocity that maximizes heat dissipation while minimizing energy consumption. By analysing the effect of different cooling velocities on battery temperature using a mathematical model and simulations in ANSYS, this project aims to contribute to the development of more efficient and reliable BTMS designs.

3. Literature Review

Efficient thermal management in battery systems is essential for their safe and optimal performance, particularly in high-demand applications such as electric vehicles, portable electronics, and renewable energy storage. Excessive heat accumulation due to poor thermal management can accelerate the degradation processes in batteries, reduce efficiency, and poses severe safety risks. This literature review examines recent studies focused on Battery Thermal Management Systems (BTMS), with particular emphasis on the role of cooling velocity in regulating battery temperature.

- **Importance of battery thermal management systems**

  A battery thermal management system (BTMS) regulates battery temperature, especially lithium-ion batteries (LIBs), to enhance safety, maximize efficiency, and extend the battery's useful life [1]. A conventional EV li-ion battery pack operates optimally between 15℃ to 35℃ [2]. If the li-ion battery pack operates below 15℃, the overall capacity drops and the battery's internal resistance increases [3]. Conversely, temperatures above 35℃ could potentially lead to an irreversible reaction occurring across the li-ion battery pack and an increased risk of thermal runaway [4]. Given these challenges, effective BTMS is crucial for applications where batteries are subject to high discharge and charge cycles.

Research on BTMS has advanced significantly in recent years, exploring a variety of cooling techniques to maintain temperature within safe limits. The most commonly used cooling methods include air cooling, liquid cooling and phase-change materials. Their research demonstrates that while air cooling is simpler and less costly, it is often insufficient for high-power applications due to its lower heat transfer coefficient. Liquid cooling systems, on the other hand, are more effective for rapid heat dissipation and have higher heat transfer efficiency, but they come with increased complexity, cost, and potential maintenance issues due to liquid leakage risks. Phase-change materials (PCMs) have been explored for passive cooling but are typically only supplementary to active cooling systems due to their limited ability to dissipate heat in dynamic conditions.

The effectiveness of each cooling method significantly depends on the cooling velocity — the rate at which the cooling medium flows over or through the battery. Optimizing cooling velocity is essential to achieve a balance between effective cooling and energy consumption, particularly in high-demand applications.

- **Role of cooling velocity in heat dissipation**

Cooling velocity is a crucial factor in Battery Thermal Management Systems (BTMS) with respect to BTMS effectiveness, especially in air-cooled design, where temperature control is established by air passing over the battery cells in order to remove heat. Since the thermal conductivity of air is minimal compared to liquids, extremely high air velocities are needed to ensure adequate heat transfer. Increased airflow also helps cool the battery by replacing hot air around the battery with cooler air and permits a larger temperature gradient to maximize convection-based heat dissipation.

However, higher cooling velocities require more power in the fans, thus increasing energy consumption and impacting the system as a whole. There is a trade-off, because the degree of cooling can saturate once past a certain airflow rate, where increased energy costs without proportional improvement in the thermal.

Air cooling is preferred because it is straightforward, inexpensive, and lightweight, in comparison to a liquid-cooled system, making it suitable for applications, such as electric vehicles and portable electronics. However, air-cooled systems are more constrained by environmental conditions. Even at maximum airflow velocities, high ambient temperatures can be limiting. This is particularly so in warm climates or high-demand scenarios, where it will then struggle to cool the battery. This, some systems add heat sinks or finned structures to augment the heat dissipation from an increased surface area and supporting airflow. These design choices extend the effectiveness of air cooling but must be integrated carefully lest they add unnecessary weight or complexity.

BTMS designs may become unbalanced between cooling velocity and energy consumption, meaning while it should deliver certain airflow rates for specific applications, it should not consume too much power. Included in this are fan power, battery layout, and airflow paths such that the cooling is balanced in all areas, including avoiding any hot spots. Air cooling for batteries demands optimal balancing under consideration of ambient conditions, designs, and requirements of efficiency. Appropriate optimisation could make it a cost-efficient and lightweight thermal management alternative. For most cases, an air-cooled BTMS will present a robust solution for reliable cooling without the added complexity introduced by liquid cooling systems.

- **Mathematical modelling and simulation approaches in BTMS**

Mathematical modelling and computational simulations have become essential for studying Battery Thermal Management Systems (BTMS), allowing researchers to analyze cooling methods, velocities, and configurations can be investigated with the advantage of cost savings through the absence of prototype building. The Finite Element Model (FEM) in software like ANSYS is widely applied to simulate heat transfer and fluid flow and gives insight into the temperature distribution under different cooling scenarios. Various engineering parameters can be simulated to promote an efficient BTMS design that enhances performance and battery life.

Xu and Chen (2023) have modelled the effects of cooling velocity on the temperature distribution of lithium-ion battery modules using ANSYS Workbench. It was found that increased cooling velocity significantly worsened thermal uniformity, which ensured battery health by mitigating hotspots that cause uneven aging. Their results show that FEM-based modelling has taken the forefront of allowing BTMS configurations to give designers better temperature management control.

Similarly, Wang et al. (2022) extracted simulation results using ANSYS Fluent for a liquid-cooled battery pack, which examined various coolant flow rates. An increase in flow rates diminished peak temperatures, and pressure dropped for these increases overlappingly increased pumping power consumption. The focus parameter here is multi-temperature management, where, independently, a balance is sought. Hence, the optimization of cooling velocity assumes further importance in terms of BTMS designs, proper disposal of energy needed for cooling but, at the same time, not exacerbating battery temperatures.

