Journal of Mines, Metals and Fuels, *73(3): 555-570; 2025. DOI: 10.18311/jmmf/2025/48185*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Simulation-Based Evaluation of Battery Thermal Management Systems for Cylindrical Li-Ion Batteries in Electric Vehicles

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Abstract

Cylindrical lithium-ion batteries are widely used in electric vehicles due to their high energy density and compact size. However, effective thermal management is crucial for their optimal performance and safety. This study evaluated the thermal performance of a battery pack by simulating three cooling strategies: air cooling, water-based liquid cooling, and ethylene glycol-based liquid cooling using CFD simulations in Ansys Fluent. The results demonstrated that ethylene glycol-based liquid cooling achieved the most uniform temperature distribution within the battery pack, with a minimum temperature of 293.2 K and a maximum temperature of 306.6 K. This indicates superior heat dissipation capabilities and improves thermal management compared to the other cooling methods. These findings provide valuable insights for optimizing battery pack design and enhancing the overall performance and lifespan of electric vehicles.

Major Findings: *The study found that ethylene glycol-based liquid cooling (Geometry 2) was the most effective cooling strategy, achieving a uniform temperature distribution with a minimum of 293.2 K and a maximum of 306.6 K. In contrast, air and immersed cooling methods exhibited limitations such as uneven temperature distribution, excessive heat absorption at the inlet, and insufficient heat removal at the outlet, which could lead to hotspots and accelerate battery degradation. Geometry 2 with ethylene glycol significantly improved temperature uniformity, reduced temperature variations, and minimized the risk of thermal runaway, ultimately enhancing battery performance and lifespan.*

Keywords: *ANSYS Fluent, Battery Thermal Management System (BTMS), Cooling Systems, Electric Vehicle Battery Pack, Lithium-Ion Battery*

1.0 Introduction

The rapidly growing Electric Vehicle (EV) market, driven by environmental concerns, government support, and technological advancements, demands reliable and efficient battery systems. Lithium-Ion Batteries (LIBs) are currently the preferred choice for EVs due to their high energy density and performance. However, maintaining optimal operating temperatures for LIBs is critical. Elevated temperatures can significantly shorten battery life and degrade performance, while low temperatures can reduce energy output and efficiency. Therefore, effective Thermal Management Systems (TMS) are essential for ensuring the safe and efficient operation of EV batteries.

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Efficient thermal management is essential not only for enhancing the reliability and safety of battery modules but also for preventing issues such as thermal runaway, which can lead to catastrophic failures. Excessive heat buildup within the battery pack can accelerate degradation processes, reduce efficiency, and, in extreme cases, lead to dangerous situations like fires or explosions. Poor thermal management design can exacerbate these issues, especially in hot climates, where the ambient temperature already places additional stress on the battery. Cold environments, on the other hand, can impede the battery's ability to deliver power efficiently, leading to reduced vehicle range and performance. To address these challenges, researchers and engineers are focused on developing advanced Thermal Management Systems (TMS) for EVs that not only control temperature but also enhance the overall implementation of the battery. These efforts include the design of sophisticated cooling systems, improved thermal insulation, and advanced temperature control mechanisms that can maintain the battery's temperature within an optimal range, regardless of external conditions[1-3]. Contemporary trends in BTMS design include the integration of Phase Change Materials (PCMs) and the use of nanomaterials to increase thermal conductivity. PCMs can absorb additional heat generated through battery operation by melting and later release it during solidification, helping to maintain a stable temperature. Additionally, the incorporation of open-cell metal foams and fin structures within the battery pack can significantly improve heat dissipation and temperature uniformity. Another emerging trend is the use of liquid cooling systems, which circulate a coolant, such as water-glycol mixtures, through channels within the battery pack. These systems can efficiently remove heat but require careful design to avoid issues like coolant leakage or added system complexity. Air cooling, although less complex, remains a widely used method due to its simplicity and cost-effectiveness. Innovations in air cooling include the use of active cooling techniques, such as fans or blowers, to increase airflow over the battery cells, as well as passive methods like heat sinks and fins that enhance the surface area for dissipation heat. Advanced air-cooling designs are increasingly incorporating Computational Fluid Dynamics (CFD) simulations to improve airflow patterns and ensure uniform temperature distribution among the battery pack. However, air cooling is easy and more cost-effective than other techniques like liquid cooling, it may be less effective in regulating temperature, particularly in high-temperature environments[4-10]. The study examined how numerous factors influence the thermal behaviour of close battery cells, focusing on cell spacing, ventilation and velocity, and incoming temperature of air. The results showed that improper spacing, whether too narrow or too wide, initially increases the temperature difference between cells. However, as wind speed increases, the temperature difference decreases. Thus, selecting a best gap between nearby cells is crucial to minimizing excessive temperature variations[11]. The paper compares air and liquid cooling systems for a high-energy lithium-ion battery module, focusing on dependent power consumption and thermal performance using CFD simulations. Previous studies show that air cooling, though simpler, often leads to higher temperatures and less uniform cooling than liquid cooling. Liquid cooling provides better thermal regulation but with increased complexity and potential energy costs. The study validates the numerical model with experimental data and finds that for the same power consumption, liquid cooling achieves lower temperatures and better uniformity. This research advances the development of energy-efficient BTMS by improving cooling strategies for battery modules[12]. Hybrid Thermal Management System (HTMS) combining air cooling and heat pipes for battery vehicles, with a focus on improving the cooling performance of a battery pack comprising 24 cells. Prior research highlights the limitations of natural air cooling, particularly in achieving uniform temperature distribution across battery cells. The study uses COMSOL Multiphysics to simulate the effects of forced-air cooling, heat pipes, and Heat Pipes With Copper Sheets (HPCS), confirming the findings against experimental data. The findings prove significant temperature reduction and improved temperature uniformity with the hybrid TMS, particularly with HPCS, which achieves the best performance among the tested configurations. This investigate contributes precious insights into the optimization of TMS for EV batteries, offering substantial improvements in both cooling efficiency and temperature uniformity. This study addresses the limitations of traditional battery thermal management systems, where uneven heat dissipation occurs due to a Single-Phase

