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Design and CFD Analysis on Battery Management System in EV

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Abstract - Battery thermal management is a critical aspect of electric vehicle (EV) performance and safety. Effective cooling systems whether air, liquid, refrigerant-based, or phase-change material (PCM) cooling is essential for maintaining optimal battery temperatures and ensuring longevity. This study employs Computational Fluid Dynamics (CFD) to analyze different cooling strategies for EV battery packs, focusing on temperature distribution, heat dissipation, liquid solidification and cooling efficiency. The research investigates various battery designs, including linear, spiral, and channel-based cooling structures, using PCM (methyl palmitate) and water-based liquid cooling. The study examines heat generation across different charge rates (1C–3C) and compares the effectiveness of air, water, and hybrid cooling methods. A meshing process with 5 – 5.5 lakh elements ensured grid independence, enabling accurate simulation results.

Key Words: Battery Thermal Management, Electric Vehicles (EVs), Computational Fluid Dynamics (CFD), Phase Change Materials (PCM), Cooling Strategies

1.INTRODUCTION

As electric vehicles (EVs) become increasingly prevalent, optimizing battery performance and safety is a top priority. A critical aspect of this is the thermal management system, which regulates heat generated during charging, discharging, and high-power operations. Effective heat analysis is key to understanding heat generation, distribution, and dissipation within the battery pack.

Cooling systems using air, liquid, refrigerants, or phase-change materials (PCM) must maintain the battery within an optimal temperature range for safety and performance. Compact and efficient designs are essential due to EV space and weight constraints. Computational fluid dynamics (CFD) simulations help engineer's model heat transfer and evaluate cooling strategies under various conditions. By predicting heat patterns accurately, engineers can optimize thermal management systems to enhance battery performance.

Lithium-ion (Li-ion) battery cells consist of four primary components. The cathode determines the battery's energy density and voltage, with common cathode materials influencing overall performance. Additionally, the separator prevents short circuits while allowing ion flow, ensuring the battery's safety and functionality.

The electrochemical reactions within Lion batteries govern their operation. During charging, lithium ions move from the cathode to the anode, following the reaction:

$LiCoO_2 + Li^+ + e^- \rightarrow Li_{1-x}CoO_2$

Conversely, during discharging, the reaction reverses as lithium ions move back to the cathode:

$Li_{1-x}CoO_2 \rightarrow LiCoO_2 + Li^+ + e^-$

These reversible reactions enable the battery to store and release energy efficiently, making Li-ion batteries a preferred choice for various applications.

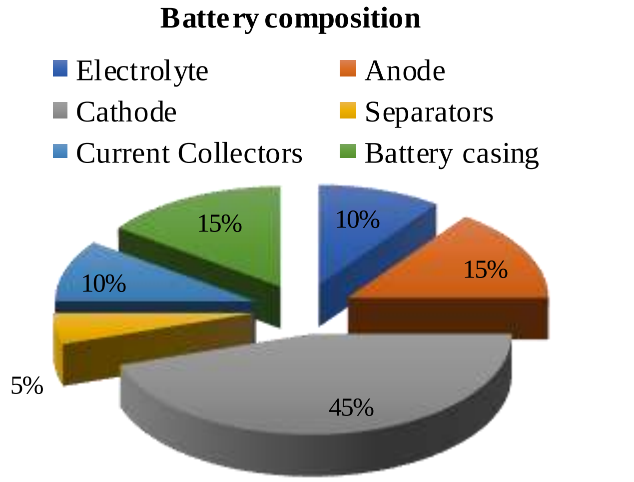

Figure 1 Typical Battery Composition Approximate % by Weight

1.1 Literature

- **Mengyao Lu & Xuelai Zhang (2019):** Lithium-ion batteries function best within a 20–40°C range, maintaining a temperature difference of less than 5°C among cells to ensure longevity and efficiency.

Every 1°C increase between 30–40°C shortens battery life by approximately two months, as excessive heat accelerates degradation, while colder conditions hinder discharge capacity.

- **Vinoth Kumar (2021):** This work investigated heat generation in EV batteries caused by close cell arrangement, recharge cycles, and discharges. It analyzed temperature distribution using CFD for various cooling configurations with ethylene glycol and nano materials. The 1S tube configuration showed high-temperature variations (300K–315K), while the 2S configuration reduced temperatures by 3K but retained uneven distribution.
- **Husam Abdulrasool, Hussein Togun (2023):** The study investigates the effect of airflow spacing on heat dissipation in lithium-ion battery cooling packs using Computational Fluid Dynamics (CFD). By analyzing airflow at varying Reynolds numbers (15,000–30,000) and different battery spacings (1–4 mm), it was found that increasing spacing enhances heat transfer efficiency.
- **Pusapati Laxmi Narasimha Raju , Chalumuru Manas (2024):** The study explores the use of Phase Change Materials (PCM) for Battery Thermal Management Systems (BTMS) in electric vehicles (EVs), simulating their effectiveness using ANSYS Fluent. A multi-scale multi-dimension (MSMD) model was applied to analyze heat dissipation in a three-cell battery setup under different C-rates (1C to 3C). PCMs methyl palmitate were tested, with methyl palmitate showing the best temperature control.

