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Design and simulation of thermal management system for lithium-ion batteries of hybrid and electric vehicles

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ABSTRACT

The growing demand for electric and hybrid electric vehicles (EVs and HEVs) has intensified research into improving lithium-ion (Li-ion) battery performance, particularly in thermal management. Li-ion batteries exhibit high energy density and efficiency but are susceptible to thermal issues, which can lead to reduced performance, safety risks, and shorter lifespans. Effective thermal management is essential to maintain optimal operating temperatures, preventing thermal runaway, and enhancing battery longevity. This study investigates the design and simulation of various cooling strategies for Li-ion battery packs used in EVs and HEVs, comparing single cooling systems with integrated solutions. A comprehensive thermal management system is developed, incorporating forced-air cooling and phase change materials (PCMs) to assess their effectiveness in mitigating temperature rise and thermal gradients within battery packs. Simulations and experimental analyses are conducted to evaluate temperature distribution, cooling efficiency, and the impact of harsh driving conditions on battery performance. The results demonstrate that a hybrid cooling approach, combining forced-air convection and PCM, significantly reduces maximum battery temperature and enhances uniform heat dissipation. The study's findings contribute to the development of more efficient battery thermal management systems, addressing safety concerns while enhancing heat dissipation and temperature regulation. These insights are valuable for advancing next-generation electric vehicle technology, optimizing energy storage solutions, and promoting the sustainable adoption of electrified transportation.

Keywords: Lithium-Ion Batteries, Thermal Management, Electric Vehicles, Phase Change Materials, Battery Cooling Systems.

1. Introduction

Development of internal combustion engines and the automotive industry following it account for the modernization of today's societies. According to statistics, there were about 1,500 million passenger cars on the road in 2018, with electric and hybrid electric vehicles comprising one percent of it [1]. Exceeding rates of air pollution, global warming, and intricate issues of oil and gas

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industry in politics are just some examples that underscore the critical need for cleaning alternatives[2]. Therefore, both strict environmental regulations and the finitude of fossil fuels motivate the automotive industry to step into electric and hybrid electric vehicles. Batteries are one of the most remarkable features of electric and hybrid electric vehicles and have been in the spotlight as energy storage systems besides fuel cells. lithium-ion batteries have attracted attention mostly due to their high energy density and efficient lifetime. However, these batteries are more prone to safety problems, one of which is linked to thermal issues. The performance of the battery unit and subsequently the powertrain is strictly linked to how the heat of batteries is managed since temperature rise in each battery cell results in weak performance, reduction in capacity and lifetime, harsh conditions, and explosions[3].

1.1. Electric and Hybrid Electric Vehicles

The basis of the electrification of vehicles (or applying electricity to the powertrain system) is to lessen the role of combustion engines for reasons such as reduction in fuel consumption and air pollution, and in some cases, noise pollution. Hybrid and electric vehicles differ in the level of electrification of the powertrain system[4],[5].

The share of total battery and plug-in electric vehicle sales in 2018 was about 1.6 million, with a growth rate of more than 90 percent in comparison to 2012. According to the Bloomberg BNF forecast, there will be a rise from 1.1 million EVs in 2018 to 11 million in 2025, with China as the major contributor. Along the same line, the battery demand market will increase since many have shown interest in lithium-ion batteries[6]. Figure 1 illustrates the annual global light-duty vehicle sales by type from 2015 to 2040, showing a clear transition from internal combustion engine (ICE) vehicles (blue) to electric vehicles (EVs) (purple). EV sales start at just 1% in 2015 but steadily increase to 8% by 2025, 24% by 2030, 43% by 2035, and surpass 54% by 2040, as represented by the yellow trend line. Meanwhile, ICE vehicle sales decline over time, despite total vehicle sales remaining relatively stable. By 2040, EVs are projected to outsell ICE vehicles, marking a significant shift in the automotive industry toward electrification. This trend highlights the increasing adoption of EVs driven by technological advancements, regulatory policies, and consumer demand for sustainable transportation.

Today's automotive industry suggests a wide range of choices for electric and hybrid vehicle customers. The list of current popular electric cars and their batteries' specifications is briefed in Table 1.

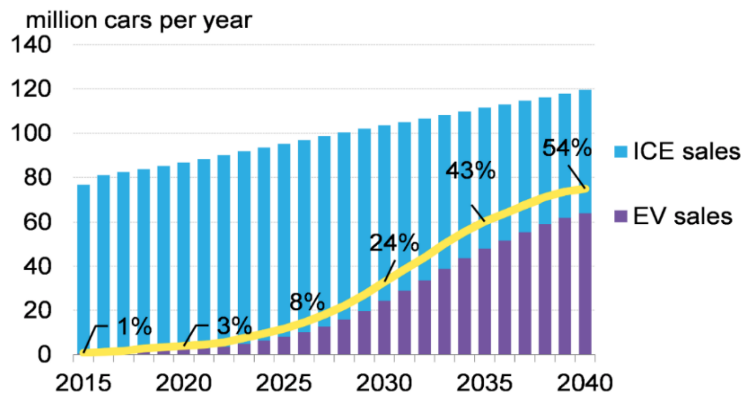

Fig. 1. Annual global light-duty vehicle sales over time[7]