Change Material (PCM) encapsulating the entire pack. Prior research has shown that central cells in such designs often face higher temperatures. The proposed solution involves a modular layout with each cell individually surrounded by a 4mm PCM layer, enhancing heat dissipation and achieving better temperature uniformity. Experimental data indicate significant improvements in cooling performance, particularly under high discharge rates and varying ambient temperatures. Additionally, the modular approach allows for easier scalability of battery capacity without adding substantial weight, offering a more efficient and adaptable thermal management solution[13,14]. Study presents an efficient optimization method for parallel air-cooled Battery Thermal Management Systems (BTMS) in electric vehicles. Unlike traditional methods that use complex or empirical approaches, the proposed method employs simplified heat transfer and flow resistance models to perfect cooling system design. By focusing on achieving uniform average temperatures across battery cells, the method significantly improves cooling performance, reducing temperature differences by up to 84%. This streamlined approach simplifies the optimization process, making it faster and more effective compared to conventional techniques. Experimental results confirm the method's effectiveness, showing notable enhancements in temperature uniformity and cooling efficiency[15]. Air cooling is favoured for its simplicity and low price, requiring it a budget-friendly option for BTMS. It relies on natural or forced airflow to remove heat, which simplifies the system design and reduces costs. However, it is less effective than advanced methods like liquid cooling, especially in high-temperature environments. In such conditions, air cooling may struggle to keep best temperatures, potentially leading to inefficiencies and thermal hotspots. Liquid cooling surpasses air cooling in efficiency due to its superior thermal properties. Liquids generally have greater thermal conductivity and capacity of specific heat than air, enabling them to absorb and transfer heat more effectively. This allows liquid cooling systems to manage heat with greater precision, resulting in a more compact and efficient design linked to air cooling systems. As a result, liquid cooling can achieve performance improvements of up to three times that of air cooling. This enhanced heat transfer capability translates into better temperature regulation, making liquid cooling particularly helpful for high-performance or high heat applications[16]. A novel modular liquid-cooled battery thermal management system through both numerical investigation and experimentation. The study finds that improving coolant flow rate notably improves uniform temperature and reduces maximum temperature, although benefits plateau beyond a certain flow rate, with higher power consumption. Parallel cooling systems outperform serial cooling by lowering both supreme temperature and variation temperature, enhancing overall temperature control. Specifically, at a discharge rate 3C and ambient temperature 30°C, parallel cooling reduces highest temperature and temperature difference by significant margins compared to serial cooling[17]. Investigates the use of nanofluids in cooling systems for high-power density Electric Vehicle (EV) battery modules, focusing on temperature distribution and pressure drop in corrugated mini channels. It finds that nanofluids significantly reduce extreme temperature by 28.65% related to other cooling methods, though at the cost of increased pressure drop. The research highlights that nanofluids offer superior cooling ability over water, enhancing thermal management in confined EV spaces. The study proves that optimizing coolant type and flow conditions can improve battery cooling performance, vital for maintaining efficiency, reliability, and safety in high-power applications[18]. Evaluates the thermal management of lithium-ion batteries using a roll bond liquid cooling plate. It highlights the plate's effective heat dissipation through its cavity and rib structures compared to direct channels. Experimental findings show that at 1C discharge, a low flow rate with a large contact area controls temperature well, while a high flow rate and optimized rib structures are needed at 2C discharge. The roll bond plate maintains temperatures under 35 °C with a pressure drop of 5818 Pa, highlighting its strong heat transfer performance, lightweight design, and cost efficiency, achieving it an indicating result for battery thermal management[19]. Recent examine on Battery Thermal Management Systems (BTMS) has largely determined on improving cooling efficiency, but the impact of vehicle vibrations has been underexplored. Liquid cooling systems, particularly serpentine channels, are common in BTMS. Studies show that incorporating vibrations into these systems enhances heat transfer,

reducing wall temperatures and increasing the Nusselt number. A novel serpentine channel design under vibration shows improved thermal performance compared to traditional designs, with minimal pressure drop increase. This suggests a new direction for BTMS design, integrating vibration effects for better thermal management in electric vehicles[20]. BTMS are essential for keeping battery efficiency, with parasitic power consumption significantly affecting the explicit power of the battery pack. Comparative studies among air and liquid cooling systems show that liquid cooling provides better temperature control and uniformity. While air cooling is simpler, liquid cooling systems, despite being more complex, result in lower largest cell temperatures for the same power consumption. Computational Fluid Dynamics (CFD) simulations, validated by experiments, confirm these findings, showing that liquid cooling can enhance thermal management, especially under high-demand conditions. This research underscores the potential of liquid BTMS for more energy-efficient battery operation in electric vehicles[21]. The Phase Change Materials (PCMs) are increasingly being combined into Battery Thermal Management Systems (BTMS) as a passive or alternative cooling solution. These materials have unique properties that allow them to absorb and release great aggregates of latent heat while phase transitions, typically from solid to liquid and liquid to solid. This characteristic makes them highly effective in regulating the temperature within battery packs, which is necessary for retaining ideal performance of battery, safety, and longevity. In a typical BTMS setup, the PCM is in direct contact between cells or modules. During battery operation, such as during charging or discharging cycles, heat is generated as a byproduct of the electrochemical outcomes within the cells. When the battery pack temperature exceeds a predefined threshold, the PCM begins to melt, absorbing the excess thermal energy in the process. This combination of heat helps inhibit the battery cells from overheating, which can otherwise lead to reduced performance, accelerated aging, or even thermal runaway in extreme cases[22,23]. The paper compares air and liquid cooling systems for a high-high-power lithium-ion cells, focusing on parasitic power use and performance of cooling using CFD simulations. Earlier studies show that air cooling, though simpler, often leads to higher temperatures and less uniform cooling than liquid cooling. Liquid cooling provides better thermal regulation but with increased complexity and potential energy costs. The study confirms the numerical model with experimental data and finds that for the same power consumption, liquid cooling achieves lower temperatures and better uniformity. This research advances the advance of energy-efficient battery thermal management system by improving cooling strategies for battery modules. As the heat within the battery pack decreases, such as when the battery is not in use or is discharging less intensively, the PCM solidifies. During this phase change back to a solid state, the PCM releases the previously absorbed heat. This continuous cycle of absorption and release of heat by the PCM helps maintain a more stable temperature inside the battery pack, which is essential for ensuring the battery's reliability and extending its service life. Incorporating PCMs into BTMS offers several key advantages. One of the most significant benefits is the potential reduction in the size and complexity of the overall cooling system. Since PCMs provide passive cooling, they can minimize the need for active cooling systems, such as liquid cooling, which are often bulky and energy intensive. Additionally, the improved temperature regulation provided by PCMs enhances battery reliability and safety, as it mitigates the risks associated with overheating. The passive nature of PCM-based cooling also reduces energy consumption, contributing to greater overall battery efficiency. These benefits collectively make PCMs an attractive solution in modern battery thermal management[24,25]. The researchers compared the melting behavior of commercial and real Paraffin Wax (PW) within straight up copper tubes of varying peaks. They observed that both types of wax melted in a similar manner. Initially, the unmelted wax formed a cylindrical shape, suggesting that heat conduction was the primary melting mechanism. However, as natural convection intensified, the unmelted wax gradually transformed into a conical shape. The liquid wax circulated down immediately the solid-liquid edge and increased along the tube wall[26]. A mathematical investigation was carried out to evaluate the cooling running of a vertical cylindrical thermal energy storage unit complete with a phase change material and nanoparticle composite, along with a unit featuring parallel radial copper extended surface. The researchers found that incorporating 5% aluminum oxide