1.2 Research Gaps

The research gap between the two studies lies in their focus on different cooling methodologies for lithium-ion battery thermal management systems.

The study (CFD simulation of effect spacing between lithium-ion batteries) investigates how varying airflow spacing and Reynolds number impact heat dissipation within a cooling pack.

In contrast, study (Computational modeling of battery thermal energy management system using PCM) explores phase change materials (PCM) as a passive cooling method.

The research gap lies in the lack of hybrid cooling approaches that combine airflow based convective cooling with PCM-based passive cooling to optimize temperature regulation.

Future studies should investigate integrating airflow with PCM-based systems for enhanced cooling performance, reducing reliance on single-method cooling strategies.

1.3 Objectives

- Validate the existing model by comparing its results with experimental values.
- Develop a battery with stable performance properties over time.
- Select an optimal coolant to enhance BTMS.
- Design a customized cooling system tailored to the battery's unique thermal needs.
- Ensure compliance with new industry standards and safety regulations.

1.4 Novelty

- Comprehensive CFD analysis on EV battery cooling using various cooling methods, including air, liquid, and PCM-based cooling.
- Implementation of PCM cooling with a multi-scale, multi-dimension (MSMD) approach, simulating phase change behavior.
- Validation using ANSYS Fluent simulations for different C-rates (1C to 3C).
- Comparative study of different battery pack designs (linear, spiral, and vertical channel cooling).
- Combination of PCM and liquid cooling found to be the most efficient thermal management strategy.

2. METHODOLOGY

2.1 Design modeling

The design of a pouch-type battery cell with an integrated cooling system, emphasizing efficient thermal management. The battery cell structure is optimized for electric vehicle (EV) applications, ensuring high energy density, lightweight construction, and superior heat dissipation.

- **Cell Structure:** The battery is a pouch-type cell, characterized by a flexible, lightweight casing rather than a rigid metal enclosure. Dimensions: 100 mm (L) × 75 mm (H) × 2.5 mm (W), making it compact and suitable for stacking in modules.
- **Cooling Channel System:** A serpentine flow path is incorporated within the cooling plate for enhanced heat dissipation. Channel Diameter: 4 mm for fluid circulation. The channels are embedded within a Phase Change Material layer to regulate battery temperature.
- **Thermal Management system:** The liquid cooling system with water or coolant flow maintains optimal cell temperatures. The design prevents thermal runaway, a major safety concern in lithium ion battery. Cooling effectiveness is improved using multiple inlets and outlets for uniform

temperature distribution.