Table 1. Electric Vehicle Battery Technologies[8],[9]

Country	Company	Vehicle Model	Battery
USA	GM	Chevy-Volt	288 Li-ion cells
		Saturn Vue Hybrid	NiMH
	Ford	Escape, Fusion, MKZ HEV	NiMH
		Escape PHEV	Li-ion
	Chrysler	Chrysler 200C EV	Li-ion
	Tesla	Roadster(2009)	Li-ion
Japan	Toyota	Pirus, Lexus	NiMH
	Honda	Civic, Insight	NiMH
	Mitsubishi	iMiEV(2010)	Li-ion
	Nissan	Altima	NiMH
		Leaf EV(2010)	NiMH
South Korea	Hyundai	Sonata	Lithium polymer
Germany	BMW	X6	NiMH
		Mini E(2012)	Li-ion
	Daimler Benz	ML450,S400	NiMH
China	BYD	E6	Li-ion
Norway	Think	Think EV	Li-ion, Sodium/Metal Chloride

1.2. Lithium-ion Batteries

The rapid market growth of electric and hybrid vehicles has drawn industry's attention to rechargeable batteries suited for high-power applications. These advancements not only improve the performance and efficiency of electric and hybrid vehicles but also play a crucial role in robotics, enabling autonomous robots, industrial automation, and mobile robotic platforms to achieve greater energy efficiency, extended operational time, and faster charging capabilities[10],[11]. Advanced battery technologies enhance the efficiency, endurance, and mobility of autonomous robots, industrial automation systems, and robotic platforms requiring high energy density and fast charging capabilities."[12],[13]. Lithium-ion batteries have proved

to be an apt option and can hold the future of electric and hybrid vehicles including lidar technology[14],[15],[16]. Their widespread adoption can be attributed to their high power density, efficiency, and long operational lifespan, making them a preferred choice for various energy storage applications[17].Integrating an energy storage system with renewable energy provides one possible solution to this key challenge. Battery Energy Storage Systems (BESS) play a critical role in balancing the variability of renewable energy sources, ensuring grid stability, and optimizing power supply reliability. This technology helps mitigate power fluctuations caused by intermittent renewable sources like solar and wind energy. Although these batteries are categorized as expensive, statistics show that their price is decreasing. For instance, according to the BNEF report in 2017, with a drop of 73 % since 2010, the price of lithium-ion batteries in 2016 was 273 \$/kWh[18].

Lithium-ion (Li-ion) batteries operate through the exchange of lithium ions between negative and positive electrodes. The ions are intercalated (inserted between layers) in positive electrodes, which have layered or tunneled structures such as lithium cobalt oxide ($LiCoO_2$) and lithium manganese oxide ($LiMn_2O_4$- and negative electrodes with a layered structure like graphite carbon. Current collectors are respectively comprised of aluminum foil and copper[19], [20]. Understanding the fatigue performance of structural materials, like is crucial for battery enclosures in electric vehicles. Recent studies highlight how manufacturing methods impact fatigue resistance, offering insights for improving battery casings[21].

Some principal specifications define and describe a battery's performance characteristics. Some of these terms are summarized in Table 2.

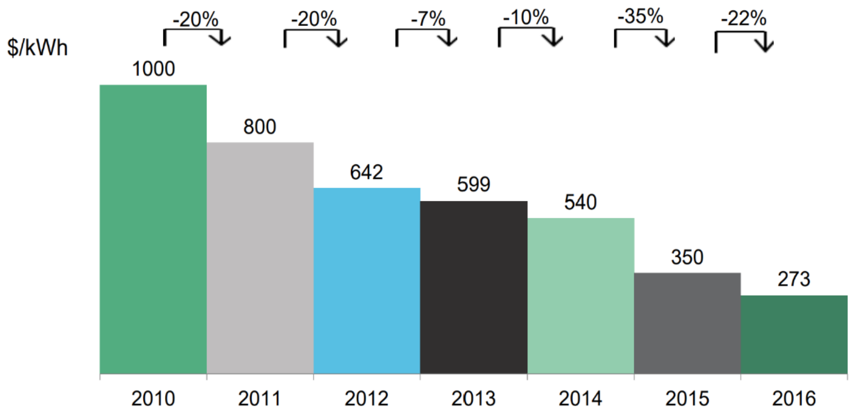

Fig. 2. Lithium-ion batteries price survey 2010-2016($/kWh)

Table 2. Battery specification

Term	Definition
C-rate	The rate at which the battery is discharged relative to its capacity
State of charge	The ratio of the available capacity of the battery to its maximum capacity
Cut-off voltage	Minimum allowable voltage
Cycle life	Total number of discharge cycles before failure
Specific energy($Whkg^{-1}$)	Nominal battery energy per unit mass
Energy density(WL^{-1})	Nominal battery energy per unit volume

Lithium-ion batteries, especially those used in electric and hybrid vehicles, rely on the exchange of lithium cations between the two electrodes [22]. This type of battery has a high charge and discharge density; thereby it can provide more energy than battery types with the same weight. The cells are manufactured in various designs mainly including cylindrical, pouch, and prismatic.