nanoparticles into the pure PCM only slightly improved melting time by 5.5%. However, the addition of copper fins to the thermal energy storage system significantly enhanced melting performance, reducing melting time by up to 25.7%[27]. The researchers examined the impact of incorporating copper foam into a PCM for a passive Battery Thermal Management System (BTMS). Their findings show that this system effectively supported battery pack temperatures within safe limits, even under demanding discharge rates of 3C and 4C[28]. A comparative analysis of refrigerant and PCM-based BTMs was conducted in various operating situations. The simulation results showed that refrigerant-cooled BTMs exhibited superior performance within ambient temperatures of 20°C to 40°C. While both systems functioned effectively under both mild and severe conditions, the refrigerant-based system proved better performance than the PCM system in cyclic operating scenarios[29]. Studied the impact of sodium polyacrylate hydrogel on the cooling performing of a 3 Ah lithium-ion battery pack below varying discharge rates through experimental and numerical methods. The findings showed that the hydrogel-based BTMS effectively improved the battery's thermal performance, even at the excellent rate of discharge of 10 A[30]. A recent study evaluated the effectiveness of incorporating fins into a Battery Thermal Management System (BTMS) that uses Paraffin Wax (PW) as the Phase Change Material (PCM). The PW, with a melting temperature of 44 °C, was chosen for its ability to absorb and store thermal energy during the phase transition. The study specifically examined the impact of adding eight fins, which occupied less than 3% of the total volume of the PCM enclosure and found a significant improvement in the BTMS performance. The inclusion of fins resulted in an 8°C decrease in the average battery temperature, which is critical for keeping battery efficiency and prolonging its lifespan. The fins helped a more even distribution of temperature through the battery surface, enhancing thermal management by promoting better heat dissipation. Moreover, this configuration led to a 55% reduction in the battery's thermal resistance, meaning that heat could be more effectively transferred away from the battery cells, further preventing overheating[31]. Additionally, multiple simulation and experimental studies have shown that the use of open cell metal foams can extensively boost the heat transfer rates and improve temperature equivalence throughout the melting process of PCM. The high surface area and interconnected pores of the metal foams enhance thermal conductivity, enabling quicker and more efficient heat absorption by the PCM. This combination of fins and metal foams represents a promising approach to optimizing BTMS performance, offering improved temperature regulation and enhanced battery safety[32,33]. An experimental setup with a 10-heater battery pack was employed to research the effect of vibration on PCM-based cooling management. The vibrations ranging from 20 to 50 Hz and 30 to 50 mm/s significantly influenced battery warmth, especially at extreme discharge rates. Investigators have employed fins within PCM to address the material's low thermal conductivity[34]. PCM cooling resulted in more evenly distributed temperatures in electric vehicle batteries compared to traditional cooling methods[35]. Different paraffin-based PCMs were evaluated for their effectiveness in cooling Li-ion batteries. These PCMs reduced the peak battery temperature by 20% during high-intensity discharge at 5C rate[36].

This research aims to determine the most effective cooling method for optimizing the performance of electric vehicles. To achieve this, three cooling configurations were designed and analyzed using ANSYS software: two channel-based systems and one direct liquid-cooled system. The study utilizes a common 18650 cylindrical lithium-ion battery pack to evaluate the performance of each cooling method. Effective thermal management is crucial for ensuring battery safety and longevity. By comparing simulation results, the most efficient cooling approach for electric vehicle operation will be identified.

2.0 Geometry model

2.1 The Channel Cooling

Figure 1 illustrates the channel cooling designs employed in this study, utilizing either pure water or a 50/50 mixture of ethylene glycol and water as coolants. These designs are crucial for understanding how different coolant compositions influence overall cooling efficiency. Figure 2 further investigates this by depicting the relationship between ethylene glycol concentration and temperature, highlighting the impact of glycol content on thermal

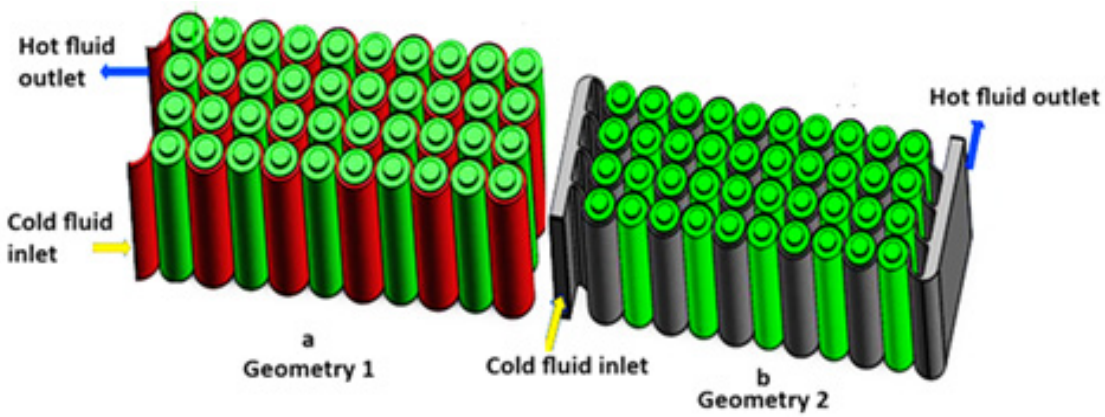


Figure 1. Photographic view of cooling model of the channel.

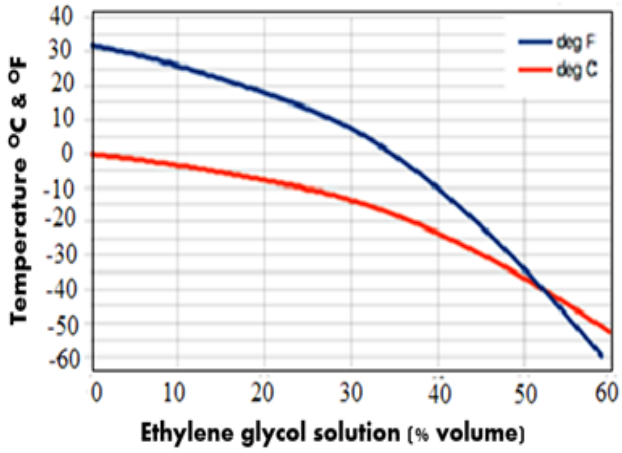


Figure 2. The solution of ethylene glycol (% by Volume) vs temperature.

properties like heat capacity and viscosity. Ethylene glycol-water mixtures are widely used in heat transfer applications due to their excellent thermal conductivity, making them suitable for both heating and cooling systems. While effective, ethylene glycol poses potential toxicity and environmental risks in case of leaks. Therefore, propylene glycol is often preferred as a safer alternative, especially in applications where human or environmental exposure is a concern.

2.1 Geometry Model for Air and Liquid Cooling

This research utilized SolidWorks to design various lithium-ion battery pack geometries, each containing 40 cylindrical cells (18 mm diameter, 70 mm height) with 3 mm spacing. To simplify the simulation and focus on inter-cell heat transfer, the top and bottom of the geometry were excluded. These models were then analyzed in ANSYS Fluent 2021 using computational fluid dynamics to simulate heat transfer. Air, water, and ethylene glycol were employed as coolants for the fluid cooling simulations, with the geometries for air and liquid cooling depicted in Figure 3.

