Design and Optimisation of PCM integrated Battery Packs

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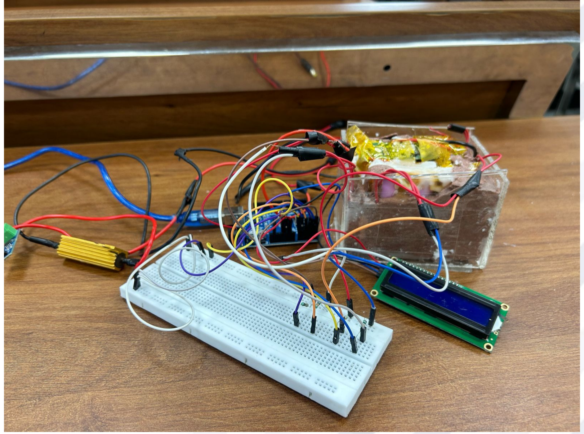


1. Introduction

1.1 Project Statement

The primary challenge addressed in this project is the need for effective thermal management in battery packs to prevent overheating, enhance performance, and extend battery life. Traditional active cooling systems are often expensive and complex. This project aims to create a cost-effective layered design incorporating CPCMs and passive heat spreaders to regulate temperature and dissipate heat efficiently. By simulating and optimizing the design and validating it experimentally, we aim to establish a reliable and scalable solution for battery thermal management.

1.2 Background Survey

The design and optimization of PCM integrated battery packs address the critical challenge of thermal management in lithium-ion batteries, which are susceptible to performance degradation and safety risks from temperature fluctuations. Research explores various Phase Change Materials (PCMs), like paraffins, for their ability to passively absorb and release heat during phase transitions, maintaining stable battery temperatures. Studies investigate diverse PCM integration techniques, often employing thermal modeling and simulation tools such as CFD and FEA for design optimization. Furthermore, hybrid thermal management strategies, combining PCMs with active cooling systems, are being developed to enhance thermal performance, while efforts to improve PCM thermal conductivity through additives like metal foams and graphite are also underway. The overarching goal is to effectively leverage PCMs to regulate battery temperatures within optimal ranges, ultimately improving battery performance, safety, and lifespan.

2. Methodology

2.1 Techniques & Approach

The project optimized battery pack design through iterative simulation and experimental validation. Autodesk Fusion 360 was used to create varied designs, with Ansys Fluent simulations determining optimal cell spacing. A literature review guided the selection of the PCM/copper ratio. An Arduino-based sensor system, incorporating noise reduction, averaging, and hardware calibration, captured real-time voltage, current, and temperature data, displayed on an LCD and logged for detailed analysis. This approach ensured accurate performance evaluation and facilitated comparison with simulation results.

2.2 System Architecture & Workflow

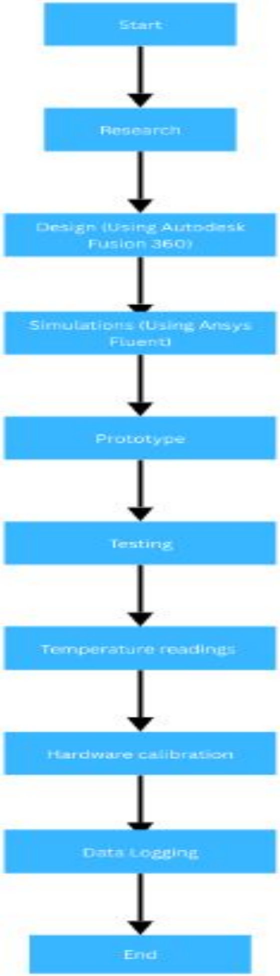
- This project was initiated with a comprehensive literature review to establish a strong theoretical foundation. Subsequently, a detailed design and simulation phase was undertaken, focusing on optimizing battery pack thermal management Autodesk Fusion 360 was utilized to develop multiple battery pack configurations, systematically varying cell spacing to analyze its influence on heat dissipation. Ansys Fluent simulations were then employed to generate detailed temperature distribution maps for each design, facilitating a comparative analysis and the identification of the most efficient spacing. In parallel, a comprehensive literature review was conducted to determine the optimal composite phase change material (CPCM) to copper ratio. This review examined existing research on thermal conductivity and heat absorption capacities, guiding the selection of a material composition that balanced performance and practicality. This combined approach, leveraging parametric design studies and informed material selection, provided a robust foundation for prototype development, ensuring the design was grounded in both computational analysis and established research.