Lithium-ion batteries are also categorized based on their chemistry and are named after the type of active material. Recent advancements in lithium battery chemistries, particularly in Nickel Cobalt Aluminum (NCA) and Lithium Nickel Manganese Cobalt (NMC) batteries, have shown significant improvements in energy density, longevity, and safety. However, these batteries still face degradation challenges, including loss of active anode and cathode material, which accounts for nearly 50% of total capacity fading over a battery's lifespan[23]. For example, NCA relates to lithium nickel cobalt aluminum oxide battery[24]. Figure 3 highlights the trade-offs among different lithium-ion battery chemistries based on key performance metrics. LCO and NCA offer high specific energy, making them suitable for portable electronics and EVs, but they compromise on safety and lifespan, whereas LFP and LTO prioritize safety and lifespan at the cost of lower specific energy. LMO and LTO provide high specific power, enabling rapid energy delivery for applications like power tools and hybrid vehicles, while NCA and LFP balance power output and cost-effectiveness. In terms of durability, LTO and LFP have longer lifespans, making them ideal for applications requiring longevity, whereas LCO and NMC degrade faster but deliver better overall performance. Cost-wise, LCO and NCA are more expensive due to cobalt content, while LFP and LMO offer a more affordable alternative, commonly used in budget-friendly EVs and stationary storage. Understanding these trade-offs is crucial in selecting the right battery for specific applications.

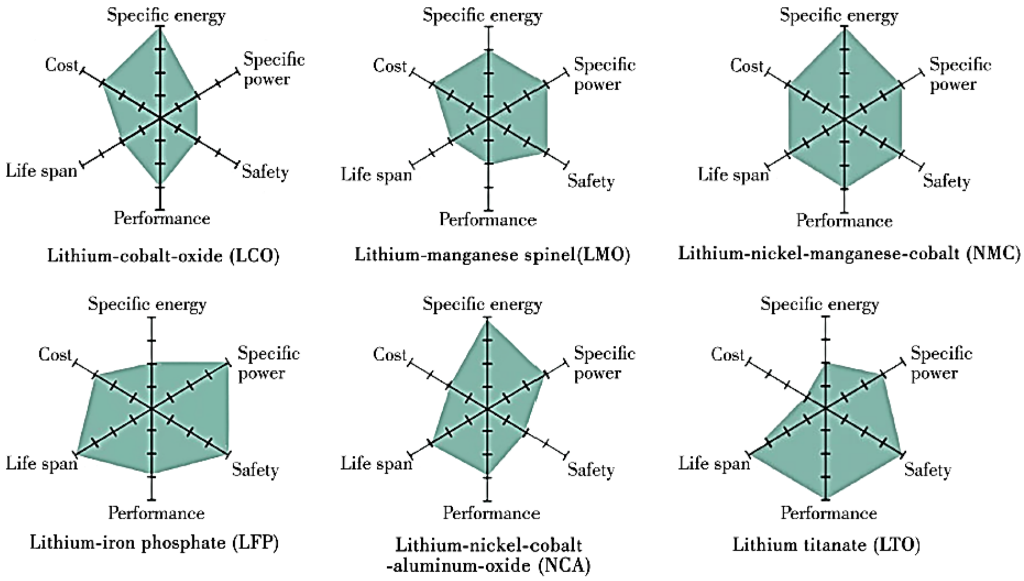

Fig. 3. Lithium-ion battery types and their characteristics comparison[25]

The batteries' commercial name includes a designation number indicating the cell's physical dimensions, which also determines the range of capacity. For instance, an 18650 cell has a capacity within the range of 1500 mAh to 3500 mAh, and has a proximate diameter of 18 mm and 65 mm.

There are several reasons lithium-ion batteries are a preferable energy source for EVs and HEVs are compared to other types of batteries, especially Ni-metal-hybrid batteries. Nickel-metal hydride batteries are one of the options for power sources, especially in EV and hybrid applications. However, the introduction of lithium-ion batteries with lower self-discharge and higher density was a turning point for the market. A nickel-metal hydride battery can provide a maximum voltage of 1.2V, while this magnitude reaches 3.6V for a lithium-ion battery. Three nickel-metal hydride batteries can be substituted by only one lithium-ion battery, and the fewer the number of batteries, the safer the automobile will be[26]. The supremacy of lithium-ion batteries in energy density is depicted in Fig. 4. Compared to lead-acid or nickel-metal hydride groups, lithium-ion batteries have longer cycle life and greater efficiency.