3.0 Methodology

3.1 Analysis of Meshing

Meshing, a crucial step in engineering simulations,

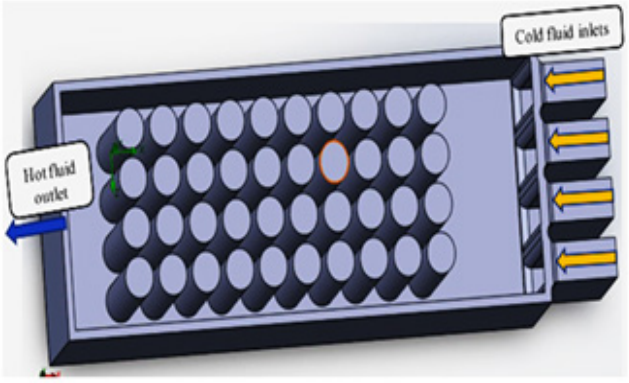


Figure 3. Geometry model of the air and liquid cooling system.

involves dividing complex geometries into simpler elements for analysis. This process enhances simulation accuracy, convergence, and speed. Suitable meshes were generated using ANSYS Fluent for the various battery module designs under various cooling conditions, as depicted in Figure 4.

3.2 Boundary Condition

3.2.1 Inlet Condition

The boundary condition at the inlet for the simulation was set based on the flow rate provided by the Seaflo 1100 GPH 12v water pump. This pump delivers an inlet flow rate of 0.001388889 m^3/s, ensuring a steady supply of coolant into the system. The fluid entering the system is at a temperature of 293 K, which serves as the initial condition for the cooling process. By accurately defining these boundary conditions, the simulation can replicate real-world conditions more closely, leading to more reliable predictions of thermal behavior. The chosen flow rate and temperature are critical for calculating the thermal performance and ensuring the system operates within the desired thermal constraints. Properly setting these conditions also aids in analyzing how effectively the cooling system manages heat dissipation under various operating scenarios.

3.2.2 Outlet Condition

The simulation was performed under standard atmospheric pressure conditions, set at 101.325 Pa, to replicate typical environmental conditions. A transient, incompressible flow was modeled, meaning the simulation captured changes over time without accounting for changes in fluid density. The pressure-based k-epsilon turbulence model was employed, which is commonly used for predicting turbulent flows due to its balance between accuracy and computational efficiency. The battery surfaces were maintained at a uniform temperature of

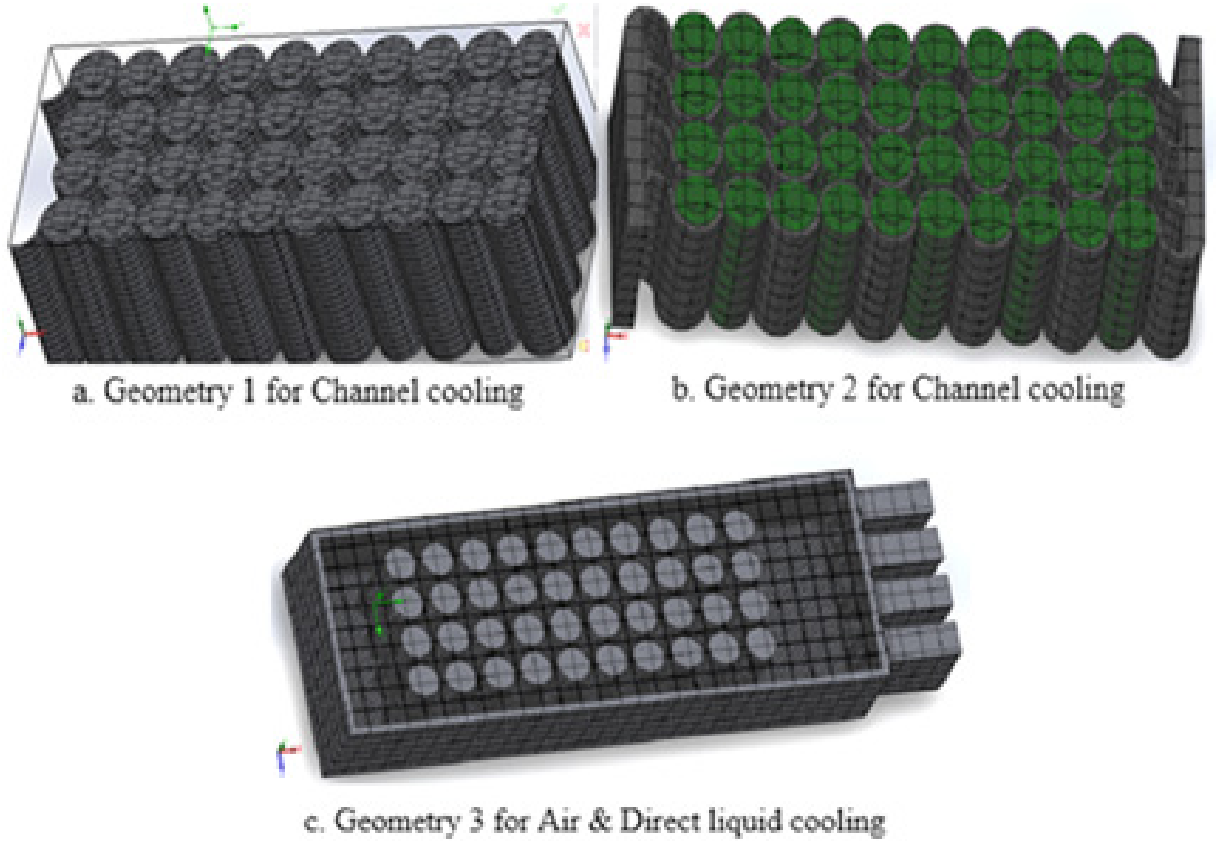


Figure 4. The cooling system of meshed geometry.

Table 1. Boundary conditions

Boundary Condition	Parameter	Value	Description
Inlet Condition	Flow Rate	0.001388889 m^3/s	Defined by the Seaflo 1100 GPH 12v water pump to ensure a steady coolant supply into the system.
	Temperature	293 K	Represents the initial temperature of the coolant entering the system.
	Flow Type	Steady	Ensures consistent coolant flow, critical for accurate thermal performance predictions.
Outlet Condition	Pressure	101.325 Pa	Standard atmospheric pressure to replicate typical environmental conditions.
	Flow Type	Transient, incompressible	Models change time-dependent without considering fluid density variations.
	Turbulence Model	Pressure-based k-epsilon	Provides a balance between accuracy and computational efficiency for predicting turbulent flow behavior.
Battery Surface	Temperature	330 K	Simulates the maximum operating temperature for evaluating the cooling system under worst-case thermal conditions.

330K throughout the simulation, simulating a worst-case scenario where the batteries operate at their maximum expected temperature. This approach helps in evaluating the cooling system's performance under the most challenging thermal conditions, ensuring that the design can effectively manage heat even in extreme situations. By studying these factors, the simulation provides a complete analysis of the cooling system's ability to maintain safe operating temperatures under pressure. All the boundary conditions are shown in table 1.

4.0 Results and Discussion

4.1 The Channel Cooling

4.1.1 Geometry 1

This study analyzed the thermal performance of a battery pack utilizing a direct-contact cooling system with water and ethylene glycol as coolants. Figure 5(a) demonstrates that when using water, significant temperature variations were observed within specific cells (cells 6, 7, and 8), indicating uneven heat distribution. This unevenness is attributed to the unidirectional flow of water, leading to reduced cooling capacity as it progresses through the circuit. In contrast, Figure 5(b) shows that ethylene glycol provided more uniform temperature distribution across these cells, with a narrower temperature range from 293.2 K to 326.3 K. Although ethylene glycol exhibited improved performance, the unidirectional flow pattern still resulted in higher temperatures near the outlet of the cooling circuit, limiting overall cooling efficiency.

