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Research Progress of Microchannel Liquid Cooling Technology in the Application of Thermal Management of Prismatic Lithium Batteries

Lithium-ion batteries have significant advantages such as high energy density, long cycle life and low self-discharge rate. Therefore, they are ideal for energy storage in electric vehicles. However, lithium-ion batteries are very sensitive to temperature, which affects the battery's cycle life, efficiency, reliability and safety. During the charging and discharging process, a large amount of heat is generated inside the battery due to the electrochemical reaction and resistance, causing the battery temperature to rise. When the temperature gets too high, thermal runaway, electrolyte fire and explosions may occur. As battery energy density increases, the demand for efficient thermal management continues to increase, and a compact and efficient battery thermal management system is essential. This paper introduces the development status of different thermal management technologies, reviews the application of microchannel liquid-cooling technology in the thermal management of prismatic lithium batteries, discusses the current research direction and status of microchannel technology, and finally looks forward to the future research and development direction of microchannel technology.

Introduction

Against the backdrop of a global energy crisis and increasing environmental pollution, governments around the world are seeking solutions to reduce carbon emissions and transform energy [1, 2]. In this context, the development of electric vehicles can achieve the conversion of clean energy, reduce the use of petroleum energy, and significantly reduce carbon emissions, which is an important part of energy conservation and emission reduction [3]. Lithium-ion batteries have the characteristics of high energy density, long cycle life and low self-discharge rate, and are widely used as the main power source for electric vehicles [4-6]. However, during operation of the battery pack, a large amount of heat may be generated inside due to electrochemical reactions and internal resistance. Operating at high and low temperatures will inevitably lead to a decrease in battery performance and accelerate the battery degradation process, thus shortening the battery life [7]. In addition, when the temperature continues to rise, potential thermal runaway may occur, bringing fatal disasters. Figure 1 is an analysis of electric vehicle fire accidents in China from 2021 to 2022 [8].

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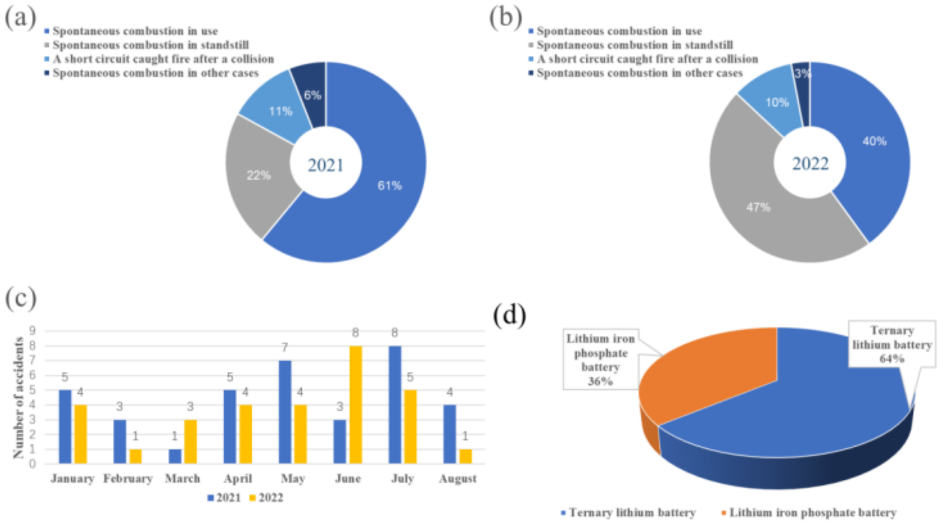


Fig. 1. Fire accident analysis of electric vehicles in China in 2021-2022 [8]

In addition to avoiding rapid increases in battery temperature, it is also necessary to avoid large temperature imbalances within the battery and battery stack, as large temperature differences may lead to uneven current density and reduced performance [9]. Figure 2 shows the thermal runaway propagation process of the vehicle battery pack triggered by the thermal runaway of a single unit battery pack. The top cover is severely bulging and there are traces of high temperature burns on the surface. The thermal runaway propagation in the battery pack causes considerable harm to driving safety [10].

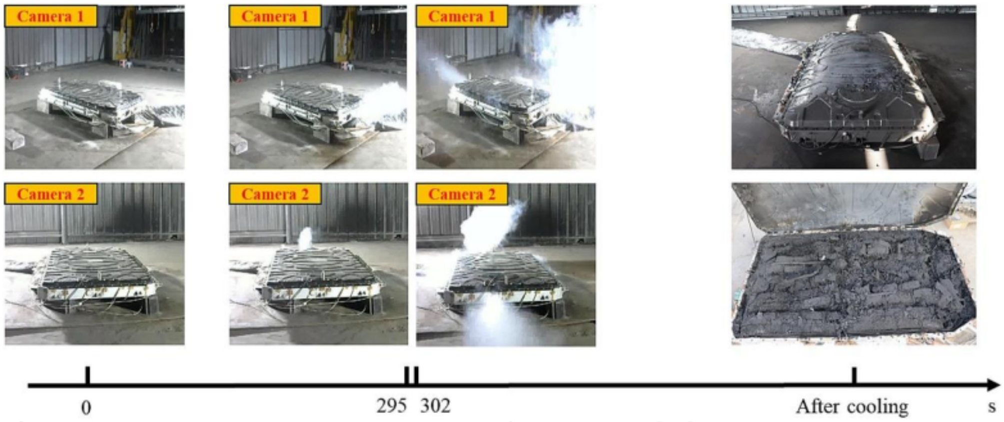


Fig. 2. Thermal Runaway Propagation Process of Battery Pack [10]

Nowadays, Li-ion batteries are developing towards high energy density, high safety, low cost, long life and waste recycling to adapt to the development trend of technology and the global economy [11]. Among them, high energy density is an important indicator for the development of lithium-ion batteries [12]. However, the improvement in energy density is limited to a certain extent by thermal management technology. Therefore, various thermal management technologies for Li-ion batteries [13-

16] have been traditionally studied to optimize the battery thermal management system (BTMS) and perform efficient heat exchange within the effective space, thereby improving the energy density of the battery and preventing the hazards of thermal runaway of the battery.

