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FROM RISK TO SUSTAINABILITY: IMPROVING LITHIUM-ION BATTERY SAFETY FOR SUSTAINABLE ENERGY APPLICATIONS

Aleksandra Stevanović[1], Jelena Mitrović[2]

Abstract

This paper addresses the critical safety issues associated with the use of lithium-ion batteries, which are indispensable in modern energy storage and various applications. Vehicles that operate on the principle of internal combustion engines produce harmful exhaust gases and are mostly responsible for pollution and global warming. An alternative to vehicles powered by internal combustion engines is electric ones. The battery of an electric vehicle is a very important component that stores energy for its propulsion. Among the familiar, batteries, lithium-ion batteries are the most popular and the most commonly used batteries. Although lithium-ion batteries make up the majority of the rechargeable battery market, there are serious concerns about their safety. Accidents, fires, and explosions of electric vehicles have been reported frequently in recent years. These adverse conditions that impair the safety of lithium-ion batteries include mechanical damage, electrochemical conditions, and thermal conditions. To ensure the overall safety of lithium-ion batteries, safety techniques must be such that they protect against all of the mentioned conditions. The battery must be protected from internal as well as external influences in order to achieve the general safety of lithium-ion batteries. There are various techniques to improve the safety of lithium-ion batteries, but improvement in the context of materials is the basic and most important technique to improve battery safety. By contributing to the development of safer lithium-ion batteries, this paper is significant in advancing sustainable energy technologies and promoting a resilient, self-sufficient economy.

Key words: *lithium-ion battery, sustainability, energy..*

[1] University of Novi Sad, Faculty of Tehnical Sciences, Serbia, aleksandrastevanovicftn@gmail.com
[2] University of Novi Sad, Faculty of Tehnical Sciences, Serbia, jelenamitrovicftn@gmail.com

1. Introduction

For the last few decades, the entire world population has been fighting pollution and global warming permanently. Vehicles powered by internal combustion engines emit harmful exhaust gases, contributing to pollution and global warming because they use carbon-based fuels. An alternative to vehicles powered by internal combustion engines is electric vehicles, because these types of vehicles use electricity as their energy source, instead of fossil fuels. Electric vehicles produce no exhaust gases, and their operation is very quiet and significantly cheaper compared to vehicles with internal combustion engines. The battery of an electric vehicle is a very important component that stores energy for its propulsion. The lithium-ion batteries are the most popular and most commonly used batteries, due to their advantages in the form of high specific energy, long working life, high efficiency, lightweight, and absence of memory effect. However, the increased interest in lithium-ion batteries arises by certain an unfortunate event associated with these batteries, which has often contributed to lower public confidence. There are various techniques to improve the safety of lithium-ion batteries, but improvement in the context of materials is considered as basic and most important technique. By contributing to the development of safer lithium-ion batteries, this paper is significant in advancing sustainable energy technologies and promoting a resilient, self- sufficient economy.

2. Mechanism of a thermal runaway in lithium-ion batteries

A thermal runaway occurs when the battery overheats or reaches a critical temperature (Yuan et al., 2019). The main causes of thermal runaway in lithium-ion batteries are critical situations at the mechanical, electrochemical, and thermal levels (Chombo & Laoonual, 2020). Mechanical accident conditions include crushing, penetration, dropping, impact, overturning, and vibration (Sahraei et al., 2012). In the conditions of mechanical accidents, lithium-ion batteries are first deformed under the mechanical action of the load, and the deformation results in the development of internal stress. Electrochemical accidents in lithium-ion batteries include forced overcharging, over-discharging, external short- circuiting (ESC), etc. Overcharging is a condition in which power is forced to flow through a lithium-ion battery cell even after the state of charge (SOC) has reached its maximum limit. Overcharging is very dangerous because overcharging adds additional energy, under current conditions (Leising et al., 2001). Heat generation due to a side reaction during electrolyte decomposition leads to a sudden rise in temperature and even thermal runaway (Kriston et al., 2017). Thermal disasters such as fire, heat stroke, and overheating are the direct causes of battery thermal runaway (Feng et al., 2018). Overheating due to conditions such as high ambient temperature, high heat transfer to adjacent cells, and inefficient heat dissipation continues to increase battery temperature. Because lithium-ion batteries are very sensitive to temperature and must operate within a limited temperature range, thermal shocks are very detrimental to their safety. The ideal operating temperature for lithium-ion batteries is between 15 ∘C and 35 ∘C, and the maximum cell temperature difference (ΔT_{max}) must be <5 ∘C (Thakur et al., 2020). When lithium-ion batteries operate outside this temperature range, they experience adverse effects that lead to thermal runaway.

