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Promotion of practical technology of the thermal management system for cylindrical power battery

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Abstract
Amidst the industrial transformation and upgrade, the new energy vehicle industry is at a crucial juncture. Power batteries, a vital component of new energy vehicles, are currently at the forefront of industry competition with a focus on technological innovation and performance enhancement. The operational temperature of a battery significantly impacts its efficiency, making the design of a reliable Thermal Management System (TMS) essential to ensure battery safety and stability. Cylindrical power batteries are widely utilized in the industry. This article outlines the four main structures and their drawbacks of TMS for cylindrical power batteries. Among these structures, air cooling falls short in meeting high heat dissipation requirements. Liquid cooling is expensive, intricate, and adds considerable weight. Phase Change Materials (PCM) are not yet prevalent in practical applications. Similarly, heat pipes are relatively uncommon in large high-power battery packs. To better align with the new energy vehicle industry's demands for top-notch performance, cost-effectiveness, eco-friendliness, and reliability, this paper strongly recommends delving deeper into composite cooling solutions. The construction of an economically viable and fully optimized composite cooling method is poised to become a significant scientific challenge for future research endeavors.

Keywords Cylindrical, Power battery, Thermal management, Active cooling, Passive cooling, Composite cooling, Optimization

Introduction

Given global climate change and growing demand for energy, environmental pollution and energy shortage have become pressing issues (Wang 2022). Statistics show that more than 80% of the world's energy consumption is derived from non-renewable sources, specifically fossil fuels. The growth of the automotive sector has led to internal combustion engine vehicles utilizing energy and releasing significant levels of carbon dioxide, contributing to the production of greenhouse gases and worsening the issue of global warming (Xu et al. 2023). The advancement of renewable batteries as alternative energy sources addresses the requirements for energy preservation, environmental sustainability, and economic progress.

In the electric and hybrid vehicle market, managing Thermal Management Systems (TMS) for power batteries is crucial. The operation of batteries produces a substantial amount of heat, which can impact their performance. Enhancing heat dissipation is vital to ensure the stability of battery operation. While lithium-ion batteries (LiBs) and hydrogen fuel cells provide benefits such as high energy storage, capacity, and efficiency, the process of charging and discharging generates heat and electrochemical reactions. This can lead to a rise in operating temperature and potentially result in issues like internal diaphragm melting, internal short circuits, and uncontrolled heating (Qian et al. 2022). In recent years, the frequent occurrence of fires in electric vehicles and energy storage stations has seriously hindered the development of the battery industry. In addition, prolonged low-temperature operation can also affect battery performance, increase battery impedance, accelerate aging and capacity degradation (Qi et al. 2022). Research has shown that the optimal operating temperature range for this type of battery is between 25 ℃ and 40 ℃ (Pesaran 2002). Within this range, the battery has the best output performance and the weakest capacity degradation. Therefore, developing a reasonable heat dissipation management system is crucial for improving the stability and safety of battery packs, which helps drive the utilization of clean, green, and low-carbon energy resources.

In this paper, the focus will be on presenting the opportunities and obstacles associated with composite cooling TMS technology for cylindrical power batteries, which are extensively utilized in electric vehicles and energy storage systems because of their structural benefits. Through a comparison of the pros and cons of current active and passive cooling methods, as well as the cooling efficiencies of diverse composite BTMS technologies, the goal is to encourage the advancement of cutting-edge cooling technologies.

Practical model of BTMS

Active cooling I - based on air cooling model

The model based on the principle of air cooling is relatively simple. By establishing a ventilation system to blow the gaps between the battery surface or modules, effective heat dissipation can be achieved. This type of model possesses advantages such as cost-effectiveness and convenient maintenance. Currently, the research direction of BTMS based on air cooling is influenced by air flow channels, wind speed and battery packs assembly methods. A numerical simulation model was established to study the impact of airflow channels on the performance of air circulation systems (Wang et al. 2014). Changed the structure of the airflow channel by installing fans at different positions on the battery module. The research results show that the temp of the tested battery can be reduced. the uniformity of it can be improved by changing the air flow rate, the temp of the air entering the pipeline and the spacing rate between the batteries. Setting a fan above the battery module can achieve optimal heat dissipation. An air-cooled heat management system is designed and built, and a heat exchanger based on metal foam is used to ensure sufficient heat dissipation capacity to ensure adequate heat dissipation performance (Giuliano et al. 2012). The battery underwent charging and discharging cycles under two different air inlet flow rates. The experimental results show that when the

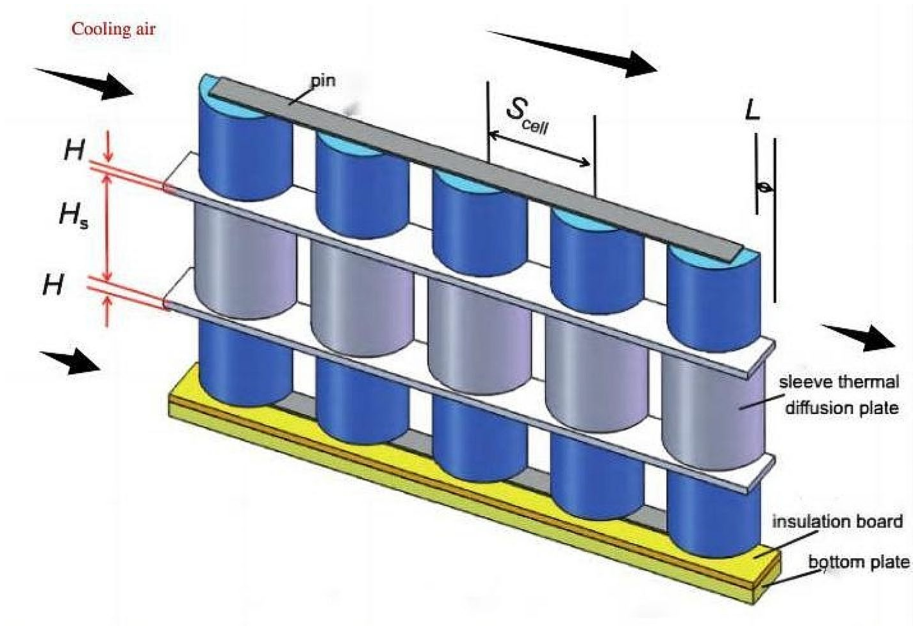

Fig. 1 Schematic diagram of the battery module structure

Table 1 The optimal configuration structural parameters of the thermal diffusion plate, $v_0 = 1.5$ m/s

Import wind speed			**$v_0 = 1.5$ m/s**		
The optimal configuration structural parameters of the thermal diffusion plate					
The thickness of the thermal diffusion plate H (mm)	The length of the thermal diffusion plate sleeve H_s (mm)	The length of the tail of the thermal diffusion plate L (mm)	The maximum temperature of the battery module T_{max} (℃)	The maximum temperature difference ΔT (℃)	The inlet and outlet pressure difference Δp (Pa)
0.5	10.5	24.7	33.09	2.89	81.79

inlet flow rate is 1100 mL / s, the current of the cooling air is 200 amperes, and the temp of system rise to be limited within 10 ℃ above the ambient temp.