Common Battery Cooling Technology

Air Cooling

Air cooling is a common cooling method at present. The application of air-cooling technology in thermal management system has the advantages of low cost, light weight, long life, easy maintenance, moderate power consumption and so on [17-19]. However, due to the small specific heat capacity of air, the battery pack is prone to large temperature difference [20]. In addition, when the battery pack has high energy density and generates a lot of heat, the air-cooled BTMS requires more air volume to avoid uncontrollable temperature, which increases power consumption [21]. Therefore, to deal with the problem of excessive temperature difference in the process of battery cooling, the current research on battery thermal management air cooling technology mainly focuses on the optimization of air duct and convection mode. For example, Park [22] used a U-shaped BTMS with the inlet and outlet on the same side, and the tapered flow channel could distribute the flow more evenly to each cooling channel. Hong *et al*. [23] improved the cooling performance by providing a secondary vent in the upper part of the sink cavity of the Z-type BTMS. In addition to the study of Z-type and U-type BTMS with single inlet and outlet, Liu *et al*. [24] introduced a J-type BTMS by combining the two BTMS types and setting adjustable valves at the two outlets to adapt the J-type BTMS to the battery working conditions to meet various heat dissipation conditions. Zhang *et al*. [25] designed T-type symmetric BTMS by combining Z-type and U-type BTMS. Luo *et al*. [26] optimized the symmetric BTMS, proposed the X-type BTMS (Figure 3), and obtained the optimal inlet angle and outlet position through orthogonal test analysis.

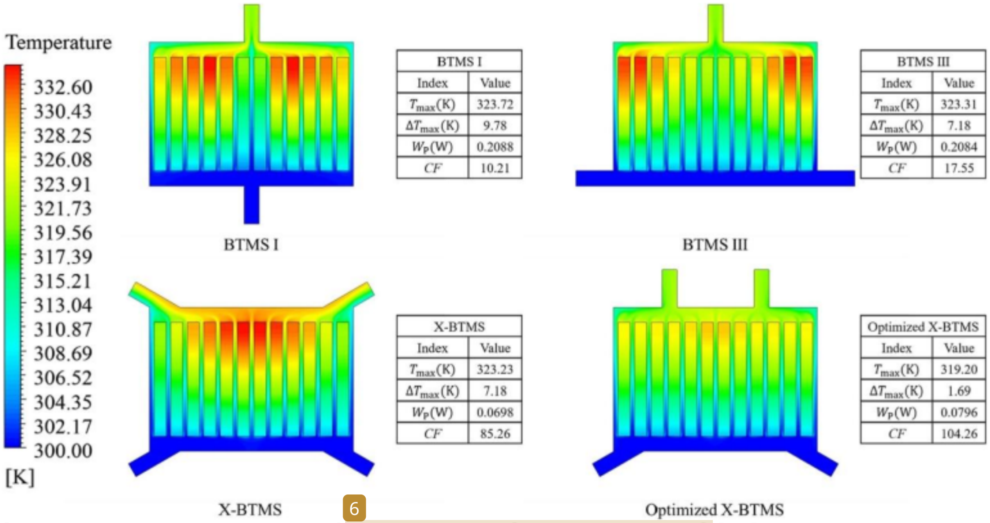
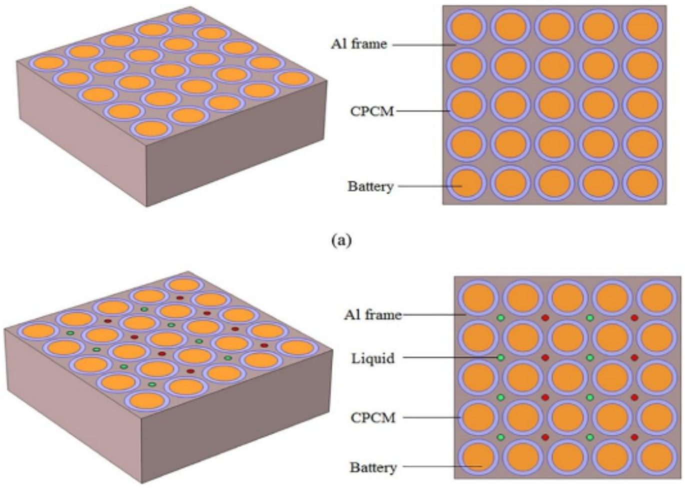


Fig. 3. Temperature distribution of symmetric BTMS and X-type BTMS [26]

Phase Change Material Cooling

Phase change materials (PCM) can store a large amount of energy through the process of phase change, and can absorb and release heat energy at almost constant temperature. Therefore, PCM is often used as a passive thermal management method in thermal management systems such as electronic devices and batteries, which need a uniform and constant temperature environment. Phase change materials in paraffin have been widely used because of their phase change temperature close to the threshold temperature of batteries and excellent cycle performance. The thermal conductivity of paraffin does not meet the requirement of rapid cooling when a large amount of heat is generated, so other materials are usually added to the paraffin to increase the thermal conductivity. Ling *et al*. [27] proposed a BTMS using paraffin/expanded graphite (EG) as a composite phase change material (CPCM) at 25°C, and compared the effects of EG mass fraction and composite bulk density on temperature through experiments and numerical simulations. The results show that the CPCM with larger EG mass fraction (25%) and packing density (890 kg·m^{-3}) is preferable. Yan *et al*. [28] studied the influence of three phase transition temperatures (36°C, 45°C and 58°C) of CPCM on the cell temperature through experiments and FLUENT simulation. The experiments were conducted at 20°C, 1C or 3C circulation rate. The results showed that the CPCM with a phase transition temperature of 45°C, which is neither too low nor too high, has a better effect. Liu *et al*. [29] employed a passive BTMS using an expanded graphite matrix and graphite sheets as the CPCM, and controlled the cell temperature through experiments and ANSYS ICEM simulations. The results showed that compared with the battery without CPCM, the maximum temperature of the battery module with CPCM decreased by 10.4°C and 13.4°C at 1C and 2C discharge rates, respectively. However, PCM only provides thermal storage capability, but not active cooling capability. Therefore, PCM is often combined with other active cooling technologies to form a composite thermal management system. For example, Xin *et al*. [30] inserted a liquid-cooled channel into a CPCM to enhance the cooling performance of a BTMS at high ambient temperatures (Figure 4). The CPCM wraps the cells, and an aluminum frame with a liquid-cooled channel wraps all the CPCM-wrapped cells to provide active heat dissipation.



