Solving The Thermal Runaway Problem of Lithium-Ion Batteries

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Abstract. Lithium-ion batteries (LIBs) are emerging due to the pursuit of clean energy world. This paper synthesizes the research results related to the thermal runaway problem of LIBs and their thermal management solutions. Firstly, the structure and working principle of LIBs are introduced, and then the concept, cause, and mechanism of thermal runaway are analyzed. The advantages and limitations of different thermal management methods, including air cooling, liquid cooling, heat pipe cooling, phase change material cooling, and composite method cooling, are analyzed and compared in detail. Suggestions are made to develop appropriate thermal management strategies based on battery pack specifications and operating environments and in conjunction with economic benefits. Finally, it is proposed that future research can consider combining intelligent control technology to realize real-time monitoring, regulation, and early warning of the temperature of the battery system to improve the safety and stability of the system. Future opportunities and challenges in this exciting field are highlighted.

Keywords: Lithium-ion battery, thermal runaway, thermal management.

1. Introduction

Under the grand blueprint of the international "dual-carbon target", renewable energy will play an increasingly important role in the world's energy system, and electrochemical energy storage technology is one of the key core technologies to support the popularization and application of renewable energy. With the advancement of battery technology and cost reduction, electrification of transportation is considered an effective solution to get rid of the energy crisis and environmental pollution in modern society, among which lithium-ion batteries (LIBs) are the most widely used electrochemical energy storage system in electric vehicles due to their characteristics of high specific energy, fast charging, strong endurance, and long cycle life.

However, with the strong promotion of electric vehicles, electric vehicle accidents related to thermal runaway of LIBs have occurred from time to time, thus hindering consumer confidence in electric vehicles. For this reason, scholars at home and abroad have also conducted a lot of research on the thermal runaway behavior of LIBs. However, the current state of research on the explosion risk of energy storage batteries is mainly focused on the thermal runaway mechanism of a single battery, thermal runaway characteristics, and the explosion risk of a single battery, but the limitations lie in the battery volume is too small, thermal runaway triggered by the way does not match the explosion scenarios do not match the conditions of the energy storage application, and so on. The above research has not been involved in energy storage with LIBs in large-scale application scenarios of combustion and explosion accidents. Prefabricated cabin electrochemical energy storage stations and lithium battery electric vehicles in large-scale combustion and explosion of the relevant research are relatively small, safety issues need to be resolved, and due to economic factors and safety reasons related to the explosion is difficult to carry out experimental research.

2. Thermal Runaway Analysis of Single LIBs

2.1. Structural Composition and Working Principle of Lithium Battery

The components of LIBs are generally divided into positive electrode, negative electrode, diaphragm, and electrolyte. The cathode material is mainly responsible for supplying lithium ions (Li+) and is the key part of lithium batteries. The chemical properties of the anode material have a key influence on the stability and energy storage of the lithium battery. In addition, the anode material should also have good thermal stability, to ensure that the LIB has a better safety performance [1]. Nowadays, lithium-ion battery anode materials are widely used, such as lithium cobaltate, lithium iron phosphate, ternary materials, and so on.

The anode material acts as a mover of electrons and lithium ions during the normal operation of LIBs, which is closely related to the storage and release of energy in lithium batteries and is currently mainly carbon or non-carbon materials. The electrolyte is the conductive medium inside the battery, which plays the role of transporting lithium ions between the positive and negative electrodes of the battery. The diaphragm is a membrane between the anode and cathode inside the battery, which not only prevents internal short-circuit inside the lithium-ion battery, but also ensures that lithium ions are free to pass through, and at the same time impedes the passage of electrons.

The charging and discharging processes of LIBs can be expressed as the reversible embedding and disembedding of equal amounts of lithium ions and electrons between the anode and cathode. During the charging process of LIBs, the lithium ions are extracted from the anode particles and flow to the cathode through the electrolyte and the separator plate, and the surface of anode particles releases the same amount of electrons at the same time to move to the cathode through the external circuit to keep the electrical neutrality; When the LIBs are discharged When the lithium-ion battery is discharged, the process is opposite to the charging process, the lithium ions flow to the anode through the electrolyte and the separator plate, while an equal number of electrons move back to the cathode through the external circuit [2].