Xu et al. (Xu et al. 2022) proposed a novel air-cooled battery model grounded in the structure of a sleeve thermal diffusion plate, as shown in Fig. 1, the battery module by orthogonal form, through the central composite experiment on the geometry parameters of the thermal diffusion plate optimization, the highest battery temperature, the maximal temp difference.

The optimization target is to focus on the drop of pressure at the inlet and outlet. The result show that the maximal temp and temp difference of the optimized battery module slipped by 16.12% (6.36 ℃) and 48.48% (2.72 ℃) respectively, compared with a group of without the thermal diffusion plate. Even though the increase of the thermal diffusion plate makes the overall system structure complex, the weight group efficiency is only reduced by 2.63%. The limitations of air cooling are evident. As shown in Table 1.

In their study, Yu et al. (Yu et al. 2014) developed a dual duct air cooling system that involves directing fluid into the battery pack from both sides using two fans (see Fig. 2). The fluid is guided through a plate and then distributed over the battery surface from the inlet and outlet ends, leading to enhanced temperature uniformity within the battery

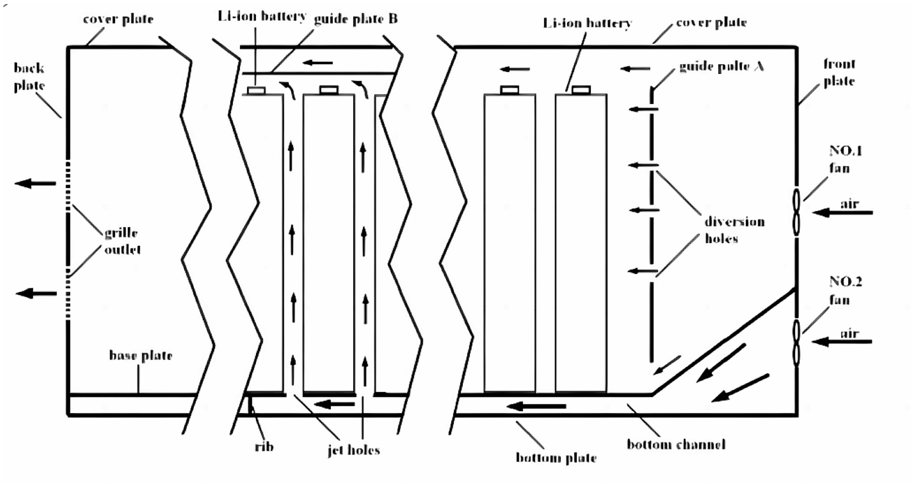

Fig. 2 Schematic diagram of dual channel air flow direction

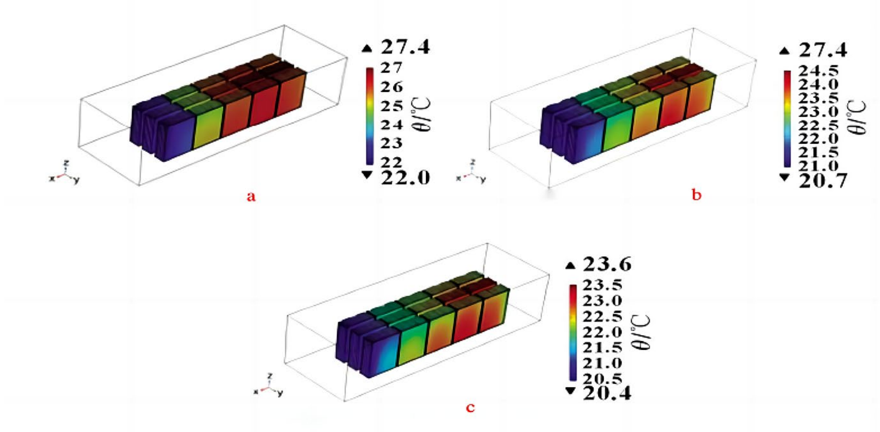

Fig. 3 The influence of wind speed on the temperature distribution of battery packs. **a** $v_0 = 1$ m/s; **b** $v_0 = 3$ m/s; **c** $v_0 = 5$ m/s; (θ:temperature)

pack. Experimental findings indicate that the system effectively maintains the temperature difference of a battery pack comprising 12 180 Ah batteries below 5 degrees.

In their research, Cai et al. (Cai et al. 2023) investigated thermal management strategies for lithium iron phosphate battery packs. They developed individual cell electrochemical and thermal coupling models, and conducted simulations to analyze heat generation and air cooling patterns within the battery packs. Through optimizing the arrangement, spacing, wind speed, and ambient temperature of the battery packs, they successfully reduced both the maximum temperature and temperature variation. Optimal air cooling heat dissipation was achieved under specific conditions: ambient temperature of 20 °C, wind speed of 5 m/s, sequential battery pack arrangement, and spacing of 32 mm in the Y direction and 4 mm in the X direction. With these parameters, they were able to control Tmax within 24 °C and keep T below 3.2 °C, as depicted in Fig. 3.

The overall layout TMS for battery-packs, compactness and maintainability of the heat dissipation system should be considered. The radiator in the system assembly is adopted for transferring the heat generated by the battery pack to the surrounding air. When choosing the radiator, its heat dissipation efficiency, surface area, material thermal conductivity and other factors. At the same time, the design of the radiator should meet the size, shape and layout requirements of different battery modules. In their study, Pan et al. (Pan et al. 2005) analyzed the flow and temperature field characteristics in air duct systems through a comparison and quantitative analysis. The researchers also examined the design variables related to nickel-hydrogen battery modules in electric vehicles. The research results show that specific air duct design, temperature distribution, and average temperature have a significant impact on the performance of the original battery module. During the research process, CFD software STAR-CD and ANSYS simulation methods were used, and the obtained analysis results were validated. The design of the guide is aimed at optimizing airflow guidance to ensure effective separation of hot and cold air. The layout of the heat sink and fan is carefully designed to maximize the airflow effect, thereby reducing battery temperature and avoiding heat circulation. In addition, the optimized design of the exhaust port also helps to improve the overall air circulation effect of the heat dissipation system, effectively avoiding the retention and circulation of hot air.

The basic principle of the air-cooled is to use a fan to blow air to the face of the cell, achieving the outward transfer of battery heat. Although the system has the merit of structure simply and low-cost, the air cooling efficiency is relatively limited when the cooling demand is high, making it difficult to meet the heat dissipation needs of the battery pack. In addition, the thermal conductivity of air cooling is relatively low, which can easily generate large temperature differences during the flow process, resulting in uneven temperature distribution of battery modules, which also limits the application of air cooling in certain situations.

Active cooling II - based on liquid cooling model

About BTMS in new energy vehicles, liquid cooling has become a mainstream technology. During high load operation, air cooling often cannot meet the demand, and the superior thermal conductivity, high heat capacity, and efficient heat dissipation capacity of liquids make them an ideal cooling method. In the TMS of liquid cooled batteries, the liquid will directly or indirectly come into contact with the battery for heat exchange, thereby accurately controlling the working temperature of the battery. The direct contact cooling method has a larger heat exchange area. Common heat transfer media include electronic grade fluorinated liquids, mineral oils, silicone oils, and nanofluids. These media not only have excellent electrical insulation performance, but also do not react with batteries and have a high flash point, ensuring the safety and reliability of the entire TMS. A set of insulated oil immersed cooling system has been successfully developed (Zhang et al. 2022). Research has found that compared to traditional air natural convection cooling methods, this new cooling system performs excellently in reducing the maximum temperature of the battery pack and improving the temperature uniformity of the battery pack. The capacity attenuation experiment of two 18,650 battery packs, namely air cooling and new immersion cooling system (Koster et al. 2023). As shown in Table 2.