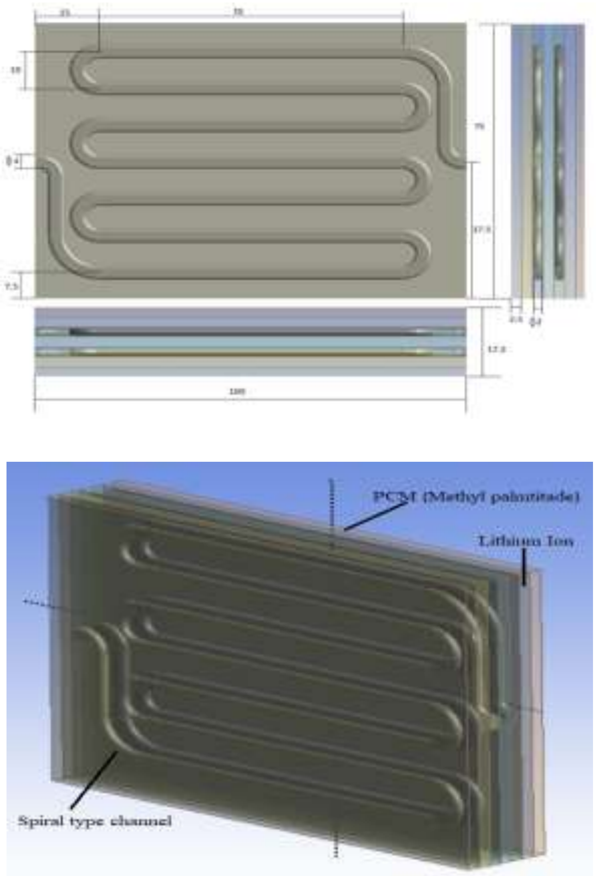

Figure 2 Geometry of the Pouch type model

2.2 Conditions setup

- **3D Computational Fluid Dynamics (CFD) Analysis:** A fine 3D mesh with 500,000+ elements ensures simulation accuracy. As the refinement meshing type for the channel.
- **Material Conditions:** PCM: Methyl-Palmitate, known for high thermal absorption capacity. Flow Conditions is around based on Reynolds number > 30,000 ensures turbulence for better heat dissipation.
- **Solver setup conditions:** Solver set Pressure-based, Absolute velocity, Transient (time dependent), gravity. Model selection Energy equation, K epsilon (Enhanced wall treatment) and Solidification & melting.
- **Performance Analysis:** Temperature Contours for validate cooling efficiency under various discharge rates. Liquid Fraction Plots will show PCM phase transition for effective heat absorption.

2.3 Governing Equations

In the thermal analysis and computational fluid dynamics (CFD) modeling of battery systems, governing equations are essential for accurately describing heat transfer, energy conservation, and fluid flow behavior. These equations help simulate temperature distribution, predict heat dissipation, and evaluate the effectiveness of different cooling strategies. By incorporating numerical formulations, CFD models can solve complex thermal interactions within battery packs under various operating conditions. This enables engineers to optimize thermal management systems, ensuring battery efficiency.

- **Energy Conservation Equation**: Describes the heat transfer mechanism within the battery and cooling system, ensuring thermal balance.

$$\partial t/\partial H=\nabla\cdot(k\nabla T)$$

- **Total Volumetric Enthalpy**: Accounts for both sensible and latent heat storage within the battery materials and phase change materials (PCM).

$$H(t)=h(t)+\rho f(t)L$$

- **Sensible Volumetric Enthalpy**: Represents the heat stored in the system based on temperature variations.

$$h=\int\rho CpdT$$

- **Phase Change Enthalpy**: Defines the heat absorption during the phase transition of materials used in thermal management.

$$H=\rho lfLT=Tm$$

- **Heat Generation**: Captures internal heat production in the battery due to Joule heating and electrochemical reactions.

$$Q=I^2R,\ q'''=V/Q$$

- **Momentum Equation (Navier- Stokes Equations)**: Governs fluid flow characteristics in the battery cooling system, ensuring efficient heat dissipation.

$$\partial(\rho u_i u_j)/\partial x_j= -(\partial p/\partial x_i) + (\partial/\partial x_j[\mu(\partial u_i/\partial x_j)+(\partial u_j/\partial x_i)]-(2/3)\mu(\partial u_k/\partial x_k)\delta_{ij}$$

- **Reynolds Number**: Determines the flow regime (laminar or turbulent) within the cooling channels, influencing convective heat transfer.

$$Re=(\rho vD)/\mu$$

Table 1 Mesh-independence study for simulation of battery

Properties	Mesh 1	Mesh 2	Mesh 3	Mesh 4
No. of elements	315783	431985	552483	614824
Max. Surface temp.(K)	293.613	294.547	295.152	295.348

Table 2 Material properties of cell

Properties Material of cell	Properties Material of cell
Density (kg/m^3)	2092
Specific heat (J/kg.K)	678
Thermal conductivity (W/m.K)	18.4

Table 3 Thermal properties of Methyl Palmitate

Properties Material of cell	PCM Solid phase	PCM Liquid phase
Density (kg/m^3)	862.1	823.8
Specific heat (J/kg.K)	0.192	0.1785
Thermal conductivity (W/m.K)	1610	2248
Viscosity (Kg/m-s)	0.0045	
Latent heat (J/kg-K)	229500	
Solidus temperature (K)	297	
Liquidus temperature (K)	300	

In this summary emphasizes a simulation study of a battery thermal management system using computational fluid dynamics (CFD). The model incorporates phase change material (PCM) for improved heat dissipation. Key parameters like geometry, material properties, and governing equations are outlined. The study aims to optimize battery temperature distribution and ensure efficient operation for electric vehicles.

3. SOLUTION METHODOLOGY AND PROCESS

The solution methodology for the CFD analysis of the Battery Management System in an Electric Vehicle (EV) follows a structured approach that ensures accurate thermal performance assessment and optimization. The process includes the following key steps:

- The primary goal is to maintain an optimal battery temperature using efficient cooling methods. Various cooling techniques, including phase change materials (PCM) and liquid cooling, are explored for enhanced thermal management.
- Different battery pack configurations are analyzed, such as linear and spiral channel designs. Battery cell dimensions and cooling channel structures are optimized to enhance heat dissipation.
- A refined meshing approach is applied to divide the complex battery geometry into smaller elements. A grid independence test is conducted to ensure accurate simulations with minimal computational cost.
- The numerical model is governed by energy conservation, momentum (Navier-Stokes), and heat transfer equations. Appropriate boundary conditions, such as temperature, velocity, and heat generation, are imposed.
- The CFD simulations are performed for different cooling methods, discharge rates, and coolant types. Temperature, velocity, and liquid fraction contours are analyzed to evaluate heat dissipation efficiency.
- Various cooling techniques, including air cooling, liquid cooling, and PCM-based cooling, are compared. The effectiveness of PCM combined with water cooling is assessed based on temperature distribution and heat dissipation.
- It determines that a combination of PCM and water-based liquid cooling provides optimal battery thermal management. The findings emphasize the importance of optimized cooling channel designs and coolant selection.
- This structured methodology ensures a comprehensive understanding of the thermal behavior of EV battery packs and helps in designing efficient battery cooling systems.