A summary of the pros and cons of lithium-ion batteries compared to other types is presented in Table 3.

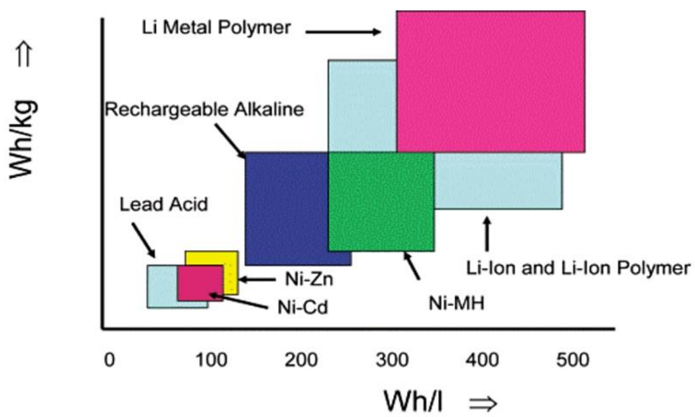

Fig. 4. Energy density and specific energy comparison between battery types

Table 3. Lithium-ion Batteries: Pros and Cons[26]

Advantages	Disadvantages
High energy efficiency	More expensive
High specific energy and energy density	Degrade at high temperature
Long cycle life	Need for protective circuitry
Rapid charge capability	Over-charge limits and capacity fade
High operating rate capability	Venting and thermal runaway when crushed
Broad operating temperature range	Energy density more than one order of magnitude lower than that of fuels such as gasoline
Low self-discharge	Limited range or expensive and bulky battery packs
No memory effects	

It is noteworthy that according to the “Towards the Battery of the Future" report, published by the European Commission, lithium-ion batteries cannot be landfilled due to flammability and toxicity, nor can they be incinerated, as the ashes are also toxic. While almost 100% of lead acid is being recycled, a solution should be discovered for the disposal of lithium-ion batteries [17]. Future research directions include integrating multiple imaging modalities to enhance performance and developing methods to estimate prediction uncertainty, enabling more informed decision-making[27].

1.3. Thermal Issues in Li-ion Batteries

For high-power applications, managing heat dissipation becomes more critical due to the increase in specific heat. The weak design of the battery pack results in the formation of hot spots on the battery surface. Besides, the performance parameters, including cycle life, discharge capacity, and voltage platforms, are also affected by the operating temperature.

Overheating accelerates the battery degradation process [28]. In addition to the high rate of oxidation and reduction in Li-ion batteries, safety mechanisms also play an important Role in heat dissipation [29]. Managing the heat of a battery pack can cost a lot, but it reduces the damage caused by overheating. Since the cells that are available in the market are not designed optimized size, designing an efficient thermal management system becomes significant [30]. High operating temperature and uneven heat distribution will affect the battery life cycle and may lead to more serious damage, like thermal runaway [31]. Numerous cells packed next to each other for power usage, like EVs, will also add for better management [32].

1.4. Phase Change Materials

Phase change materials are one of the suitable choices in thermal storage and management applications[33], [15],[34]. They are widely used in renewable energy applications[35].The theory of using phase change material for thermal storage is based on their high heat of fusion in comparison to their specific heat. In other words, the temperature varies significantly during the process of phase change. There are some factors involving the application that affect PCM selection. Information regarding phase transition and solid/liquid phases' thermophysical properties is considered a criterion for selection [36]. The application temperature range is also another notable element. Therefore, important factors in choosing phase change material include latent heat, phase change temperature, and being non-explosive.

PCMs are placed in two organic and inorganic categories according to their chemical constituents [37]. Organic PCMs are preferable in thermal management applications due to their congruent melting, no phase separation problems, and no corrosiveness [38]. The issue with PCMs is that their thermal conductivity is mostly around 0.17 to 0.35 Wm-1K-1, which leads to negligible heat conduction [39]. Studies on grid-connected battery energy storage systems (BESS) suggest that improving thermal conductivity in PCMs is crucial for ensuring battery efficiency and safety [40]. However, in some studies, this issue is resolved by adding elements such as carbon-fiber chips, aluminum powder, or nanomaterials, using porous materials like graphene, metal foam, or its combination of metal spheres and _ns can help increase thermal conductivity [41]. Zhu et al. [42] studied the performance of a matrix block of micro-fibrous media and phase change material (MFM-PCM) in heat transfer improvement of the pack of heavy-duty LFP-based Li-ion batteries with active cooling tubes so that cells can be operated at their maximum rates in harsh conditions (60°C ambient temperature)[43].

1.5. Outline

In this project, we discussed the process of developing a cooling system for lithium-ion battery packs used in electric and hybrid vehicles, based on harsh driving conditions. This work will use an electric passenger car (class B) as an example. The comparative study is conducted in a simulation to evaluate the improvements in the cooling system. After that, prototypes that mimic the simulation in the standard US06 cycle are built and subjected to experiments in a laboratory. Finally, the results of experiments are compared to the simulation outcomes for validation.