Table 2 The capacity attenuation experiment of two 18,650 battery packs

Data	air cooling	liquid cooling
ΔT (℃)	15℃	1.5℃

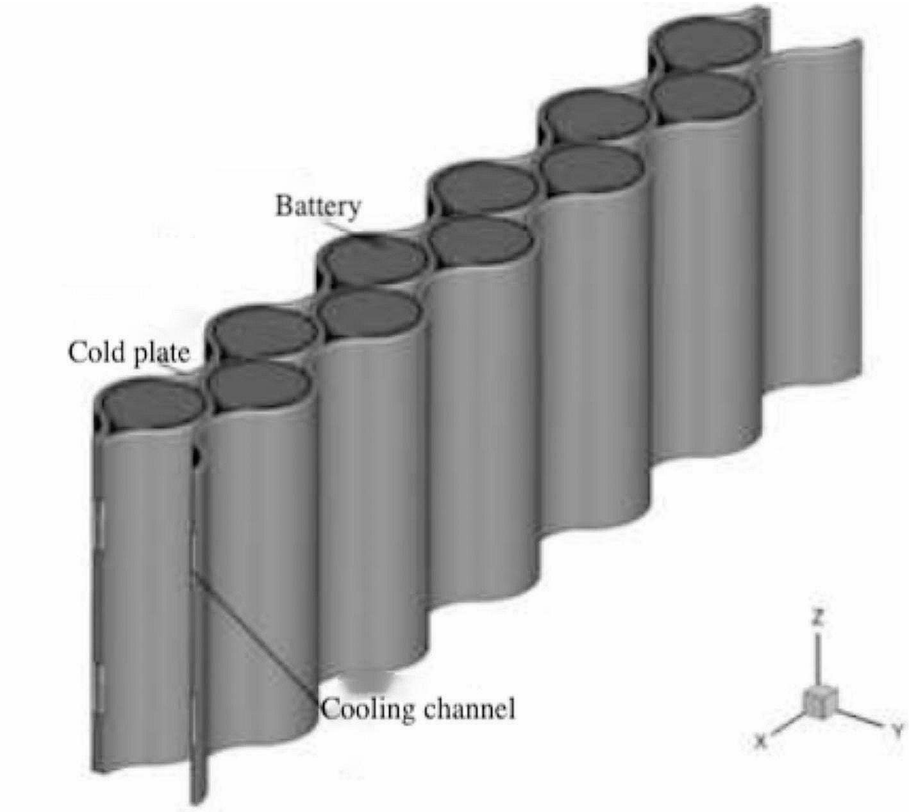

Fig. 4 Schematic diagram of the cylindrical battery pack

Table 3 Display implementation effect values of inlet flow-rate cooling

Display	T_{max} (℃)	ΔT (℃)
↓	7.449	9.064

After 600 charge-discharge cycles, the immersion-cooled battery pack reduced the capacity attenuation by 3.3%. Indirect liquid cooling is the channel through which the coolant flows through the battery surface, and capable of convective heat transfer effect. Due to its structural advantages, coolant can be selected more. Cylindrical battery thermal management conditions based on the snake micro channel cold plate is designed (Xie 2020), as shown in Fig. 4.

The results display that the inlet flow-rate of cooling working medium has significant impact factors on thermal properties of battery pack, when the inlet mass flow rate is 1210^{-4}At kg / s. As shown in Table 3.

In their study, Zhou et al. (Zhou et al. 2023) developed an innovative three-dimensional transient numerical model of a bypass liquid cooling tube. They examined how variations in the cooling tube channel height, coolant flow direction, inlet flow rate, and temperature impact the cooling efficiency and pressure drop of battery modules, as illustrated in Fig. 5.

The findings indicate that the winding cooling tube outperforms the serpentine cooling tube in terms of ensuring uniform temperature across battery modules. Utilizing opposing directions for the coolant flow can enhance temperature evenness. Increasing the flow rate leads to a reduction in maximum temperature (T_{max}). Both cooling pipes

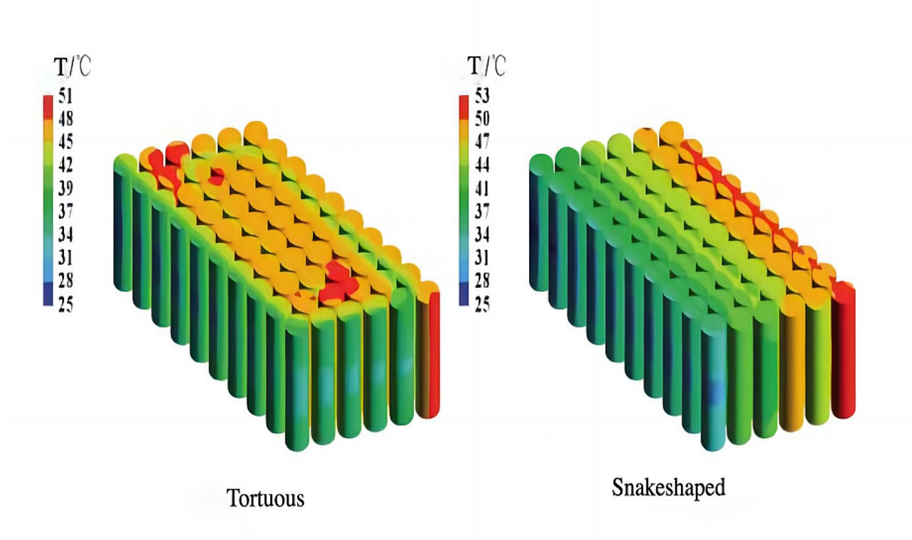

Fig. 5 Temperature diagram of battery module

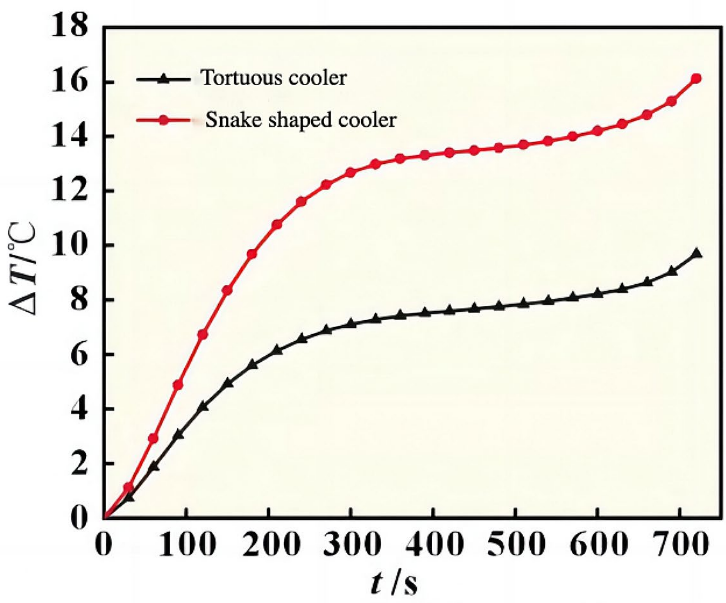

Fig. 6 ΔT variation curves for two types of cooling tubes

start with an initial temperature and inlet temperature of 25 °C, a flow rate of 3 g/s at the inlet, and a discharge rate of 5 C. Figure 6 displays temperature distribution cloud maps and temperature variation curves. For the tortuous cooling system, the battery temperature is 50.2 °C, which is 2.1 °C lower than the 52.3 °C observed for the serpentine cooling tube. The tortuous cooling tube helps in curbing the rise in highest temperature and enhancing temperature uniformity. Simulation results indicate that the maximum temperature difference between the serpentine cooling tube is 16.1 °C, while for the winding shape it is merely 9.2 °C. Ultimately, the winding cooling tube performs better in terms of cooling efficiency.