- **Optimal cooling velocity: balancing performance and energy efficiency**

The concept of "optimal cooling velocity" has gained prominence in Battery Thermal Management Systems (BTMS) research, as studies establish velocity ranges that optimize heat dissipation without significantly increasing energy consumption levels. Both liquid and air cooling are equally valid methods; however, air cooling is generally preferred because of simplicity, cost-effectiveness, and lighter weight, particularly in electric vehicles and portable electronics. A parametric study done by Kim et al. (2021) showed that there are ranges within which cooling velocities maximize heat removal at low-energy input. This range is critical in air cooling because of the increased velocity needed due to the lower thermal conductivity of air, but must be balanced against high fan power consumption negatively influencing efficiency. Beyond this optimal range, additional airflow offers little cooling advantage and can result in counterproductive energy demands.

The conclusions of Kim et al.'s work highlight a fine balance necessary to maintain efficacy of BTMS with air cooling, requiring sufficient airflow to achieve effective cooling without excessive energy costs. The balance is greatly governed by the kind of battery used, applications, and the environmental conditions, especially in high-power applications where thermal regulation is critical for safety and battery lifespan. Chen et al. (2023) reinforced this idea in their research regarding various cooling techniques and velocities, demonstrating that the minor changes in air velocity have a substantial effect on temperature uniformity, which is key for preventing localized overheating in battery cells.

Most of these studies highlight the determination of an optimal cooling velocity as a significant factor for efficient, reliable thermal management in air-cooled systems, providing a structured review of the research literature on the optimal cooling velocity involved in air system design modelling and simulations, which allow for tuning of the independent variable in the BTMS design to enhanced performance while avoiding unnecessary energy costs. Air cooling, amplified to velocity, becomes a balanced manner to maintain safe and steady temperatures in the simplified, cost-effective, light-weight applications.

- Conclusion

The literature on BTMS and cooling velocity demonstrates that while higher cooling velocities generally lead to better heat dissipation, there is a point of diminishing returns where further increases in velocity do not significantly improve cooling efficiency but do increase energy costs. Optimal cooling velocity, therefore, is crucial in designing efficient BTMS. This review has highlighted studies that utilize mathematical modelling, simulation, and experimental analysis to determine this optimal range, providing a foundation for future research. By building on these findings, this project seeks to utilize ANSYS simulation to identify the optimal cooling velocity for a BTMS, balancing effective heat dissipation with energy efficiency and contributing to improved battery performance and lifespan.

4. Methodology

The methodology for this project follows a systematic approach to analyze the effect of cooling velocity on battery temperature. The process is outlined in five key stages: **Problem Definition**, **Data Collection**, **Mathematical Model Development**, **Simulation**, and **Result Evaluation**. Below is a brief description of each step, as illustrated in the flowchart.

1. Define Problem Statement

The objective of this project is to study how varying cooling velocities influence temperature distribution in a lithium-ion battery pack. This research aims to optimize the Battery Thermal Management System (BTMS) to ensure uniform cooling and safe thermal performance.

2. Data Collection

Accurate and comprehensive data is essential for developing a reliable simulation model. This stage involves gathering the necessary inputs, such as:

- **Battery cell specifications:** Each lithium-ion cell in the pack has dimensions of 100 mm × 145 mm × 22 mm and operates at a voltage of 10 V.
- **Battery pack configuration:** The pack comprises 12 cells in a 3×4 arrangement with a 5 mm gap between each cell to facilitate airflow.
- **Cooling system parameters:** Air-cooling is used, with airflow velocities of 2 m/s, 5 m/s, and 10 m/s being considered for analysis.
- **Thermal properties of materials:** Thermal conductivity, specific heat, and density of the battery materials and cooling air are collected for precise thermal modeling.

3. Develop Mathematical Model

Once the data is collected, a mathematical model is developed to simulate the heat generation and dissipation processes in the battery pack. This model is implemented in ANSYS to create a virtual representation of the battery pack and cooling system. Key aspects of this step include:

- Setting up the thermal boundary conditions.
- Defining heat generation rates based on the battery's operating conditions.
- Incorporating airflow dynamics and thermal properties to simulate heat transfer via convection.

This step provides the foundation for simulating the thermal behavior of the battery pack under different cooling velocities.

4. Simulation and Analysis

The next stage involves performing simulations using the developed mathematical model. In ANSYS, the battery pack is subjected to airflow velocities of 2 m/s, 5 m/s, and 10 m/s to observe their effects on temperature distribution. The simulations are designed to:

- Measure the maximum, minimum, and average temperatures of the battery pack.
- Analyze the uniformity of temperature distribution across all cells.
- Identify hotspots and evaluate the effectiveness of airflow in mitigating them.

5.Visual Representation

The flowchart provided is a concise and effective way to represent the methodology. Each arrow represents the sequential progression from one step to the next. The reiteration of "Data Collection" and "Mathematical Model Development" highlights the iterative nature of the process, ensuring accuracy and refinement of the model before conducting the final analysis.

6.Integration of Figures and Tables

To enhance the understanding of the methodology, the following can be included in the report:

- **Images:**
  Visual representations of the battery cell and pack configuration can be added to the "Data Collection" section.
- **Tables:**
  A table summarizing the key input parameters (dimensions, material properties, airflow velocities, etc.) should be included for reference.

This comprehensive methodology ensures that the research is conducted systematically, providing accurate and reliable results to meet the project's objectives.