(a)

(b)

Fig. 4. Structures of battery module with only CPCM (a) and hybrid with liquid (b) [30]

Heat Pipe Cooling

Heat pipe achieves the function of efficient cooling by evaporating the working fluid from the high temperature end to the other end to exchange heat with the outside world. Heat pipes are gaining more and more attention in thermal management of battery packs in electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to their superconductivity, robustness, low maintenance, and durability [31]. In recent years, the research on heat pipes has conducted comprehensive and systematic research on the heat pipe core structure design, heat transfer characteristics of different working fluids, pipe body shape and pipeline layout. Gan *et al*. [32] investigated circular heat pipes and showed that increasing the length of the condenser section and the height of the aluminums casing at the evaporator end can lower the maximum component temperatures and improve the temperature uniformity. He *et al*. [33] further optimized the design by reducing the maximum temperature and temperature difference to 37.58°C and 3.67°C, respectively, at a discharge rate of 3C. Combining heat pipes with phase change liquid (HP-PCL) cooling has proven to be an effective way to maintain optimal battery temperature, preventing critical conditions such as thermal runaway by controlling the temperature to 185°C [34]. Nasir *et al*. [35] used 1.5% volume of Al_2O_3 as a nanofluid in a heat pipe embedded in an aluminum plate and showed that it was possible to reduce the battery surface temperature by 7.28% and the overall thermal resistance by 15%. Zhu *et al*. [36] believed that flat heat pipes are more suitable for thermal management of square lithium batteries and designed a flat heat pipe thermal management system (Figure 5). Under transient high-rate discharge conditions, the improved flat heat pipe can reduce the maximum battery temperature by 6.4%, and reduce the maximum battery temperature and state of charge difference by 18.4% and 16.3%, respectively.

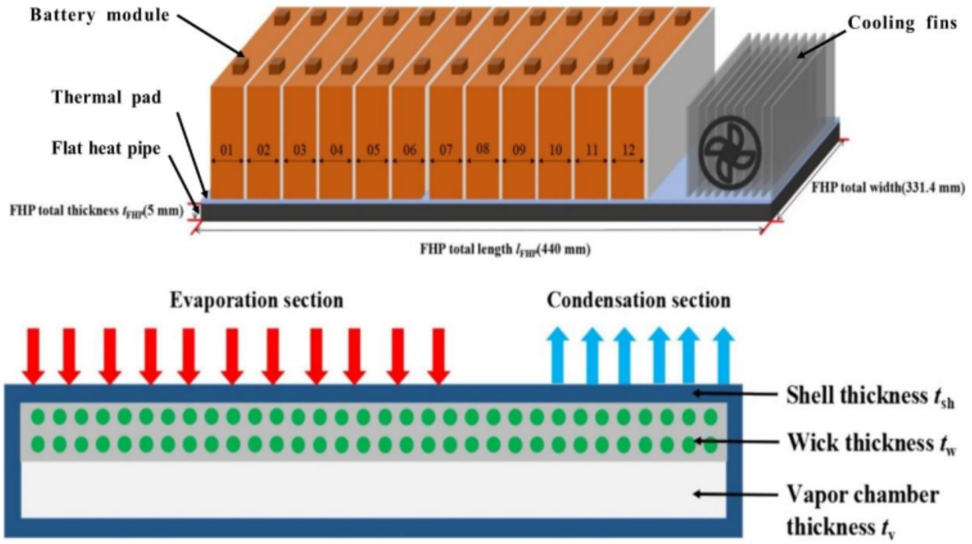


Fig. 5. Flat heat pipe cooling system

Microchannel Liquid Cooling Technology

In order to meet the demand for increased energy density of automotive batteries, on-board power batteries need efficient thermal management systems without taking up too much space. Since microchannel liquid cooling plates occupy a small volume, have high heat transfer efficiency and uniform heat transfer, they are suitable for placement between batteries for thermal management. In recent years, there has been an increasing amount of research on the optimal design of microchannel heat transfer systems. The optimization research on microchannel liquid cooling is mainly divided into the optimization of the channel structure and flow direction, the optimization of the microchannel liquid cooling material, and the improvement of the microchannel liquid cooling plate material and processing technology. Figure 6 depicts the research division of microchannel battery thermal management at this stage.

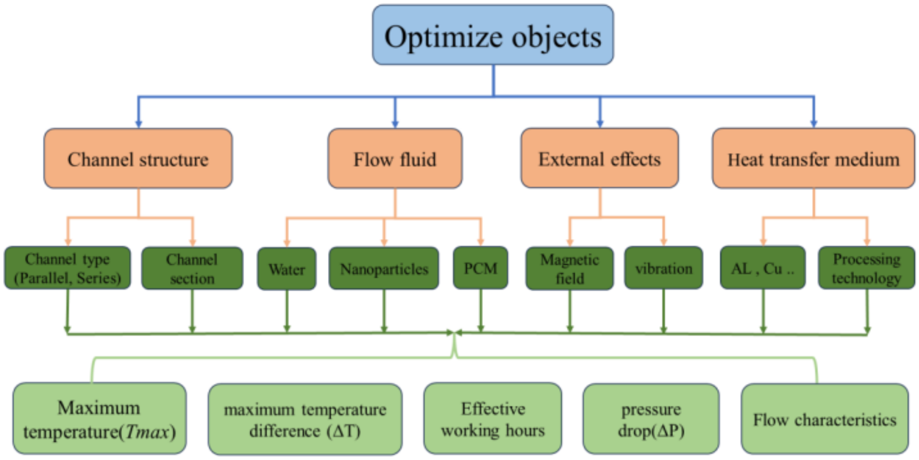


Fig. 6. Technical routes and optimization indexes of microchannels optimized for battery thermal management applications

The channel structure of microchannel cold plate is mainly classified into two categories: serial and parallel. Qian *et al*. [37] established a 3D model of a straight channel cold plate (Figure 7a) and investigated the effects of the number of channels, inlet mass flow rate, flow direction, and channel width on the thermal performance of the battery module. It's found that a 5-channel cold plate is sufficient to obtain a good cooling effect. Huang *et al*. [38] applied the streamline concept to a microchannel liquid cooling plate to reduce flow resistance (Figure 7b) and performed CFD analysis on its flow and heat transfer capabilities. The results showed that the streamline design increased the heat exchanger efficiency by up to 44.52% and also effectively improved the temperature uniformity. The microchannel structures are categorized into series and parallel type structures as shown below (Figure7c) [39].