This paraphrase incorporates specific details like cell numbers (cells 6, 7, and 8) and the temperature range (293.2 K to 326.3 K) to enhance the clarity and in formativeness of the summary.

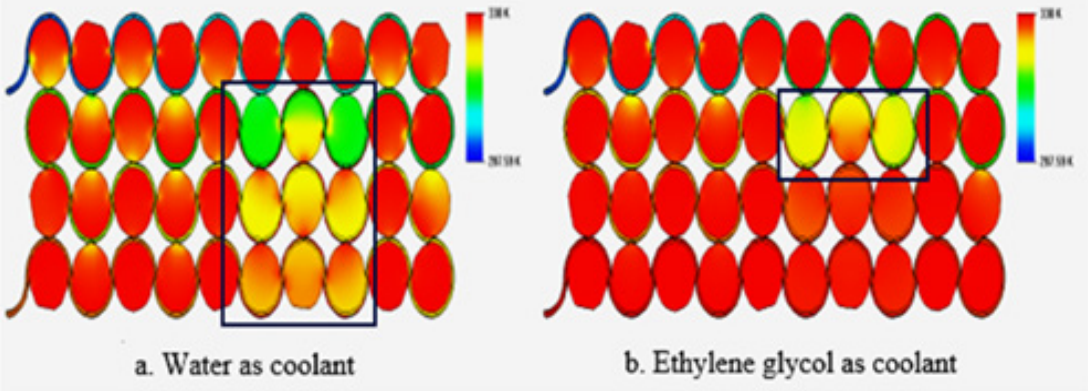


Figure 5. The temperature distribution across the channel cooling System **(a)** water as coolant **(b)** Ethylene glycol as coolant.

4.1.2 Geometry 2

In a next experimental demonstration, a new cooling setup was devised to further explore the cooling management of lithium-ion battery cells. Similar to the initial model, this setup involved placing the battery cells in direct contact with cooling pipes to maximize the efficiency of heat transfer. The primary aim was to evaluate the cooling performance of two different fluids-water and ethylene glycol-by analysing how effectively each coolant managed the heat distribution inside the battery pack. The fluids were directed from the inlet to the outlet, with the temperature distributions captured in Figures 6(a) and 6(b) for water and ethylene glycol, respectively. When water was used as the cooling medium, the results demonstrated that the cells located closer to the coolant inlet consistently exhibited lower temperatures compared to those near the outlet. This trend mirrored the findings from the previous model, where the unidirectional flow of the coolant led to a gradual decrease in its cooling capacity as it absorbed heat from the battery cells along the path. Although water is a widely used coolant due to its availability and thermal properties, the temperature distribution was still uneven, particularly towards the outlet, where the cells experienced higher temperatures due to the diminished cooling efficiency of the water as it travelled through the system.

In contrast, when ethylene glycol was used as the cooling fluid, a significant improvement in thermal management was observed. Ethylene glycol, known for its superior heat absorption properties, provided a more

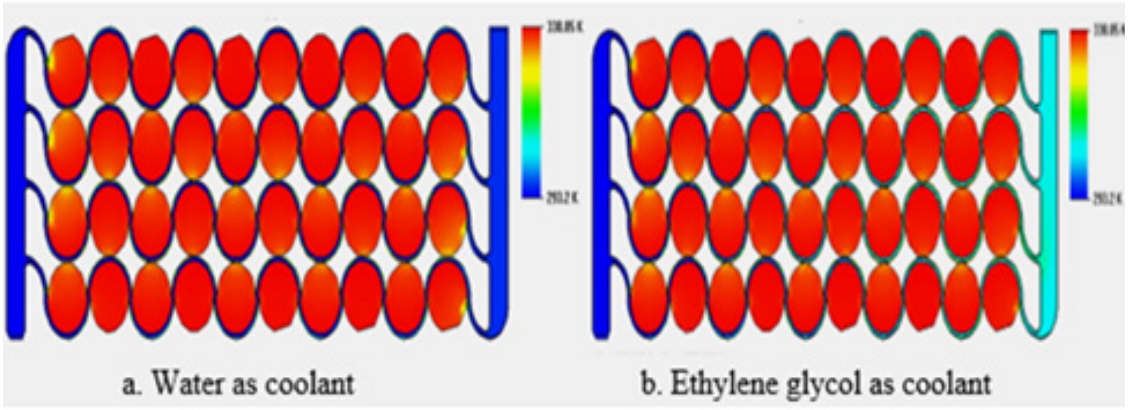


Figure 6. The temperature distribution across the channel cooling System: **(a)** water coolant, **(b)** Ethylene Glycol Coolant.

favourable and controlled temperature range within the battery pack. The temperatures across the battery cells varied between 293.2 K and 298.4 K, with the highest recorded temperature reaching 306.6 K. This stood for a much narrower and more stable temperature range compared to the earlier setup, where water was used as the coolant. The effectiveness of ethylene glycol in this setup was further underscored by the achievement of a lower average bulk temperature of 305.2 K. This shows that ethylene glycol was more successful in keeping a uniform and minimum temperature across the battery cells, lowering the hazard of hotspots and ensuring that the cells used within a safer and more efficient temperature range. The improved design, which ensured better immediate contact among the battery cells and the cooling pipes, played a crucial role in enhancing the heat transfer efficiency. This direct contact maximized the surface area for heat exchange, permitting the coolant to realize and disperse heat more effectively.

4.2 Air Cooling System

This study investigates the cooling performance of the same geometric model using two different coolants: air and ethylene glycol. Air cooling primarily relies on convection for heat dissipation, while ethylene glycol, a liquid coolant, generally exhibits superior heat transfer properties due to its higher thermal conductivity. By employing the same geometric model, the study isolates the impact of the cooling medium while keeping the object of the cooling system constant. This approach enables a direct comparison of the efficiency and effectiveness of air cooling versus liquid cooling within the identical physical setup.

4.2.1 Geometry 3

Figure 7 provides a detailed illustration of the cooling process within a battery pack when air is utilized as the cooling fluid. In this setup, air flows around the battery cells, functioning as the primary medium for heat removal. The airflow is unidirectional, meaning that it moves in a single, consistent direction from the inlet to the outlet throughout the system. As the air circulates around the battery cells, it absorbs heat generated by the cells during operation. This process highlights both the strengths and limitations of using air as a cooling medium for battery

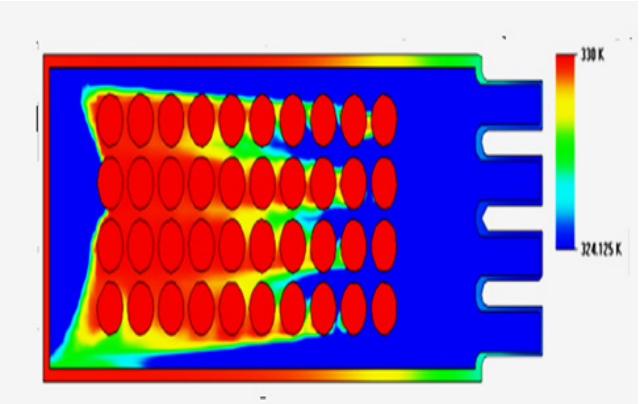


Figure 7. Air cooling temperature distribution.

thermal management system. As the air contacts the battery cells, it gradually picks up heat, which indicates an enhancement in the air temperature near its path. At the point of entry (inlet), the air begins at a relatively low temperature of 293 K. However, as it progresses through the system, the air temperature rises due to continuous heat absorption from the battery cells. By the time the air reaches the outlet, it has absorbed a substantial measure of heat, leading to the highest recorded temperature of 330 K at this point. This substantial temperature increase from the inlet to the outlet reflects the air's ability to absorb and carry away heat but also underscores a key challenge: managing the temperature rise effectively within the battery pack.