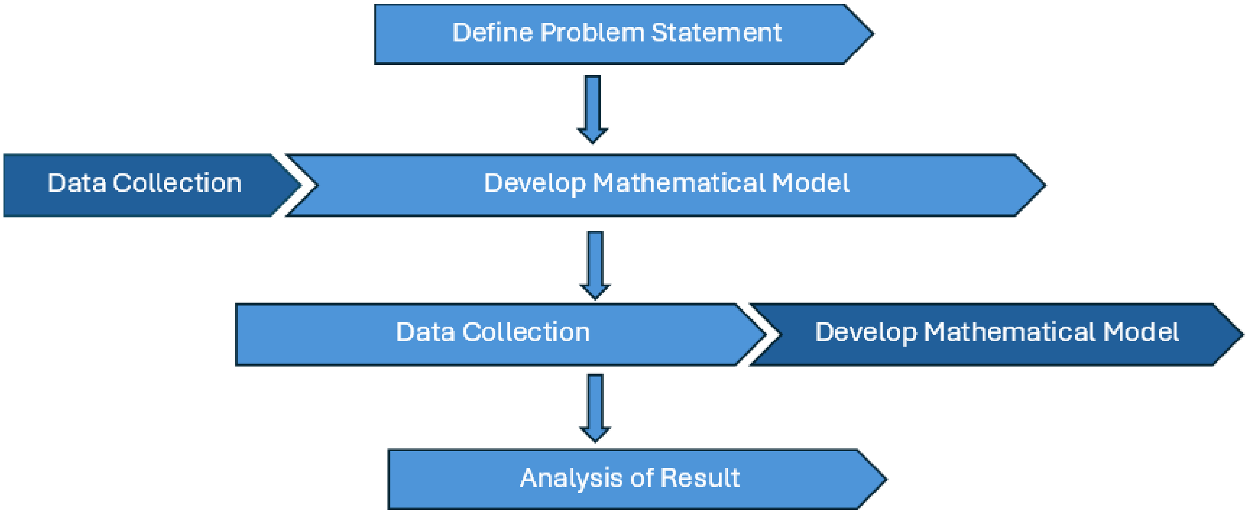


fig 2 Flowchart of the methodology used in this project, illustrating steps from problem statement definition to result analysis

5. Design and Setup

A. Battery Cell Design:

- **Overview of the Battery Cell:** The project uses a size of 100 mm x 145 mm x 20 mm dimension with the given nominal voltage of 10 V. Such cells are specifically designed to exhibit a balance between maximum energy capacity and an efficient management of heats; therefore, such a form factor will easily fit into the battery pack while maximizing the surface area for heat dissipation.
- **Thermal Management of the Battery Cell:** Since heat is generated during charging and discharging, the cell structure shall comprise of thermal conductivity-enhancing materials. The external casing of the cell is made from a thermally conductive material to support the dissipation of heat. Internal components are arranged to minimize thermal resistance. The cell operates within safe temperature limits.
- **Heat Generation and Dissipation:** The heat inside this cell is produced due to the electrochemical reactions and internal resistances. The large surface area along one of the faces measured 100x145mm ensures adequate dissipation. The cell is 20 mm in thickness thus allowing heat conduction outwards, which saves from creating a hotspot that may degrade or even be dangerous to the performance.
- **Cooling Interfaces:** Cooling interfaces are integrated at the major surfaces of the cell, ensuring that heat is transferred effectively to the external cooling system. The design allows for optimal thermal coupling, whether using air or liquid cooling, ensuring uniform temperature distribution and preventing localized overheating.

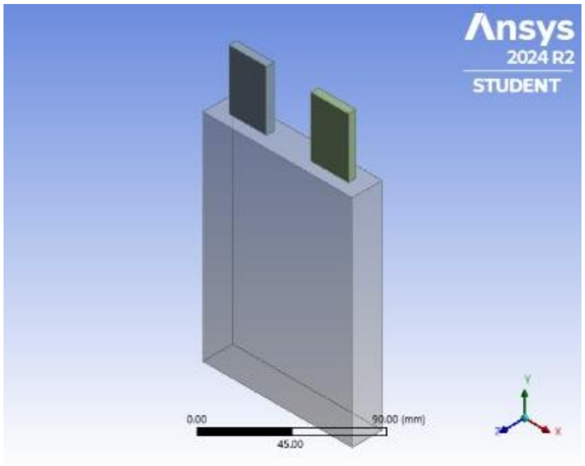


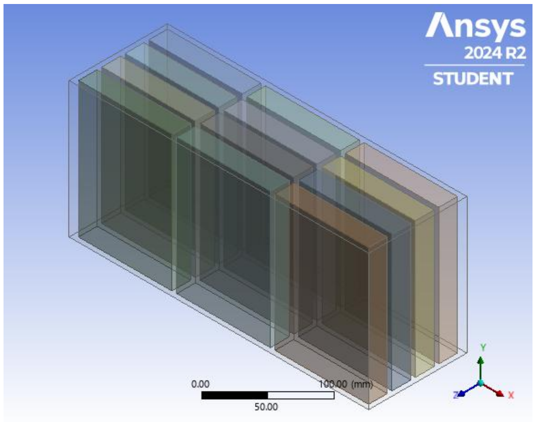
fig 3 3D representation of the battery cell design

B. Battery Pack Configuration:

This is a 3x4 grid cell arrangement for the battery pack. Each cell measured at 100 mm x 145 mm x 22 mm, and the whole pack measures 310 mm x 140 mm by 105 mm in dimension. The cells are spaced at 55 mm to create inter-cell gaps to allow for effective airflow cooling. It is thereby optimized for air cooling since air passes through gaps between cells to cool itself, due to the heat released when it is in operation.