- Following the design and simulation phase, a prototype battery pack was constructed, incorporating the optimized cell spacing and material composition. An Arduino-based sensor system was deployed to capture real-time voltage, current, and temperature data, providing a comprehensive understanding of the battery pack's operational characteristics. Sophisticated data processing techniques, including noise reduction algorithms, averaging, and moving average filtering, were implemented to enhance the accuracy and stability of the sensor readings. This ensured the captured data was reliable and representative of the prototype's actual performance.
- To ensure the reliability and usability of the acquired data, a multifaceted approach to data management was adopted. Real-time data visualization was achieved through an LCD display, providing immediate feedback during testing and facilitating quick adjustments. Simultaneously, all data was continuously logged into an Excel spreadsheet for detailed post-analysis, allowing for in-depth comparative studies. Hardware calibration was performed to mitigate systematic errors, ensuring the precision of the sensor measurements and the overall data integrity. This comprehensive data acquisition and processing framework allowed for a thorough comparison between simulation results and experimental findings, validating the efficacy of the optimized battery pack design.

2.3 Tools & Technologies Used

- **Software:** Autodesk Fusion 360, Ansys Fluent and Arduino IDE
- **Hardware:** NTC Thermistors (with 10KΩ resistors) , Arduino Uno microcontroller, current sensors, voltage sensors, resistors and LCD screen.