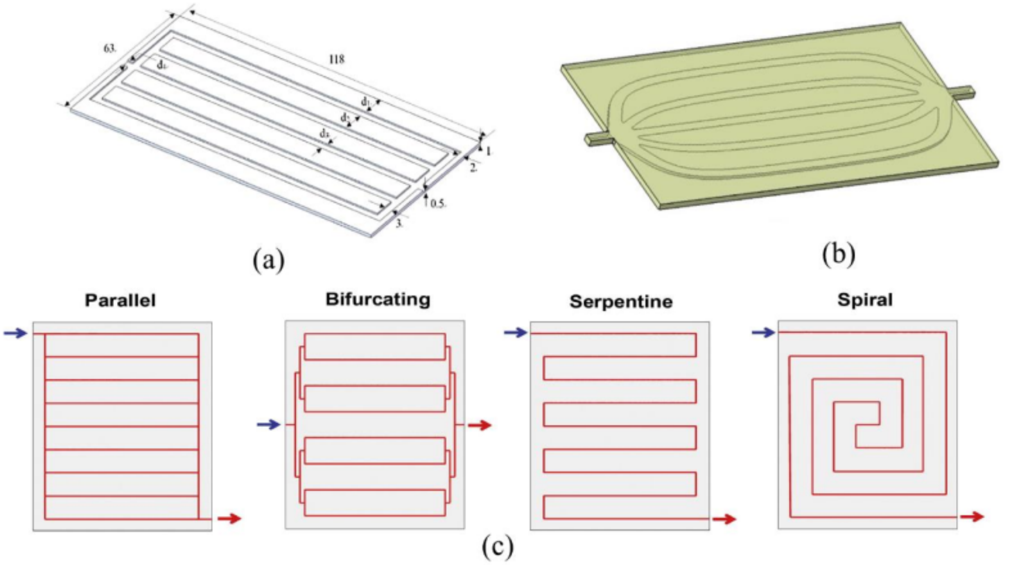


Fig. 7. Straight-through-channel cold plate (a), streamlined microchannel liquid-cooled plate (b) , parallel and serial-traveling cold plate (c) [37-39]

Wu [40] used a multi-objective topology optimization method to optimize the design of the through-channel cold plate (Figure 8). Velocity, temperature, and pressure fields were calculated using the finite element method. The numerical results of computational fluid dynamics show that the optimized branch flow linear microchannel cold plate has the advantages of reducing pressure drop and improving the comprehensive heat transfer performance. With the optimized cold plate, the average temperature of the hottest Li cell (LIB), the maximum average temperature deviation between LIBs, and the pressure drop were reduced by 10.3%, 59.4%, and 23.9%, respectively, compared with the conventional straight-through-channel cold plate at an inlet velocity of 0.4 m·s^{-1}. The optimized cold plate exhibited a 63.0% increase in heat transfer coefficient and Nussle number compared to the conventional one using the same inlet velocity of the water coolant. Wu *et al.* [41] performed topology optimization on a branching flow-through cold plate to enhance the temperature uniformity of the structure by using the temperature variations as constraints during the topology optimization process. The optimized topology is obtained by checking the effect of topology optimization penalty factor, Reynolds number, objective function weights and temperature variance constraints on the optimization results. The average temperature of the cold plate optimized using the topology is 302.9 K and the maximum temperature is 304.25 K. The internal temperature difference is 4.7 K. The average temperature is lower by 1.18 K and the maximum temperature is lower by 1.8 K as compared to the cell with parallel channel cold plate.

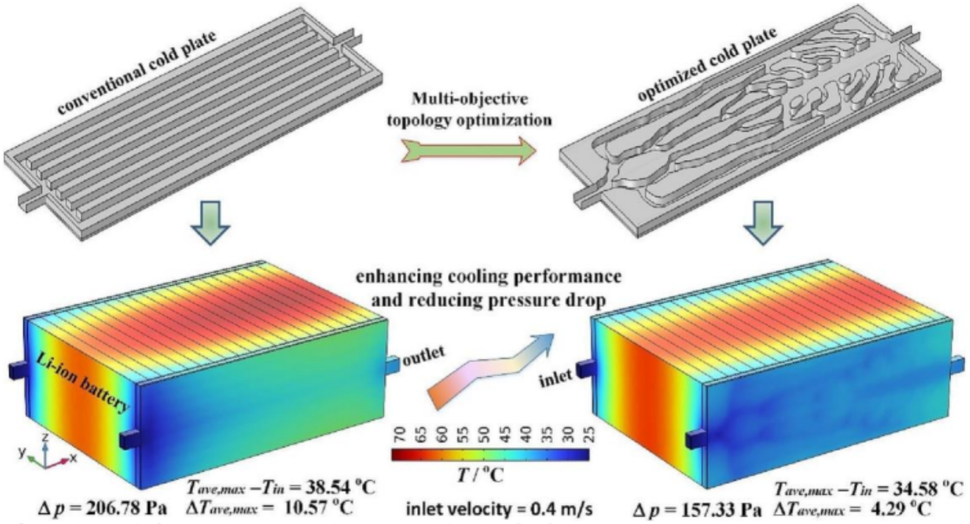


Fig. 8. branch flow linear microchannel cold plate [40]

Series liquid-cooled microchannels are effective in reducing pump power consumption. Lin and Zhou [42] designed a new serpentine microchannel cooling system (Figure 9), studied the thermal performance of the microchannels using numerical simulation, and built an experimental setup for verification. The effects of key parameters such as inlet Reynolds number, discharge current, aspect ratio, inlet temperature and coolant on the cooling performance were systematically investigated. The experiments showed that the cooling system has good thermal performance at low pumping power.