- Air Cooling System: The cooled strategy of this battery pack is air circulated through the intercell gaps. The airflow channeled through the gap of 55 mm brings equal cooling effects on the surfaces of batteries. The air-cooled cooling system is a very efficient means by which excessive heat generated from cells is evacuated during their charge and discharge cycles.
- Inlet air velocity: To gain insight into the effect of cooling velocity, air is introduced at three different velocities in the cooling channels between the cells.
    - 2 m/s (low speed)
    - 5 m/s (intermediate speed)
    - 10 m/s (high speed)

These different inlet velocities test the thermal performance of the battery pack to different changed cooling conditions. The airflow encourages carrying heat away from the surfaces of the batteries, such that it does not exceed its specified limits for operation.



- Thermal and structural concerns: A 5 mm gap between cells is essential to ensure adequate airflow, minimizing pressure drop and allowing the cooling system to efficiently manage the heat load. The design maximizes airflow exposure across each cell’s surface for optimal heat dissipation and uniformity, preventing thermal hot spots caused by localized overheating. The battery casing and pack material are designed to enhance heat transfer between the cells and the surrounding airflow, further improving cooling efficiency.

C. Design Constraints and Assumptions:

When designing the lithium-ion battery pack for this project, several constraints and assumptions were made to ensure a feasible and accurate simulation, especially considering the dimensions, cooling strategy, and thermal management requirements.

- **Assumptions**
  - **Uniform Heat Generation:** It is assumed that each cell generates heat uniformly during the operation. This simplifies the thermal model by ignoring local hotspots or variations in heat generation due to non-uniform reactions within the cell.
  - **Steady-State Thermal Conditions:** The analysis assumes steady-state conditions for thermal simulations, meaning that heat generation and dissipation are constant over time. Dynamic changes such as charging cycles and sudden load increases are not considered in this model.
  - **Perfect Contact between Cells and Cooling Medium:** It is assumed that there is perfect thermal contact between the battery cells and the surrounding air, with no thermal resistance or gaps between the cells and the air cooling system. This ensures maximum heat transfer efficiency in the simulation.
  - **No Heat Loss through Radiation:** Heat loss due to radiation is assumed to be negligible in this analysis. The dominant mode of heat transfer is convection between the cell surfaces and the air passing through the gaps.
- **Design Constraints**

Design Aspect	Constraint
Battery Cell Dimensions	100 mm x 145 mm x 22 mm
Battery Pack Configuration	3x4 cell arrangement with overall dimensions of 310 mm x 140 mm x 105 mm
Cell Spacing (Gap)	5 mm gap between each individual cell
Cooling Method	Air cooling through gaps between cells
Inlet Air Velocities	2 m/s, 5 m/s, 10 m/s
Cell Material	High thermal conductivity material (e.g., aluminum for casing)
Temperature Limits	25°C to 50°C for safe operation
Battery Pack Material	Thermally conductive material for casing
Thermal Contact	Perfect thermal contact assumed between cells and air
Heat Loss Mode	Convection, neglecting heat loss through radiation

6. Analysis and Results

A. <u>Introduction to the Analysis:</u>

The Introduction to the Analysis section serves as a brief overview that sets the stage for the detailed presentation of your results. It helps the reader understand what will be analyzed, the approach you took, and why certain parameters or factors are critical. Here's what it typically includes:

1. Restate the Objective of the Analysis

- Begin by reminding the reader of the key goal of the analysis. For instance: The primary objective of this analysis is to examine the impact of cooling velocity on the temperature distribution within the battery during operation. Understanding this relationship is essential for optimizing thermal management systems and ensuring battery safety and efficiency.

2. Define Key Parameters

- Introduce the variables or parameters that were varied in your simulations. In your case, cooling velocity is the most important factor. Mention that different cooling velocities were applied in the simulations to observe their effect on battery temperature.
- You might also briefly mention other factors that remained constant, such as the battery material properties or the cooling medium, to set a clear context.

3. Set the Framework for Evaluation

- Explain how you will evaluate the results. This can include:
  - Maximum temperature observed within the battery.
  - Average battery temperature.
  - Temperature uniformity across the battery surface.
- If you are also evaluating energy efficiency, mention that the power required to achieve different cooling velocities will be discussed.

4. Preview of Results

- Without going into specific data, give a general sense of what the analysis will reveal. For example: The analysis focuses on identifying how increasing cooling velocity improves heat dissipation and whether an optimal velocity can be determined where further increases do not significantly affect temperature reduction.