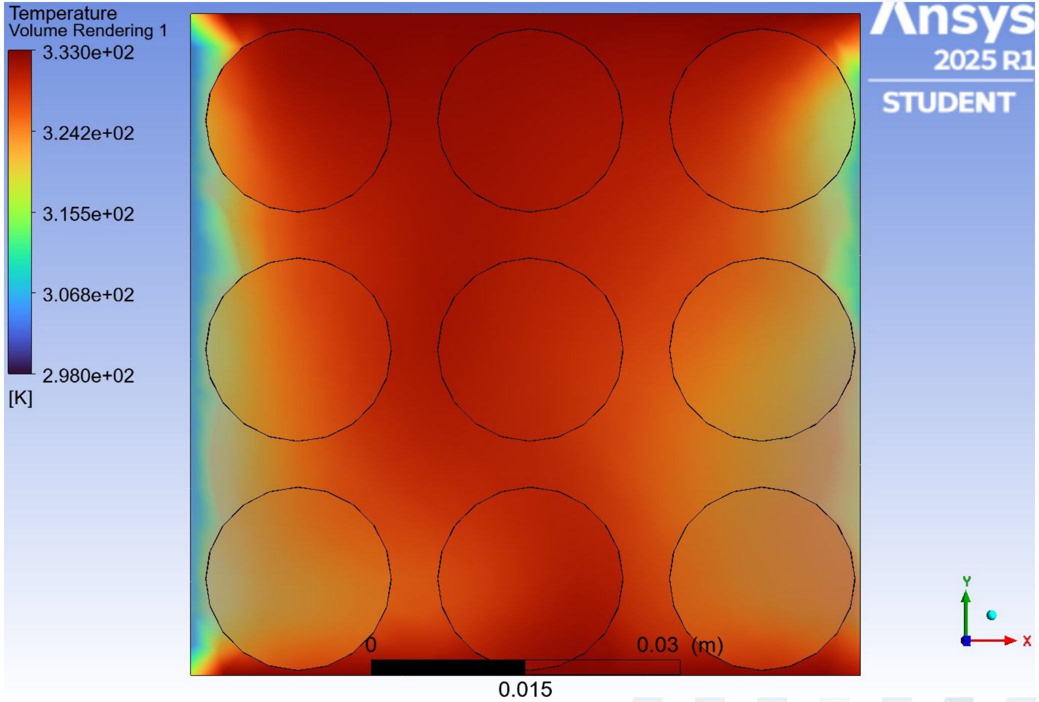
Methodology

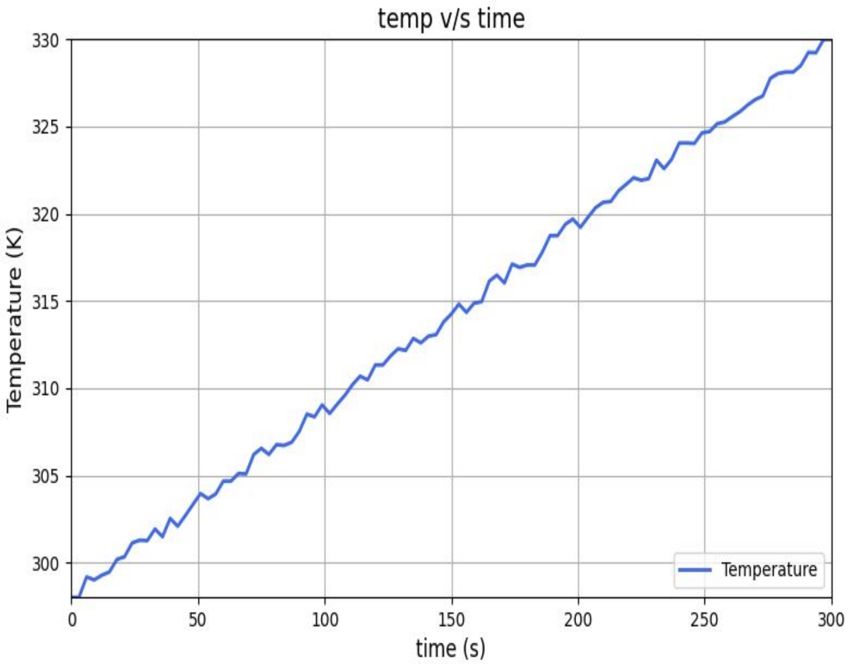


3. Results & Analysis

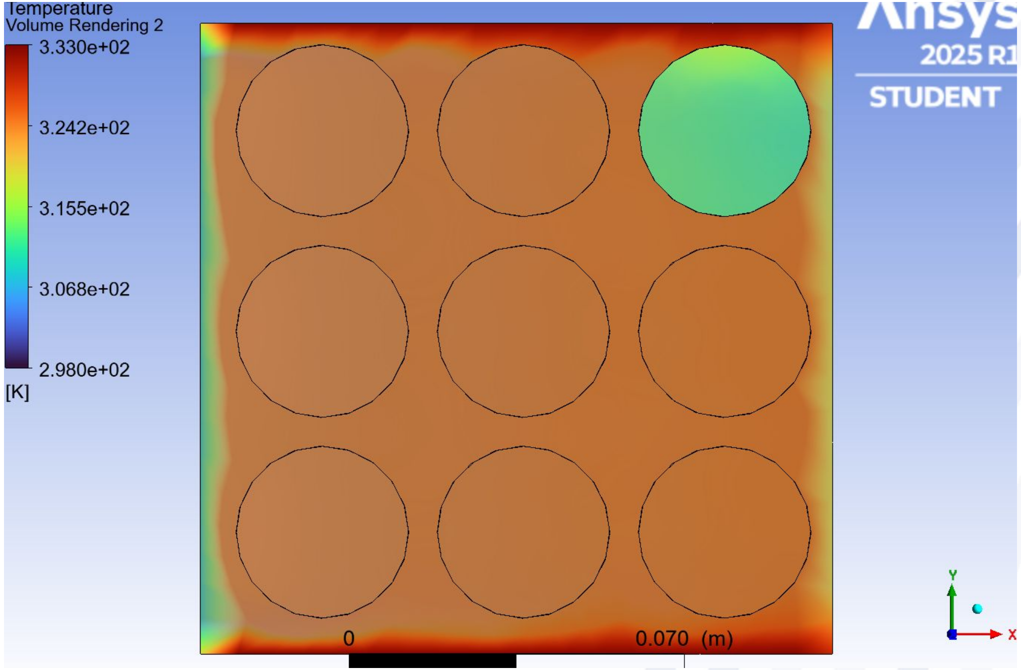
a. Theoretical results(found using ansys):

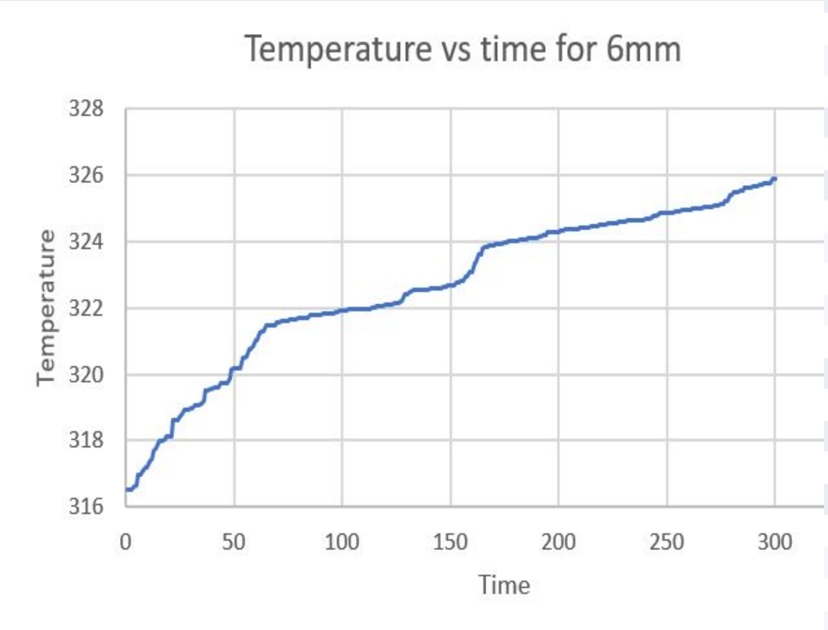
1. With 4.5 mm spacing between the cells



