Low-Temperature Heating for Lithium-Ion Batteries

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Lithium-ion batteries (LIBs) have the advantages of high energy/power densities, low self-discharge rate, and long cycle life, and thus are widely used in electric vehicles (EVs). However, at low temperatures, the peak power and available energy of LIBs drop sharply, with a high risk of lithium plating during charging. This poor performance significantly impacts the application of EVs in cold weather and dramatically limits the promotion of EVs in high-latitude regions.

lithium-ion battery   low temperature

1. Introduction

With the rapid development of industrialization, the global energy shortage and environmental pollution are becoming increasingly serious, greenhouse gas emissions are increasing year by year, and the awareness of energy saving and environmental protection has become deeply rooted in people's hearts. The theme of electric vehicles (EVs) in today's world is energy saving and environmental protection, and EVs have become the main direction of transformation and development of the global automotive industry and an important engine to promote world economic growth. China released the "New Energy Vehicle Industry Plan", striving to reach the international advanced level of core technology of new energy vehicles by 2035, and the quality brand has strong international competitiveness [1]. According to the regulations previously approved by the EU Council, the sale of non-zero-carbon emission new fuel vehicles will be banned in the EU from 2035 onwards [2]. In 2021, U.S. President Joe Biden signed an executive order proposing that by 2030, the U.S. should achieve a goal of 50% of total new vehicle sales for EVs, aiming to address the threat of climate change [3].

With continued support from national policies and increased public awareness of energy conservation and environmental protection, EVs are growing rapidly. From 2015 to 2022, the EV sales share grew 20 times worldwide, which increased by 29 times, grew 17.5 times, and 9.9 times in China, Europe, and America. The global EV sales grew from 0.55 million to 10.2 million [4].

Compared with traditional lead-acid and nickel–cadmium batteries, lithium-ion batteries (LIBs) are widely used in the field of electric vehicle power drive as a key component because of their advantages such as high energy and power densities, low self-discharge rate, no memory effect, long cycle life, and environmental friendliness. However, the performance of LIBs is greatly reduced at low temperatures. The researchers studied the charging, discharging, electrochemical impedance spectroscopy (EIS), and degradation of LIBs at low temperatures, where the charge transfer kinetics at the LIB interface is hysteretic and the conductivity of the electrolyte is reduced. The solid-phase diffusion of LIBs is slower, which leads to an exponential increase in LIB impedance and a sharp decrease in available energy and peak power, resulting in a sudden decrease in EVs' driving range and hill-climbing performance in low-temperature environments [5] and limited performance in scenarios requiring wide-temperature domain use. Moreover, LIBs suffer from extremely poor charging performance in low-temperature environments, limited at a very small C-rate [6], and it is basically impossible to charge the LIB below −10 °C. Compared with the room temperature state, the charging and discharging capacity of the battery is greatly reduced [7]. When the lithium plating reaches a certain level, the generated lithium dendrites will pierce the battery diaphragm, causing the risk of internal short circuit inside the battery, and even cause an explosion, resulting in safety accidents [8].

China accounted for 59% of global EV sales in 2022, cementing its position as the world's largest EVs market. The country is also the world's biggest EVs producer, with 64% of global volume [9]. Therefore, through the Chinese market, people can see the pattern of new energy vehicles in the global market. Winter temperatures in northern China are often below 0 °C, and even extreme temperatures in some areas can reach −30 °C [10]. However, the optimal operating temperature range of LIBs is often considered to be from 15 to 35 °C [11]. When the operating temperature of LIBs exceeds the optimal operating zone, such as subzero temperatures, the internal electrochemical reaction of the battery becomes slower, the internal resistance becomes larger, and its available capacity and energy are abruptly reduced [12][13]. According to the latest 2022 China EV sales statistics, the amount of EVs' sales in the north of China is quite low, which primarily attributed to the poor performance of LIBs due to the low-temperature regions. The unevenness of the promotion and application of EVs mainly stems from the problem of wide-temperature domain environmental adaptability of LIBs. Therefore, understanding the poor performance of LIBs in low-temperature environments has become a hot research topic.