2. Methodology

This study employs a combination of numerical simulation and experimental validation to evaluate the effectiveness of different thermal management systems (TMS) for lithium-ion (Li-ion) battery packs in electric and hybrid vehicles. The methodology consists of three main components: (1) Battery Modeling and Heat Generation Analysis, (2) Thermal Management System Design, and (3) Experimental Testing and Validation.

2.1. Battery Modeling and Heat Generation Analysis

A thermal-electrochemical model of the Li-ion battery pack was developed using COMSOL Multiphysics, incorporating heat generation mechanisms, thermal conduction, convection, and radiation models. The governing equations were derived from heat transfer principles and electrochemical reaction models.

2.1.1. Heat Generation Model

The Li-ion battery's total heat generation (Qtotal) results from ohmic heating (Joule heating), reaction heat, and polarization losses. The general heat generation equation is given as:

$$Q_{total} = Q_{ohm} + Q_{reaction} + Q_{polarization} \quad (1)$$

where:

- Q_{ohm} is the ohmic heating due to internal resistance, given by:

$$Q_{ohm} = I^2 R_{int} \quad (2)$$

where I is the current and R_{int} is the cell's internal resistance.

- $Q_{reaction}$ represents the entropy change and heat generation from the electrochemical reaction:

$$Qreaction = -IT\frac{dE}{dT} \quad (3)$$

where T is the temperature, and $\frac{dE}{dT}$ It is the temperature dependence of the open circuit voltage.

- $Q_{polarization}$ accounts for heat due to activation and concentration overpotential losses:

$$Q_{polarization} = I(\eta_{act} + \eta_{conc}) \quad (4)$$

where η_{act} and η_{conc} are the activation and concentration overpotentials, respectively.

The heat generation rate per unit volume is given by:

$$\dot{q} = \frac{Qtotal}{Vcell} \quad (5)$$

where V_{cell} is the volume of the battery cell.

2.1.2. Heat Transfer Model

The thermal energy balance equation governing heat conduction in the battery pack is given by:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q} \quad (6)$$

where:

- ρ is the density of the battery material,
- Cp is the specific heat capacity,
- k is the thermal conductivity,
- ∇ is the gradient operator,
- $\dot{q}$ is the heat generation rate per unit volume.

Boundary conditions applied include convective heat transfer at the battery surface, described by Newton's law of cooling:

$$q_{conv} = h\left(T - T_{amb}\right) \quad (7)$$

where:

- h is the convective heat transfer coefficient,
- Tamb is the ambient temperature.

Radiative heat transfer is included using the Stefan-Boltzmann law:

$$q_{rad} = \varepsilon\sigma\left(T^4 - T_{amb}{}^4\right) \quad (8)$$

where:

- ε is the emissive,
- σ is the Stefan-Boltzmann constant.

2.2. Thermal Management System Design

To mitigate excessive heat accumulation, three different cooling strategies were simulated and analyzed:

2.2.1. Forced-Air Cooling System

A forced-air cooling system was modeled by incorporating turbulent airflow across the battery pack. The Navier-Stokes equations describe airflow behavior:

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla_p + \mu\nabla^2 u + F \quad (9)$$

where:

- u is the velocity vector,
- p is the pressure,
- μ is the dynamic viscosity,
- F is the external force term.

The heat dissipation due to forced convection is expressed as:

$$Q_{forced-air} = h_{air} A_{surface}\left(T_{battery} - T_{air}\right) \quad (10)$$

where h_{air} is the convective heat transfer coefficient for air.

2.2.2. Phase Change Material (PCM) Cooling System

A PCM-based thermal management system was integrated into the battery pack, relying on latent heat absorption during phase transition. The enthalpy formulation governs PCM behavior:

$$\rho pcm C_{p,PCM} \frac{\partial T}{\partial t} + \rho pcm L \frac{\partial f}{\partial t} = \nabla \cdot (k_{PCM} \nabla T) \quad (11)$$

where:

- L is the latent heat of fusion,
- f is the liquid fraction of the PCM.

2.2.3. Hybrid Cooling System (Air + PCM)

A combined air and PCM cooling approach was simulated to enhance heat dissipation. This system benefits from both convective heat transfer and latent heat storage.

2.3. Experimental Testing and Validation

To validate the accuracy of the numerical simulations, an experimental prototype of the Li-ion battery pack was constructed and tested under controlled conditions. A 4P3S battery module was assembled using commercially available cylindrical Li-ion cells, like those used in the simulation model. Temperature sensors (thermocouples) were strategically positioned at multiple points within the battery pack to monitor real-time temperature variations during discharge cycles. The prototype was subjected to a simulated US06 driving cycle, which mimics aggressive driving conditions with high discharge rates, replicating real-world thermal stress on the battery system. The cooling systems, including forced-air cooling, PCM-based cooling, and a hybrid air-PCM cooling system, were applied separately, and their effects on battery temperature were recorded. The experimental setup was designed to closely match the boundary conditions and input parameters of the simulation model to ensure reliable comparisons.