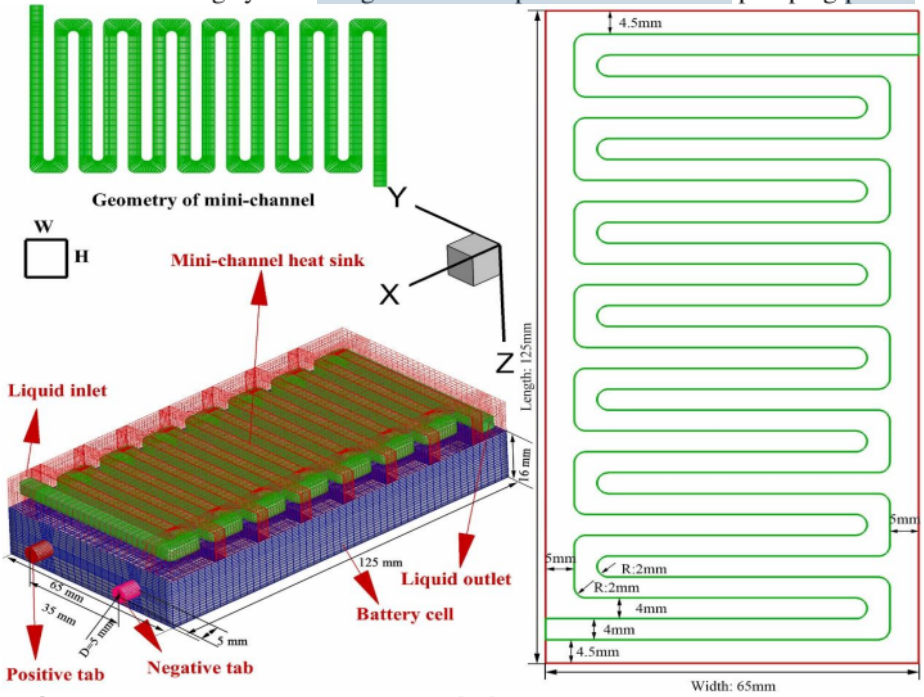


Fig. 9. Serpentine microchannel cooling system [42]

Inspired by the flow characteristics of the Tesla valve, Monika *et al*. [43] designed and analyzed a multi-stage Tesla valve with forward and reverse flow structures and applied it to the battery thermal management system. The results showed that for a standard 20 Ah pouch lithium-ion battery with dimensions of 160 mm × 227 mm × 7.25 mm, the reverse flow in a multi-stage Tesla valve enhances heat transfer mainly due to flow bifurcation and mixing mechanisms, but at the expense of pressure drop. A cold plate with four channels and a valve-to-valve distance of 8.82 mm exhibited the most efficient cooling performance. Based on this study, Monika *et al*. [44] further analyzed the structural optimization of the multi-stage Tesla valve. The simulation results show that the use of a larger channel width, a larger outer curve radius R, and a smaller valve angle θ can effectively reduce the peak temperature rise of the battery (Figure 10). Furthermore, for a certain Reynolds number, the increase in the outer curve radius and valve angle, in addition to the channel width, has little effect on the pressure drop.

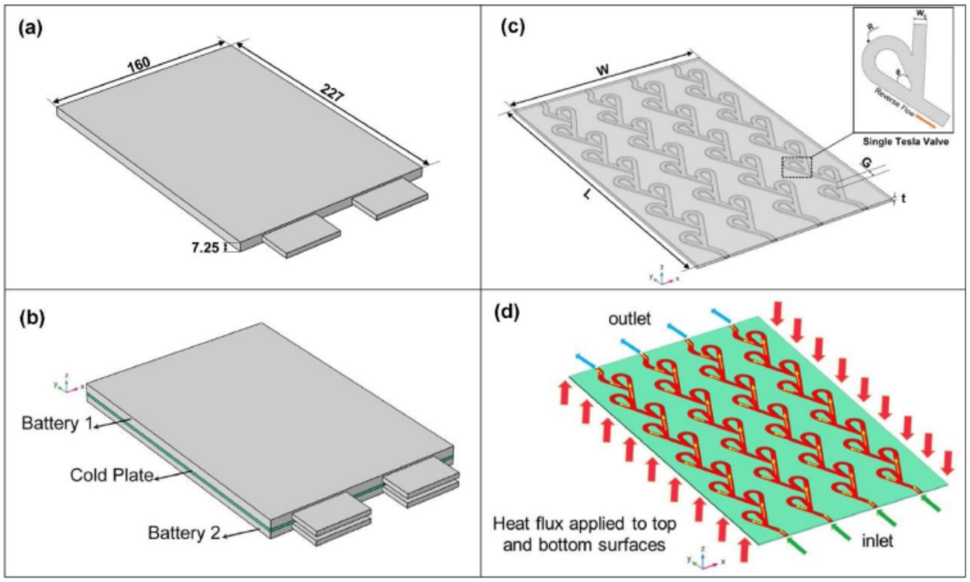
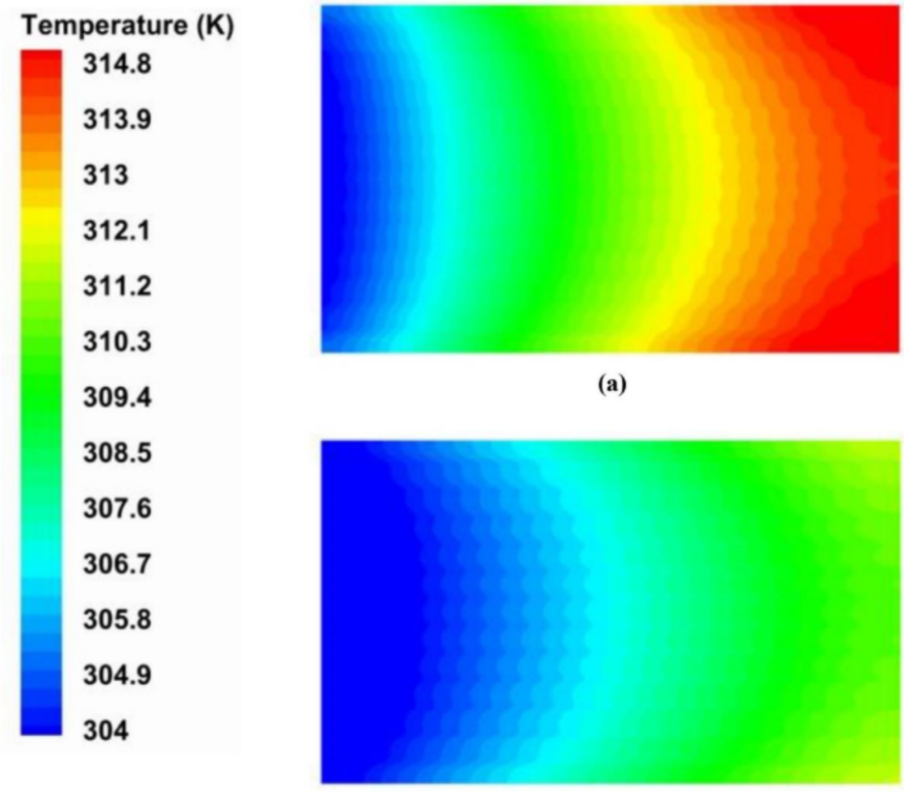