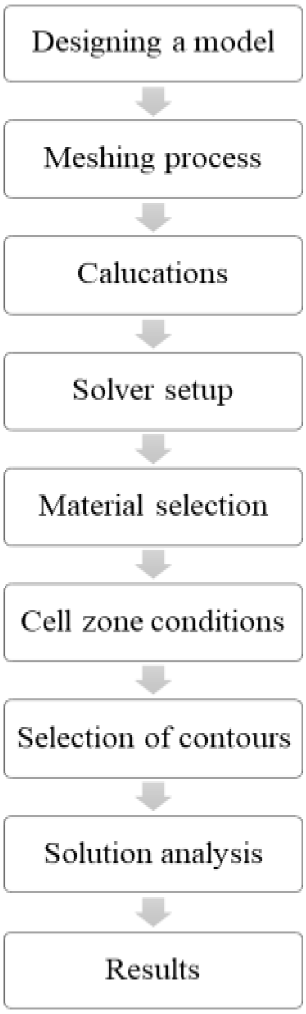

Figure 3 Work flow process

The methodology for a CFD analysis of a battery thermal management system in an electric vehicle. It focuses on maintaining optimal battery temperature using various cooling techniques. The process involves model design, meshing, solver setup, and material selection. Different battery pack configurations and cooling methods, including PCM, are compared. The study aims to determine the most effective combination of cooling strategies for efficient heat dissipation.

4. RESULTS

The CFD analysis on the battery management system in electric vehicles (EVs) focused on optimizing cooling mechanisms to maintain battery temperature within safe limits. Various cooling methods, including air, liquid, and phase-change material (PCM) cooling, were compared. Among them, water-based liquid cooling was found to be the most effective in maintaining optimal battery temperature, air and water liquid cooling.

In this analysis they are different battery designs, such as vertical, horizontal, multi-inlet, and spiral channel configurations, concluding that spiral channels with multiple inlets provided better thermal performance. Ultimately, PCM and liquid cooling demonstrated superior temperature regulation, making them ideal for high-performance EV battery thermal management.

- PCM (Methyl Palmitate) combined with water-based liquid cooling effectively maintains battery temperature at high discharge rates, ensuring optimal performance.
- Different geometric designs of battery packs were analyzed, including spiral channels and linear channels, to determine the most effective cooling method.
- A meshing process with 5 lakh – 5.5 lakh elements ensured grid independence, confirming accurate temperature distribution in simulations.
- Heat generation increased from 3.64×10^4 W/m³ at 1C to 1.09×10^5 W/m³ at 3C discharge rate, requiring efficient cooling mechanisms to control rising temperatures.
- Among different cooling methods, water-based liquid cooling proved to be more effective compared to air cooling, enhancing thermal performance.
- A combination of PCM and water liquid as the coolant resulted in more efficient temperature control compared to using either method alone.
- Temperature, velocity, and liquid fraction contours were analyzed for different C-rates, confirming that the designed cooling system provides reliable thermal management for EV batteries.

4.1 Temperature variation at different Heat Generations

The graph represents the variation of temperature over time at different C-rates, which are labeled as 1C, 1.5C, 2C, and 3C. The x-axis denotes time in seconds, while the y-axis represents temperature in Kelvin (K). The different curves indicate how the temperature increases as the C-rate increases.

From the graph, it is observed that at lower C-rates (1C and 1.5C), the temperature rise is relatively gradual, whereas at higher C-rates (2C and 3C), the temperature increases more significantly over time. The highest temperature is recorded for the 3C rate, indicating that higher discharging rates lead to more significant heat generation.

Table 4 Various discharge rates and corresponding Heat generation

Discharge rates	**Heat generation(W/m³)**
1C	3.64×10^4
1.5C	5.46×10^4
2C	7.28×10^4
3C	1.09×10^5

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The temperature increase is observed over a period of 1500 seconds, showing that higher C-rates result in a greater temperature rise due to increased heat generation during battery discharge. PCM helps regulate temperature, but at higher C-rates, its effectiveness reduces due to increased heat accumulation.