The performance of the different cooling methods was assessed based on key thermal management metrics, including maximum temperature reduction, temperature uniformity, and cooling efficiency. Experimental results were compared with simulation data to evaluate the model's predictive accuracy. Any deviations between simulated and experimental results were analyzed to identify potential sources of error, such as material property assumptions, sensor placement effects, or environmental variations. The findings confirmed that the hybrid cooling system (air + PCM) provided the most effective thermal regulation, achieving significant temperature reduction and uniform heat dissipation across the battery pack. This validation process demonstrated the feasibility of integrating advanced cooling strategies to enhance the thermal stability and performance of Li-ion batteries in electric and hybrid vehicle applications.

3. Results

In this study, four different cases were analyzed to evaluate the effectiveness of various cooling strategies for lithium-ion battery packs under harsh operating conditions. Case I represents the scenario without any cooling system, Case II involves a forced-air cooling system, Case III implements phase change material (PCM) cooling, and Case IV combines PCM with forced-air cooling. The results of these cases are discussed below to compare their impact on temperature control and thermal uniformity.

Case I: Temperature Distribution of the Model Without Cooling System

In Case I, the battery pack was analyzed without any cooling system under a harsh driving cycle. The results showed a significant temperature rise, with the maximum temperature reaching 90.6°C at 2136 seconds. The domain and boundaries of the model without a cooling system are shown in Fig. 5.

Additionally, the temperature gradient within the pack was 19°C, indicating severe thermal non-uniformity. The highest temperature was observed at the center of the pack due to limited heat dissipation. As the battery continued discharging at increasing C-rates, the internal heat generation intensified, surpassing safe operating limits. These findings highlight the necessity of an effective cooling system to prevent excessive thermal buildup and ensure battery longevity. Figure 6 also presents the temperature distribution at the end of a cycle. It was found that the battery in the center of the pack (one in the front-left corner of the model) experiences the maximum temperature.

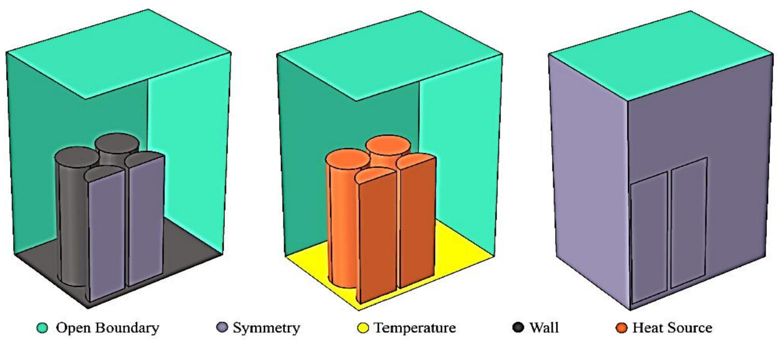

Fig. 5. Domain and boundaries of the model without a cooling system

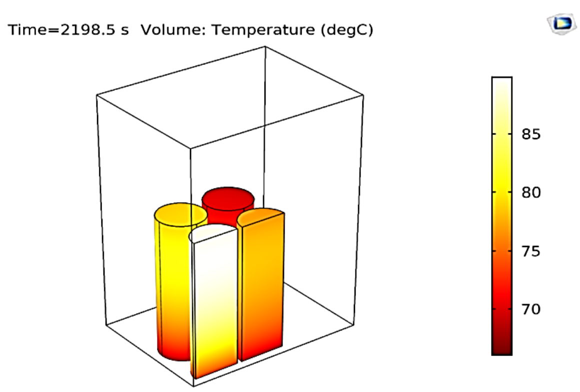

Fig. 6. Temperature distribution in a battery pack without cooling, highlighting thermal accumulation risks

Case II: Temperature Distribution of the Model with Fan Cooling System

Temperature Distribution of the Model with Fan Cooling System: The first method of cooling applied to the model is removing heat using forced air created by a fan. In this model, the air is blown to the pack with a constant velocity of 0:5 m/Temperature Distribution of the Model with a Fan Cooling System.

Figure 7 depicts how the heat generation and temperature of the three selected sensors change over time. Temperature distribution at t = 2236:2 s is also presented in Fig. 8. According to simulation results, the maximum temperature of 63.7 °C happens at t = 2071s, which shows a 29.7% decrease compared to the model without cooling. However, the temperature difference between the coolest and hottest spots on the surface of the battery in this model is considerable and has a maximum of 24.0 °C, and obviously, between batteries at the top of the first row and the bottom of the last row.