Fig. 10. Multistage Tesla valve microchannel cooling system [44]

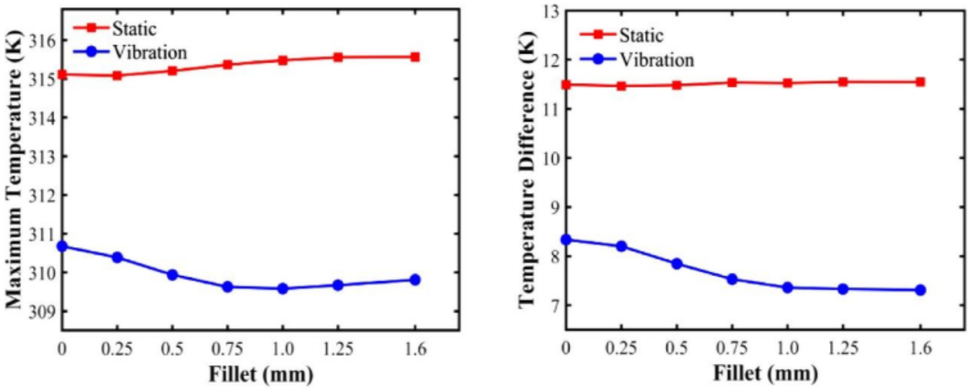
Zuo *et al*. [45] investigated the performance of a microchannel cold plate in a liquid cooling system under vibration conditions, considering the effect of vibration on microchannel heat transfer during vehicle driving. The effects of vibration frequency, amplitude and inlet mass flow rate on vibration were numerically simulated. A method of adding rounded corners of square cross-section channels was proposed to further improve the vibration enhanced heat transfer effect. The results showed that vibration can enhance the heat transfer capacity of the cold plate, and its enhancement effect is related to the vibration frequency, amplitude and mass flow rate. Figure 11 shows the temperature contour comparison between static and vibrating conditions when the mass flow rate is 5 g/s at 10 Hz, 0.8 mm vibration. Compared with the static state, the maximum temperature of the cold plate is reduced by 4.35 K, while the temperature difference is reduced by 3.03 K. Meanwhile, the vibration state also causes an increase in the pressure drop in the microchannel, placing higher demands on the power of the pump. Adding rounded corners to the channel cross-section can enhance the enhanced heat transfer effect of vibration and reduce the pressure drop. Compared with the original square cross-section, the overall performance of the cold plate with R1.0 mm fillet is improved by 33.7%, as shown in Figure 12.



(a)

(b)

Fig. 11. Temperature contours of the cold plate under static conditions (a) and vibration conditions (b) [45]



(a) (b)

Fig. 12. Effect of fillet size on cold plate properties (a) maximum temperature (b) temperature difference [45]

Application of Nanofluids in Microchannel Liquid Cooling

Nanofluids are colloidal suspensions consisting of nano-sized particles suspended in a base fluid such as oil, water, glycol and other conventional fluids commonly used for heat transfer. Metals (*e.g*., Cu and Ag) and oxides (*e.g*., Al_2O_3, CuO, and TiO_2) as well as carbon nanotubes (CNTs) can be used as additives. Figure 13 shows a comprehensive classification of nanoparticles. Numerous studies have demonstrated experimentally and numerically that nanofluids can achieve higher thermal conductivity [46, 47]. Therefore, nanofluids are widely used to improve heat transfer performance, especially for electronic devices [48, 49]. Their thermal properties can be modulated along their suspension stability during the preparation of nanofluids by particle size, which is usually considered as the main physical criterion. In order to improve the efficacy of thermal management systems, scientists are looking for ways to utilize the special properties of nanoparticles to prepare highly stable and conductive heat transfer fluids [50-52].

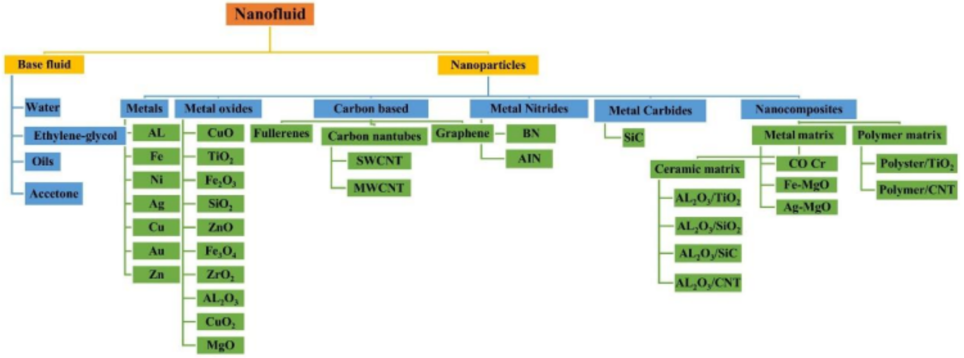
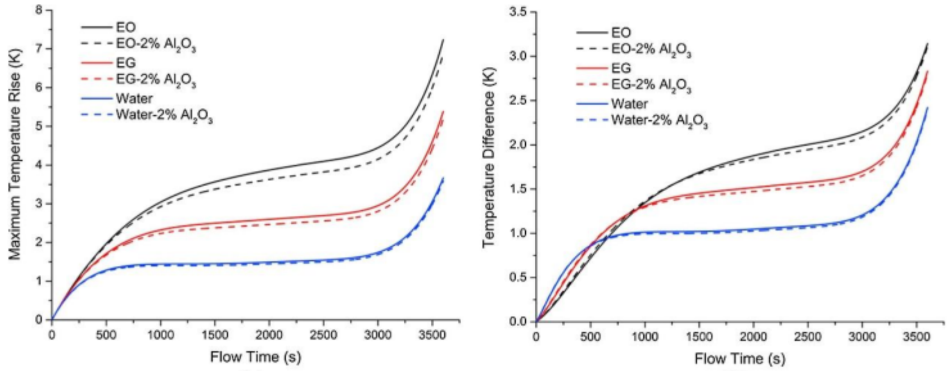