3. Internal Material Advancements for Safer Lithium-Ion Batteries

Materials enhancement is a technique to improve the safety of a lithium-ion battery, and recent advances in internal battery materials to improve its safety include improvements in cathode and anode materials, the use of non-flammable electrolytes, flame retardant additives, overcharge protection additives, and advances in external materials such as advances in battery thermal management and battery case material.

The internal material of the lithium-ion battery should be such that it has a high tolerance in situations of different types of disasters because each component directly affects the safe functioning of the lithium-ion battery. Advances in internal battery materials are effective techniques for improving battery safety that include improvements in cathode and anode materials, using non-flammable electrolytes, flame retardant additives, overcharge protection additives, etc. help to improve battery safety from electrochemical and thermal hazards such as overcharge, over-discharge, short circuit, overheating, thermal shock, etc. These internal material improvements include material modification, the use of new materials, and the use of additives to improve the safety of the lithium-ion battery.

Overcharging is a type of damage that lithium-ion batteries experience by passing current through it in a situation where the battery is already fully charged (Wen et al., 2012). To prevent overcharging the battery, an external battery management system device is also used to maintain the optimal charge and discharge voltage and current for each cell. But the battery management system increases the cost, weight and volume of the battery, also, in some cases, the failure of the battery management system risks overcharging. Electrochemically reversible additives should be added to protect the battery internally from overcharging. These additives based on their functions are categorized as redox shuttle additives and shut-off additives.

Further, various techniques have been considered to improve the thermal stability of the cathode material and two main safety techniques are proposed - element replacement and surface protective coating. The replacement of elements led to improved thermal stability of layered oxide cathodes because it stabilizes the crystal structures. Replacing elements such as Ni and Mn with other metal cations such as Mg, Ti, Zr, Ga, F and Al can improve the thermal stability of layered oxide cathodes (Luo, 2010).

The coating material can be inorganic compounds such as Al2O3, AlF3, AlPO4, ZnO, MgO, TiO2, ZrO2, FeF3, and SnO2, which are capable of conducting Li-ions after being lithiated or organic films such as poly (diallyl dimethylammonium chloride), or protective films formed with additives g - butyrolactone and multicomponent additives consisting of vinylene carbonate, 1,3-propylene sulfite and dimethyl-acetamide.

Graphite is a commercially used material for the anode of a lithium-ion battery due to its advantages such as: low cost, high insertion capacity, layered structure, high electrical conductivity, relatively small volume change during cycling, and high reversibility. $Li_4Ti_5O_{12}$ (LTO) is used in commercial lithium-ion batteries for its ability to operate at high charge/discharge rates, improved thermal stability, and long lifetime. Unfortunately, the use of LTO anodes does not eliminate the risk of surface reactions (Duan et al., 2020).

The separator of lithium-ion batteries is a very important component for their operation and from the point of view of their safety. A separator is a thin porous membrane placed between electrodes to retain, separate and prevent internal short circuit (Schadeck et al., 2018). To maintain the safety of the battery and its smooth operation, the mechanical integrity of the separator must remain intact, otherwise at higher temperatures the separator can shrink and cause an internal short circuit that releases a huge amount of energy and causes the battery to explode. Therefore, researchers are working to minimize shrinkage and destruction of the separator at higher temperatures.

When thermal runaway is triggered, reactions are set in motion that increase the rate of heat release, causing gases to form and increase the internal pressure of the battery. The low flash point or thermal stability of organic solvents poses a serious threat to battery safety, for example, the flash point of ethyl methyl carbonate, diethyl carbonate, dimethyl carbonate and propylene carbonate is 33 $^\circ$C, 15 $^\circ$C and 22 $^\circ$C, respectively. Flammable organic electrolytes have the lowest thermal stability and during the process of thermal runaway release large amounts of flammable gases, which can cause the battery to catch fire. To solve this problem to increase the safety of lithium-ion batteries, a method has been developed that adds flame retardant (FR) additives to the electrolyte to reduce its flammability.

Flame retardant additives include organic phosphorus compounds are: triethyl phosphate (TEP), bis(2-methoxyethoxy) methylallylphosphonate, trimethyl phosphate (TMP), triphenyl phosphate (TPP), tris(2,2,2- trifluoroethyl) phosphite (TTFP), (ethoxy)pentafluoro cyclotriphosphazene (PFPN) and ethylene ethyl phosphate (EEP).

Changing the properties of conventional electrolytes with electrolyte additives has a limited effect on improving battery safety. Therefore, researchers have proposed replacing the current flammable electrolyte with nonflammable electrolytes such as: ionic liquids, low molecular weight hydrofluoroethers, and solid state electrolytes to improve battery safety (Wang et al., 2016). It was concluded that by increasing the ionic liquid content to 40%, the mixed electrolyte becomes hardly flammable and has very good electrochemical stability.