The gradual enhances the air temperature throughout the system indicates that while the air-cooling system can remove heat, it does so unevenly. Cells positioned closer to the inlet benefit from cooler air, which results in lower temperatures around these cells. In contrast, cells closer to the outlet experience higher temperatures as they are exposed to air that has already absorbed considerable heat. This uneven cooling can lead to temperature gradients inside the battery pack, where some cells operate at higher temperatures than others. Such gradients can be problematic as they may cause certain cells to degrade faster, reduce overall battery efficiency, and increase the hazard of thermal escape in extreme cases. The average temperature of the entire system was measured at 308.7 K, which is significantly more than the initial air temperature at the inlet. This average is a key indicator of the overall cooling performance of the air-cooling system. The rise in the average temperature from the inlet to the

outlet highlights the challenge of heat accumulation within the system. Despite the cooling effect of the air, the unidirectional flow pattern allows for some degree of heat buildup, particularly towards the end of the cooling path. This suggests that while air is relatively efficient as a cooling medium, its effectiveness diminishes as the air travels further through the battery pack.

The temperature distribution and the average temperature readings suggest that the air-cooling system, in its current form, could benefit from optimization. The unidirectional airflow, while simple and straightforward, may not be the most effective approach for ensuring uniform cooling across all battery cells. The temperature variation amongst cells near the inlet and those near the passage indicates a potential for thermal imbalance, which could lead to uneven aging of the battery cells and a reduction in the total lifespan of the battery pack. To address the limitations observed in the air-cooling system, several improvements could be considered. One approach could involve optimizing the airflow pattern to ensure more even cooling. This could be achieved by implementing multi-directional airflow, where the air is directed in different directions across the battery cells, rather than following a single path from inlet to outlet. Such a design could help distribute the cooling effect more evenly and reduce the temperature gradients inside the battery pack.

Another consideration could be the integration of supplementary cooling methods. For instance, combining air cooling with liquid cooling or using Phase Change Materials (PCMs) could enhance the overall cooling efficiency and give an additional stable temperature conditions for the battery cells. PCMs could absorb excess heat during cycles of high thermal charge, reducing the burden on the air-cooling system and helping to provide a more constant temperature across the battery pack.

4.3 Direct Liquid Cooling System

4.3.1 Geometry 3

The simulation was revisited using the same geometric setup, but this time ethylene glycol was employed as the immersion fluid for cooling, as depicted in Figure 8. This change from air cooling to ethylene glycol significantly influenced the cooling management performance of the battery cells. Ethylene glycol, being denser and more viscous than air, possesses superior thermal properties, including higher capacity of heat and thermal conductivity, which enables it to absorb and transfer heat extra efficiently. In the initial air-cooling scenario, the system encountered several limitations, notably heat stagnation and inadequate heat dissipation. These issues led to a maximum recorded temperature of 330 K, a figure that highlighted the shortcomings of air as a preservation medium in managing the heat produced by battery cells. The temperature rise was attributed to air's lower density and specific heat capacity, which limited its ability to absorb and transport heat away from the battery cells efficiently. By contrast, when ethylene glycol was used, the maximum temperature within the battery system dropped significantly to 302.5 K. This substantial reduction in peak temperature by nearly 27.5 K demonstrates the effectiveness of ethylene glycol in thermal management. The fluid's higher density and viscosity allow it to absorb extra heat from the battery cells and transport it away more effectively than air, thereby preventing the buildup of excessive heat. This improvement is crucial, as it reduces the thermal stress on the battery cells, minimizing the risk of thermal degradation and enhancing the total longevity and safety of the battery system.

In addition to decreasing the maximum temperature, the use of ethylene glycol also led to a significant improvement in the average temperature distribution across the battery cells. The simulation results indicated a remarkable 12°C reduction in the overall temperature when using ethylene glycol compared to air cooling. This decrease not only underscores the superior heat

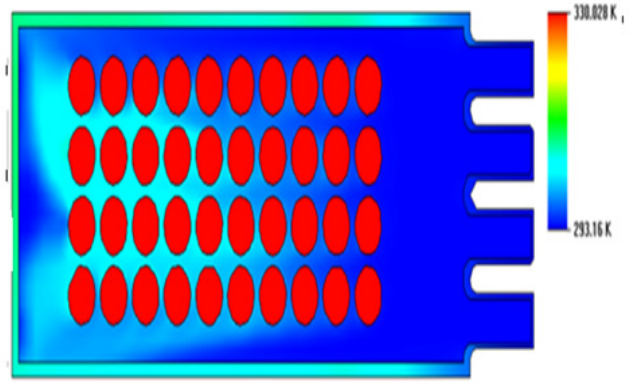


Figure 8. Temperature distribution of liquid cooling.

absorption capacity of ethylene glycol but also highlights its ability to maintain a more uniform temperature across the battery cells. Uniform temperature distribution is critical in battery thermal management, as it ensures that all cells operate within an optimal temperature range, reducing the likelihood of hotspots that can lead to uneven cell aging and potential safety hazards. The uniform cooling effect provided by ethylene glycol also contributes to maintaining consistent performance across all battery cells, preventing performance drops due to overheating in specific areas. This is specifically critical in high-power functions, such as electric cars, where consistent and reliable battery performance is essential for vehicle safety and efficiency.

To provide a broader perspective on the effectiveness of various cooling strategies, Table 2 offers a comparative analysis across different cooling geometries and methods, including air cooling, direct liquid cooling, and channel cooling with different fluids. The table presents key metrics such as outlet average temperature, most temperature, and temperature distribution, allowing for a clear evaluation of the strengths and weaknesses of each cooling strategy. In this context, the immersion cooling method using ethylene glycol demonstrated superior performance compared to air cooling. The substantial decrease the both maximum temperature and overall temperature distribution highlights ethylene glycol's potential as an optimal cooling fluid for Battery Thermal Management Systems (BTMS). Its ability to maintain lower and more consistent temperatures across the battery pack enhances the system's reliability and longevity, making it a more effective solution than traditional air-cooling methods.