In addition to studying the performance of batteries at low temperatures, researchers have also investigated the low-temperature models of batteries. The accuracy of LIB models directly affects battery state estimation, performance prediction, safety warning, and other functions. Commonly used battery models work well at room/high temperatures, but their accuracy decreases significantly at low temperatures. By improving traditional models for application in low-temperature environments, researchers can more accurately simulate the battery operating state at low temperature. At the same time, the electrothermal coupling behavior of the battery in the low-temperature environments will directly affect the accuracy of the battery model, and the establishment of the electrothermal coupling model is essential to accurately describe the low-temperature characteristics of the battery.

Finally, plenty of efforts have been made to restore the performance of batteries at low temperatures, and two main methods are currently used: (1) Improving the positive and negative electrode materials or electrolyte materials [14]. Improvement of low-temperature performance of LIBs involves various aspects. Currently, research on electrolytes mainly focuses on modifying solvents and lithium salts, adding a small amount of organic compounds, or combining modification methods. Research on electrode materials mainly focuses on metal or nonmetal doping, surface coating, and morphology control. There are also studies on other battery components such as separators, binders, and conductive agents. The purpose of these studies is to improve the low-temperature performance of

LIBs. However, there are many factors affecting the low-temperature performance of LIBs, which is a complex systematic problem, and improved electrode materials can only meet part of the performance requirements of LIBs. High-performance electrode materials that can balance cost, energy density, and safety performance are difficult to achieve in a short time. (2) Preheating the battery. Since the performance degradation of LIBs at low temperatures is recoverable, that is, if the operating temperature of the battery is raised to room temperature (RT), the performance of the LIB will be restored to the level at RT. LIB low-temperature heating technology is well adapted to meet the use of power batteries under low-temperature conditions, and it is also the mainstream solution to solve the problem of low-temperature LIBs. At present, research on the classification methods of low-temperature heating for LIBs [15][16] mainly includes the internal heating method, external heating method, and hybrid heating method.

2. Low-Temperature Heating

Because the performance decrease of LIBs in low-temperature environments is recoverable, the performance of LIBs will be restored to the level under normal temperature if the operating temperature of LIBs is raised using the techniques, such as low-temperature heating approaches. The low-temperature heating technology of LIBs has good adaptability, which can meet the use of power battery under low-temperature conditions, and is also the mainstream solution to solve the poor low-temperature performance of LIBs at present. According to the different modes of heat transfer and generation in the heating process, the low-temperature heating of LIBs can be generally divided into internal heating, external heating, and hybrid heating, as shown in **Figure 1**. According to whether the heat is generated by the internal resistance of the battery itself or by an external heat element, the heating method can be categorized into internal heating [17][18][19][20][21][22][23] and external heating [24][25][26]. Hybrid heating is a heating method that includes internal and external heating [27][28][29][30]. The most special is the self-heating lithium-ion battery [31][32], the battery internal embedded nickel foil to realize the heating of the battery. On the one hand, the nickel foil is a part of the battery in terms of physical structure, which is the “internal resistance” of the battery and can be seen as internal heating; on the other hand, the nickel foil is an external component of the battery in terms of electrochemical reaction, which is not the internal resistance of the battery and can be regarded as hybrid heating.