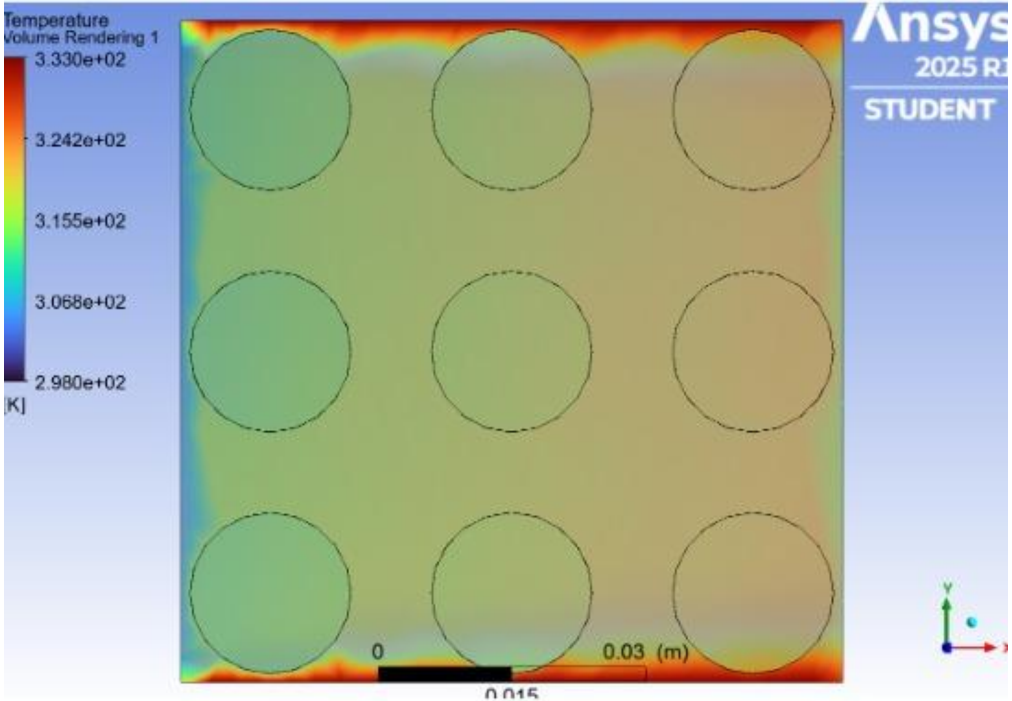


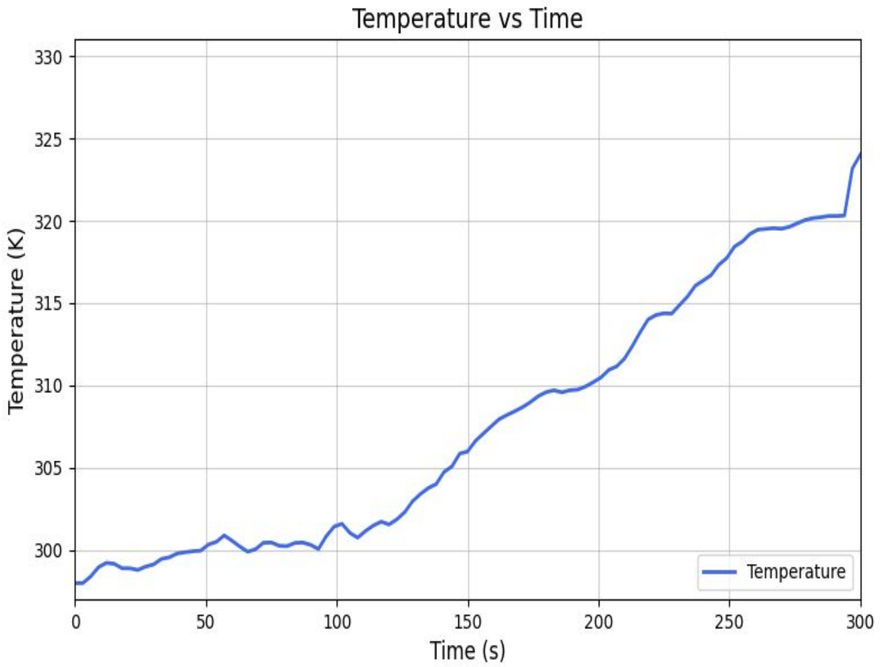
2. With 6 mm spacing between the cells