Fig. 13. Classification of nanoparticles [53]

In order to realize a high energy prismatic Li battery thermal management system (LIB TMS), Liu *et al*. [54] incorporated Al_2O_3 particles in a straight-through-channel type liquid microchannel cooling system and numerically investigated the cooling system using various coolants such as engine oil (EO), water and ethylene glycol (EG) in addition to Al_2O_3 nanofluids. As shown in Figure 14, the thermal performance of the cells using all these fluids is significantly improved compared to the adiabatic condition. Water provides the best cooling effect among these pure fluids due to its superior thermal conductivity and heat capacity. The thermal performance of base fluids such as EO, water, and EG was improved by the addition of Al_2O_3 nanoparticles with various release rates, *i.e*., 1C, 2C, and 3C, even at elevated fluid pressure drop. The lower the thermal conductivity of the base fluids, the more pronounced the improvement. The addition of nanoparticles had a limited effect on temperature uniformity, although the maximum temperature rise was greatly reduced. The effect of various factors on microchannel cooling execution was then investigated using aqueous alumina nanofluids and water. The higher volume fraction of nanoparticles further reduced the temperature rise inside the cell near the aluminum cold plate and reduced the temperature rise due to better cooling influence. In addition, the coolant flow rate had an effect on both temperature uniformity and maximum temperature. Increasing the velocity at the cost of greater energy utilization contributes to the improvement of the heat transfer factor.



(a) (b)

Figure 14. Cooling performance enhancement of nanoparticles on (a) maximum temperature rise and (b) temperature difference [54]

Kiani *et al*. [55] designed a novel battery thermal management system consisting of a metal foam-paraffin PCM composite, nanofluid cooling, and a heat sink to study how metal nanoparticles Fe_3O_4 and CuO affect the battery temperature under an external alternating magnetic field. The experimental results shown in Figure 15 shows that the addition of nanoparticles significantly enhances the thermal performance of the hybrid BTMS, especially after adding the influence of the magnetic field. This increase is attributed to the heat transfer inside the cell by forced convection in the presence of nanofluids. The presence of nanofluids delayed the runaway state of the battery, allowing it to remain in a safe state for a longer period of time. In addition, they measured the temperature uniformity of the battery in the presence and absence of the porous medium. Compared with the base case, the maximum temperature of the battery in the best case was reduced by about 7.5°C, while the operating time of the system increased by 179% at Re = 1250. Similarly, the improvement in battery cooling is 151% when the Reynolds number is 890. In addition, the temperature difference of the proposed hybrid battery thermal management system (BTMS) is mainly below 4°C.

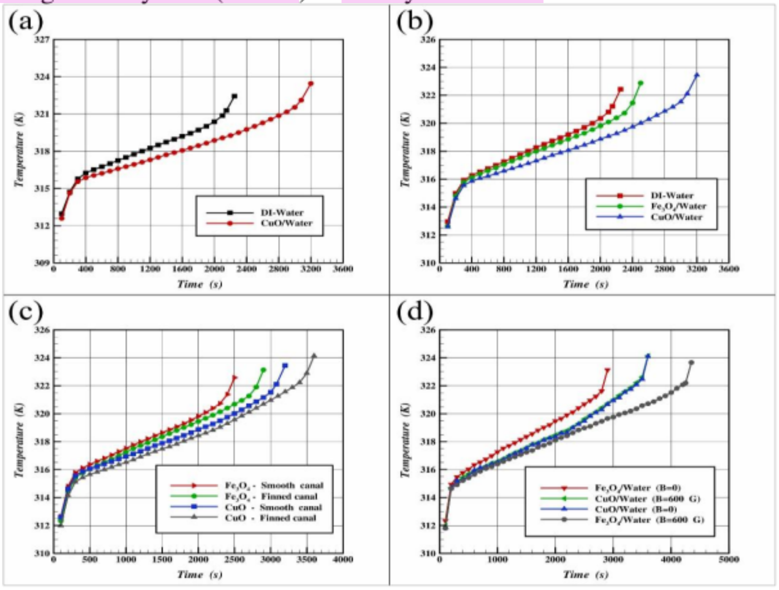
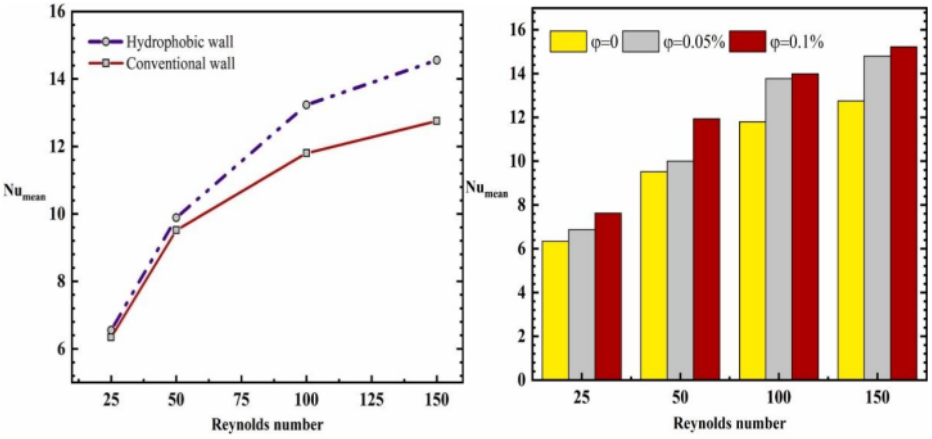


Fig. 15. Influence of additional magnetic field on the heat transfer effect of (Fe3O4 and CuO) nanofluidic microchannels [55]

Anqi [56] used a mathematical model of the properties of graphene nanosheet-platinum nanofluid [57] to numerically simulate the flow and thermal behavior of the nanofluid in serpentine microchannels and battery surfaces. The results confirmed that the nanofluid was able to increase the heat transfer between the serpentine microchannel and the battery by up to 20% (Figure 16). In addition, the most effective parameter for heat transfer improvement was the Reynolds number, and when the Reynolds number was varied from 25 to 150, the heat transfer increased from 6.34 to 12.75. More importantly, the hydrophobic wall of the microchannel can enhance the heat transfer by 14.4% compared with the conventional wall.