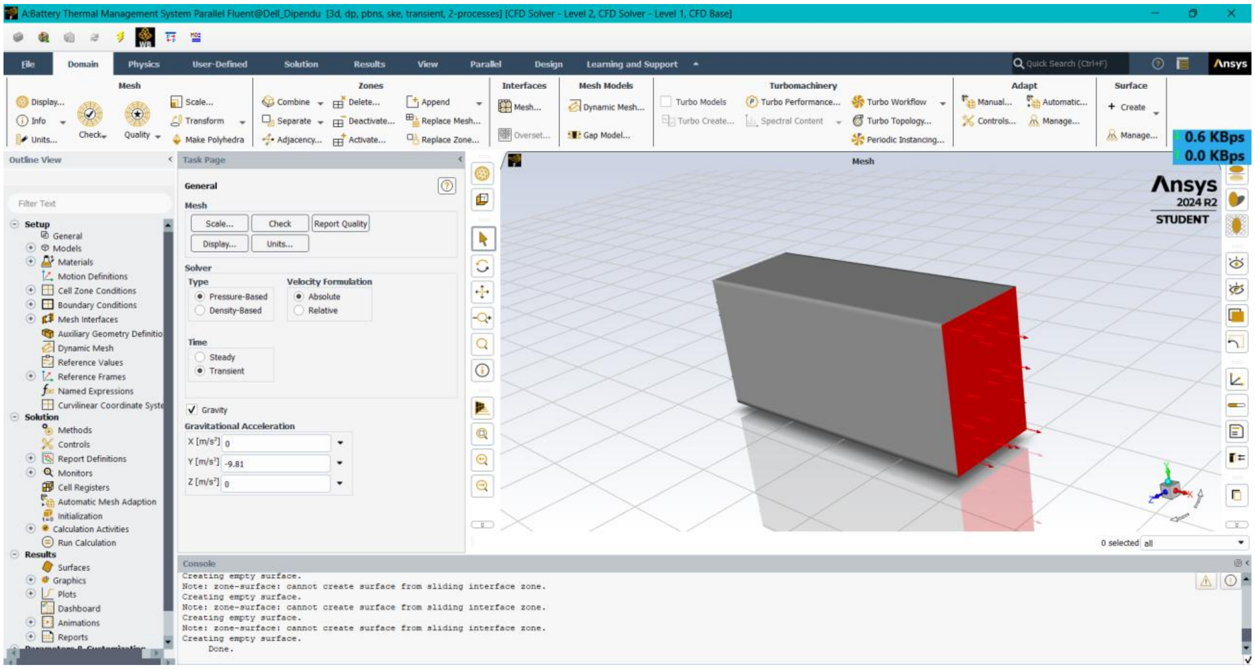


fig 4 Schematic highlighting ansys workspace.

B. <u>Presentation of Results:</u>

In this section, we discuss the results of the simulation outcomes to measure how changing cooling velocity affects the regulation of battery temperature. Maximum and average temperatures, along with distributions of temperature and cooler efficiency, were some of the key performance metrics under consideration. Velocities would be measured and analyzed to assess various effects attributed to thermal management. Results are shown in graphs and temperature contour plots demonstrating how cooling velocity affects battery temperature and dissipation of heat. We also consider the cooling rate to temperature distribution relation, which will give us the optimal cooling rate so that the thermal management can be done efficiently. These apparently portray the best cooling for the maximization of battery safety and performance.

An analysis of the thermal performance of a lithium-ion battery pack under air cooling with 2 m/s, 5 m/s, and 10 m/s velocities provides emphasis on results related to temperature reduction trends, uniformity in cooling, and the influence of airflow on the thermal management of the battery.

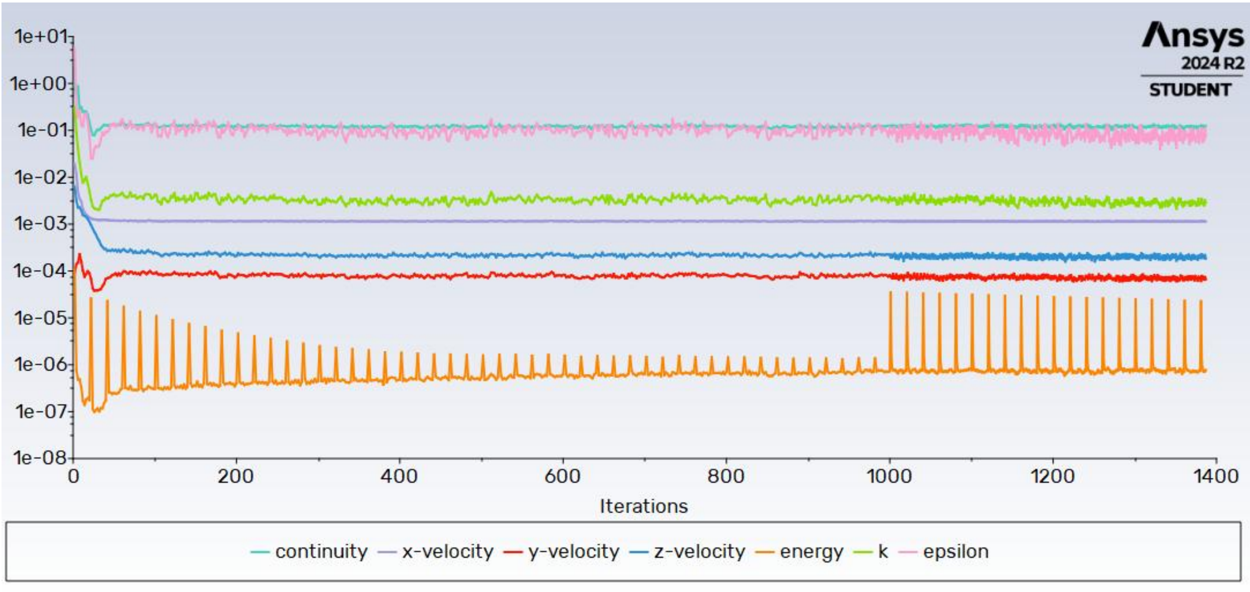


fig 5 Temperature profile of the battery cell at different cooling velocities (2 m/s, 5 m/s, and 10 m/s) under air cooling.

Temperature vs. Cooling Velocity

The analysis demonstrates how the cooling velocity significantly affects the thermal behavior of the battery pack. Three different air inlet velocities 2 m/s, 5 m/s, and 10 m/s were tested to evaluate their impact on battery temperature. The results show a clear trend of temperature reduction with increasing airflow velocity.

