Thermal Runaway and Thermal Management of Lithium-Ion Power Batteries in New Energy Vehicles

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Abstract. As the cornerstone of new energy vehicles, lithium-ion batteries pose significant safety concerns due to the risk of thermal runaway, which can lead to inoperability, fires, explosions, and the release of toxic and combustible gases. This paper examines the safety hazards associated with lithium-ion power batteries in new energy vehicles, focusing on the phenomenon of thermal runaway. Thermal runaway not only compromises vehicle functionality but also elevates the risk of fires and explosions, endangering human lives and property. Statistical analysis reveals that fire incidents during charging sessions account for approximately 26% of all cases, attributed to direct battery ignition, charging equipment malfunctions, and overcharging. Moreover, fires occurring while vehicles are parked represent a significant portion (about 13%) of incidents, particularly in climates with considerable day-to-night temperature variations, exacerbated by drivers' lack of safety awareness. The underlying cause of these safety issues is thermal runaway within the battery pack, which, upon reaching a critical threshold, triggers fires and other hazardous events. This study underscores the urgent need for enhanced safety measures and awareness to mitigate the risks posed by lithium-ion batteries in new energy vehicles.

Keywords: Lithium-ion battery; thermal runaway; thermal management; new energy vehicles.

1. Introduction

Climate issues due to greenhouse gas emissions are of increasing concern worldwide. Concepts related to carbon peaks and carbon neutrality are developed and implemented in depth. China's Peak Carbon Action Programme by 2030, was proposed in October 2021 [1]. Green and low-carbon transport is a priority for Peak Carbon. Thanks to technological progress and policy backing, China's new energy vehicle industry is developing rapidly. The number of electric vehicles in the country continues to rise. Lithium-ion batteries have the advantages of high energy density, long cycle life, and low self-discharge rate, and are widely used as one of the key technologies for electric vehicles. Due to the poor thermal stability of lithium-ion batteries, thermal runaway is prone to occur in external abuses such as overcharging, crushing, and collision. A chain exothermic reaction occurs in the cell monomer under thermal runaway, leading to an uncontrollable rise in cell temperature [2]. The study of thermal runaway and thermal management of lithium-ion power batteries is of great significance to improving the safety of electric vehicles and enhancing consumer confidence.

Thermal runaway refers to the phenomenon in which a chain exothermic reaction occurs within the lithium-ion battery under mechanical, thermal, electrical, and other triggers, and the constant accumulation of heat leads to damage to the battery, thus triggering a battery combustion or explosion. The triggers of thermal runaway in Li-ion batteries are mechanical abuse due to crushing and collision, electrical abuse due to overcharging and internal short circuits, and thermal abuse. To reduce the occurrence of thermal runaway, this paper starts from the direction of thermal management of battery packs, which can prevent thermal runaway and improve safety through different ways such as air cooling, liquid cooling, and phase change. In this paper, the study of thermal runaways will start with the mechanism of thermal runaways, and abuse conditions. The research will be centered around an overview of ways to improve the safety of electric cores. And compare the advantages and disadvantages of different thermal management methods.

2. Power Battery Thermal Runaway Mechanism

Through the study of the lithium-ion battery, it is found that the thermal runaway of a lithium-ion battery can be divided into several stages: the first step of thermal runaway is that when the temperature of the lithium battery exceeds the normal working range, the solid electrolyte interface film (SEI) on the surface of the negative electrode will decompose; The second part is that the negative electrode, electrolyte, and adhesive further react and release heat. When the diaphragm melts, the positive and negative electrodes short-circuit, accelerating the thermal runaway, and the electrolyte decompositions to produce combustible gas and burn [3]. Thermal runaway of lithium-ion power batteries is an irreversible failure phenomenon caused by a sharp rise in battery temperature, usually caused by a chain reaction of materials inside the battery. There are several possible mechanisms.