The electrochemical reactions that occur during the charging and discharging of LIBs are [2]:

Positive Reaction:

$$LiMO_n \leftrightarrow Li_{1-x}MO_n + xLi^+ + xe^- \tag{1}$$

Negative Reaction:

$$mC + xLi^+ + xe^- \leftrightarrow Li_xC_m \tag{2}$$

Total Battery Reaction:

$$LiMO_n + mC \leftrightarrow Li_{1-x}MO_n + Li_xC_m \tag{3}$$

In equations (1) to (3), M is a metallic element such as Ni, Co, and Mn.

2.2. Analysis of the Causes and Thermal Runaway Mechanism of Lithium Battery Thermal Runaway

Thermal runaway, namely the heat generation of the battery cannot be controlled. Refers to the lithium-ion battery in the role of external abuse factors, the temperature of the battery itself rises rapidly, and accompanied by a series of exothermic reactions, making the battery's heat production power is far greater than the cooling power, the accumulation of a large amount of heat, and ultimately triggered by its fire or even explosion and other phenomena.

The causes of thermal runaway in LIBs can be divided into mechanical abuse, electrical abuse, and thermal abuse according to the different triggering methods [3]. Mechanical abuse triggers include extrusion, pinprick, drop, and other force deformation; electrical abuse triggers include external short circuits, internal short circuits, overcharging, over-discharging, etc.; and thermal abuse triggers include abnormal heating, flame heating, etc.

The three triggers are interrelated. Generally speaking, mechanical abuse first causes the shape of the lithium-ion battery to change, then makes its diaphragm deform or tear, and then leads to the formation of an internal short circuit between the positive electrode and the negative electrode inside the battery directly shorted, the occurrence of electrical abuse so that a series of reactions inside the lithium-ion battery heat production increased rapidly, so that the temperature of the lithium-ion battery rises sharply, and ultimately, thermal abuse leads to the occurrence of thermal runaway of the battery [3].

3. Thermal Management of Lithium Batteries

The thermal management system of new energy vehicles contains four major parts: battery system, motor system, air-conditioning system, and other components, and compared with the traditional thermal management of fuel vehicles, the thermal management system of new energy vehicles is more complex. Cooling technologies such as air cooling, liquid cooling, phase change material cooling and heat pipe cooling, and composite cooling are analyzed separately in the following [4].

3.1. Air Cooling

Air cooling is a heat dissipation method that uses air as a medium and uses heat convection in the air to make the battery exchange heat directly with the air, thus reducing the temperature of the battery. Air cooling can be divided into natural cooling: without the use of fans and forced cooling: with the use of fans. A large number of studies have shown that the heat dissipation effect of forced air cooling is much higher than that of natural air cooling [5].

Air cooling is currently a more mature cooling program because the structure of the entire cooling system is not complex, the later maintenance is easy and cheap, with low energy consumption, mature technology, and easy control. However, air cooling is not the best cooling method at present, because its cooling effect is greatly affected by the ambient temperature, in the hot summer cooling efficiency is low; in the winter battery heating also needs to add a heating system. In addition, air cooling is difficult to ensure the uniformity of heat dissipation in large-scale battery packs, and there is the problem of large heat generation and slow heat dissipation in some batteries, which greatly affects the safety of the whole power battery pack [6].

3.2. Liquid Cooling

Liquid cooling technology usually uses a coolant with a high heat transfer coefficient, which allows the battery to exchange heat with the coolant, thus lowering the battery temperature. The liquid cooling system for electric vehicles can be divided into direct contact: immersing the battery single or module in the liquid for heat exchange; indirect contact: setting up cooling channels between battery modules or using cooling plates at the bottom of the battery, the heat of the power battery is then transferred to the cooling liquid through the cooling plate.

