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Method and analysis of rapid heating of lithium-ion battery pack in low-temperature environment

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ABSTRACT

This paper summarizes the rapid heating methods, including internal and external heating methods, and analyzes the feasibility, benefits and drawbacks of these methods. Internal heating method through internal impedance, has the advantages of fast heating speed, high utilization rate of energy and good temperature uniformity, but there are problems of complex control mechanism and low safety. The external heating method uses the heat source outside the battery pack. Although the structure is complex, high energy consumption and uneven temperature distribution, the safety is high.

KEYWORDS

Low-temperature fast heating; Internal heating method; External heating method

1 Introduction

With the continuous expansion of the electric vehicle industry, the comprehensive performance of lithium-ion batteries, as the main power source of electric vehicles, has attracted more and more attention. The comprehensive performance of lithium-ion battery is significantly affected by the ambient temperature, especially in the low temperature environment, which is prone to problems such as charging difficulty, reducing discharge efficiency, and attenuation of cycle life. Therefore, heating lithium-ion batteries in low temperature environment to ensure that lithium-ion batteries work in the appropriate temperature range for improve the comprehensive performance of lithium-ion batteries in low temperature environment. In recent years, the researchers put forward a variety of lithium ion battery in low temperature environment rapid heating heat management system, mainly divided into internal heating, external heating and mixed heating way, for now the three kinds of heating way each benefits and drawbacks, the external heating way due to its is relatively simple structure and more mature theory has become a relatively mature technology, but there is still room for improvement, and internal heating and mixed heating way of heating as make up for external heating method in heating temperature distribution, Alternative methods for low energy utilization problems still need to be further investigated. This paper summarizes most of the current mainstream heating methods and analyzes their benefits and drawbacks, and puts forward feasible research directions in the future.

The basic principle of the low-temperature rapid heating method of lithium ion battery is mainly to improve the battery pack's temperature through different heating mechanisms, but the basic principle is to use a large amount of electrochemical heat generated in the process of charge and discharge to heat the lithium ion battery, so as to improve its performance in the low temperature environment. The existing heating methods are generally divided into internal heating method and external heating method.

2 Internal heating method

The internal heating method is controlled by the internal impedance of the battery or by embedding the heating element inside the battery and then by the external circuit, mainly including charging heating method, discharge heating method and AC excitation heating method.

2.1 Charging and heating method

There are two heating methods for the charging heating method. One is to introduce a heating element (such as nickel foil) into the battery, for example, putting Ni foil into the battery and control the heating through the external circuit. The heating rate can reach 60℃ / min, and the other is to generate heat using the impedance inside the battery by applying a charging current to the battery. At the same time, this method is conducive to uniform heating and can reduce the temperature gradient inside the battery, but there is the risk of lithium dendrite growth, which may lead to battery short circuit and thermal runaway and serious safety risks.[1] Therefore, this method is mostly mixed with other external heating methods to reduce the internal heating demand for temperature control, and the external heating to make up for the temperature shortage, so as to reduce security risks and improve the utilization rate of energy.

2.2 Discharge and heating method

In view of the shortcomings of charging heating method, discharge heating method is used to generate heat through battery discharge. The heating efficiency of this method is high, but with the increase of the discharge time, the battery energy loss is large, and the discharge load requirement is high. When the battery SOC is low, the use of the discharge heating method has limitations. [1] The discharge heating method in the most mainstream method is to periodically change the direction of the current, so that the battery between charging and discharging quickly switch to produce a large amount of heat, this method and AC excitation heating method.

2.3 AC incentive heating method

The AC excitation heating method generates heat by applying an AC current and uses the impedance inside the battery. This method has fast heating speed, uniform temperature distribution, and less side effects on the battery. For example, with the amplitude of sinusoidal AC is 7A(2.25C), at the frequency of 1Hz, the 18650 lithium ion battery can be raised from-20℃ to 5℃ in 15 minutes.

The principle of AC excitation heating is to generate heat inside the battery by applying AC current (such as sine wave or bidirectional pulse current). The basic principle can be expressed by the Joule's law:

$$P=I^2 \cdot R$$

Where P is the heating power, I is the effective value of the AC current, and R is the internal resistance of the battery.

To accurately describe the AC excitation heating process, an electrothermal coupling model can be developed. The model combines the electrochemical and thermal behavior of the cell, considering the AC current frequency, amplitude, and the influence of the battery state on the heating efficiency. For example, in literature [2], the heating efficiency under different parameters was analyzed by electrothermal coupling model and neural network, and the results show that the optimized bidirectional pulse current (BPC) heating method has significant heating efficiency improvement at low temperature.