(a) (b)

Fig. 16. Effect of Reynolds number and hydrophobic wall on heat transfer (a), Effect of nanoparticle volume fraction φ on heat transfer at different Reynolds numbers (b) [56]

Microencapsulated phase change materials (MPCM) with nanofluids composed of microencapsulated phase change slurry (MPCMS) with excellent fluidity and heat exchange efficiency are suitable to be used as an active heat transfer material, capable of storing and transferring more thermal energy without occupying additional space [58, 59]. Chen *et al*. [60] explored the feasibility of slurries with phase change properties for thermal management systems of liquid-cooled batteries by using suspension method. The MPCMS was prepared and evaluated with three base fluids (water, ethanol and silicone oil). The results showed that the silicone oil could keep the slurry from settling for 7 d and had the best stability. In addition, graphene (GE) was introduced to increase the heat transfer rate of the slurry. The prepared pastes were then applied to prismatic Li-ion battery modules to verify their thermal management performance. Figures 17(a, b) show that without forced cooling, the T_{max} of the blank module exceeded 58°C at the first charge/discharge cycle and reached 66.72°C after 5 cycles. When the coolant was introduced, the temperature of the cell was reduced to varying degrees as the circulating coolant removed heat in time through convective heat transfer. As shown in Figures 17(c, d), pure silicone oil and MPCMS-Si helped ΔT_{max} reach 3.98°C and 8.23°C, respectively. The GE-MPCMS-Si module showed the best thermal stability and durability during charge/discharge cycles. There was no serious heat buildup after 5 cycles. The ΔT_{max} was maintained at about 52.23°C. The thermal stability and durability of the GE-MPCMS-Si module were also improved. In addition, the ΔT_{max} has exceeded 14.49 °C.

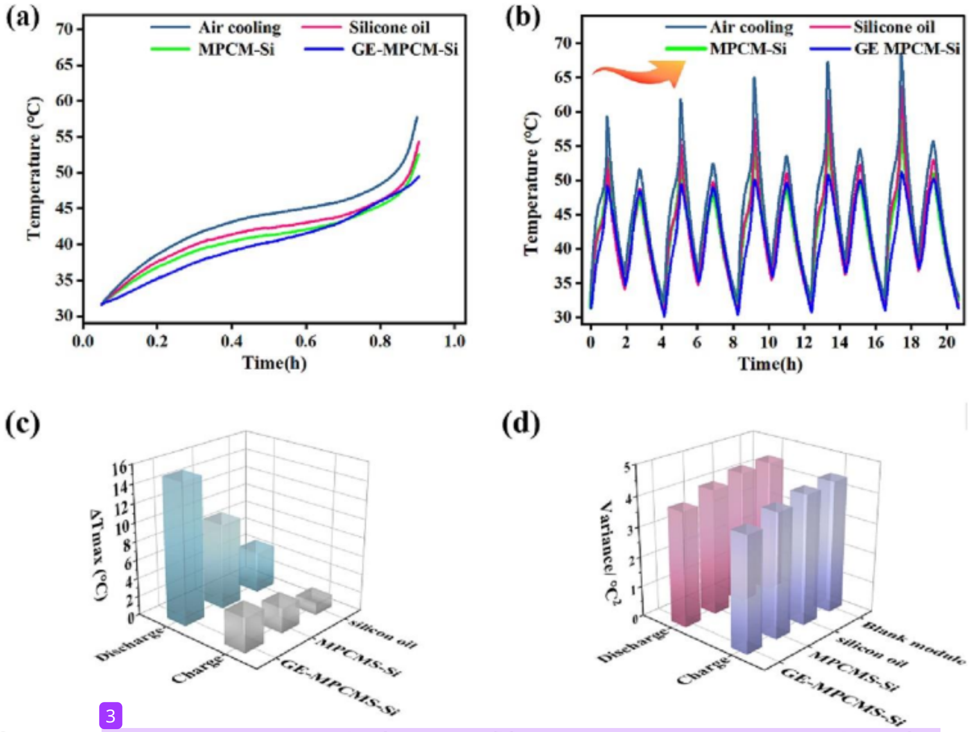


Figure 17. Temperature curves at the first cycle; (b)Temperature response curves during five cycles; (c) ΔTmax, and (d) variance (σ2) of battery modules with different coolant [60]

CONCLUSIONS

According to the papers published in recent years, most of the research on microchannel liquid cooling technology has been applied to prismatic batteries, which is due to the compact structure of the microchannel cold plate, the larger heat exchange area, and the ability to better articulate between prismatic batteries. At present, the optimization of microchannels mainly includes the optimization of the channel structure of the microchannel cold plate, the study of the flow medium (such as nanofluids, phase change materials, etc.), and the coupling relationship of the additional external effects. There are relatively few studies on coupling the above three for battery thermal management. Therefore, this is also the main direction of future research on the application of microchannel liquid cooling technology in battery thermal management.

In view of the current research status of microchannel liquid cooling technology applied to battery thermal management, this article makes the following prospects for the future development of this technology:

1. The research on flow materials tends to have better flow properties, heat transfer performance and higher heat storage capacity, but these three optimization indicators are difficult to achieve at the same time, and a lot of experimental analysis is needed to find

the optimal solution. Therefore, the optimized formulation of composite nano phase change pastes has become a promising research direction.

2. The microchannel liquid cooling plate structure itself has high strength, so using a microchannel liquid cooling plate instead of the core wall material combined with the core body to form an integrated core body can not only save space to a greater extent, but also more effectively enhance the heat exchange capacity.
3. The combination of microchannels and other thermal management methods is a hot topic in current and future research. For example, the heat transfer efficiency can be greatly improved by using the microchannel cold plate as a heat pipe [61]. Combining it with phase change materials can improve the uniformity of battery temperature.
4. The combination of microchannel technology and control technology is the future research direction. Through the combination of channel design and microfluidic control system, targeted centralized heat transfer can be achieved. At the same time, precise cooling can be achieved according to the predicted battery temperature changes, which can better realize real-time monitoring of temperature.

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