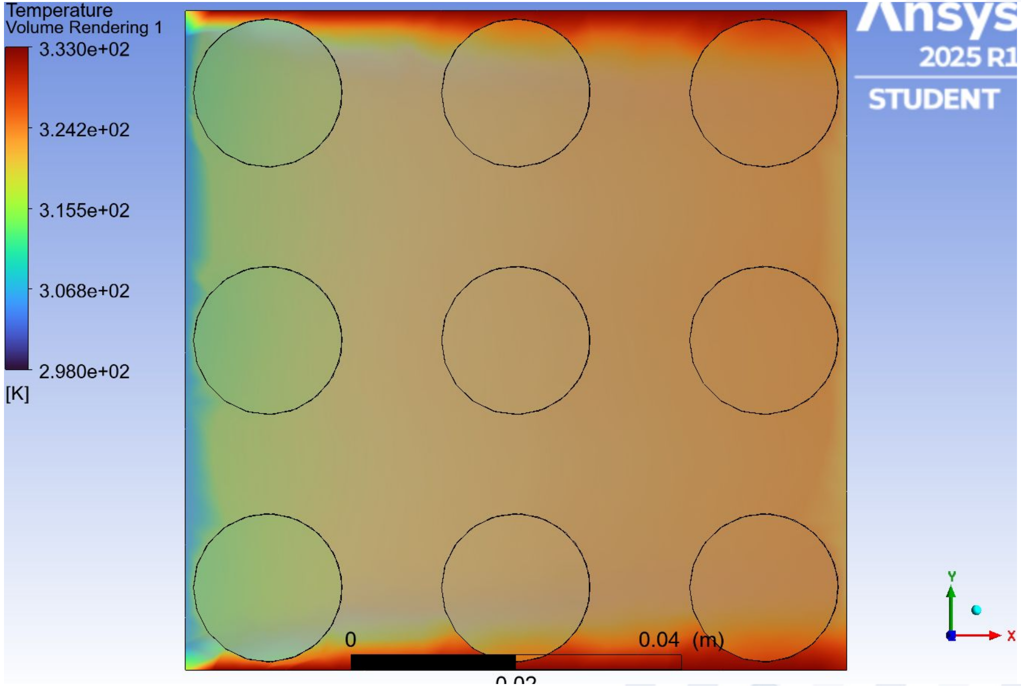


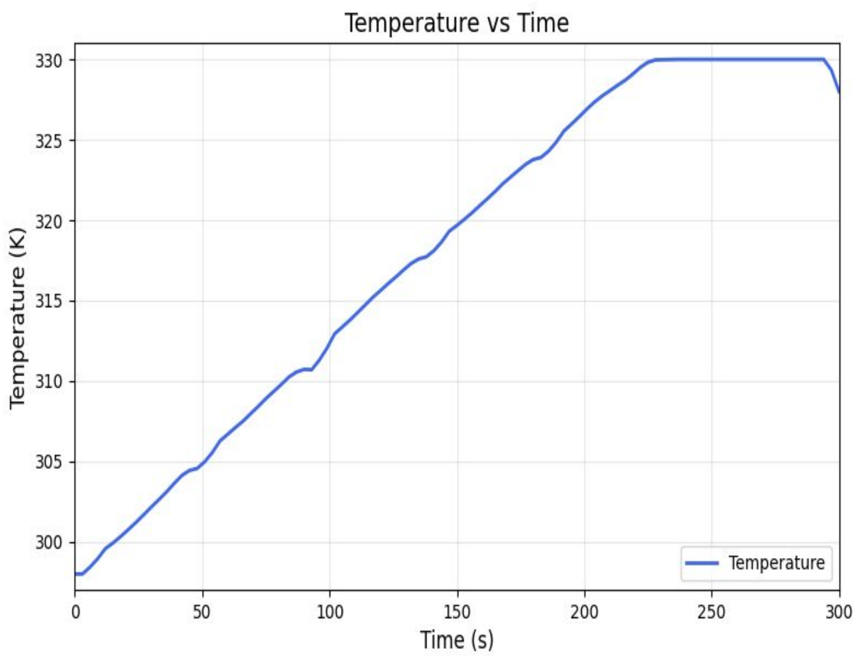
3. With 9 mm spacing between the cells