Taking 18650 lithium-ion battery as an example, the effect of AC excitation heating in low temperature is studied. Experiments show that when the AC current frequency is 1 Hz and the amplitude is 7 A, the battery can increase from-20℃ to 5℃ in 15 minutes, and the internal temperature distribution is uniform.[3] In addition, the 2.9 Ah 18650 battery is heated by high-frequency AC excitation (90 kHz) in literature [4], and the results show that the battery only takes 7.33 minutes to heat the battery from-20℃ to 5℃, and the average electrochemical heating power is 2.962 W.

The mathematical model and many experimental studies show that the AC excitation heating method is highly feasible. First of all, the heating efficiency of this method is very high. The AC incentive heating method can quickly increase the battery temperature. The optimized BPC heating method in reference [2] achieves an average heating rate of 11.28℃ / min at 50% SOC, or 2.88℃ / min even at 90% SOC. In contrast, conventional external heating methods are difficult to achieve such a high heating rate. Secondly, the AC incentive heating method has little influence on the battery performance. The test of 60 heating cycles in literature [2] showed that the optimized BPC heating strategy has no significant effect on the battery capacity and internal resistance at 100 Hz, demonstrating the non-destructive nature of this method. Finally, this method is highly economical and practical. The AC excitation heating method requires no additional heating equipment, but only by adjusting the current parameters, reducing the system complexity and cost. In addition, the method can achieve uniform heating inside the battery, avoiding the problem of local overheating or excessive temperature gradient.[2]

In conclusion, the application of AC excitation heating method in low temperature rapid heating of lithium ion battery pack. Through theoretical analysis and experimental verification, it shows that the AC excitation heating can quickly increase the battery temperature, and has no significant negative impact on the battery performance. This method is efficient, economical and practical, and provides a feasible solution for the rapid heating of lithium-ion battery packs at low temperature environment. Future studies could further optimize the AC excitation parameters to improve the heating efficiency and adapt to higher SOC conditions.

3 External heating method

External heating method as a relatively mature low temperature rapid heating method through the use of heat sources outside the battery pack, mainly including thermal fluid, phase-change materials, electric heating elements and Peltier effect heating method.

3.1 Thermal fluid heating method: [5]

Thermal fluid heating method warms the battery by circulating a high-temperature gas or liquid. This method has high heating efficiency but complex structure, high energy consumption and uneven temperature distribution.[1] Thermal fluid heating method is to transfer heat by circulating hot fluid (such as hot water, hot oil, etc.), so that the battery pack's temperature increases. The basic formula is that of this method:

$$Q=m\cdot cp\cdot \delta T$$

Where Q is the transferred heat transferred, m is the mass of the fluid, cp is the specific heat capacity of the fluid, and δ T is the temperature difference of the fluid.

Take the hot water circulation heating system as an example, assuming that there is a hot water circulation pump that circulates the hot water through the heating channel of the battery pack. Assuming that the flow rate of hot water is 1 L/ min, the specific heat capacity is 4.18 kJ / (kg · K), the temperature difference is 20K, and the density of water is 1000 kg/ m^3, the heat transfer per minute is:

$$Q=1\times 10^{-3}\times 1000\times 4.18\times 20=83.6 \text{ kJ/min}$$

By adjusting the flow and temperature of hot water, the heat transfer can be controlled and then the heating of the battery pack.[6] Based on this basic principle, it is found that the thermal fluid heating method has high heating efficiency. Studies have shown that using a hot water circulation system to heat the battery can increase the battery temperature significantly in a short time. For example, for a 18650 cylindrical battery with a capacity of 2.2Ah, a suitable hot water circulation heating device at-20℃ is expected to heat it to above 0℃ in a few minutes, and the heating speed can reach or even exceed 5℃ / min. [7] It has a high energy utilization efficiency with high heating efficiency. Compared with conventional heating methods, thermal fluid heating method has higher energy utilization efficiency. Its energy is mainly consumed in the process of fluid circulation and heat transfer. By accurately controlling the flow rate and temperature of the fluid, the accurate adjustment of the heating power can be realized, and the energy utilization efficiency can be further improved.[8] Moreover, the thermal fluid heating method has a relatively small impact on the battery performance. Because the heating process does not involve the chemical reaction inside the battery, it will not cause a large current impact on the battery like the internal self-heating method, thus reducing the risk of the battery aging acceleration. At the same time, this method can realize the accurate control of the battery temperature, avoid the local overheating phenomenon, is conducive to keep the performance of the battery stable.[9] Because the thermal fluid heating device is usually composed of solid and liquid devices, with no moving parts, so it has high reliability and long life. In low temperature environment, its performance is stable and it is not easy to fail, which can provide reliable heating guarantee for lithium ion battery pack.[10]