When the heat of the battery cannot be dissipated in time, the heat of the battery will gradually increase. High temperatures may cause the devices inside the battery to react faster, generating more heat, which further increases the temperature. At such high temperatures, anode and cathode materials will break down into their respective components, such as graphite and lithium cobaltate into lithium ions and carbon. These breakdown products can lead to reduced battery performance and release more heat. The internal reason for the mechanism is that when the electrolyte inside the battery is out of control in the case of overheating, the heat generated by the electrode inside the battery accumulates in the lithium-ion battery, causing the rapid rise in the temperature of the lithium-ion battery, resulting in the shrinkage of the diaphragm, melting, decomposition of positive and negative active substances and other spontaneous exothermic reactions. The external reason for the mechanism is that under the action of external factors, the lithium battery pack is deformed by external forces, and different parts of its relative displacement occur. At the same time, for the battery cell inside the battery pack, due to the external force of the battery pack, a relatively large collision will occur inside the battery, as well as the extrusion of the internal electrode, which will cause the positive and negative electrodes inside the battery pack to directly short circuit, resulting in thermal runaway inside the battery pack.

3. Power Battery Thermal Runaway Inducement

According to the condition of the crashed car, the reason why thermal runaway happens can come down to the following: Mechanical inducements, electrical inducements, thermal inducement, and internal short circuits. When a single battery in the battery pack is abused by mechanical, electrical, thermal, and other factors, the local temperature will rise sharply. When a lot of heat accumulates in a single battery, it will burn and ignite other cells around it, which causes a large thermal runaway [4].

3.1. Mechanical Inducement

Mechanical inducements of power batteries include squeeze, bump, puncture, etc. The study found that under the state of external pressure, the diaphragm inside the battery will break, and the structural problem will first occur, which will lead to a short circuit of the positive and negative electrodes releasing a lot of heat in a short time, resulting the thermal runaway phenomenon of the battery. Similar to the extrusion load is the needing load. The direct result of the needing load is the battery has a short circuit at the needing point, the short-circuit region makes a lot of heat creating a local high temperature inside the battery. In addition, the electrolyte leakage problem caused by the shell deformation of the battery pack caused by the collision will also increase the risk of short circuits outside the battery pack, thereby increasing the probability of accidents.

3.2. Thermal Inducement

Thermal inducements are generally developed from mechanical inducements and electrical inducements, and the contact problem of components in the battery pack is also a major factor in the generation of thermal inducements. For example, overcharging the battery can cause a battery fire. A short circuit or poor contact in a certain area of the battery leads to changes in the internal resistance, which increases the probability of local overheating, and also leads to thermal runaway [4]. In addition, it has been found that when the temperature is too high, the oxygen released by the cathode material of the battery can react with the reducing gas, which leads to the occurrence of side reactions in the battery without serious internal short circuit, which is also a potential risk of thermal runaway [5].

3.3. Electrical Misuse

3.3.1 Over- and under-discharge

Another typical cause of thermal runaway is overcharging. If a battery is fully charged and stays that way, a significant amount of lithium ions in the positive electrode material will be de-embedded, pass through the diaphragm, and form lithium dendrites on the surface of the negative electrode. Concurrently, the reaction between the lithium ions and the electrolyte will produce a significant amount of gas and heat. Lithium dendrite development combined with overcharging will eventually puncture the diaphragm, creating a short circuit and resulting in thermal runaway.

Many researchers used to mimic the process of thermal runaway. Because thermal runaway resulting from electrical abuse is directly connected to heat, Qi et al. recreated the overcharging process because a separate model of electrical abuse would be quite different from the real scenario [6]. They used a three-dimensional thermo-electric coupling model to simulate the changes of the battery in the thermal runaway of overcharging and discovered that the charging multiplicity affects the critical time, the critical temperature, and the heat distribution of the battery when thermal runaway occurs. abuse model will be a large discrepancy with the actual situation. The greater the overcharge current, the shorter the thermal runaway time, the greater the critical temperature, the greater the regional temperature differential, and the greater the difference in temperature between the interior and outside. Three phases may be distinguished in the thermal runaway process, according to the tests that were conducted. The thermal equilibrium stage is the initial step. The shift in temperature is typical at this point. The second step, known as the thermal development stage, is when the negative electrode starts to show trace lithium dendrites, which causes a micro-short circuit. The third stage, known as the thermal runaway stage, is characterized by a massive chemical reaction within the battery, an expansion of the short-circuit area, the melting of the diaphragm, the breakdown of the SEI film, the oxidation of the electrolyte, and a significant increase in temperature due to the anode material's decomposition. Huang et al. studied the effects of battery size on thermal runaway using a square shell-type battery [7]. He found that decreasing the thickness can effectively strengthen the heat dissipation ability and reduce the internal temperature rise heat production rate. He also found that the longer the decomposition time, the thicker the SEI film, and the greater the degree of aging. These findings suggest that multiplicity affects thermal runaway in addition to charging. One of the contributing factors to thermal runaway is over-discharge. The idea is the same as for over-charging; an excessive discharge current will let a lot of lithium ions pass through the SEI membrane for a brief amount of time, which could cause a large-scale rupture of the membrane structure. As a result, the battery will age more quickly. After the battery reaches the minimum discharge voltage, it will dissolve into divalent copper ions in the negative electrode collector. These ions will then pass through the electrolyte to reach the positive electrode, which has a lower potential. This will result in the formation of copper ion dendrites and the shorting of the positive and negative electrodes, which will cause a thermal runaway. Thermal runaway mishaps are often not caused by over-discharge. On the other hand, an internal short circuit will be induced as the over-discharge continues, and early in the internal short circuit, thermal runaway will also occur.