- **At 2 m/s:**
  The cooling effect is minimal, leading to relatively high peak temperatures. The airflow is insufficient to dissipate heat effectively, resulting in hotspots and non-uniform cooling across the battery pack.
- **At 5 m/s:**
  There is a noticeable improvement in temperature reduction. The airflow is adequate to achieve better heat dissipation, leading to a significant drop in both average and peak temperatures. Cooling uniformity also improves, minimizing thermal gradients within the pack.
- **At 10 m/s:**
  Optimal cooling is achieved with the lowest average and peak temperatures observed. The higher velocity ensures efficient heat removal and nearly uniform temperature distribution across the pack. However, the trade-off is higher energy consumption to maintain this airflow velocity.

The results indicate that increasing cooling velocity improves thermal management, with 10 m/s providing the best performance. However, 5 m/s presents a balance between cooling efficiency and energy cost, making it a practical choice for this design.

Visualization:

1. **Graph:** Plot maximum, average, and temperatures for each velocity.

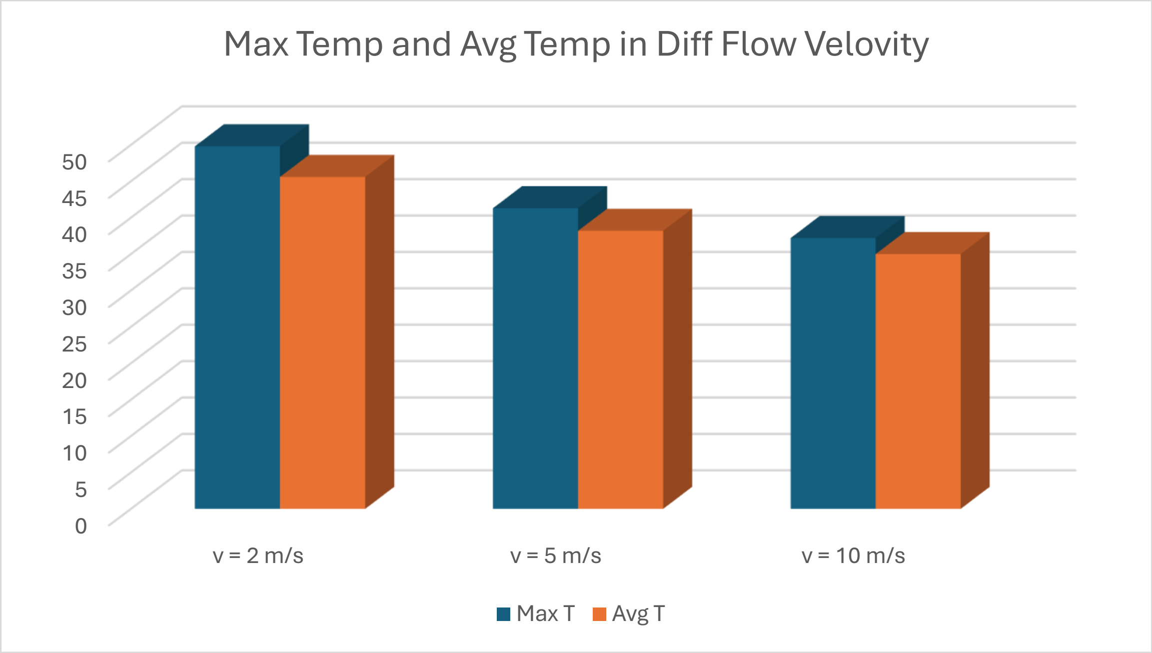
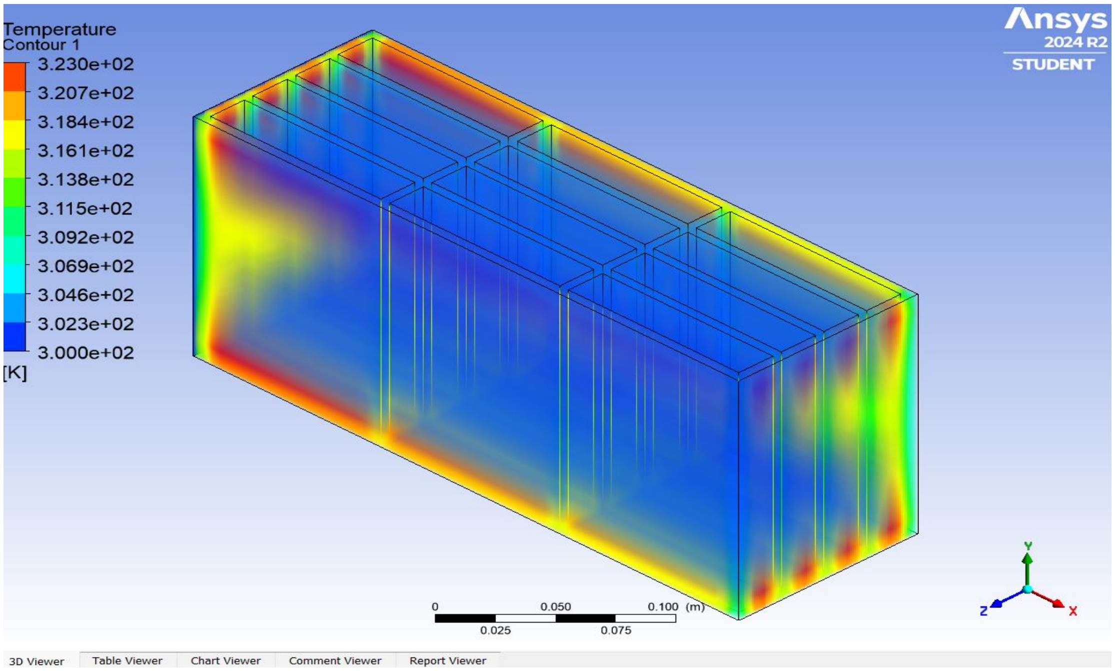
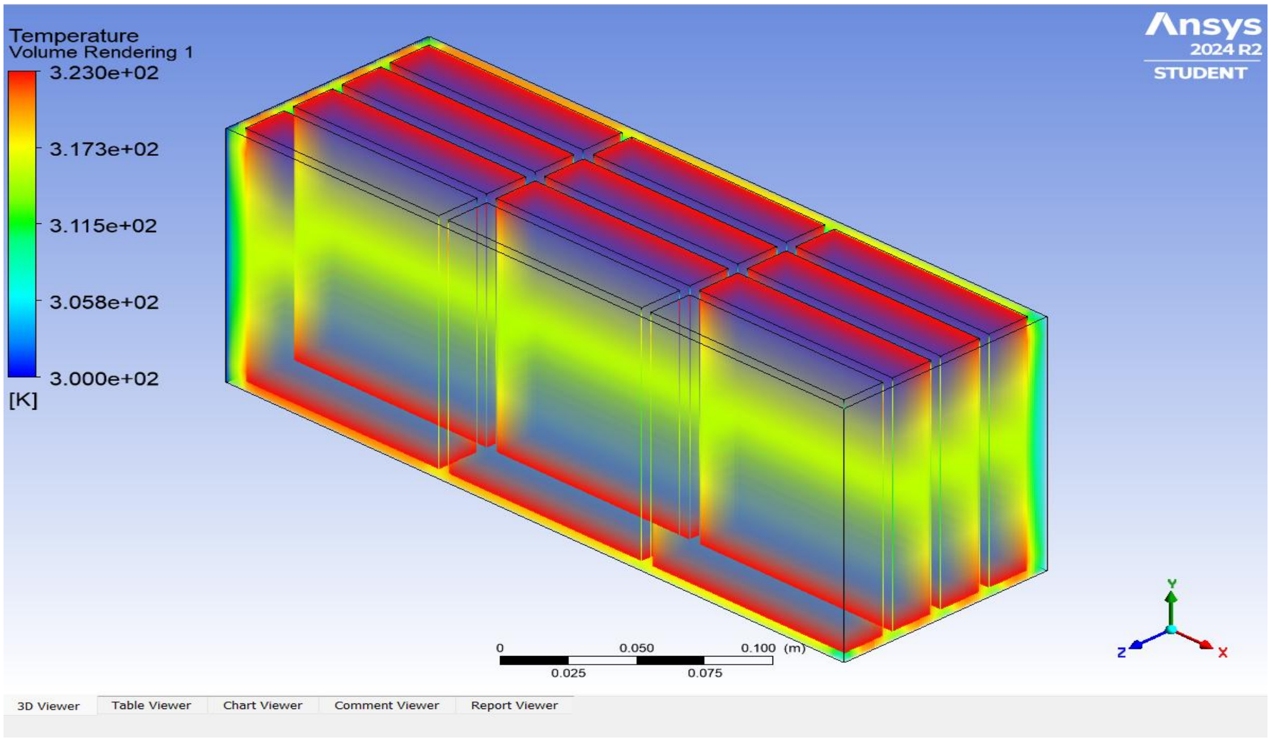