Liquid cooling technology, while offering superior cooling performance, often utilizes coolant containing metals and organic substances to enhance efficiency. However, this can lead to environmental pollution, impacting ecology and health. Some coolants may also have acidic properties, diminishing alkalinity and causing corrosion to metals and rubber components (Zeng et al. 2023). The addition of soft water to the coolant can generate harmful substances and block the radiator. Addressing coolant waste management, inspecting cooling systems, and creating environmentally-friendly, non-toxic, and leak-resistant coolants present significant challenges. Efficiency and cost remain critical factors for BTMS. An ideal coolant should possess high conductivity, low heat capacity, stability, and be suitable for large-scale use, while addressing cost concerns. Research and development of cost-effective and efficient coolants are essential for enhancing the economy and competitiveness of BTMS. The reliability of BTMS heavily relies on leakage design, necessitating effective sealing, leak detection, and emergency preparedness to minimize environmental impacts. Future research should concentrate on formulating eco-friendly, efficient, and affordable coolants, as well as enhancing leak prevention measures and emergency response plans (Zhong et al. 2024).

When comparing the performance, cost, and maintenance needs of air versus liquid cooling thermal management systems (TMS), it becomes evident that liquid cooling is more efficient and long-lasting when it comes to powering batteries. Liquid cooling utilizes coolant circulation to control battery temperature, ultimately improving both performance and lifespan. It is worth noting that different liquid cooling setups demonstrate varying levels of efficiency. While air cooling systems are economical and easy to maintain, they fall short in terms of heat dissipation abilities compared to liquid cooling systems. In contrast, the advanced liquid cooling systems used in BYD electric vehicles notably boost vehicle range and reliability (Zhang et al. 2024).

Air cooling systems are advantageous in terms of cost due to their simple design and lower initial investment. In contrast, liquid cooling systems, while more expensive upfront, provide better long-term performance and safety because of their superior heat dissipation capabilities. Moreover, the maintenance of liquid cooling systems can be complex, requiring regular upkeep such as coolant replacement and radiator cleaning, leading to increased maintenance expenses. Nevertheless, ongoing technological progress is helping to reduce these costs. In addition, the incorporation of smart maintenance management systems improves the effectiveness and accuracy of liquid cooling system maintenance by offering real-time monitoring of operational status and detection of faults (Zhang 2023a, b; Hong et al. 2023).

Passive cooling I - based on PCM cooling model

Unlike active cooling methods, represented by air and liquid, passive cooling does not require additional energy costs such as fans, pumps, and condensers. Among them, the property of PCM realizes the absorption and storage of energy during the phase change process, exhibiting rapid temperature response, thereby effectively preventing the rise of battery temperature and achieving better temperature balance effect. This type of system based on the cooling of PCM has low maintenance cost, small system volume and simple structure, which mainly includes inorganic materials and organic materials. Inorganic materials include aqueous solution and molten salt, but they have poor thermal stability and high super-cooling degree. Taking paraffin as an example, organic materials are

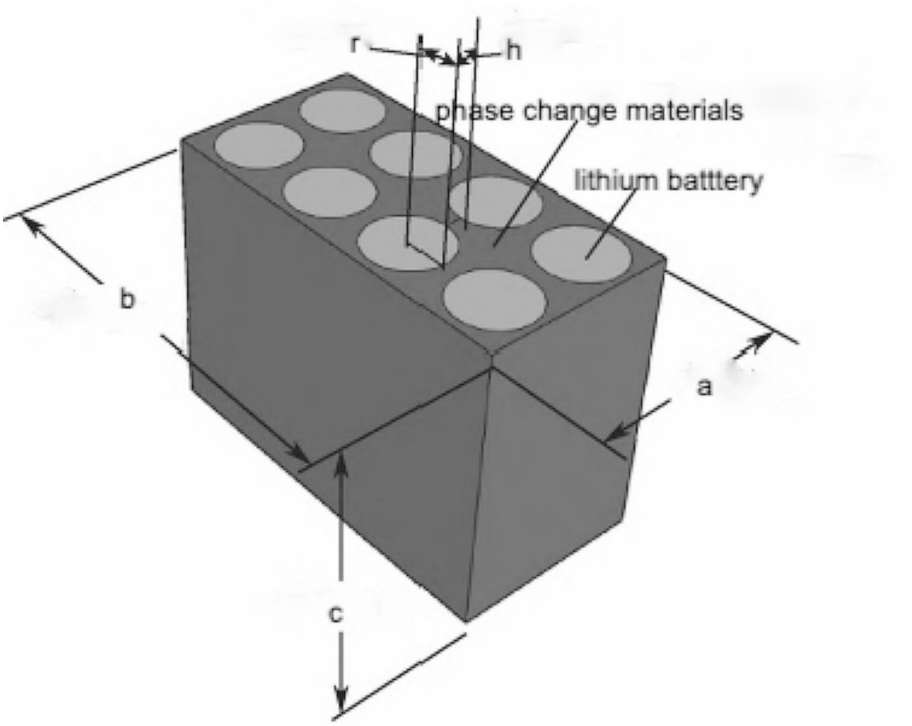

Fig. 7 The cylindrical battery pack model diagram

Table 4 Optimal parameter value of the PCM

Thermal conductivity W / (m · K)	Thickness (mm)	Melting point (℃)	Latent heat value (J / g)
2.0	4	36–38	212

designed to be combined with porous materials to improve the thermal conductivity of PCM while maintaining high latent heat properties. Research has found that the latent heat value of paraffin is much higher than its sensible heat value, which can significantly slow down the temperature rise rate of batteries (Wang et al. 2020). As the amount of paraffin increases, this effect becomes more pronounced. But we must note that the phase transition point of specialized paraffin should comply with the preferred temperature range of the battery. When adding thermal fillers to PCM and reaching a specific mass value, the relationship between thermal conductivity and latent heat is established (Lin et al. 2021). Continuing to increase the proportion of thermal fillers will lead to a decrease in the latent heat value of composite PCM. The cooling device based on composite PCM battery pack was simulated and shown in Fig. 7 (Yin et al. 2022).

The results show that the optimal parameter value for such structural design should maintain the values in Table 4 of the PCM, and the highest temperature value and temperature uniformity of the battery device are optimal.

Ling (Ling and Doctoral 2016) developed modules that mimic AllCell products by placing cylindrical batteries into an expanded graphite composite PCM to assemble a battery thermal management module, as illustrated in Fig. 8.