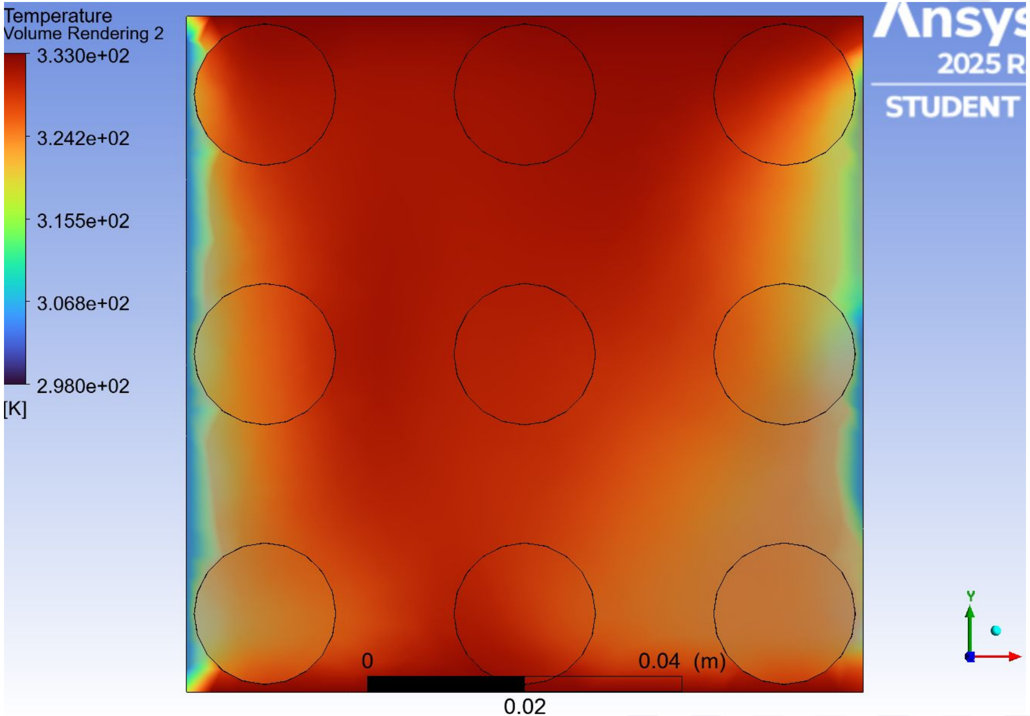


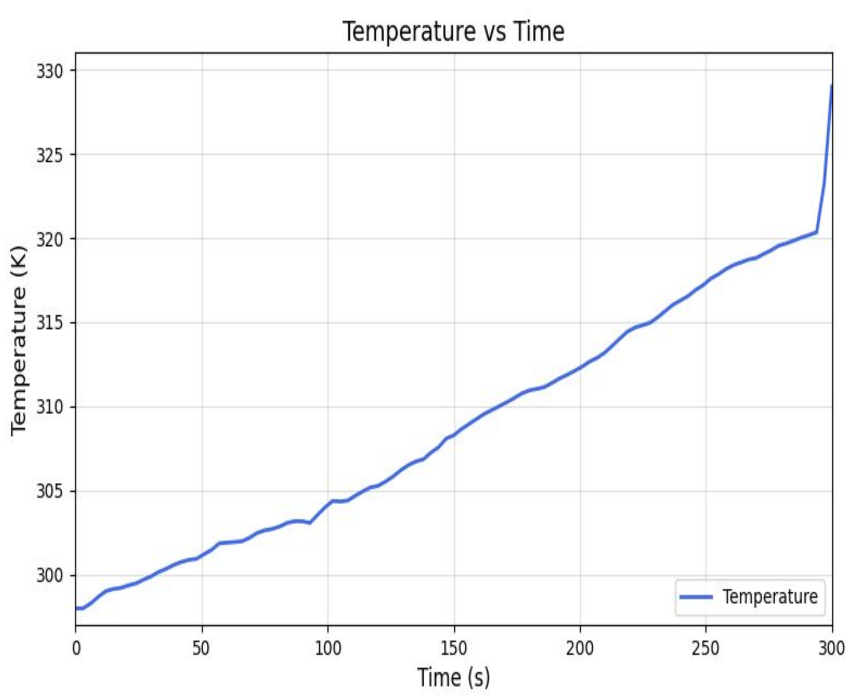
4. **With 12 mm spacing between the cells**