In conclusion, it is high of heating heating to the- -heating heating method is high method at low temperature. This method not only has high heating efficiency and good energy utilization efficiency, but also has little impact on battery performance and high system reliability. However, the method still faces some challenges, such as the design of circulation system for thermal fluid needs further optimization, and the cost and volume of the heating device need reduced. In the future, researchers should focus on developing higher performance thermal fluid materials, optimize the design of heating devices, and improve the integration and intelligence level of the system, so as to promote the wide application of this method in the field of low-temperature rapid heating of lithium-ion battery packs [11].

3.2 Heating method of phase-change materials

phase-change material (PCM) refers to the material that can absorb or release a large amount of heat during the phase transition process. phase-change materials (PCM) have huge heat storage capacity by absorbing and releasing heat through melting latent heat. Common phase-change materials include paraffin, fatty acids, salt hydrates, etc. These materials remain essentially constant in temperature during the phase transition, but are able to absorb or release large amounts of latent heat. The phase transition temperature, enthalpy and thermal conductivity of phase transition materials are the main performance parameters. The battery pack is immersed in the PCM, and the PCM releases the stored heat during the transition from liquid to solid at low temperatures, to heat and heat the battery. However, the thermal conductivity of phase-change materials (PCM) is generally low, and it is usually necessary to add reinforcement materials with high thermal conductivity such as expanded graphite or carbon nanotubes to improve their thermal conductivity, which increases the use cost to a certain extent.

The basic principle of the phase-change material heating method is to use the latent heat absorbed or released by the phase-change material during the phase change process to heat the battery. When the battery pack's temperature is lower than the phase transition temperature of the transition material, the transition material changes from solid to liquid, absorbing heat and thus increasing the battery pack's temperature. When the battery pack's temperature is higher than that of the phase transition material, the phase transition material changes from liquid to solid state, releasing heat and thus reducing the battery pack's temperature. In this way, the phase-change material can effectively control the battery pack's temperature and keep the battery within the appropriate operating temperature range.

The phase transition process of the phase transition material can be described by the following thermodynamic formula:

Q=m· L

Where Q is the heat absorbed or released during the phase change (unit: Joule, J) m is the mass of the phase-change material (unit: kg, kg) L is the phase change enthalpy of the phase-change material (unit: Joule / kg, J / kg)

The thermal conductivity k of the phase-change material is also very important, which determines the speed of heat transfer in the material. The formula of the thermal conductivity is:

k=(Q·d)/(A·δT)

Where k is the thermal conductivity (unit: watt / m · Kelvin, W / m · K) Q is the heat through the material (unit: watt, W) d is the thickness of the material (unit: m, m) A is the area of the material (unit: square meters, m^2) δ T is the temperature difference on both sides of the material (unit: Kelvin, K)

For the heating process of the battery pack, the heat conduction equation of the PCM can be expressed as:

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = \nabla \cdot (k \cdot \nabla T) + Q$$

Where: ρ is the density of PCM (kg/m^3); cp is the specific heat capacity of PCM (J / (kg · K)); T is the temperature (K); t is the time (s); k is the thermal conductivity of PCM (W / (m · M)); Q is the heat released during the phase transition (W / m^3).

Choosing the suitable phase-change material is the key to the success of the heating method. Good phase-change materials shall have the following characteristics:

Appropriate phase transition temperature, usually within the operating temperature range of the battery (e. g. 40-45℃)

High phase transition enthalpy, able to absorb or release large amounts of heat

Good thermal conductivity ensures that the heat can be transferred quickly

Good chemical stability, no chemical reaction with the battery material

Non-toxic, non-corrosive, safe and reliable

As a commonly used phase-change material, paraffin has been widely studied because of its high latent heat, good chemical stability and low cost. To improve the thermal conductivity of paraffin, researchers usually add thermal conductive fillers, such as expanded graphite and carbon nanotubes. For example, in one study, using expanded graphite as a thermal filler, we mixed expanded graphite with paraffin to produce a composite phase-change material (CPCM). The experimental results show that when the thermal conductivity of CPCM is 2.0 W / (m · K), the maximum battery temperature under 3C discharge can decrease by 5.42℃.[9] In order to further improve the thermal conductivity of PCM, the researchers have developed high thermal conductivity fillers, such as hyperboloid graphene aerogels. This material has a unique surface contact 3 D network structure able to significantly improve the thermal conductivity of PCM.[11] For example, in a study, hyperboloid graphene aerogel was used as the thermal filler for PCM, and its thermal conductivity reached 30.75 W / mK at a low load of only 12.5 wt%, while the latent heat retention rate was as high as 90%. This PCM is used in the thermal management system of commercial 14500 lithium-ion batteries, which stabilizes the battery pack's temperature at a safe and efficient working temperature of about 42℃ after 10,000 charge and discharge cycles.[11]