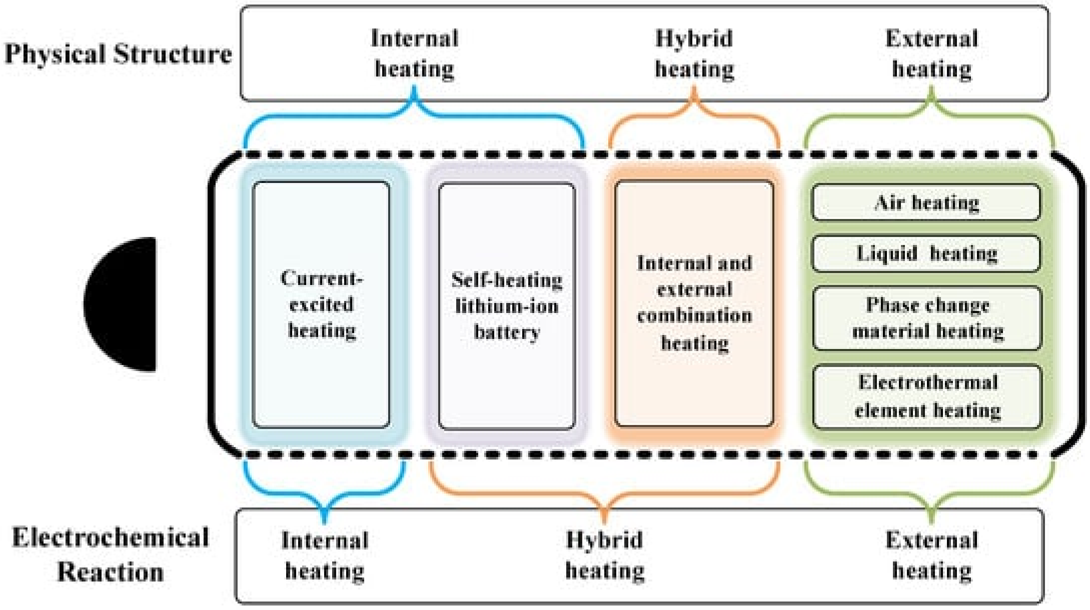

Figure 1. Classification of low-temperature heating for LIBs.

2.1. Internal Heating

Classified from the perspective of physical structure, internal heating includes current-excited heating and SHLB technology; current-excited heating is categorized according to different current excitations applied to the battery, including direct current (DC) heating, AC heating, and AC–DC-superimposed heating.

2.1.1. Current-Excited Heating

Constant-current discharge (CCD) heating means that the current remains constant during the heating process. Wu et al. [17] studied the relationship between discharge rate, heating time, and power consumption under constant-current discharge condition based on the battery temperature rise model and the ampere-hour integral. The results show that when the discharge rate is 2 C-rate, the heating rate is 3.21 °C/min, and the power consumption does not exceed 15% of the rated capacity; when the discharge rate is 1 C-rate, the heating rate is 0.83 °C/min, and the power consumption is almost 30% of the rated capacity; when the discharge rate is less than 1 C-rate, the heating time and power consumption are significantly increased.

Constant-voltage discharge (CVD) heating means that the voltage remains constant during the heating process. Ji et al. [18] studied the effect of constant-voltage discharge on the low-temperature heating of the battery. For constant-voltage discharge mode, the lower the voltage, the shorter the heating time. The heating rate corresponding to 2.8 V discharge voltage can reach 6.6 °C/min.

Ruan et al. [19] proposed an optimized heating strategy based on discharge voltage, aiming at minimizing both heating time and capacity decay. The capacity loss is obtained by establishing the attenuation model, and the Pareto front of heating time and capacity loss is obtained by genetic algorithm. After normalization, the influence of weight coefficient on heating effect is discussed, and the optimal heating strategy is obtained. The experimental results showed that lower discharge cut-off voltage will shorten the heating time but will increase the capacity decline. The optimal heating voltage is 2.43 V. In order to achieve the constant discharge cut-off voltage during the heating process, the trapezoidal current method is used to ensure the constant voltage. This heating method can raise the battery from −30 °C to 2.1 °C in 103 s, and the average temperature rise rate can reach 18.7 °C/min. After 500 cycles of heating, the battery capacity loss is 1.4%, indicating that this heating method has little impact on capacity loss and greatly improves the low-temperature performance of the battery. This heating method comprehensively considers the impact of the discharge cut-off voltage on the heating time and capacity decline, but the energy of the battery during the discharge process is not fully utilized. Therefore, how to maximize the energy efficiency for the battery low-temperature preheating is a future research direction.