The ideal phase transition temperature for the chosen material of this battery product falls between 40 and 45. Increasing the density of the phase change material (PCM) boosts thermal conductivity, which in turn improves temperature consistency, decreases

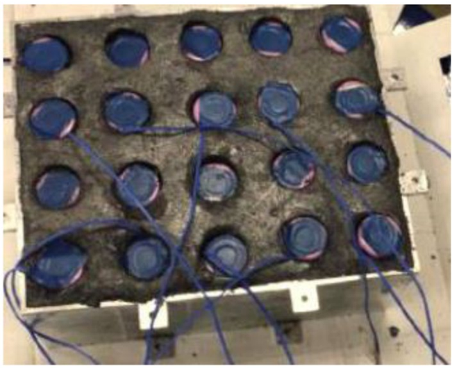

Fig. 8 Physical diagram of PCM BTMS

Table 5 Changes in thermomechanical behavior of composite PCM with immersion time

Property parameters		**Immersion time(h)**				
		12	**9**	**6**	**3**	**1**
Composite density(kg/m^3)		789	775.4	766.3	660.4	622.5
Graphite density(kg/m^3)		210	210	210	210	210
Thermal conductivity(W/(m·K))		14.5	14.3	14.1	13.6	13.0
Tensile strength (kPa)	22℃	1040	1060	1072	1100	892
	45℃	196	186	194	260	264
compressive strength (kPa)	22℃	2571	2546	2394	2317	2292
	45℃	292	280	280	267	241
Blast strength (MPa)	22℃	650	630	600	560	530
	45℃	110	130	140	140	160

thermal resistance between the battery and PCM, and lowers the overall battery temperature. Nonetheless, overly high density during implementation may compromise the pore structure of expanded graphite, resulting in potential liquid leakage within the melted composite PCM. Currently, most approaches utilize composite materials coupled with various reinforcement techniques to optimize thermal conductivity, mechanical properties, and more, as detailed in Table 5.

In their study, Alashdan et al. (Alrashdan et al. 2010) explored how the combination of packing density in composite PCM and ambient temperature impacts material thermal conductivity, tensile pressure, and burst strength. They found that enhancing the packing density of paraffin at room temperature can boost tensile and compressive strength, although this improvement lessens at elevated temperatures. Meanwhile, alterations in the paraffin ratio influence blasting strength positively at room temperature but negatively at higher temperatures. Strategies to enhance mechanical properties involve polymer doping, reinforcing metal structures, and encapsulating microcapsules. Zhou et al. (Zhou 2023)successfully developed a novel shaped composite phase change material (CPCM), consisting of a metal organic framework (MOF) porous carrier MIL-101 (Cr) - NH2 and reduced graphene oxide (RGO) thermal conductive filler. MOFs have a crystalline porous structure, high specific surface area and volume, and exhibit high-strength adsorption capacity. RGO also has good thermal stability. Research has found that the optimal ratio of MOF/RGO/PW (paraffin) CPCMs is 35:5:60. The experimental results show that CPCM-60% PW has excellent thermal physical properties, with a 472% increase in thermal conductivity compared to pure paraffin, and greatly improved thermal stability. Under different operating conditions, the T_{max} trend of CPCM battery modules significantly slows down, and ΔT decreases with increasing ambient temperature. This indicates that CPCM-60% PW has excellent temperature control performance and thermally induced high thermal conductivity. In the experiment, CPCM-60% PW has excellent anti leakage performance and no paraffin leakage phenomenon. Chen et al. (Chen 2022)introduced a new composite phase change material incorporating sodium dihydrogen phosphate dode cahydrate, modified aluminum nitride, and carbon fibers using techniques like melt blending, ultrasonic dispersion, and vacuum adsorption. In order to combat issues related to undercooling and phase separation of disodium hydrogen phosphate dodecahydrate, an initial modification was made using 4wt% (wt: Weight ratio) sodium silicate hydrate and 4wt% carboxymethyl cellulose. Subsequently, 12wt% modified aluminum nitride and 6wt% carbon fiber were included for further enhancement. A comparison between the results of the two modification processes revealed a reduction in undercooling to 1.9℃ and an increase in thermal conductivity to 1.86 W/(m·K) in the latter case. The modified composite material exhibited a phase transition temperature of 35℃, latent heat of 249 J/g, and excellent molding properties, resulting in improved temperature control effects.

Effective cooling of batteries using the heat absorption characteristics during solid-liquid phase transition. This type of system has an excellent thermal response speed and a cooling efficiency. The main limiting factors for the widespread application of PCM in practical applications include the complexity of the preparation process, high cost, and the degradation of heat dissipation performance during long-term use. Especially how to maintain the stable form of PCM, prevent leakage, and develop high ignition point PCM. These issues are areas that future scientific research needs to tackle.

Phase change materials (PCMs) hold great promise for various market applications related to energy preservation, temperature control, and thermal energy storage. However, the entire lifecycle of these materials involves multiple stages, including extracting raw materials, manufacturing, use, and disposal. Each of these stages carries unique environmental impacts, emphasizing the need for comprehensive optimization. Waste disposal marks the conclusion of PCMs' lifecycle, with a significant challenge being the long-lasting environmental pollution caused by most PCMs post-disposal. Thus, an essential focus for improvement lies in enhancing the chemical stability of PCMs to facilitate their recyclability. Furthermore, the reuse potential of discarded PCMs is often limited, raising the question of how to amplify their value for reuse. One feasible solution is to repurpose discarded PCMs for generating low-grade construction materials or energy storage devices, thereby maximizing their reuse potential (Zhou and Wang 2024; Yang 2023; Gu 2023).

Passive cooling II - based on the heat pipe cooling model

One of the passive cooling methods, heat pipe cooling, exhibits high thermal conductivity, compact structure, and efficient working conditions, which can maintain stable working ability in harsh environments. This has laid a solid foundation for its widespread application in fields such as solar energy, power electronics, and aerospace. There is a capillary core structure in the heat pipe, one part of which contacts with heat source as heat end. Upon heat transfer from the heat source to the heat pipe, the liquid within the capillary tube is vaporized due to the absorbed heat, resulting in an increase in pressure. The pressure difference formed causes the evaporated gas to be directed towards the cold end, gradually condensing into a liquid and flowing back to the hot end under the influence of gravity. The heat pipe also has applicability in the field of heat dissipation of batteries. The main research direction in the current academic community is how to enhance the heat transfer speed, adaptability to working conditions, and response speed of the cold end. The experimental results indicate that introducing thermal conductive elements between the battery and heat pipe aims to enhance thermal conductivity efficiency and achieve the goal of reducing the maximum temperature and temperature difference of the battery pack (Gan et al. 2018). Under the condition of a contact angle of 95°, it is verified that the contact area between the thermal conductive element and the battery is positively correlated with the cooling capacity. Heat pipe cooling needs to fully consider its operating mechanism: the phase change conversion of the working fluid filled in the heat pipe achieves heat dissipation effect, and relies on capillary and self gravity to achieve self circulation of the working fluid. To enhance the flow stability of ultra-thin loop heat pipes, the Flat Plate Loop Heat Pipe features a closed loop design where the evaporator, condenser, and steam pipelines run parallel to the liquid pipeline. This configuration not only improves anti-gravity and heat transfer efficiency but also offers increased flexibility in the system layout (Hong et al. 2017).

The results show that compared with the loop heat pipe, the critical working Angle of the parallelogram channel heat pipe is lower, which is more conducive to the circulation of liquid in the heat pipe and has faster response speed. As shown in Fig. 9.