3.3.2 Circuits within the body

Low resistance between the positive and negative collectors, which is frequently the result of diaphragm deterioration, causes an internal short circuit, a self-discharge occurrence [8]. Batteries may internally short circuiting due to mechanical mistreatment from the outside or faults in the battery itself. The external environment can also cause an internal short-circuit in a battery when it is exposed to mechanical abuse such as collision, extrusion, and puncture. From an internal short-circuit perspective, the battery's raw material is contaminated, and diaphragm defects and other issues deteriorate to form dendritic crystals during future use.

Internal short circuits in batteries can be classified into four categories: negative electrode material-aluminum collector, copper collector-aluminum collector, negative electrode material-positive electrode material, and copper collector-positive electrode material. The first category of internal short circuits has a low short circuit resistance value and poor thermal conductivity, making thermal runaway highly likely. The second category of internal short circuits has a very low short circuit resistance value but very good thermal conductivity, which poses a risk. In addition, the third group of internal short circuits has a low short circuit resistance value but a high thermal conductivity, which is harmful. Typically, thermal runaway does not cause an internal short circuit in this category of internal short circuits. Internal short circuits of category 2 are more harmful due to their high heat conductivity and low short circuit resistance. Batteries may lose capacity permanently as a result of internal short circuits [9].

Sazhin et al. used the self-discharge characteristics of the internal short circuit battery and connected a constant voltage source in parallel at both ends of the battery [10]. It can be determined that the battery is internally short-circuited when the constant voltage source is charging the battery or when the direction of the current of both of them is changed. These researchers looked into the method of checking the internal short circuit within the battery. By using the variation in the residual charging capacity of the batteries, Kong et al. were able to identify internal short circuits in lithium-ion batteries online [11]. Using the difference in residual charging capacity across batteries, Kong et al. were able to identify internal short circuits in lithium-ion batteries online [11].

3.3.3 External short circuit

The external short circuit of lithium-ion batteries is one of the important factors leading to the thermal runaway of the battery. Zhou et al. analyzed the single-level external short circuit and system-level external short circuit of lithium iron phosphate cylindrical lithium-ion batteries [12]. It is proved that the external short circuit of lithium iron phosphate battery has three forms: rupture leakage, internal fusion, and cumulative loss. To improve the safety of the battery, the current should be allowed to touch the fusing boundary in advance of the fusing protection according to the inverse time limit characteristic of the external short-circuit boundary of the battery. Chen et al. have established a battery protection method with graded fusing to ensure that the fuses can fuse in time to protect the battery system when thermal runaway has already occurred [13]. Also, ensure that the fuse thresholds are not too low to cause frequent fusing.

4. Thermal Management Methods

People need to carry out thermal management of the battery, also mainly need to improve the structural strength of the power pack and increase the thermal efficiency of the battery to start, the current common management methods are air cooling: including natural convection and fan cooling, the arrangement of the battery's internal electric core is also an important cooling effect consideration. But the specific heat of air is relatively low, considering the specific heat is much larger than air, now the automotive industry commonly uses coolant to cool down the battery, but liquid cooling is more flexible, it can be direct contact cooling, can also be indirect contact cooling. In addition, people are also researching the filling material inside the battery pack, the use of thermal conductivity and strength of the phase change material is now the direction of research.