Current collectors (CC) are a key component of lithium-ion batteries as they work as a link to support active components, such as binders, conductive additives, cathode and anode materials, and as such electrochemically connect the entire anode and cathode structure to the external circuit. The thickness of the current collector has been reduced in the last two decades to improve the energy density of the battery in the range of 16 to 26% (Mahmud et al., 2022). Al is widely used as a current collector material due to its excellent resistance to. Although the current collector does not participate in the electrochemical reactions, it has a significant effect on the performance of the electrodes. However, rapid self- extinction under extreme circumstances such as overheating and short- circuiting poses a serious threat to the safety of lithium-ion batteries (Kong et al., 2020).

3.1 External Material Advancements for Safer Lithium-Ion Batteries

External material improvements to improve battery safety include improvements to the battery thermal management system (BTMS) and battery case protection materials. The battery thermal management system improves the safety of Li-ion batteries from thermal accidents such as: overheating, thermal shock, etc., by keeping the battery temperature within limits, while the protective battery case helps to protect Li-ion batteries from mechanical accidents such as : crushing, vibrations, penetrations, and thermal disasters such as: fire, thermal shocks, etc.

The main factors for thermal runaway conditions in Li-ion batteries are - overcharging, internal short circuits, high charge/discharge rates, and sudden increase in internal battery temperature leading to battery burnout or explosion (Luo et al., 2010). Therefore, it is very important to maintain the internal temperatures of lithium-ion batteries within optimal limits. The optimal operating temperature of lithium-ion batteries is 15–35 ∘C, and the maximum power limit is also achieved in this temperature range. In a situation where lithium-ion batteries operate outside this temperature limit, the battery has a negative impact on its electrochemical performance. When the battery's temperature rises above 35 ∘C, it experiences degradation during discharge, and high power shuts down during charging.

Further, along with battery cooling, the battery thermal management system also helps maintain a uniform temperature inside the battery and maintains ΔTmax below 5 ∘C inside the battery (Liang et al., 2018). If the internal battery ΔTmax exceeds 5 ∘C, then a thermal runaway condition occurs, leading to a fire and ultimately endangering the safety of the battery. The battery's heat generation can be reduced by reducing the battery's internal resistance, but the heat produced by the electrochemical reaction occurring inside the battery cannot be avoided. Therefore, the battery thermal management system is very important from the point of view of battery safety.

An air cooling based battery thermal management system uses either natural air cooling for heat management or forced air cooling using a fan/blower. Due to various attributes such as simple design, no leakage, low cost and light weight, this battery thermal management system technique was the first to be used by various electric vehicle manufacturers such as: Honda Insight, Nissan Leaf, Toyota Prius, Renault Zoe, etc (Liang et al., 2018).

Initially, the researchers discovered that the phase change material (PCM) has a significant amount of latent heat, which can allow the battery's operating temperature to remain relatively constant. Therefore, the phase change material is considered in the context of battery thermal management systems.

As the technology develops, the rate of charging and discharging also increases and the pure phase change material does not remain as efficient due to excessive heat generation and localized temperature rise caused by its poor thermal conductivity. Therefore, researchers have focused on increasing the thermal conductivity of phase change materials so that good thermal management can be achieved (Mitra et al., 2022).

The protective case or battery housing plays a key role in ensuring the safety of electric vehicles by providing protection to the batteries. With the rapid increase in battery energy density, the needs of long-range electric vehicles are met. With higher energy density, more energy stored in the battery helps electric vehicles to cover long distances, but the negative effect of this is explosions and fires in the event of a crash or accident.

The protective casing of the battery must include characteristics such as electromagnetic compatibility, anti-corrosion properties, rigidity, integrity, thermal management and fire safety. It is important to use a battery case with a lightweight design to increase and decrease the range of the negative effect of the electric vehicle battery on the dynamics and acceleration of the performance vehicle (Chen et al., 2021).

4. Conclusions

The paper provides an overview of the safety challenges in the context of lithium-ion batteries, including mechanical, electrochemical and thermal. To date, significant progress has been made in developing materials development strategies to address these challenges and improve battery safety. Advanced materials and additives have shown improvements in terms of stability and reducing the risk of thermal runaway. The design and engineering of advanced electrode materials, separation materials and protective coatings contribute to better thermal management and overall safety of lithium-ion batteries. Looking ahead, future research should focus on advanced characterization techniques, modeling and integration of safety features into battery management systems. Interdisciplinary collaboration and knowledge sharing is critical to solving complex challenges and accelerating progress toward safer lithium-ion batteries. In conclusion, the field of materials to improve the overall safety of lithium-ion batteries is rapidly evolving to meet the demand for safer and more reliable energy storage solutions.

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