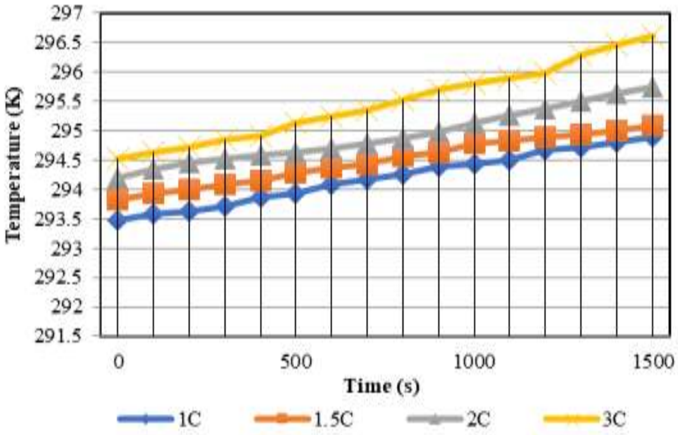

Figure 4 Variation of temperature with time for cell with PCM (Methyl-palmitate) at all C-Rate

4.1.1 Temperature Contours

In ANSYS CFD analysis, a temperature contour is a graphical representation that depicts the temperature distribution across a surface or within a fluid domain. It provides a visual insight into heat transfer patterns, allowing engineers to analyze thermal performance effectively.

The contour plot uses a color gradient, where different shades represent varying temperature levels, highlighting hot and cold regions within the system. This helps in identifying hotspots, thermal gradients, and inefficiencies in cooling strategies. By studying these contours, engineers can optimize heat dissipation, enhance cooling performance, and improve battery thermal management. Temperature contour analysis is crucial for designing efficient thermal management systems in applications like electric vehicle batteries.