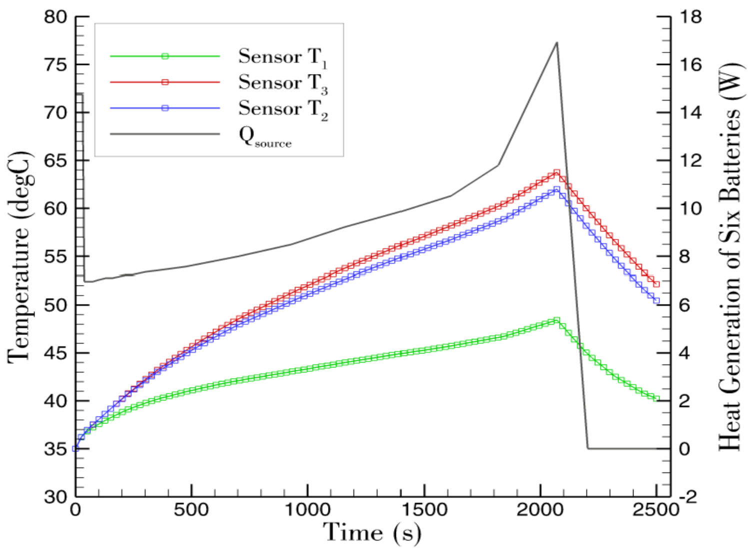

Fig. 7. Temperature of three sensors and total heat generation(model with fan cooling system)

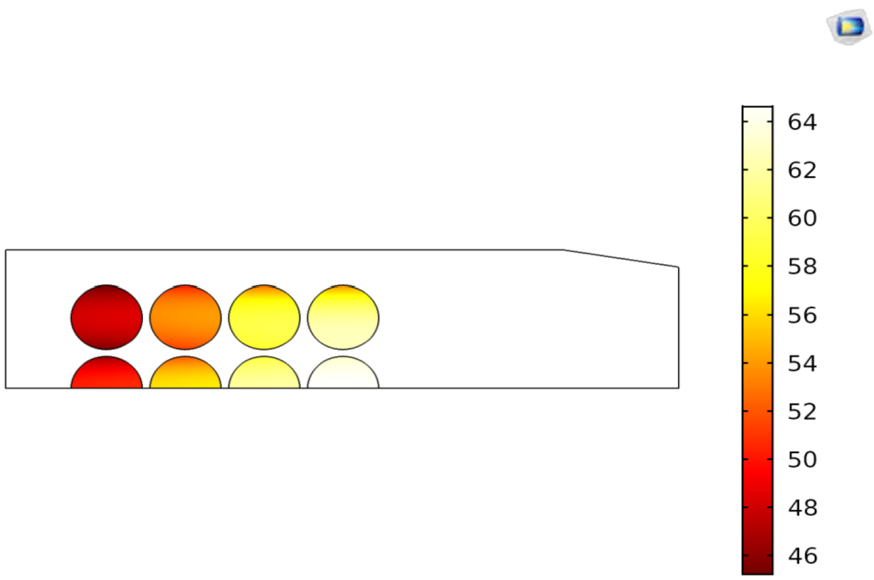

Fig. 8. Temperature distribution in Batteries at t=2071s(model with fan cooling system)

Case III: Temperature Distribution of the Model with PCM Cooling System

In Case III, the thermal performance of the battery pack was analyzed using a phase change material (PCM) cooling system. The PCM, n-docosane, was incorporated around the battery cells to absorb excess heat during operation. The simulation results showed that the temperature distribution was more uniform compared to previous cases, with PCM effectively delaying the temperature rise. The maximum battery temperature reached 68.1°C, lower than in the cases without cooling, but the cooling effect diminished over time. By 1665 seconds, the PCM had fully melted, reducing its ability to absorb additional heat. Despite providing better thermal uniformity, PCM cooling alone was not sufficient for sustained temperature regulation under harsh operating conditions. As shown in Fig. 9, PCM on the inner side starts to melt at t = 400s where the surface maximum temperature is 44°C. N-decosane is not a proper choice for cooling methods depending solely on latent heat.

Case IV: Temperature Distribution of the Model with and PCM Cooling System

In Case IV, a hybrid cooling system combining phase change material (PCM) and forced-air cooling was implemented to enhance thermal management. The simulation results demonstrated that this combined approach significantly improved both temperature reduction and uniformity compared to previous cases. The maximum battery temperature dropped to 54.86°C, marking the lowest peak among all cases, while the temperature gradient was reduced to 14.82°C, ensuring a more balanced heat distribution. The forced airflow helped maintain the cooling efficiency of PCM by preventing premature saturation and extending its effectiveness over time. This hybrid system proved to be the most effective solution, offering enhanced heat dissipation, prolonged cooling capacity, and improved battery safety under harsh driving conditions. Figure 10 presents the temperature distribution at t = 2165s. It can be found from the simulation that a maximum temperature of 54:86◦C happens at t =2167s, which shows 39.45%, 13.88%, and 19.44% decrease compared to the model without cooling, the one with fan, and the system with PCM, respectively. Table 4 presents a comparison of maximum temperature and temperature gradient for different cooling cases based on COMSOL simulation results. Case IV (PCM & forced-air cooling) achieved the best thermal management performance, reducing the maximum temperature to 54.86°C (a 39.45% improvement) and maintaining a temperature gradient of 14.82°C. In contrast, Case II (forced-air cooling) significantly lowered the maximum temperature to 63.7°C, but it also increased the temperature gradient to 24.0°C, highlighting the limitations of airflow-only cooling.