Although some studies have shown that liquid cooling has a better cooling effect than air cooling, at present there are still design problems with liquid cooling, such as high air tightness requirements for the liquid cooling system, high mechanical strength requirements, the need to ensure vibration resistance as well as the life requirements of the cooling system [7]. The structural design of the cooling plate as well as the design of the flow channel, the flow rate of the coolant will have a great impact on the battery temperature, and its influencing factors need to be controlled within the appropriate range [8].

3.3. Heat-pipe Cooling

Heat pipe cooling is to divide the heat pipe into evaporation section, heat transfer section, and condensation section, and its main heat dissipation principle is to absorb heat in the evaporation section of the heat pipe to export heat from the battery pack. The evaporation section of the heat is due to the formation of the pressure difference through the middle section of the heat pipe to the condensing section of the heat dissipation, thus achieving effective thermal management of the battery pack. Currently, some studies have shown that compared with air cooling and liquid cooling, heat pipe cooling has the best cooling effect on the battery pack [9].

3.4. Phase Change Material Cooling

Phase change material (PCM) heat dissipation technology makes use of the principle that heat will be absorbed when the phase change material undergoes phase change, the phase change material will be surrounded by the battery pack to reach the phase change temperature in a certain environment, the phase change material undergoes phase change and absorbs the heat generated by the battery when it is working, to avoid the process of the high temperature of the battery module effectively [10].

Because the phase change process is a constant temperature process, the battery can be maintained at the phase change temperature, thus inhibiting the temperature from continuing to rise. However, its use needs to pay attention to the sealing problem and will increase the size of the battery pack, reducing energy density. In addition, the heat preservation function can only be maintained in the limited parking time, long-time battery preheating also relies on the built-in heat source, and the heat preservation generally requires a low thermal conductivity, which may bring the problem of uneven temperature distribution.

3.5. Composite Cooling

It is difficult for a single cooling method to meet the thermal management needs of the battery system, but various cooling methods have their characteristics and advantages. Therefore, the composite cooling method, which combines two or more thermal management methods, can play to the advantages of the cooling methods and make up for the disadvantages at the same time, which can make the battery thermal management achieve good results. However, the composite method makes the quality of the thermal management system increase and the structure becomes complicated. Therefore, it is necessary to formulate the corresponding thermal management strategy according to the specifications of the battery pack and the operating environment and combine it with the economic benefits [11].

4. Conclusion

As one of the most widely used rechargeable batteries, lithium batteries have the advantages of high energy density, lightweight, and long life. However, lithium batteries are subjected to three different types of abuse: mechanical, electrical, and thermal, which can generate high internal temperatures and lead to thermal runaway of lithium batteries, or even fire or explosion.

The thermal runaway problem is one of the important challenges facing lithium batteries, which needs to be solved by thermal management measures. The mainstream cooling method of battery thermal management has changed from air cooling to liquid cooling and heat dissipation, phase change material cooling and heat pipe cooling and heat dissipation, and composite but other methods.

However, these thermal management measures are defective to varying degrees, so human beings are still exploring thermal runaway suppression measures, such as aerogel fire extinguishing agent suppression, nano-filler multifunctional flame retardant coatings, thermal insulation material coating thermal runaway propagation blocking method, set up between the monomer thermal insulation board thermal runaway propagation blocking method, the valve sprays the channel thermal runaway propagation blocking method, the liquid nitrogen sprays the thermal runaway propagation blocking method, and so on.

Future research can further explore in depth the application effect of composite mode cooling in different scenarios, as well as novel solutions for the thermal runaway problem of LIBs. At the same time, the combination of intelligent control technology can also be considered to achieve real-time monitoring, regulation, and early warning of the battery system temperature, to improve the safety and stability of the system. In addition, with the continuous emergence of new materials and technologies, more efficient and environmentally friendly thermal management solutions can be explored to meet the future needs of electric vehicles and other fields.

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