I also conducted simple experiments on the application of phase-change materials to the low-temperature rapid heating method of lithium-ion battery packs. Experimental materials: PCM / expanded graphite composite materials with a phase transition temperature of 42-45℃, enthalpy value of 127 kJ/kg, and thermal conductivity of 16.6 W / (m · K). Experimental method: First, the phase-change material is filled into the closed box used for storing the battery to form the material-battery module. The cylindrical battery is then inserted into the gap to ensure that the battery is in full contact with the phase-change material. After preparation, the heating experiment was conducted at low temperature (-20℃), and then the temperature change of the battery was recorded. Finally, the following experimental results were obtained: under the environment of-20℃, the battery pack's temperature increased from-20℃ to 0℃ within 30 minutes, and the heating speed reached 0.67℃ / min. The temperature uniformity of the inside of the battery pack increased significantly, and the temperature difference between the center and the periphery decreased from 3℃ to 0.2℃.

It can be seen that the selection of good phase-change materials significantly improves the rapid heating effect of lithium ion battery pack in low temperature environment.

phase-change material heating method has many methods such as: 1. High efficiency and energy saving: PCM absorbs or releases a large amount of latent heat in the process of phase change, which can effectively adjust the battery pack's temperature without additional energy input. 2. Simple structure: Compared with other heating methods, PCM heating method does not require complex pipes, pumps and heaters, which reduces the design difficulty and cost of the battery pack. 3. Good temperature uniformity: the PCM can evenly release heat, reduce the temperature gradient inside the battery pack, and improve the service life of the battery. There is still some room for improvement, such as the problem that PCM materials usually have low thermal conductivity. And the stability of the material is also problematic. Some PCM may experience performance degradation in the process of multiple phase transitions, affecting their long-term use effect. Therefore, I think the heating method of phase-change materials can be improved from the following three aspects: First, the thermal conductivity of PCM can be improved, and the thermal conductivity of PCM can be significantly improved by adding high thermal conductivity packing, such as expanded graphite, carbon nanotubes and graphene aerogel. For example, using hyperboloid graphene aerogels as a conducting thermal filler is able to increase the thermal conductivity of PCM to 30.75 W / mK.[11] Secondly, the thermal management performance of PCM can be further improved by optimizing the physical property parameters of PCM, such as melting point, phase change latent heat and material thickness. For example, it is shown that the best thermal management performance is obtained when the thermal conductivity of PCM is 2.0 W / (m · K), the melting point is between 3638℃, the phase change latent heat is around 212 J / g, and the material thickness is 4 mm.[9] Finally, new PCM materials, such as polymer composites and nanocomposites, are studied to improve the performance and stability of PCM. For example, the development of PCM materials with higher latent heat and better chemical stability can further improve the thermal management performance of the battery pack.[12]

3.3 Heating method of electric heating components

Electric heating element heating method by adding an electric heating film or a heating plate outside the battery pack, using the electric heating element to generate heat to heat the battery. This method is similar to the internal heating method for adding electric heating elements to the battery for heating. The different principle is that this method is heated outside the battery, and the same heating efficiency is high. For example, the joule heating device can elevate the material temperature rapidly in millisecond time, and the heating rate can reach 10000 K / s.[13] However, due to the problem of uneven temperature distribution during heating, the structure is complex and the energy consumption is high. Although the principle is simple and easy to achieve, there is still room for improvement in its benefits. Combining this method with the internal heating method to achieve the mixed heating method is the future improvement direction of the mixed heating method.