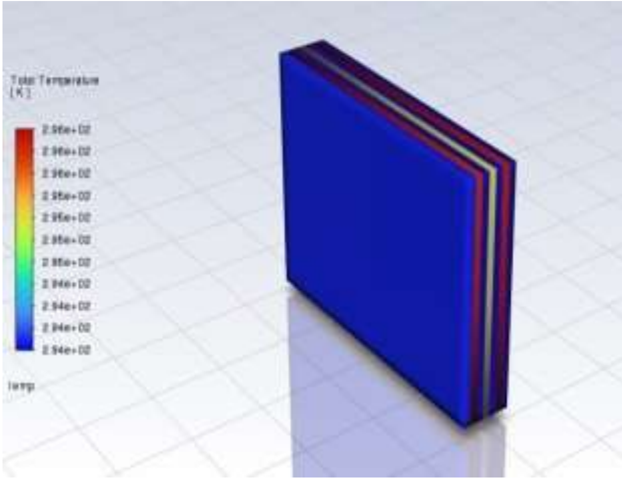

Figure 5 Temperature contour at 3C rate

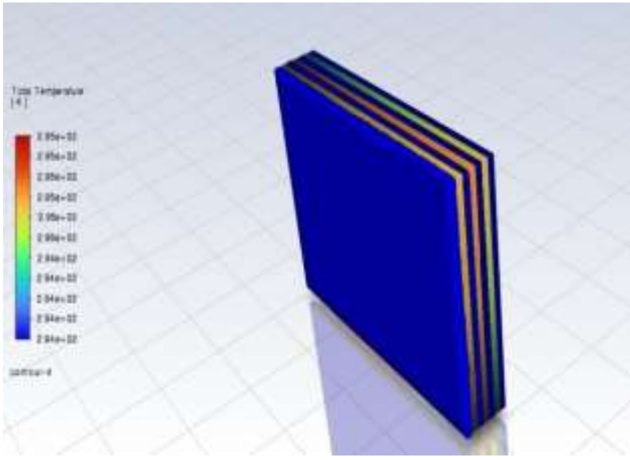

Figure 6 Temperature contour at 2C rate

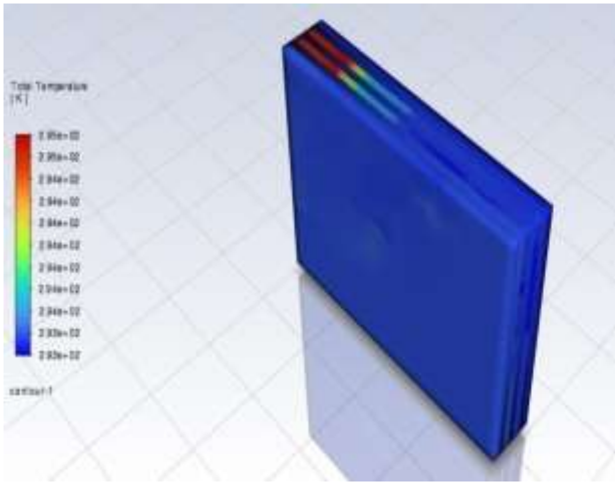

Figure 7 Temperature contour at 1.5C rate

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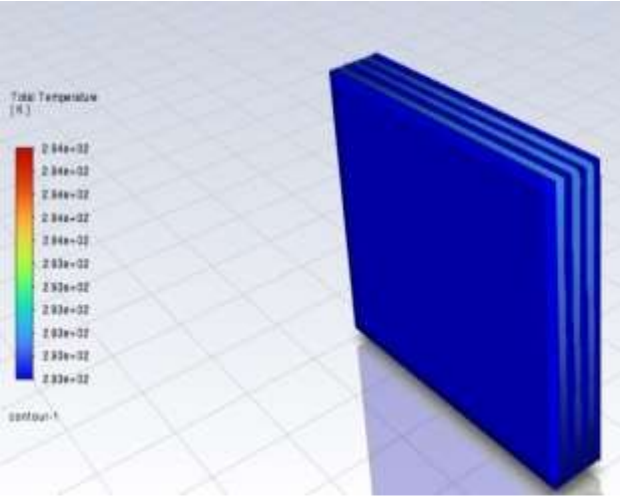

Figure 8 Temperature contour at 1C rate

4.2 Liquid fraction at different C-rates

The graph shows that the variation in liquid fraction area over time for different C-rates, specifically 1C, 1.5C, 2C, and 3C. The x-axis represents time in seconds (s), while the y-axis denotes the liquid fraction area.

This plot provides insights into the behavior of liquid formation in response to varying C-rates over time. The curves indicate that for lower C-rates (1C and 1.5C), the increase in liquid fraction is relatively slower, whereas at higher C-rates (2C and 3C), the liquid fraction grows more rapidly. This suggests that a higher discharging rate leads to a faster accumulation of liquid fraction.

The liquid fraction area stabilizes after approximately 60 seconds, indicating a limiting point where further increase in time does not significantly affect the liquid formation.

Table 5 Various discharge rates and corresponding Heat generation

Discharge rates	Liquid fraction
1C	0.041
1.5C	0.046
2C	0.052
3C	0.063

The highest liquid fraction is observed for the 3C rate, followed by 2C, 1.5C, and finally 1C, which exhibits the lowest liquid fraction throughout the process. This graph helps in understanding the impact of different C-rates on phase change processes, particularly in applications like battery cooling and thermal management.

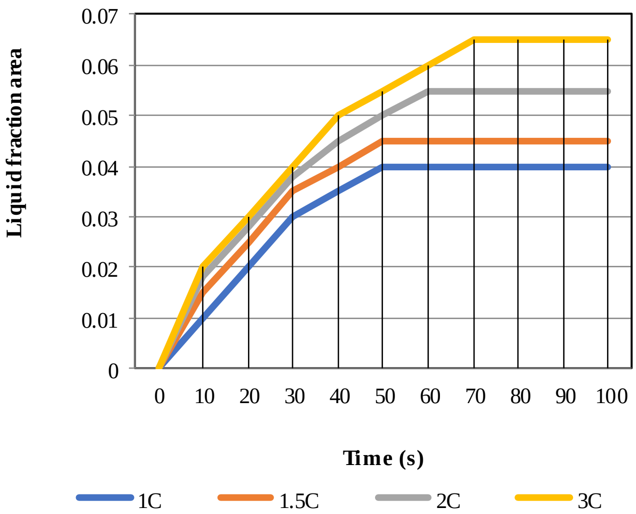

Figure 9 Area weighted average of liquid fraction vs. Time

4.2.1 Solidification melting or liquid fraction Contours

In ANSYS CFD analysis, a solidification/melting contour represents the phase change process of a material, showing regions where it transitions between solid and liquid states. It is used in thermal simulations to analyze materials like Phase Change Materials (PCM) in battery cooling systems.

The contour visualizes temperature distribution, latent heat absorption, and the melt fraction over time. Areas with higher melt fractions indicate more heat absorption, while solid regions retain thermal energy. This analysis helps in optimizing cooling efficiency for applications like battery thermal management.