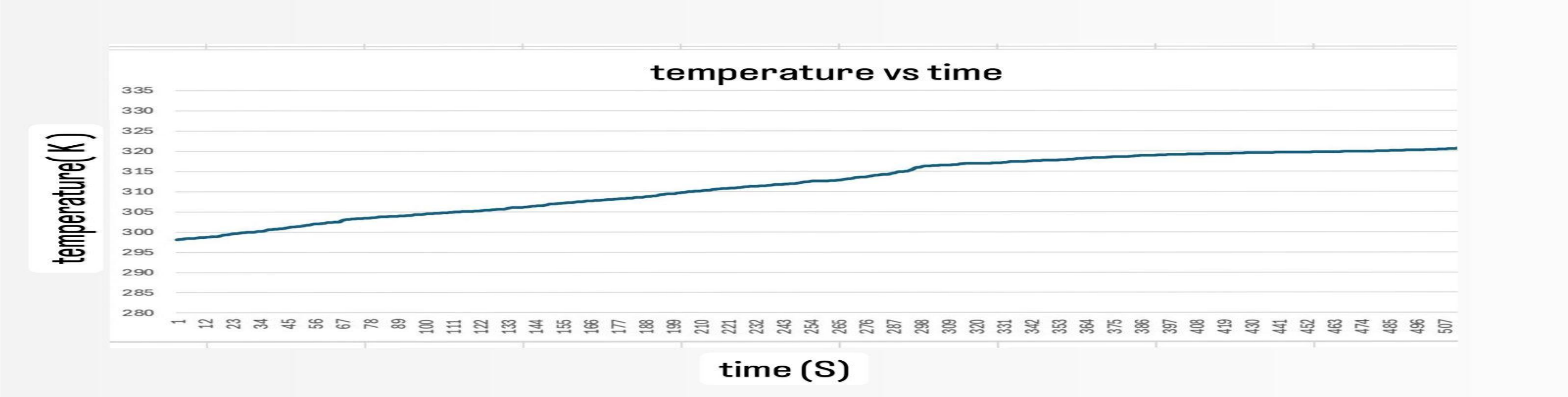
5. **With 15 mm spacing between the cells**





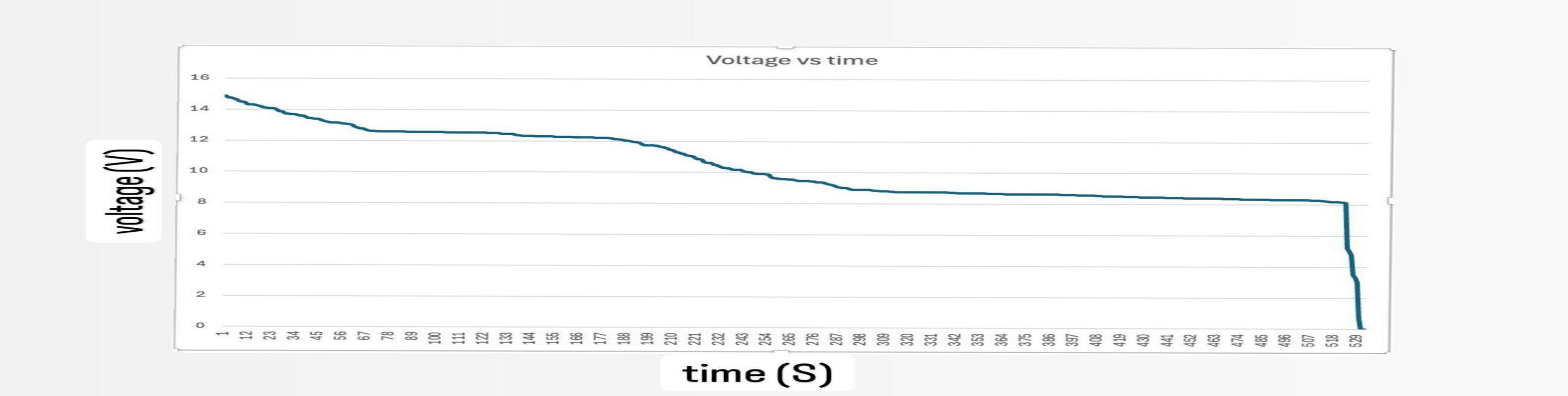
B. Experimental results:

(i). Temperature v/s time:



The battery pack reached a max temperature of 320K

(ii) Voltage v/s time



Key Findings

1. Results from simulations on Ansys Fluent:

- **The most optimum spacing was found to be 9mm as it reached a max temperature of 324K.**

2. Temperature Stabilization at 320K:

- The system’s **maximum recorded temperature was 320K**, after which the temperature increase slowed down.
- This suggests effective heat absorption by the **paraffin wax PCM**, delaying excessive temperature rise.