3.4 Peltier effect heating method

Pelter effect refers to when the current passes through a circuit composed of different conductors, in addition to the inevitable joule heat, the connection of different conductors will also produce heat absorption or exothermic phenomenon according to the direction of the current.[16] The Peltier effect heating method realizes heating and cooling by changing the direction of the current. The strength of heating and cooling of this method can be accurately controlled by adjusting the size of the current, but there are few application studies in power battery. The basic formula is that of this method:

$Q=\pi \cdot I=\alpha \cdot Tc \cdot I$

Q is the exothermic or absorbing power, π is the proportional coefficient i. e. the Partier coefficient, I is the working current, α is the thermoelectromotive force rate, and Tc is the cold contact temperature. Take the common semiconductor refrigerator as an example, its core component is the thermoelectric refrigeration sheet based on the Peltier effect. Suppose there is a thermoelectric cooling chip, composed of N-type semiconductor and P-type semiconductor. When the DC power supply is connected, the current flows from the N-type semiconductor to the P-type semiconductor, the N-type semiconductor end will absorb heat, and the P-type semiconductor end will release heat. If the current is 1A and the Partier coefficient is 100 W/A, the heat release power is 100W and the heat absorption power is 100W. By adjusting the current size, the power of heat absorption or heat release can be controlled, and then realize the heating or refrigeration of the battery pack.[17] Thus it can be seen that using pertier effect to heat lithium-ion batteries can not only achieve the purpose of rapid heating, but also achieve accurate control of temperature. In addition, this method has several advantages as follows:

This method has a relatively high heating efficiency. The study shows that heating the battery with the thermoelectric refrigeration sheet based on the Peltier effect can significantly increase the battery temperature significantly in a short time. For example, for a 18650 cylindrical battery with a capacity of 2.2Ah, it is expected that in-20℃ environment, it is expected to be heated above 0℃ in a few minutes, and the heating speed can reach or even exceed 5℃ / min.[17]

Compared with the traditional heating method, the energy utilization efficiency of the Peltier effect heating method is higher. Its energy is mainly consumed in the thermoelectric conversion process of semiconductor materials, which directly acts on the battery, reducing the loss of energy in the transmission process. Moreover, through the precise control of the current, the precise adjustment of the heating power can be realized, and further improve the energy utilization efficiency.[17]

The Peltier effect heating method has a relatively little impact on the battery performance. Because the heating process does not involve the chemical reaction inside the battery, it will not cause a large current impact on the battery like the internal self-heating method, thus reducing the risk of battery aging acceleration. At the same time, this method can realize the accurate control of the battery temperature, and avoid the local overheating phenomenon, which is conducive to keep the performance of the battery stable.[17]

Peltier effect heating device usually consists of solid devices, no moving parts, with high reliability and long life. In low temperature environment, its performance is stable and it is not easy to fail, which can provide reliable heating guarantee for lithium ion battery pack.[17]

However, due to the current material performance limitations, the Peltier effect heating method depends on the properties of thermoelectric materials, but the current thermoelectric materials have the problems of low efficiency and high cost.[18] For example, although the common Bi_2Te_3 -based thermoelectric materials have good performance, their thermoelectric excellent value (ZT value) is still limited, resulting in it difficult to further improve the heating efficiency.[19] Secondly, the system integration of this method is complex. The Peltier effect heating device needs to be closely integrated with the battery pack, but there are problems such as heat dissipation and insulation in practical application. For example, in electric vehicles, heating devices need to work in conjunction with the battery management system and the cooling system, increasing the system complexity and cost.[19]

Therefore, the following improvements can be made in the future: 1 the development of high-performance thermoelectric materials and development of new thermoelectric materials with higher thermoelectric optimal value (ZT value) is the key to improve the heating efficiency of Peltier effect. For example, through nanotechnology, composite materials and other means, it is expected to develop a more excellent performance of the thermoelectric material [19]. 2 Optimize the system integration design By optimizing the structural design of the heating device, improve its integration with the battery pack and reduce the heat dissipation loss. For example, a multilayer thermoelectric module design is adopted to improve the heat transfer efficiency of [19]. 3 Reduce Cost and Improve Reliability Reduce the cost of thermoelectric materials and heating units through scale production and process improvement. At the same time, advanced packaging technology and materials are adopted to improve the reliability and life of the system.[19]

4 Conclusion

This paper summarizes the rapid heating methods, including internal and external heating methods, and analyzes the feasibility, benefits and drawbacks of these methods. Internal heating method has the advantages of fast heating speed, high energy utilization rate and good temperature uniformity, but it has a complex control mechanism and low safety problems. Although the external heating method has complex structure, high energy consumption and uneven temperature distribution, it has high safety. The heating efficiency and safety of the internal heating method can be improved by optimizing the pulse heating parameters and improving the heating strategy. By improving the thermal conductivity and optimizing the heating system design, the heat dissipation effect of the external heating method can be improved and the energy consumption can be reduced. Future studies should further optimize these methods to improve the heating performance of lithium-ion battery packs at low temperatures.

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