When the current excitation is AC, the SOC of the battery is kept unchanged, and the commonly used AC is a sinusoidal one. Zhang et al. [20] established a frequency domain heating model based on the equivalent circuit and studied the influence of the amplitude and frequency of the constant sinusoidal current (CSC) on the low-temperature heating method of the battery. Taking the 18650 batteries as an example, the battery temperature rises from −15 °C to 5 °C. When the AC amplitude is 7 A (2.25 C-rate) and the frequency is set to 1 Hz, the temperature rise rate of the battery can reach 2.33 °C/min, and the internal temperature uniformity of the battery is good. After repeated AC preheating tests, the battery capacity decline is experimentally validated as low. According to the preheating test results, when the AC frequency is constant, the heating time decreases with the increasing AC amplitude; when the AC amplitude is constant, the heating time increases with the increase of AC frequency. Besides the consideration of heating performance when selecting AC parameters, the possibility of lithium deposition also needs to be heeded.

Ruan et al. [21] proposed the optimal frequency heating strategy based on constant polarization voltage (CPV), taking into account the factors of heating time and life decay, based on the electrochemistry–thermal coupling model. The optimal heating frequency is deduced for maximum heat generation. The battery was heated from −15.4 °C to 5.6 °C in 338 s, with an average heating rate of 3.73 °C/min, and the temperature distribution is basically uniform. The experimental results show that the heating method has little effect on the battery life.

Jiang et al. [22] proposed a low-temperature heating strategy of AC plus DC. Through analysis and derivation, the expression of DC and AC amplitude ratio to prevent lithium deposition is obtained. The battery heating is realized by generating AC-superimposed DC current waveform through the soft-switch resonant circuit. This method takes the battery itself as the heat source. By periodically controlling the MOSFET switch, the current passing through the battery can be AC-superimposed DC. By controlling the parameters such as capacitance and inductance, the ratio of DC to AC amplitude can be adjusted to reduce the risk of lithium plating in the battery. Through this circuit, the battery can be raised from −20.8 °C to 2.1 °C in 600 s, and the temperature difference between battery packs is less than 1.6 °C, which means that the heating method can achieve the goal of uniform temperature distribution of LIBs. After 600 cycles of heating, no obvious aging characteristics of the battery were found, indicating that the heating method has a low impact on the battery life.

Qu et al. [23] used MOSFET as the switch control element to realize pulse heating by designing the circuit, with the control circuit. The effects of switching frequency (0.1 Hz, 0.5 Hz, 1 Hz), different initial temperature, and SOC on heating were studied. The results showed that the switching frequency has little effect on heating rate, while the ambient temperature and initial SOC of battery have a significant effect on heating rate, and the heating rate can reach 6.86 °C/min.

2.1.2. SHLB Heating

Wang et al. [31] achieved self-heating inside the battery by embedding nickel foil inside the battery. The nickel foil leads out two tabs, one connected to the negative terminal and the other extended to the outside of the battery to form the active terminal. When the switch is closed, the current will generate a large amount of heat through the nickel foil, which will increase the battery temperature. When the battery temperature reaches the threshold, the switch is disconnected, and the battery stops self-heating and returns to the normal mode. The temperature-rise rate of this method can reach 60 °C/min. Yang et al. [32] compared the external heating method using a resistance heater with SHLB heating method and showed that the heating rate of SHLB is increased by nearly 40 times. The more nickel foils embedded in the battery, the higher the heat production of the battery, the faster the temperature rise of the battery, and the better the temperature uniformity of the battery.

It can be seen that the heating rate of the battery internal heating method is fast, and the temperature uniformity of the battery is good. However, DC self-heating would waste a certain amount of power, indicating low heating efficiency; AC self-heating battery power remains unchanged, but the need for an AC generator would increase the complexity of the heating circuit, and heating at high SOC poses a high risk of lithium plating; AC and DC superposition of the method avoids the risk of lithium plating, but it also reduces the heating rate, and requires additional design of circuits, increasing the complexity of the system. Compared with the traditional heating method, SHLB can achieve the purpose of rapid and efficient heating of the battery. However, because the heating scheme needs to change the internal structure of the battery, it is a huge uncertainty around the safety of the battery. At the same time, in order to reduce the temperature difference, it is necessary to embed multiple nickel sheets inside the battery, which increases the manufacturing difficulty and cost of the battery.