fig 6 Comparative plot of maximum battery temperature versus cooling velocity.

2. **Images:** Include heat maps from simulations showing temperature distributions for 2 m/s, 5 m/s, and 10 m/s.



- **Temperature Analysis for V = 2 m/s**



- **Temperature Analysis for V = 10 m /s**

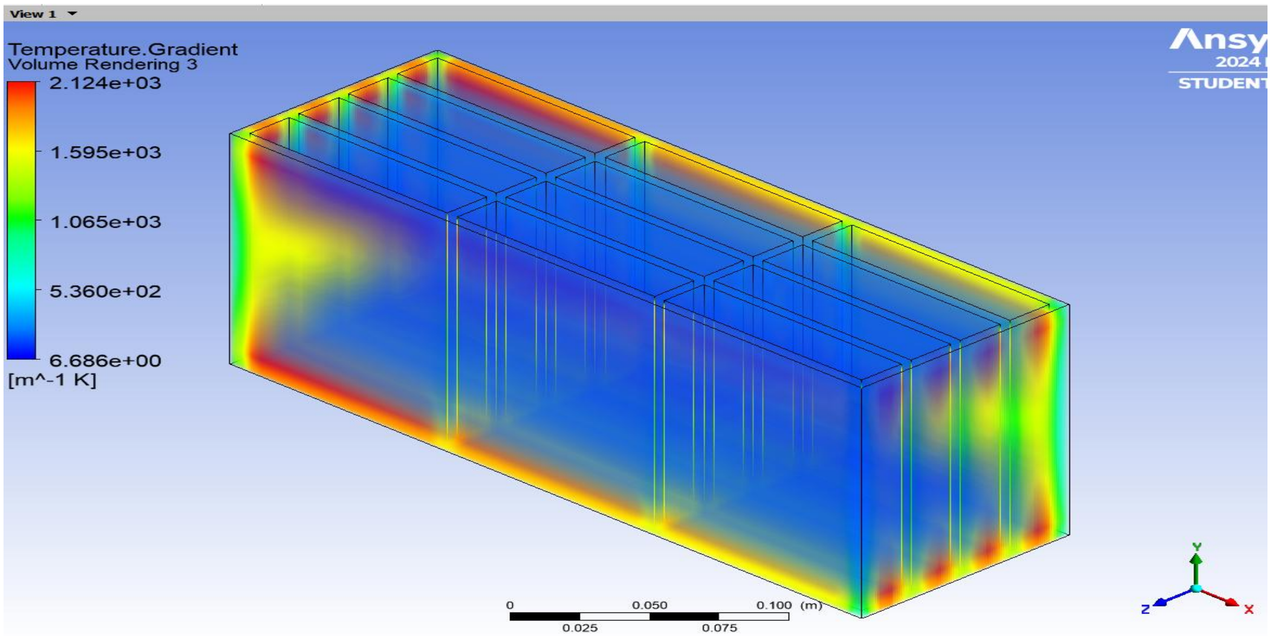
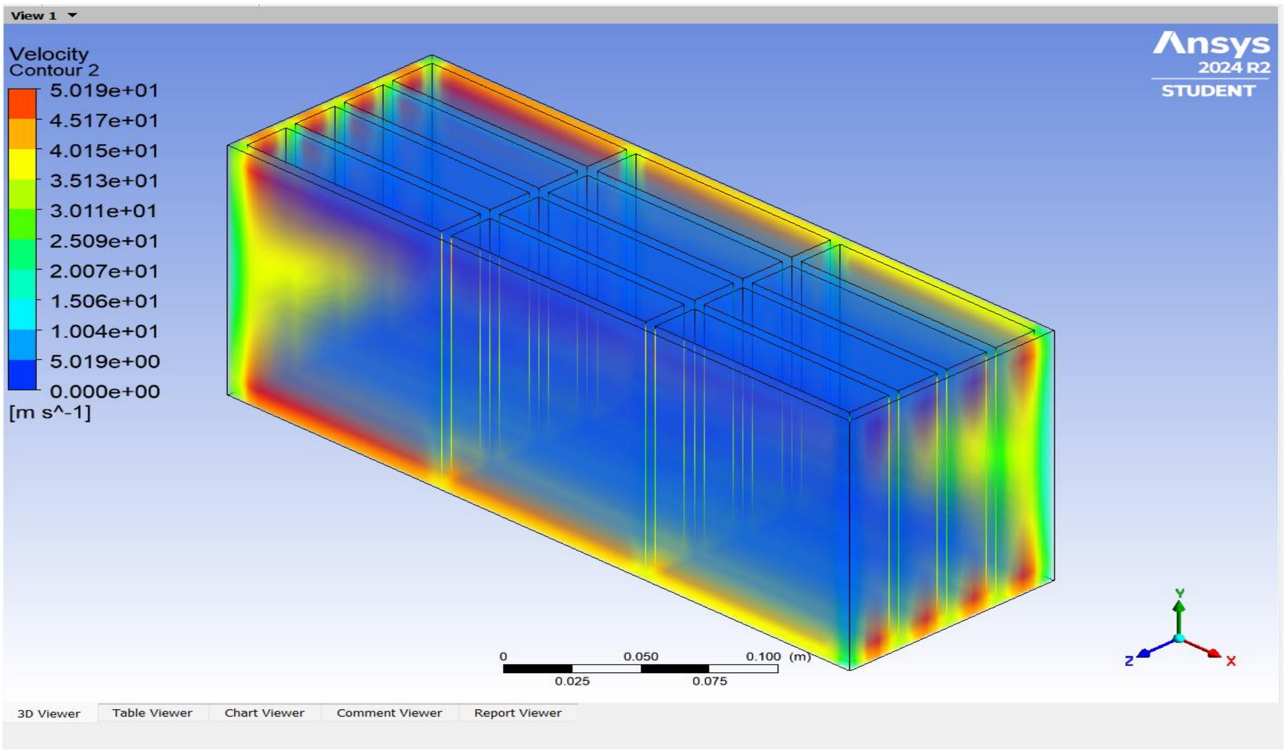


fig 7 Temperatur gradient



3. Table Example:

Cooling Velocity (m/s)	Average Temperature (°C)	Peak Temperature (°C)	Temperature Reduction (%)
2	45.6	49.8	-
5	38.2	41.3	17%
10	35.0	37.2	25%

7. Conclusion

The aim was to conduct an analysis of cooling velocity effects on the thermal performance of a lithium-ion battery pack. Using air cooling as the thermal management approach, ANSYS simulations looked at temperature variation at varied airflow velocities (2 m/s, 5 m/s, and 10 m/s). These results reveal interesting information related to how airflow velocity affects reductions and uniformity and overall efficiency in cooling.

The experiments show that as cooling velocity increased, average and peak temperatures inside the battery pack significantly decreased. At 2 m/s, airflow was not sufficient to cool with efficiency, resulting in hotspots and uneven cooling. With an airflow velocity of 5 m/s, the system showed considerable efficiency improvement in cooling, getting a good balance between effective heat removal and energy consumption. The lowest average and peak temperatures coupled with excellent uniformity in the distribution of temperature across the pack were observed at 10 m/s. High energy cost involved in sustaining such a velocity may pose significant limitations to practical application.

The fact that 5 mm inter-cell spacing was enough to allow proper airflow throughout the pack confirmed the need for careful design to ensure optimal thermal management, thus mitigating the risk of thermal runaway due to reduced temperature gradients in the pack.

In conclusion, the project demonstrates well the need to maintain adequate cooling velocities to minimize risks associated with thermal behavior of lithium-ion battery packs. The results indicate that it is reasonable that for 5 m/s airflow velocity, cooling performance is balanced with good energy efficiency to be achieved in the field. Future work includes further improvements of the thermal performance with reduced energy costs by studying alternative cooling methods: liquid or hybrid cooling systems. This work lays the basis for designing more efficient and safer battery thermal management systems, contributing to the broader goal of improving the reliability and lifespan of batteries in energy storage and electric vehicle applications.

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