Under conditions of elevated temperatures, heat pipes exhibit remarkable cooling capabilities along with compact and lightweight structural features. Nevertheless, the utilization of heat pipes in large-scale high-power battery packs remains somewhat constrained, primarily attributed to the intricate manufacturing procedures, substantial costs, and the immature state of application technology within this domain. Consequently, the key to future advancements lies in broadening the application scope of heat pipes and mitigating their associated costs (Xu 2024).

Compared to traditional air-cooled or liquid-cooled technologies, heat pipe battery thermal management technology offers significant advantages in terms of heat dissipation efficiency, temperature uniformity, and system reliability. These benefits not only enhance battery performance and lifespan but also improve the overall performance and safety of electric vehicles. The initial cost of investment is higher, mainly due to the research and production costs of heat pipe materials and the design and manufacturing

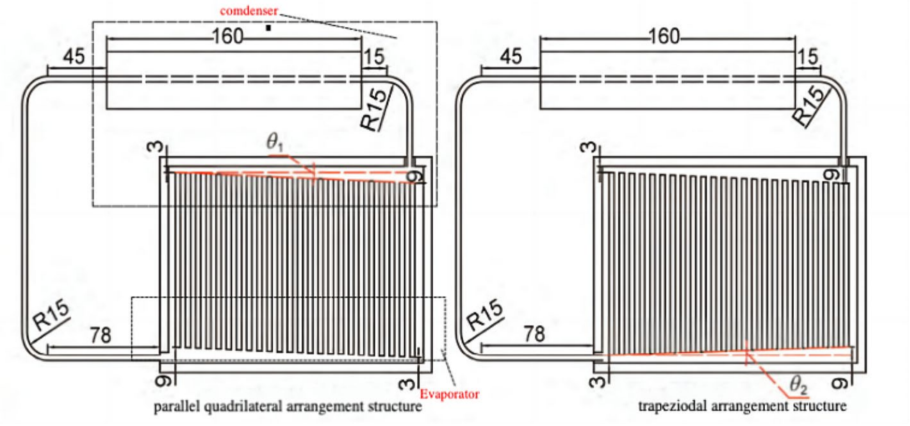

Fig. 9 Schematic diagram of the two structural heat tubes

costs of heat pipe systems. However, as technology matures and the market grows, these costs are expected to decrease gradually. Operating and maintenance costs of heat pipe BTMS are relatively low (Tang et al. 2002). The efficient heat dissipation and temperature uniformity provided by heat pipe systems significantly enhance battery performance and lifespan in the long term. Improved battery pack temperature control leads to enhanced charging and discharging performance and energy density, extending battery life and enhancing the range and performance of electric vehicles. The reliability and stability of heat pipe systems also help in reducing the failure rate and maintenance costs of electric vehicles. In conclusion, heat pipe battery thermal management technology has promising prospects in the electric vehicle sector. Despite the higher initial investment, its long-term benefits in performance enhancement, extended lifespan, and reduced maintenance costs make it a cost-effective solution (Wang et al. 2022).

Composite cooling model-different cooling strategy

Overview of technology and needs of BTMS

Active convection cooling uses fans or pumps to circulate air or liquid to improve heat transfer efficiently. However, it consumes a significant amount of energy, produces noise, and can be affected by extreme temperatures or humidity. Conversely, PCM is a passive cooling method that relies on temperature-induced density gradients for heat transfer. Although it is simple and energy-efficient, it may not be suitable for high heat loads or confined spaces due to slow natural convection. The performance of PCM cooling is influenced by equipment layout and environmental conditions. Heat pipe technology efficiently transfers heat by utilizing the latent heat of phase change, which has made it popular in electronics and aerospace industries for its high conductivity, quick response time, and uniform temperature distribution. Nevertheless, the high cost and complexity of heat pipe technology might hinder its performance in environments with high vibration or radiation levels (Li et al. 2023).

Table 6 illustrates how the composite cooling strategy can create ideal combinations according to specific operational conditions. Through evaluating the pros and cons of four cooling techniques– air cooling, liquid cooling technology, PCM, and heat pipe– a new thermal conductive material was introduced, heat exchanger design was enhanced, and the cooling system’s structure and parameters were optimized to achieve efficient heat dissipation (Liu et al. 2022).. This approach enables automatic switching of the cooling mode based on battery temperature and load conditions, thereby enhancing system coherence and stability. By closely monitoring each battery’s status in real-time based on its charging and discharging characteristics, potential issues like overcharging, over discharging, and thermal runaway can be preempted, ultimately prolonging the batteries’ lifespan.

For example, in specific situations, if the heat generated by the battery is too large and the latent heat capacity of PCM cannot meet the demand, the system is usually designed to increase active heat dissipation to ensure heat dissipation, thereby enhancing battery storage capacity. The research results show that the combination of PCM and liquid cooling plates can be applied to battery cooling systems (Du et al. 2022). This composite cooling system can effectively reduce the maximum temperature of battery operating conditions and control the maximum temperature difference within a safe range. In the study of the combination process between the cold end of heat pipes and air cooling,

Table 6 Characteristics and performance of different thermal management technologies

TMS	**Built in**	**External**			
		Forced air cooling	**Forced liquid cooling**	**PCM**	**heat pipe**
System complexity	complex	moderate	complex	simple	complex
Shape adaptability	difference	good	good	good	difference
Battery temperature rise	low	high	low	moderate	moderate
Battery temperature uniformity	good	difference	good	good	good
Environmental adaptability	moderate	difference	good	difference	moderate
System energy consumption	moderate	low	high	Zero energy comsumption	low
System cost	high	low	high	moderate	high
Leakage risk	high	zero	middle-high	moderate	low
Applicable heat range	moderate	moderate	high	moderate	low
Controllability	high	high	high	low	low
Battery shape	Universality	Universality	Universality	Universality	Square, Soft packaging
function	preheating/cooling	cooling	preheating/cooling	preheating/cooling	cooling
Commerciality	low	commercially	commercially	high	moderate

the influence of wind speed on the temperature characteristics of batteries was explored (Wang 2016). The experimental results show that as the wind speed increases, the operating temperature of the battery pack significantly decreases, and the temperature difference gradually decreases. This discovery has important practical significance for composite heat dissipation.

PCM + liquid cooling I

Jiang et al. (Jiang and Li 2024) developed a Battery Thermal Management System (BTMS) designed to function effectively in environments with high temperatures and discharge rates, by incorporating phase change materials (PCM) and cooling plates. To validate its efficiency, the team conducted numerical simulations and conducted a detailed comparison with traditional PCM cooling methods. The research findings indicate that the implementation of liquid cooling effectively resolves issues related to excessive temperature rise and heat build-up within the battery core, caused by PCM liquefaction at high temperatures and discharge rates. In comparison to pure phase change cooling, the hybrid cooling system can reduce battery spacing to 3 mm at a coolant flow rate of 0.5 m/s. Further increasing the coolant flow rate shows diminishing returns in enhancing thermal management. Additionally, integrating liquid cooling plates helps mitigate the impact of the initial charge-discharge cycle on subsequent cycles, thereby prolonging the battery’s lifespan, as illustrated in Fig. 10.