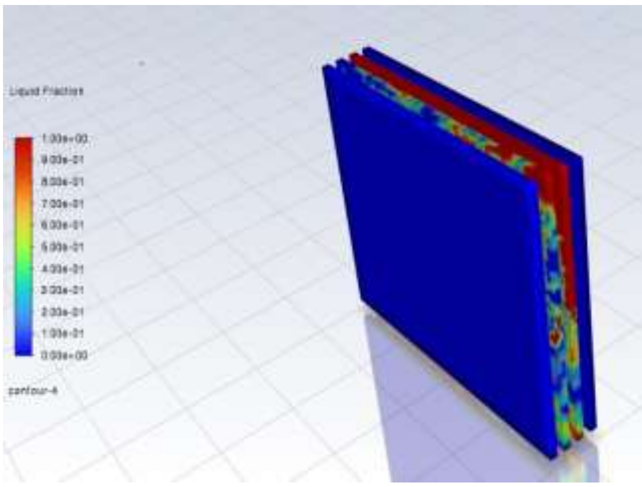

Figure 10 Liquid fraction contour at 3C rate

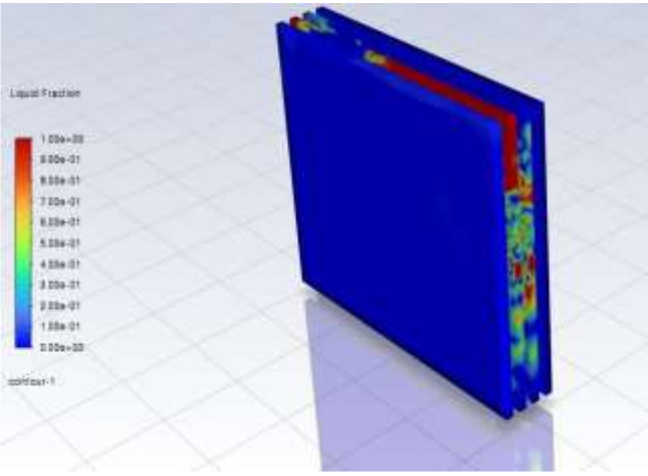

Figure 11 Liquid fraction contour at 2C rate

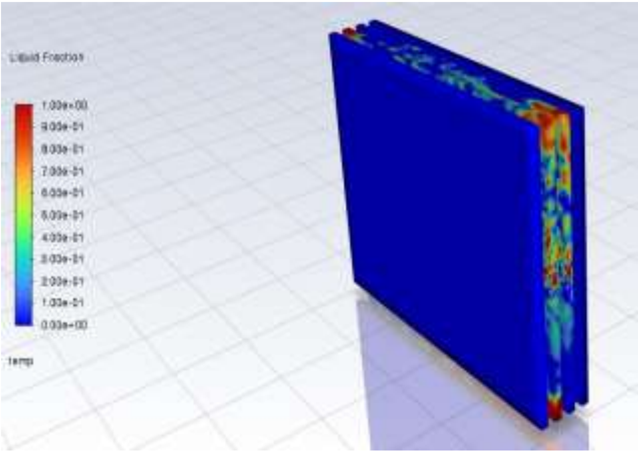

Figure 12 Liquid fraction contour at 1.5C rate

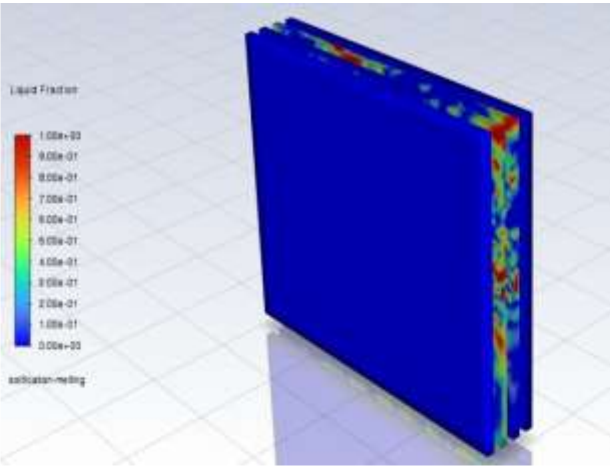

Figure 13 Liquid fraction contour at 1C rate

4.3 Velocity Contours

A velocity contour in ANSYS CFD analysis represents the distribution of velocity magnitudes across a fluid domain using color gradients. It visually illustrates how fluid flows around objects, highlighting regions of high and low velocity. These contours help analyze flow behavior, turbulence, and pressure drops in a system. Engineers use them to optimize aerodynamics, cooling efficiency, and fluid interactions in designs. In battery cooling applications, velocity contours help evaluate how effectively coolant circulates around battery cells for heat dissipation.