2.2. External Heating

External heating mainly uses external heat sources to raise the temperature of the battery through convection or conduction heat transfer. It can be classified according to different external heat transfer methods, mainly including air heating, liquid heating, phase-change material (PCM) heating, and electric heating element heating. The efficiency of external heating is generally low, and the heating rate is slow.

Ji et al. [18] proposed an air-heating method and studied the influence of different heating resistance on heating efficiency and heating time. If the selected heating resistance is smaller, the heating time is shorter and the heating efficiency is higher. When the battery is raised from −20 °C to 20 °C, the heating resistance of 0.4 Ω is selected, and the temperature-rise rate can reach 28.24 °C/min. It can be seen that the speed of temperature rise has increased significantly, but the internal temperature gradient of the battery is large, the fan increases additional costs, and the system construction is relatively complex, taking up a large space, which is not reasonable for the current lightweight requirements of EVs.

Wang et al. [24] evaluated the performance of the immersion preheating system by developing a three-dimensional Computational Fluid Dynamics (CFD) model. Silicon oil is used as the heat-transfer fluid. Based on the simulation model, it is found that the heating rate is as high as 4.18 °C/min, and the temperature difference of the battery pack is less than 4 °C. However, the design of liquid heating systems is often complex, and costly, and requires good sealing performance, which is a huge challenge for practical engineering applications.

He et al. [25] proposed a PCM-based coupled heating rate measurement system with two hot plates at low temperatures for battery modules. This strategy allows for a more uniform temperature distribution in the battery module.

Liu et al. [26] used the heating film and UMHP method to heat the battery at low temperatures and compared the heating effects of the two heating methods. Due to the long heat transfer path, the UMHP heating has a hysteresis. The reason is that the heat is transferred through UMHP, and the transfer path is long. When the ambient temperature was −20 °C, the battery was heated by the heating-film method and the UMHP method, and the heating rate was 6 °C/min and 4.8 °C/min, respectively.

The external heating method is simple in principle and easy to implement, but there are obvious drawbacks such as large heating distance, slow heating speed, high energy consumption, and poor temperature uniformity.

2.3. Hybrid Heating

Hybrid heating is a heating method combining internal battery heating and external battery heating, which can improve the heating rate and efficiency of the battery and reduce the temperature gradient of the battery.

Ruan et al. [27] proposed a compound heating method based on DC internal heating and external contact heating, which utilizes the battery’s own discharge energy without additional power supply. A distributed ECM is established to simulate the temperature change during low-temperature heating. Three conflicting targets, heating time, capacity loss, and temperature gradient, are considered and optimized by genetic algorithm. After normalization, the optimal heating strategy is obtained by analyzing the different weights. This heating method can raise the battery from −30 °C to 2 °C within 62.1 s, and the average temperature rise rate can reach 31 °C/min. The low-temperature heating speed of the battery is very high, which reduces the heating energy consumption and reduces the battery life decline.

Luo et al. [28] proposed a low-temperature battery pack preheating technique based on conductive cPCM, and the system can achieve a temperature rise rate of 17.14 °C/min and a temperature gradient of 3.58 °C. An energy conversion model is developed to explain the energy conversion relationship of the battery under low-temperature heating to obtain the optimal heating strategy.

Xu et al. [29] proposed a battery low-temperature hybrid heating method in order to fully utilize the heat generated by the battery and the heating circuit. The battery and MOSFET are used as heat sources with a temperature rise rate of 11.22 °C/min, which shortens the heating time and reduces the energy consumption of the heating process.