4.4 Comparative Analysis of Cooling Methods

The table presents a comparative analysis of cooling methods across different geometries, focusing on the performance of air, ethylene glycol, and water as cooling mediums. The analysis evaluates the outlet average temperature, temperature distribution, and

Table 2. Comparative analysis of cooling methods across different geometries

Cooling Type	Outcomes	Cooling Medium		
		Air	Ethylene Glycol	Water
Geometry 1 (Channel cooling)	The outlet average temperature	--	328.7 K	323.8 K
	The temperature distribution	--	35.7 K	30.8 K
Geometry 2 (Channel cooling)	The outlet average temperature	--	305.3 K	295.6 K
	Temperature distribution	--	12.3 K	2.6 K
Geometry 3 (Direct liquid cooling)	The outlet average temperature	--	295.5 K	--
	The maximum temperature	--	302.5 K	--
Geometry 3 (air cooling)	The outlet average temperature	302.6 K	--	--
	The maximum temperature	329.7 K	--	--

maximum temperature across three different cooling geometries.

4.4.1 Geometry 1 (Channel Cooling)

The outlet average temperature with ethylene glycol as the cooling medium is 328.7 K. The temperature distribution, indicating the variance between the maximum and minimum temperatures, is 35.7 K. Water cooling performs better than ethylene glycol in this geometry, with a lower outlet average temperature of 323.8 K. The temperature distribution is also extra identical, with a smaller difference of 30.8 K.

4.4.2 Geometry 1 (Channel Cooling)

Ethylene glycol shows a significant improvement in performance in Geometry 2 compared to Geometry 1, with a much lower outlet average temperature of 305.3 K. The temperature distribution is also more uniform at 12.3 K. Water continues to outperform ethylene glycol, achieving the outlet average temperature of 295.6 K in this configuration. The temperature distribution is exceptionally uniform, with a minimal difference of only 2.6 K, indicating very effective cooling and temperature management.

4.4.3 Geometry 3 (Direct Liquid Cooling)

For direct liquid cooling, the outlet average temperature is further reduced to 295.5 K with ethylene glycol, making it the most effective use of this coolant in the given geometries. The maximum temperature recorded is 302.5 K, suggesting excellent temperature control within the system. Air cooling in geometry 3 yields a higher outlet average temperature of 302.6 K, which is lower than in geometry 1 but still higher than liquid cooling methods. The maximum temperature recorded with air cooling is 329.7 K, which is substantially higher compared to liquid cooling methods, indicating that air cooling is less effective at managing peak temperatures.

5.0 Conclusion

This study aimed to identify the most effective Battery Thermal Management System (BTMS) for lithium-ion batteries in electric vehicles. To achieve this, three distinct cooling geometries were designed and simulated using SolidWorks and Ansys Fluent. Among the evaluated strategies, Geometry 2, featuring multiple flow paths converging at a single point, exhibited the most effective heat distribution. This design significantly reduced temperature variations within the battery module compared to Geometry 1, which had a single flow path and resulted in more pronounced temperature differences due to limited heat transfer efficiency.

- Air cooling, despite its simplicity and cost-effectiveness, exhibited limitations in this study. Excessive heat absorption at the inlet and insufficient heat removal at the outlet resulted in uneven temperature distribution, particularly within the core of the battery pack. This unevenness can lead to hotspots, accelerating battery degradation and reducing overall efficiency. Moreover, air cooling struggled to effectively manage extreme temperatures within the battery module.
- Immersed cooling, while showing some improvement over air cooling, also exhibited challenges in achieving uniform temperature distribution. The viscosity of the cooling fluid contributed to temperature variations, similar to those observed with air cooling. This suggests that the effectiveness of immersed cooling is limited by fluid dynamics, particularly when compared to more advanced cooling strategies.
- The study demonstrated that Geometry 2, utilizing ethylene glycol as the cooling medium, provided the most effective thermal management. This configuration achieved a lower maximum temperature (306.6 K) and a higher minimum temperature (293.2 K), resulting in a more consistent and stable temperature profile across the battery pack. This uniform temperature distribution is crucial for preventing thermal hotspots and reducing the risk of thermal runaway, ultimately enhancing battery lifespan and reliability.
- Geometry 2 with ethylene glycol cooling proved to be the most effective method, offering significant improvements in temperature distribution and thermal stability. As electric vehicle adoption continues to grow, the findings from this study

provide valuable insights into the design of more efficient and reliable Battery Thermal Management Systems (BTMS), ensuring optimal performance of lithium-ion batteries under various operating conditions.

6.0 Future scope

This work can be further extended by:

- Investigating the impact of nanoparticles: Incorporating nanoparticles (such as graphene or carbon nanotubes) into the coolant can significantly enhance the thermal conductivity and heat transfer capabilities. This approach should be investigated to assess its impact on battery pack performance at different discharge rates, particularly under high discharge conditions (up to 5C).
- Optimizing flow patterns and channel design: Exploring alternative flow patterns (e.g., serpentine, helical) and increasing the number of liquid channels within the cooling system through optimization techniques can further improve heat distribution and minimize temperature gradients between cells.

These advancements in cooling system design will contribute to more effective Battery Thermal Management Systems (BTMS), enabling the battery pack to operate within the optimal temperature range and significantly reducing the maximum temperature difference between cells, ultimately enhancing battery life, safety, and overall performance.

7.0 References

1. Wu W, Wang S, Wu W, Chen K, Hong S, Lai Y. A critical review of battery thermal performance and liquid-based battery thermal management. Energy Convers Manag. 2019; 182:262-81. https://doi.org/10.1016/j.enconman.2018.12.051
2. Mali V, Saxena R, Kumar K, Kalam A, Tripathi B. Review on battery thermal management systems for energy-efficient electric vehicles. Renew Sustain Energy Rev. 2021; 151:111611. https://doi.org/10.1016/j.rser.2021.111611
3. Qin P, Sun J, Yang X, Wang Q. Battery thermal management system based on the forced-air convection: A review. eTransportation. 2021; 7:100097. https://doi.org/10.1016/j.etran.2020.100097
4. Zhao G, Wang X, Negnevitsky M, Zhang H. A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles. J Power Sources. 2021; 501:230001. https://doi.org/10.1016/j.jpowsour.2021.230001
5. Wang Y, Yu Y, Jing Z, Wang C, Zhou G, Zhao W. Thermal performance of lithium-ion batteries applying forced air cooling with an improved aluminium foam heat sink design. Int J Heat Mass Transf. 2021; 167:120827. https://doi.org/doi:10.1016/j.ijheatmasstransfer.2020.120827
6. Singh LK, Mishra G, Sharma AK, Gupta AK. A numerical study on thermal management of a lithium-ion battery module via forced-convective air cooling. Int J Refrig. 2021; 131:218-34. https://doi.org/10.1016/j.ijrefrig.2021.07.031
7. Wu W, Yang X, Zhang G, Ke X, Wang Z, Situ W, Li X, Zhang J. An experimental study of thermal management system using copper mesh-enhanced composite phase change materials for power battery pack. Energy. 2016; 113:909-16. https://doi.org/10.1016/j.energy.2016.07.119
8. Chen K, Wu W, Yuan F, Chen L, Wang S. Cooling efficiency improvement of air-cooled battery thermal management system through designing the flow pattern. Energy. 2019; 167:781-90. https://doi.org/10.1016/j.energy.2018.11.011
9. Chen K, Chen Y, She Y, Song M, Wang S, Chen L. Construction of effective symmetrical air-cooled system for battery thermal management. Appl Therm Eng. 2020; 166:114679. https://doi.org/10.1016/j.applthermaleng.2019.114679
10. Vali PS, Murali G. Battery thermal management system on trapezoidal battery pack with liquid cooling system utilizing phase change material. ASME J Heat Mass Transf. 2024; 1-24.
11. Zhao J, Rao Z, Huo Y, Liu X, Li Y. Thermal management of cylindrical power battery module for extending the life of new energy electric vehicles. Appl Therm Eng. 2015; 85:33-43. https://doi.org/10.1016/j.applthermaleng.2015.04.012
12. Akbarzadeh M, Kalogiannis T, Jaguemont J, Jin L, Behi H, Karimi D, Beheshti H, Van Mierlo J, Berecibar M. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. Appl Therm