4.3.1 Velocity Contours at different C-rates

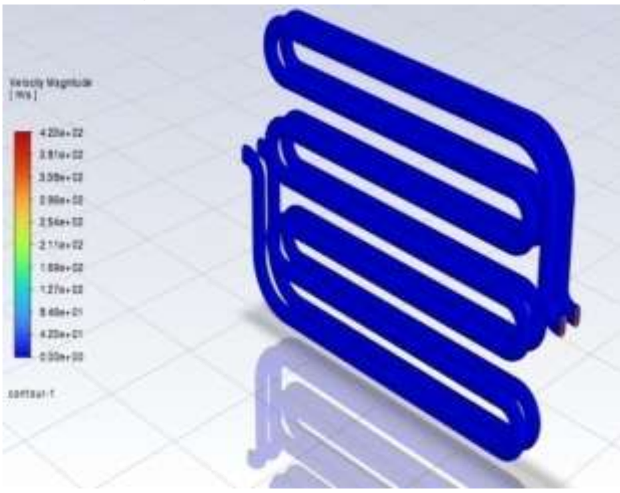

Figure 14 Velocity contour at 1C rate

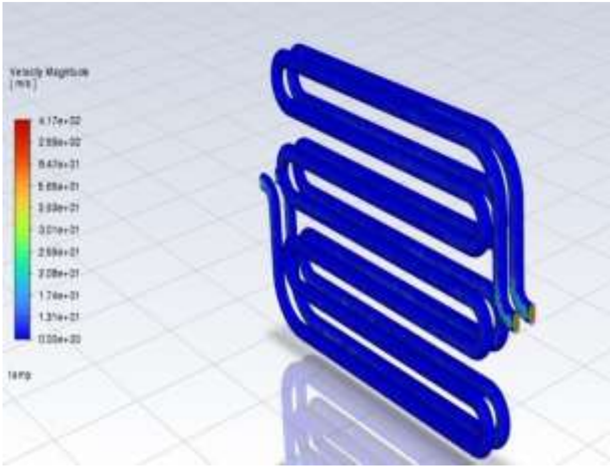

Figure 15 Velocity contour at 2C rate

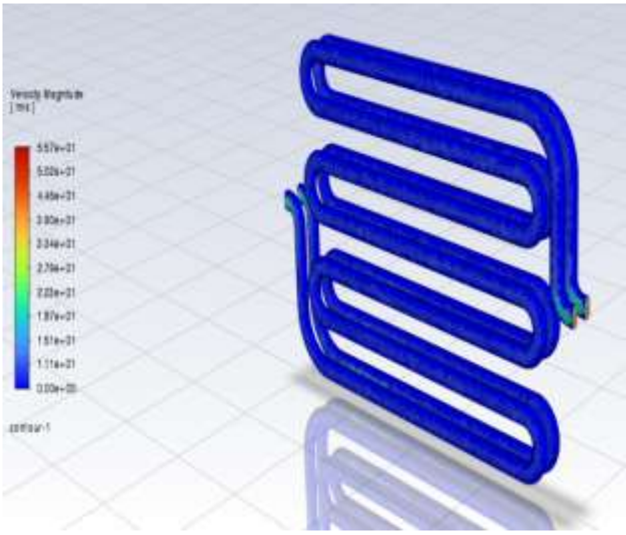

Figure 16 Velocity contour at 2C rate

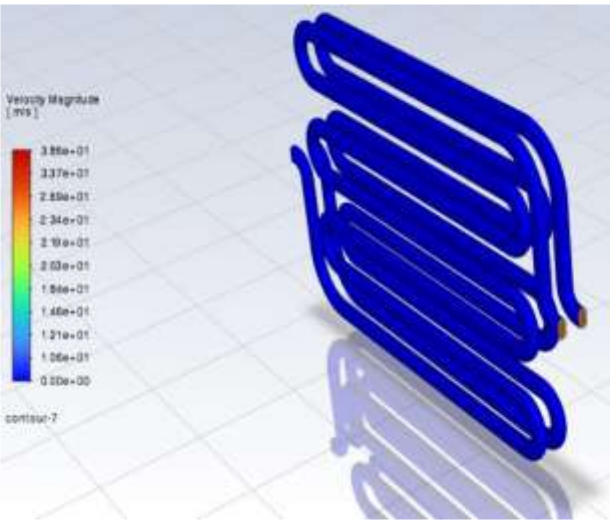

Figure 17 Velocity contour at 2C rate

5. CONCLUSION

The combination of PCM (Methyl Palmitate) with a water-based liquid cooling system effectively maintained battery temperature, particularly at high discharge rates. Through extensive analysis of various battery pack designs, including different geometries and cooling channel dimensions, the study optimized heat dissipation for improved thermal management. Additionally, detailed evaluations of temperature, velocity, and liquid fraction contours confirmed the accuracy and effectiveness of the designed cooling system, demonstrating its potential for enhancing battery performance and longevity

- A mesh refinement of 5 – 5.5 lakh elements was found to be the most effective, ensuring consistent temperature distribution in CFD simulations.
- Heat generation increased from at 3C, requiring efficient thermal management to prevent overheating.
- Water-based liquid cooling was the most effective cooling method, outperforming air cooling and PCM-only systems.
- The combination of PCM and water liquid cooling provided superior temperature regulation, making it the most efficient cooling strategy.

Further research can optimize cooling system energy consumption, improve PCM material properties, and enhance battery thermal performance for next-generation EVs.

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