Ruan et al. [30] developed a composite heating system including two externally heated aluminum sheets, which helps to fully utilize the discharge energy of the externally heated sheets. The basic electrical and thermal modeling of the heating system is performed and experimentally verified. Four key but conflicting heating metrics—heating time, heating efficiency, cell degradation, and temperature uniformity—are used to optimize the resistance of the external heater with an adaptive particle swarm optimization algorithm.

Compared with other heating methods, hybrid heating methods feature a higher heating rate, and at the same time, they generally show less impact on the life of LIBs. Furthermore, the engineering realization for the hybrid methods is often easier, which is a more promising method of low-temperature heating for LIBs.

References

1. New Energy Vehicle Industry Plan (2021–2035). Available online: https://www.ndrc.gov.cn/fggz/fzzlgh/gjjzxgh/202111/t20211101_1302487.html (accessed on 15 August 2023).
2. Deal Confirms Zero-Emissions Target for New Cars and Vans in 2035. Available online: https://www.europarl.europa.eu/news/en/press-room/20221024IPR45734/deal-confirms-zero-emissions-target-for-new-cars-and-vans-in-2035 (accessed on 15 August 2023).
3. FACT SHEET: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/ (accessed on 15 August 2023).
4. Global EV Data Explorer. Available online: https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer (accessed on 15 August 2023).
5. Zhang, S.S.; Xu, K.; Jow, T.R. Charge and discharge characteristics of a commercial LiCoO2-based 18650 Li-ion battery. J. Power Sources 2006, 160, 1403–1409.
6. IEA. Global EV Outlook 2019: Scaling-Up the Transition to Electric Mobility; OECD: Paris, France, 2019.
7. Ouyang, M.; Chu, Z.; Lu, L.; Li, J.; Han, X.; Feng, X.; Liu, G. Low temperature aging mechanism identification and lithium deposition in a large format lithium iron phosphate battery for different charge profiles. J. Power Sources 2015, 286, 309–320.

8. Zhang, G.; Wei, X.; Tang, X.; Zhu, J.; Chen, S.; Dai, H. Internal short circuit mechanisms, experimental approaches and detection methods of lithi-um-ion batteries for electric vehicles: A review. Renew. Sustain. Energy Rev. 2021, 141, 110790.
9. Electric Vehicle Sales Leapt 55% in 2022—Here's Where That Growth Was Strongest. Available online: https://www.weforum.org/agenda/2023/05/electric-vehicles-ev-sales-growth-2022/ (accessed on 15 August 2023).
10. China Meteorological Administration. China Meteorological Yearbook 2021; China Meteorological Press: Beijing, China, 2021.
11. Buidin, T.I.C.; Mariasiu, F. Battery Thermal Management Systems: Current Status and Design Approach of Cooling Technologies. Energies 2021, 14, 4879.
12. Xu, W.; Chan, K.W.; Or, S.W.; Ho, S.L.; Liu, M. A Low-Harmonic Control Method of Bidirectional Three-Phase Z-Source Converters for Vehicle-to-Grid Applications. IEEE Trans. Transp. Electrif. 2020, 6, 464–477.
13. Liu, J.; Xu, W.; Chan, K.W.; Liu, M.; Zhang, X.; Chan, N.H.L. A Three-Phase Single-Stage AC–DC Wireless-Power-Transfer Converter with Power Factor Correction and Bus Voltage Control. IEEE J. Emerg. Sel. Top. Power Electron. 2019, 8, 1782–1800.
14. Zhu, G.; Wen, K.; Lv, W.; Zhou, X.; Liang, Y.; Yang, F.; Chen, Z.; Zou, M.; Li, J.; Zhang, Y.; et al. Materials insights into low-temperature performances of lithium-ion batteries. J. Power Sources 2015, 300, 29–40.
15. Vlahinos, A.; Pesaran, A.A. Energy Efficient Battery Heating in Cold Climates. SAE Trans. 2002, 111, 826–833.
16. Osmani, K.; Alkhedher, M.; Ramadan, M.; Choi, D.S.; Li, L.K.; Doranehgard, M.H.; Olabi, A.G. Recent progress in the thermal management of lithium-ion batteries. J. Clean Prod. 2023, 389, 136024.
17. Wu, X.; Chen, Z.; Wang, Z. Analysis of low temperature preheating effect based on battery temperature-rise model. Energies 2017, 10, 1121.
18. Ji, Y.; Wang, C.Y. Heating strategies for Li-ion batteries operated from subzero temperatures. Electrochim. Acta 2013, 107, 664–674.
19. Ruan, H.; Jiang, J.; Sun, B.; Su, X.; He, X.; Zhao, K. An optimal internal-heating strategy for lithium-ion batteries at low temperature considering both heating time and lifetime reduction. Appl. Energy 2019, 256, 113797.
20. Zhang, J.; Ge, H.; Li, Z.; Ding, Z. Internal heating of lithium-ion batteries using alternating current based on the heat generation model in frequency domain. J. Power Sources 2015, 273, 1030–1037.