Eng. 2021; 198:117503. https://doi.org/10.1016/j.applthermaleng.2021.117503
13. Behi H, Karimi D, Behi M, Ghanbarpour M, Jaguemont J, Sokkeh MA, Gandoman FH, Berecibar M, Van Mierlo J. A new concept of thermal management system in Li-ion battery using air cooling and heat pipe for electric vehicles. Appl Therm Eng. 2020; 174:115280. https://doi.org/10.1016/j.applthermaleng.2020.115280
14. Jilte RD, Kumar R, Ahmadi MH, Chen L. Battery thermal management system employing phase change material with cell-to-cell air cooling. Appl Therm Eng. 2019; 161:114199. https://doi.org/10.1016/j.applthermaleng.2019.114199
15. Zhang J, Wu X, Zhou D, Li QY, Li X, Chen K. Experimental and numerical investigation on efficient optimization of battery thermal management systems. Appl Therm Eng. 2023; 221:119821. https://doi.org/10.1016/j.applthermaleng.2022.119821
16. Wang M, Hung TC, Xi H. Numerical study on performance enhancement of the air-cooled battery thermal management system by adding parallel plates. Energies. 2021; 14(11):3096. https://doi.org/10.3390/en14113096
17. Wang H, Tao T, Xu J, Mei X, Liu X, Gou P. Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium ion batteries. Appl Therm Eng. 2020;178:115591. https://doi.org/10.1016/j.applthermaleng.2020.115591
18. Wiriyasart S, Hommalee C, Sirikasemsuk S, Prurapark R, Naphon P. Thermal management system with nanofluids for electric vehicle battery cooling modules. Case Stud Therm Eng. 2020; 18:100583. https://doi.org/10.1016/j.csite.2020.100583
19. Chen Z, Yang S, Pan M, Xu J. Experimental investigation on thermal management of lithium-ion battery with roll bond liquid cooling plate. Appl Therm Eng. 2022; 206:118106. https://doi.org/10.1016/j.applthermaleng.2022.118106
20. Yin B, Zuo S, Xu Y, Chen S. Performance of liquid cooling battery thermal management system in vibration environment. J Energy Storage. 2022; 53:105232. https://doi.org/10.1016/j.est.2022.105232
21. Akbarzadeh M, Kalogiannis T, Jaguemont J, Jin L, Behi H, Karimi D, Beheshti H, Van Mierlo J, Berecibar M. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. Appl Therm Eng. 2021; 198:117503. https://doi.org/10.1016/j.applthermaleng.2021.117503
22. Murali G, Sravya GS, Jaya J, Vamsi VN. A review on hybrid thermal management of battery packs and its cooling performance by enhanced PCM. Renew Sustain Energy Rev. 2021; 150:111513. https://doi.org/10.1016/j.rser.2021.111513
23. Luo J, Zou D, Wang Y, Wang S, Huang L. Battery Thermal Management systems (BTMs) based on phase change material (PCM): A comprehensive review. Chem Eng J. 2022; 430:132741. https://doi.org/10.1016/j.cej.2021.132741
24. Vali PS, Murali G. Experimental study on thermal management of nano-enhanced phase change material integrated battery pack. ASME J Heat Mass Transf. 2024; 1-20. https://doi.org/10.1115/1.4064155
25. Vali MP, Govindarajan M, Chinnasamy S. Comparison study on cooling management of composite phase change material battery pack: Two different cases. Therm Sci. 2023; 218. https://doi.org/10.2298/TSCI220816218V
26. Lin C, Xu S, Chang G, Liu J. Experiment and simulation of a LiFePO4 battery pack with a passive thermal management system using composite phase change material and graphite sheets. J Power Sources. 2015; 275:742-9. https://doi.org/10.1016/j.jpowsour.2014.11.068
27. Mousavi S, Siavashi M, Heyhat MM. Numerical melting performance analysis of a cylindrical thermal energy storage unit using nano-enhanced PCM and multiple horizontal fins. Numer Heat Transf Part A Appl. 2019; 75(8):560-77. https://doi.org/10.1080/10407782.2019.1606634
28. Javani N, Dincer I, Naterer GF, Rohrauer GL. Modeling of passive thermal management for electric vehicle battery packs with PCM between cells. Appl Therm Eng. 2014; 73(1):307-16. https://doi.org/10.1016/j.applthermaleng.2014.07.037
29. Park S, Jang DS, Lee D, Hong SH, Kim Y. Simulation on cooling performance characteristics of a refrigerant-cooled active thermal management system for lithium ion batteries. Int J Heat Mass Transf. 2019; 135:131-41. https://doi.org/10.1016/j.ijheatmasstransfer.2019.01.109
30. Zhang S, Zhao R, Liu J, Gu J. Investigation on a hydrogel-based passive thermal management system for lithium ion batteries. Energy. 2014; 68:854-61. https://doi.org/10.1016/j.energy.2014.03.012
31. Wang Z, Zhang H, Xia X. Experimental investigation on the thermal behavior of cylindrical battery with composite paraffin and fin structure. Int J Heat Mass

Transf. 2017; 109:958-70. https://doi.org/10.1016/j.ijheatmasstransfer.2017.02.057

32. Yang X, Wei P, Cui X, Jin L, He YL. Thermal response of annuli filled with metal foam for thermal energy storage: An experimental study. Appl Energy. 2019; 250:1457-67.
33. Yang X, Yu J, Guo Z, Jin L, He YL. Role of porous metal foam on the heat transfer enhancement for a thermal energy storage tube. *Appl Energy*. 2019; 239:142-56. https://doi.org/10.1016/j.apenergy.2019.01.075
34. Joshy N, Hajiyan M, Siddique AR, Tasnim S, Simha H, Mahmud S. Experimental investigation of the effect of vibration on phase change material (PCM)-based battery thermal management system. *J Power Sources*. 2020; 450:227717. https://doi.org/10.1016/j.jpowsour.2020.227717
35. Al Hallaj S, Selman JR. A novel thermal management system for electric vehicle batteries using phase-change material. *J Electrochem Soc*. 2000; 147(9):3231. https://doi.org/10.1149/1.1393888
36. Wang Z, Li X, Zhang G, Lv Y, Wang C, He F, Yang C, Yang C. Thermal management investigation for lithium-ion battery module with different phase change materials. *RSC Adv*. 2017; 7(68):42909-18. https://doi.org/10.1039/C7RA08181B