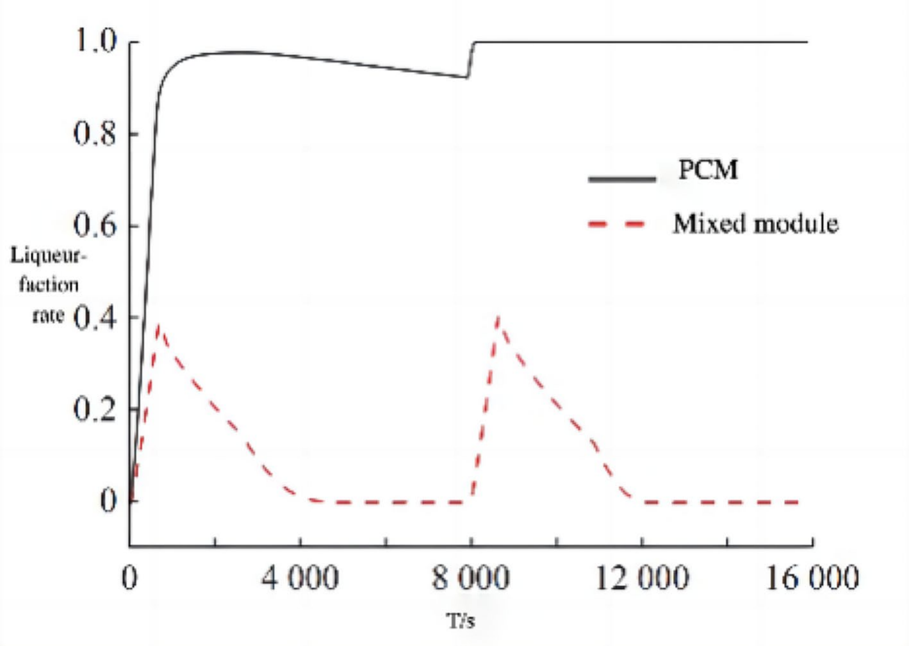

Fig. 10 Changes in liquefaction rate of PCMs over time during charge discharge cycles

PCM + liquid cooling II

Following careful design, researchers like Cao (Cao 2022) have devised a thermal management system that combines paraffin/expanded graphite composite phase change materials (PCMs) with forced liquid cooling. To assess its heat transfer efficiency, the team carried out experimental and numerical simulation analyses. In their study, they introduced flexible composite PCMs with high thermal conductivity and nano phase change solutions with a high specific heat capacity as alternatives to traditional carbon matrix composite PCMs and water-cooled fluids. This shift led to a notable enhancement in system performance. In order to further enhance thermal management effectiveness, the research team proposed an innovative delayed liquid cooling approach. According to this method, the liquid coolant's inlet temperature should closely match the PCM's phase change temperature to uphold a stable temperature environment for the battery pack during operation. This enhancement not only improves temperature consistency within the battery pack during high-rate discharges but also reduces the liquid cooling system's operational duration, thus cutting down the entire system's energy consumption. This is illustrated in Fig. 11.

Experimental data indicates that when the ambient temperature is set to 40 degrees Celsius and the battery pack is discharged at a 4 C rate, it can maintain a maximum planar temperature difference within 4 degrees Celsius. Furthermore, the battery pack's maximum temperature, planar temperature difference, and axial temperature difference are strictly controlled below 55 degrees Celsius, 4 degrees Celsius, and 1 °C, respectively. It is important to note that as the discharge rate decreases, the system's operating time and energy consumption also decrease accordingly. At a discharge rate of 1 C, the system requires minimal additional cooling energy. In conclusion, the coupled Thermal Management System (TMS) based on paraffin/expanded graphite composite Phase Change Materials (PCMs) and forced liquid cooling, as designed by researchers like Cao, not only demonstrates excellent heat transfer performance but also significantly reduces

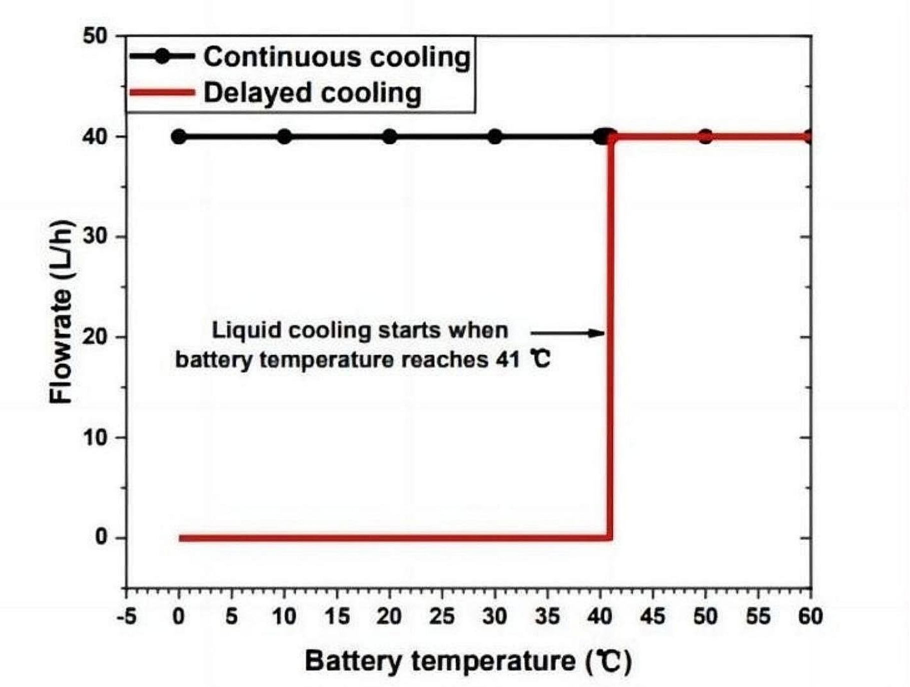

Fig. 11 Comparison between delayed liquid cooling strategy and continuous cooling strategy

system operation time and energy consumption, offering a new efficient solution for battery pack thermal management.

Aluminum plate + PCM + liquid cooling

In order to more accurately regulate the working temperature of the battery, CFD software simulation is used to build a heat dissipation structure model of aluminum plate / PCM / liquid cooled battery heat management system (Li et al. 2020). The parameters are optimized to calculate the influence of aluminum heat guide plate thickness, hot water pipe quantity, mass flow, thermal conductivity, phase change temperature and water inlet temperature on the heat dissipation of battery. Reasonable control to meet the operating temperature requirements of the battery. To verify the feasibility of the best binding parameters based on the three heat dissipation modes. The research objective for parameter optimization is to evaluate the impact of multiple variables on battery heat dissipation performance. These variables include aluminum thermal conductivity plate thickness, number of hot water pipes, mass flow rate, thermal conductivity, phase change temperature, and inlet water temperature. Optimize parameter values to achieve reasonable temperature control to meet the normal operating temperature requirements of the battery. Verify the optimal parameter combination based on three heat dissipation modes to evaluate the application effect.

PCM + heat pipes

To test the possibility of integrating thermal management technology using both PCMs and heat pipes, a specialized cooling system was created by combining a stepped heat pipe with a PCM, focusing on the 1P11S battery pack configuration. This design is illustrated in Fig. 12.