21. Ruan, H.; Jiang, J.; Sun, B.; Zhang, W.; Gao, W.; Ma, Z. A rapid low-temperature internal heating strategy with optimal frequency based on constant polarization voltage for lithium-ion batteries. Appl. Energy 2016, 177, 771–782.
22. Jiang, J.; Ruan, H.; Sun, B.; Wang, L.; Gao, W.; Zhang, W. A low-temperature internal heating strategy without lifetime reduction for large-size automotive lithium-ion battery pack. Appl. Energy 2018, 230, 257–266.
23. Qu, Z.G.; Jiang, Z.Y.; Wang, Q. Experimental study on pulse self-heating of lithium-ion battery at low temperature. Int. J. Heat Mass Transf. 2019, 135, 696–705.
24. Wang, Y.; Rao, Z.; Liu, S.; Li, X.; Li, H.; Xiong, R. Evaluating the performance of liquid immersing preheating system for Lithium-ion battery pack. Appl. Therm. Eng. 2021, 190, 116811.
25. He, F.; Li, X.; Zhang, G.; Zhong, G.; He, J. Experimental investigation of thermal management system for lithium ion batteries module with coupling effect by heat sheets and phase change materials. Int. J. Energy Res. 2018, 42, 3279–3288.
26. Liu, F.F.; Lan, F.C.; Chen, J.Q.; Li, Y.G. Experimental Investigation on Cooling/Heating Characteristics of Ultra-Thin Micro Heat Pipe for Electric Vehicle Battery Thermal Management. Chin. J. Mech. Eng. 2018, 31, 179–188.
27. Ruan, H.; Sun, B.; Zhu, T.; He, X.; Su, X.; Cruden, A.; Gao, W. Compound self-heating strategies and multi-objective optimization for lithium-ion batteries at low temperature. Appl. Therm. Eng. 2021, 186, 116158.
28. Luo, M.; Lin, X.; Feng, J.; Ling, Z.; Zhang, Z.; Fang, X. Fast self-preheating system and energy conversion model for lithium-ion batteries under low-temperature conditions. J. Power Sources 2023, 565, 232897.
29. Xu, J.; Mei, X.; Wang, H.; Wang, J. A Hybrid Self-Heating Method for Batteries Used at Low Temperature. IEEE Trans. Ind. Inform. 2020, 17, 4714–4723.
30. Ruan, H.; Sun, B.; Cruden, A.; Zhu, T.; Jiang, J.; He, X.; Su, X.; Ghoniem, E. Optimal external heating resistance enabling rapid compound self-heating for lithium-ion batteries at low temperatures. Appl. Therm. Eng. 2022, 200, 117536.
31. Wang, C.Y.; Zhang, G.; Ge, S.; Xu, T.; Ji, Y.; Yang, X.G.; Leng, Y. Lithium-ion battery structure that self-heats at low temperatures. Nature 2016, 529, 515–518.
32. Yang, X.G.; Liu, T.; Wang, C.Y. Innovative heating of large-size automotive Li-ion cells. J. Power Sources 2017, 342, 598–604.