4.1. Air-Cooling

Air cooling is a traditional cooling method that removes heat by accelerating air thermal convection. Air cooling can be divided into two types of cooling: active and passive. Active cooling is the introduction of cooled outside air into the heat exchanger using a fan or air pump. Passive cooling is the direct entry of windward airflow into the interior of the battery pack for heat exchange while the vehicle is in motion. Air cooling has the advantages of low cost, simple structure, and small space occupied, widely used in lithium-ion battery cooling. However, there are many disadvantages of air cooling, such as the small specific heat capacity of air, the difficulty of maintaining the same temperature of the cells in the battery module, and the setup of the exhaust port and air inlet affecting the sealing of the battery pack, etc. Therefore, the application of air cooling has been limited to a certain extent.

Aiming at the shortcomings of air cooling, many scholars have made improvements and optimizations from the battery arrangement, inlet and outlet structures, spoiler plates, etc. by building a simulation to improve the temperature consistency of the battery pack and enhance the heat dissipation efficiency of air cooling. Yang et al. investigated the effect of different arrangements of cells on the temperature and showed that aligned arrangement has 26.1% higher cooling efficiency and better thermal uniformity than staggered arrangement [14]. Shao investigated the effect of the location and number of air inlets on the temperature of cylindrical 18650 lithium-ion batteries and found that the closer the air inlet is, the lower the temperature is; and the further away from the air inlet, the higher the temperature is [15]. Inter-cell temperature consistency can be enhanced by increasing the number of longitudinal upper battery box air inlets. Wang et al. study the influence of the shape of the inlet and outlet on the heat dissipation efficiency of the law and found that when the inlet and outlet area are unchanged, the shape of the inlet and outlet for the circular heat dissipation effect is the best [16]. Dong et al. found that increasing the inlet tilt angle and adding a spoiler can significantly improve the battery temperature consistency [17]. Lin found that the larger the spoiler tilt angle, the higher the cooling efficiency, and the best battery cooling performance is achieved when the angle is 80° [18].

The heat dissipation efficiency of air cooling can also be improved by algorithmic optimization of each parameter. Xia et al. optimized the deflector plate angle and battery row spacing according to the flow resistance network model and genetic algorithm, which reduced the maximum battery temperature and the temperature difference of the battery pack and improved the heat dissipation efficiency [19]. Li et al. used a multi-objective optimization method with orthogonal experiments, which converged after many iterations to arrive at the optimal solution for the inlet and outlet heights and battery spacing, which reduced the maximum temperature of the battery pack by 9.55% and the temperature difference by 25.89% compared to the pre-optimization period [20].

4.2. Liquid Cooling

4.2.1 The way of liquid cooling

The principle of liquid cooling is to carry out convection heat transfer through the liquid medium, taking away the heat inside the battery, and thereby reducing the battery temperature. To reduce the maximum temperature of the battery pack and improve the consistency between the monomers, the heat transfer coefficient, heat capacity, and cooling speed of the liquid medium should be increased as reasonably as possible. At the same time, to greater vehicle space and reduce the mass of the vehicle, the liquid cooling system should minimize the volume.

4.2.2 Advantages of the liquid cooling system

Compared with the air-cooling system, the cooling effect of the cooling system is better than the air-cooling system with the same volume and velocity. In addition, liquid cooling has a flexible cooling method, it is divided into direct cooling and indirect cooling.

4.2.3 Cooling plate

If the temperature distribution of the battery pack is not uniform, the capacity of the battery pack will be reduced, the charging and discharging efficiency will be reduced, and the service life will be reduced. If the temperature of the battery pack is too high, it will cause a thermal runaway, resulting in a series of safety accidents. To further improve the heat dissipation capacity of the thermal management cooling system, the cooling plate plays a key role as a key component in the cooling system, and its layout form, flow channel width, coolant quality, flow rate, tube distance, plate thickness, and changes will have an impact on the cooling effect.