3. Latent Heat Absorption Effect:

- The temperature curve shows a **gradual slope**, indicating that **paraffin wax absorbed heat while undergoing phase change**.
- This confirms the **thermal buffering capability** of the PCM.

4. Role of Copper Powder as Heat Spreader:

- The smooth and uniform increase in temperature suggests that **copper powder improved heat distribution**.
- This prevented localized overheating and enhanced the **overall thermal conductivity** of the system.

5. Potential for Thermal Energy Storage Applications:

- The system **delayed temperature rise**, making it useful for **passive cooling systems** in electronics, batteries, or building insulation.
- PCM-based systems like this **can reduce temperature fluctuations** and improve energy efficiency.

Limitations

Although the experimental setup demonstrated effective thermal regulation, some measurement inconsistencies and fluctuations were observed. These could be due to sensor calibration errors, electronic noise, or fluctuations in ambient conditions.However, these deviations were minimal and did not significantly impact the overall findings.

4. Challenges & Learnings

Obstacles Faced

- The availability of only one laptop capable of running the necessary simulation software presented a significant bottleneck. This slowed simulation progress, which was essential for subsequent prototype development.
- In the initial phase of simulation work, the Multi-Scale Multi-Domain (MSMD) model was used which was very sensitive and prone to many errors.
- The process of acquiring accurate temperature data with the Arduino involved addressing several key challenges like a lot of variations in temperature due to noises and a few values that were off scale. The load resistor also was overheating very quickly.

Solutions & Insights

- One of the mentees borrowed a laptop to run the simulations to speed up the process.
- To improve simulation efficiency, the k-epsilon turbulence model was implemented, which proved to be more computationally efficient for the specific simulation parameter
- Through systematic experimentation and troubleshooting, involving code optimization and connection adjustments, a robust and reliable system configuration was established. To mitigate excessive heat generation from the load resistor, a water-cooling solution was incorporated

5. Conclusion & Applications

Conclusion:

This experiment successfully demonstrated the **thermal regulation capability** of a **paraffin wax-based PCM system enhanced with copper powder**. The results indicate that:

- **Paraffin wax effectively absorbed and stored heat** through phase change, preventing rapid temperature spikes.
- **Copper powder acted as a passive heat spreader**, improving thermal conductivity and ensuring uniform heat distribution.
- The **maximum recorded temperature was 325K**, after which the rate of temperature increase slowed, confirming the **latent heat absorption effect** of PCM.
- This system shows potential for **thermal energy storage applications**, such as **battery cooling, electronics thermal management, and passive building insulation**.

Final Takeaway:

By combining **paraffin wax as PCM** and **copper powder for enhanced heat spreading**, this setup provides an **efficient and cost-effective method for thermal regulation**. The findings highlight its **practical application in passive cooling solutions**, reducing overheating risks and improving energy efficiency.

Real world applications:

- The inherent fire-resistant properties of Phase Change Materials (PCMs) offer a potential safety enhancement for battery thermal management, particularly in applications where batteries are subjected to high thermal loads. For example, in the electric vehicle sector, where thermal management is critical for safety and performance, companies like Ola Electric, among others, could benefit from the implementation of PCM-based cooling solutions to mitigate the risk of thermal runaway.
- In aerospace, where weight and reliability are paramount, PCMs can provide lightweight and passive thermal management for batteries and electronic systems. This is particularly important in:
  - Satellite and spacecraft applications.
  - Electric aircraft.
- High-power electronic devices, such as those in data centers and telecommunications equipment, generate significant heat. PCMs can be used to:
  - Provide passive cooling, reducing the need for energy-intensive active cooling systems.
  - Maintain stable operating temperatures, improving the reliability and efficiency of electronic components.

6. Future Work & Enhancements

- The study was conducted using paraffin wax as the sole PCM in a 3x3 battery pack configuration. However, performance enhancements may be achievable through the utilization of a mixture of two or more PCMs with differing thermal properties. This approach allows for a more tailored thermal response across a broader temperature range. Furthermore, the substitution of copper with a metal or an alloy of higher thermal conductivity, could improve the rate of heat transfer within the system, leading to more effective thermal management.
- Further studies could also explore the effectiveness of the PCM configuration with a larger number of cells, and a comparative analysis with liquid cooling methods to ascertain relative efficiency would be beneficial.

7. References

1. *Study on thermal aspects of lithium-ion battery packs with phase change material and air cooling system - Science Direct*
2. Layer-by-layer assembled phase change composite with paraffin for heat spreader with enhanced cooling capacity - Science Direct
3. Study on the effect of different additives on improving the thermal conductivity of organic PCM - Science Direct

THANK-YOU!