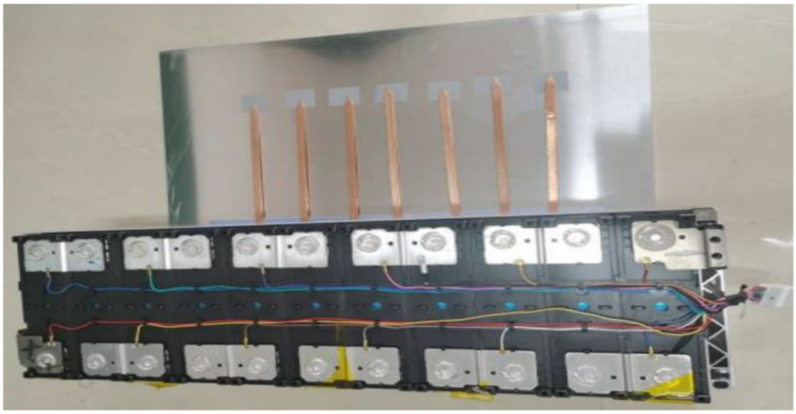

Fig. 12 PCM and heat pipes coupling

Table 7 Results of simulation and experimental analysis

Experimental parameters	1P11S Model			
	PCM	**PCM + Heat pipe**	**PCM**	**PCM + Heat pipe**
	Simulation		**Actual testing**	
T_{max} 25℃-2 C	40.5	35.7	41.1	36.2
ΔT 25℃-2 C	5.2	2.4	4.7	2.3

A comparative and analytical study was conducted to examine the thermal management impact of power batteries, combining simulation and experimental analysis, as outlined in Table 7. The simulation results show a consistent temperature trend that closely matches the findings from real-world testing and simulations. This finding emphasizes the significant improvement in thermal management of power batteries through the combination of PCMs and heat pipes. By adopting this optimized approach, it effectively reduces the battery temperature rise and improves the internal temperature consistency within the battery pack (Xia 2023).

Heating pipe + air cooling

Pulsating heat pipe (PHP) is a metal capillary tube with a simple structure as shown in Fig. 13. It can be bent in various shapes, usually resembling a snake. Inside the tube, a liquid cooling working fluid is present. When the liquid reaches its boiling point in the evaporation section, it undergoes phase change, producing numerous bubbles (Qu et al. 2018).

The expanding bubbles push the fluid towards the condensation section, while at lower temperatures, the contracting bubbles rupture and flow back to the evaporation section. Unlike conventional heat pipes, pulsating heat pipes do not require a liquid suction core. By undergoing phase changes, the working fluid changes the pressure inside the pipe, causing oscillatory movement between the evaporation and condensation sections to facilitate effective heat transfer.

Suggestion

The progress in developing batteries for new energy vehicles faces technical challenges, such as managing heat effectively and dealing with the associated costs. Using Phase Change Materials (PCMs) is crucial for maintaining battery safety and stability.

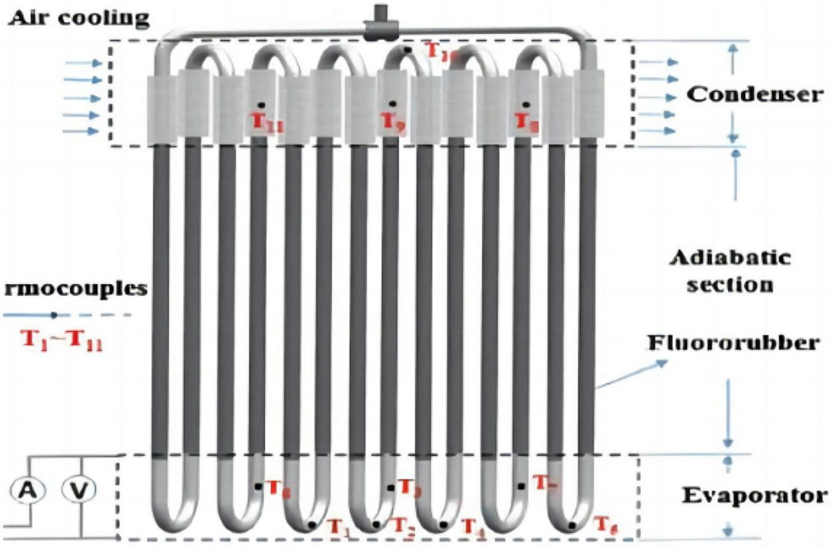

Fig. 13 Schematic diagram of air-cooled and pulsating heat pipe

To overcome these obstacles, it is necessary to enhance basic research, improve heat dissipation methods, and refine design strategies. Collaboration among different fields, such as material science, chemical engineering, and related disciplines, is essential for advancing thermal conductivity and PCMs through innovative approaches (Liu 2023; Yan 2023).

Moreover, developing a simulation model that accounts for multiple scales and physical fields is crucial for evaluating and improving the efficiency of heat dissipation. The cooperation between different areas of expertise is essential for driving technological progress in this complex field, ultimately facilitating the development of battery thermal management technologies that are both efficient and environmentally friendly, as well as cost-effective. With the expanding market and ongoing advancements in battery technology, the significance of composite cooling systems in battery thermal management will grow, ultimately contributing to the wider adoption and sustainable development of new energy vehicles (Chen et al. 2023).

Upcoming research opportunities and challenges include: (1) Exploring new material cooling agents to enhance efficiency and environmental sustainability. (2) Developing leak-proof architectures and heat dissipation methods for energy conservation and environmental protection. (3) Investigating collaborative solutions for composite cooling systems to improve precision and energy efficiency. (4) Advancing integration technology for lightweight and compact application systems to support energy conservation and convenience. (5) Studying heat recovery technology to promote energy conservation and environmental preservation.

Conclusion

Although BTMS has achieved significant advancements in the electric vehicle sector, it still grapples with challenges stemming from high currents, such as accelerated heating and uneven distribution. Thus, there is an urgent call for continuous research and enhanced efforts. The main objective of the article is to propose various composite cooling strategies and analyze experimental findings. It emphasizes structural optimization, comparative effects, energy efficiency display, and cost maintenance elucidation. The article strongly advocates for in-depth exploration and advancement of composite cooling solutions. The advancement of multiple composite cooling technologies has emerged as a pivotal focus for future progress, aiming to attain high performance, cost efficiency, and environmental sustainability within the new energy sector. These breakthroughs will facilitate the flourishing growth of their respective industries, including electric vehicles and energy storage (Li 2020).

The innovative composite cooling optimization method holds great promise and deserves recognition for its potential benefits. This technology not only enhances energy efficiency but also contributes significantly to sustainable development and economic advantages. The primary challenge faced by humanity today is the rising global energy demand, extensive energy consumption, and environmental degradation resulting from conventional cooling approaches, necessitating sustainable economic alternatives (Li and Xu 2023). By employing unique composite techniques, composite cooling optimization technology effectively reduces energy usage, promotes conservation, cuts down operational and maintenance expenses for businesses, and advances the strategic objective of sustainable social development. By delivering tangible economic benefits to enterprises, improving industry competitiveness, and addressing the economic downturn on a global scale, this technology demonstrates significant potential in enhancing energy efficiency, economic gains, and sustainability. As technological advancements continue, composite cooling optimization is poised to play a pivotal role in societal progress and contribute to a more promising future for humanity (Su 2022; Yuan et al. 2022; Zhang 2023a, b; Liu 2024).

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Ge Li wrote the manuscript text.

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Not applicable.

Consent to participate
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