4.2.4 Cooling plate runner structure type

The common cooling plate runner structure types are mainly: S-type, linear, and more complex curve type. Although the linear structure is simple and the resistance is small, it has the disadvantages of short cooling path, low efficiency, and unequal flow rate. Although the S-type has been improved to improve the heat transfer coefficient, the problem of large temperature differences at the outlet still exists [21].

Zou et al. studied the influence of different cooling channels on the temperature field and finally concluded that the 90°S type fixed channel has a strong heat dissipation capacity. The smooth curved fixed runner is beneficial to improve the temperature consistency [21]. Fu et al. analyzed the flow channel structure of six groups based on the uniform distribution of the liquid cooling system and liquid cooling plate size and took 217000 lithium batteries as a single battery [22]. Finally, he concluded that too low or too high flow channels for 21700 lithium-ion battery modules would affect the temperature control effect. Only when the number of flow channels in the cooling plate is controlled within a certain number can the overall temperature control effect be achieved. The 8-channel structure can effectively control the operating temperature, and the overall average temperature of the battery is the lowest, and the effect is the best.

4.3. Phase-Changing Substance (PCM)

In addition to having a straightforward structure devoid of extra energy consumption, phase change material (PCM) is a type of high thermal conductivity material that is well-suited for batteries of any shape and is frequently utilized in lithium-ion thermal management systems. PCMs utilized for battery thermal control currently mostly consist of eutectic materials, inorganic materials (salt hydrates, aqueous solutions, and molten salts), and organic compounds (paraffin, alkanes, and organic acids) [23]. It has been the focus of current research to composite several high thermal conductivity materials to improve the phase change energy storage materials' performance [24]. The combination of composites and phase transition materials is also a potential avenue, as metals can enhance mechanical strength while graphite can significantly boost heat conductivity [24]. To maximize the cooling impact in real-world applications, phase change materials are typically utilized in conjunction with other cooling methods. modeling and experimentation, Xia Yufeng built a stepped heat pipe-phase change material cooling device using the 1P11S battery pack as a prototype. He then compared and studied the power battery's thermal management effect before and after optimization [25]. The findings demonstrate a smoother temperature change curve, a decrease in the simulation experiment's temperature standard deviation from 5.2 °C to 2.4 °C, and a reduction in the real experiment's temperature standard deviation from 4.7 °C to 2.3 °C [25]. According to research by He et al., thermoplastic elastomers (TPEs) are used as the carrier of phase change materials to form flexible composite phase change materials (FCPCMs) [26]. TPEs are used to compensate for the low mechanical properties, low shape stability, and low thermal conductivity of phase change materials in battery thermal management applications. A thorough examination of the FCPCM's vibration resistance, flexible material research, and other related topics is required.

5. Conclusion

This essay mainly discusses the thermal runaway and thermal management of lithium-ion power batteries in new energy vehicles and some related literature. 1) First of all, the authors introduce some mechanisms of thermal runaway of the battery, which is mainly due to the influence of temperature, and it also talks about the external causes and internal reasons. 2) Secondly, regarding the inducement of thermal runaway, some points can be summarized about mechanical inducement, electrical inducement, thermal inducement, internal short circuit, and external short circuit. 3) In terms of thermal management, the authors can further use air cooling, liquid cooling, and phase change materials that can prevent or reduce thermal runaway, which can further improve safety.

Up to now, although the researchers have achieved a lot of conclusions and experimental results on the thermal runaway and thermal management of lithium-ion batteries. In the actual situation, its safety has not been completely improved, even though many areas are still blank. Therefore, on thermal runaway and thermal management of batteries, there are only a few experiments and conclusions that can support these views.

In recent years, new energy vehicles have gradually entered the market, and most of these cars need to use a charged battery. However, these batteries often face a variety of problems during the charging process, nowadays, the current average temperature is gradually rising. The battery might also burn and explode when they are always exposed to such high temperatures for a long time. About this problem in the area, people have not been able to get a complete theory that can thoroughly prevent this safety problem. Therefore, the thermal management of the battery is now in exploration, some methods may deal with the harm caused by the high temperature of the battery. For example, cars can take the self-detection of temperature to produce some cooling measures that can prevent the harm caused by thermal runaway effectively. There are also some expectations for the future, hoping that in the future, the safety performance of batteries can get some reasonable solutions that prevent and resist such problems.

Author contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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