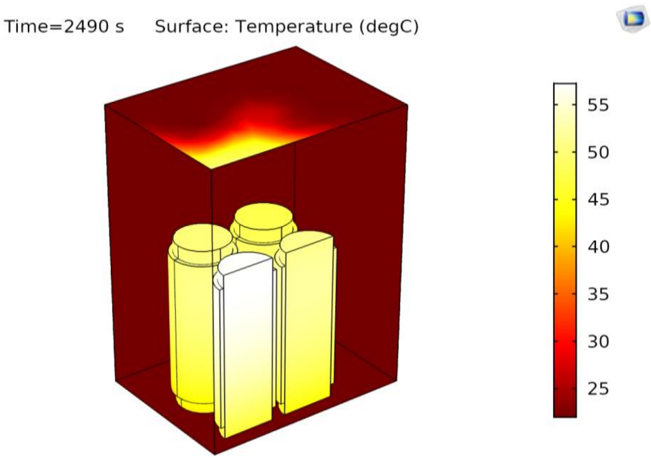

Fig. 9. Temperature distribution in batteries-model with PCM cooling system

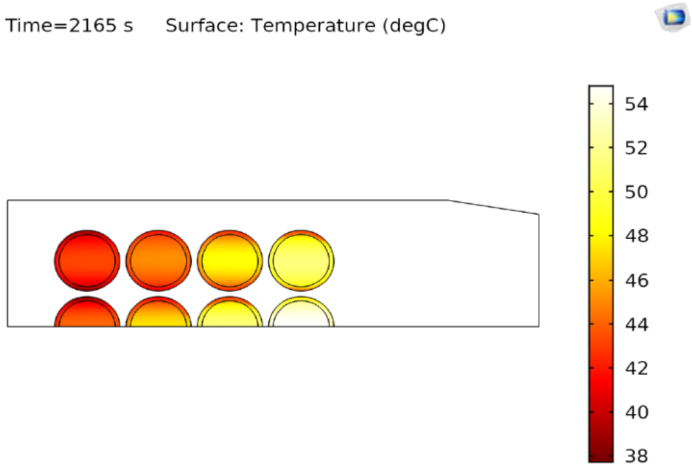

Fig. 10. Temperature distribution in batteries with PCM and fan

Table 4. Comparison of maximum temperature and temperature gradient in cases based on COMSOL simulation

Case	Maximum temperature (°C)	% Reduction	Temperature Gradient(°C)	%Reduction
I: No TMS	90.6	-	19.0	-
II: Forced air	63.7	29.69%	24.0	Increased by 17.24%
III: PCM	68.1	24.83%	12.0	36.84%
IV: PCM & Forced air	54.86	39.45%	14.82	22%

4. Conclusion

The simulation results in this study reveal that a battery pack consisting of 12 batteries with a capacity of 3350mAh exceeds thermal safety limits, necessitating effective cooling solutions. Three cooling methods were evaluated, focusing on temperature gradient and maximum temperature within the pack. The PCM cooling system promotes uniform heat dissipation but has a moderate effect on reducing peak temperatures, while forced-air cooling significantly enhances heat removal but increases temperature gradients and requires more space. A hybrid approach integrating both methods provides a more efficient and balanced cooling solution.

Further validation showed that simulation results aligned well with experimental outcomes, though some discrepancies were observed due to model simplifications and assumptions. These include differences in heat generation modeling, the exclusion of the relationship between temperature and internal resistance, and variations in the heat transfer coefficient for free convection in real-world conditions. Additionally, in the fan-cooled system, the 2D model used in simulations led to faster temperature variations than in actual experiments, causing deviations. Another source of inconsistency was the PCM used in tests, which differed slightly from n-octadecane, as it was a blend of materials from various sources with varying thermal properties. Despite these limitations, the findings provide valuable insights into optimizing battery thermal management systems.

5. Future work

This study opens numerous opportunities for future research. Different battery arrangements can be explored, as their configuration significantly impacts heat dissipation. Additionally, further investigation into the use of phase change materials (PCMs) as a cooling system is warranted, particularly in addressing their low thermal conductivity. Future studies could replicate this research with the inclusion of high thermally conductive materials to enhance cooling efficiency. Moreover, the design optimization of PCM and fan channels remains an open area for exploration, offering potential improvements in thermal management systems.

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