Enhance the Market Competitiveness of Electric Vehicles by Improving the Design of Lithium-ion Batteries

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Abstract. Electric vehicles (EVs) are increasingly popular because they are energy efficient and capable of providing a good driving experience. However, the performance and market competitiveness of electric vehicles has been limited by a series of shortcomings, which are mainly caused by the limitations of the power source, lithium-ion batteries. To address these problems from the origin, this research analysed the causes of these problems and proposed some possible solutions based on the characteristics and working principles of lithium-ion batteries. The limitations of electric vehicles such as safety issues, low range, high cost, and limited life span are all proved to be related to the EV batteries. Lithium-ion batteries used by electric vehicles have the risk of fire and explosion when broken, overcharged, or exposed to high temperatures. The capacity and life span of them can easily be affected by different factors, which leads to the dissatisfaction of customers with the range and EV batteries' life span. Furthermore, the production of lithium-ion batteries is very costly. Different ways to improve the performance of lithium-ion batteries are collected and evaluated. Finally, it is concluded that Li-S batteries and lithium titanate batteries are likely to become the solutions to what limited the development of electric vehicles. Since Li-S batteries and lithium titanate batteries still have some disadvantages, researchers should manage to tackle them in the future before they can be widely applied. This paper provides directions for the future development of EV batteries to improve the market competitiveness of electric vehicles.

Keywords: Electric Vehicle, Lithium-ion Battery, Safety, Capacity.

1. Introduction

With the development of the global economy, the expectation of the quality of travel is higher and higher. The number of private vehicles keeps increasing, which causes a large amount of fossil fuel consumption and other problems. In order to tackle a series of problems, the electric vehicle, which has been proven to be energy-saving and able to provide a much better driving experience, seems to be a good alternative [1-4]. However, in spite of all the advantages, it remains doubtful whether electric vehicles are better than traditional internal combustion ones. It should be admitted that there are still a few limitations in electric vehicles compared with internal combustion ones, and the main origin of these limitations is electric vehicles' power source, the lithium-ion battery, whose limitations in safety, capacity, life span, and other aspects affect the performance and market competitiveness of electric vehicles directly or indirectly. Electric vehicles can hardly achieve better performance and be widely accepted by the public unless the problems of EV batteries are solved and new batteries with higher capacity, better safety characteristics, longer life span, and lower cost are applied [5].

At present, there is a great deal of research investigating the problems that limited the development of electric vehicles. However, to tackle them, most of the research seeking solutions focus on political, economic, mathematical modelling, or automated detection methods. Some research mentions the design of EV batteries in one aspect. For example, ZHOU [6] and SHAN [7] both summarise and suggest some methods in their research to modify the electrode and electrolyte, which can enhance the safety of electric vehicles by raising the safety of lithium-ion batteries. However, only solving one limitation is not enough. For the purpose of boosting the performance and market competitiveness of electric vehicles, future lithium-ion batteries are supposed to be able to address the limitations of electric vehicles in as many aspects as possible. Therefore, it is necessary that systematic research analyse how EV batteries result in the limitations of electric vehicles and how EV batteries can solve them.

In this research, based on the characteristics and the working principles of lithium-ion batteries, the links between EV batteries and the shortcomings of electric vehicles were analysed. After that, different kinds of new designs of lithium-ion batteries were summarised and assessed. In the end, the most helpful designs of lithium-ion batteries were proposed, providing possible directions for the development of EV batteries.

2. Lithium-ion battery

2.1. The characteristics of lithium-ion batteries

The secondary batteries commonly used in electric vehicles are mainly lead-acid batteries, nickel metal hydride batteries, and lithium-ion batteries. Compared with the others, lithium-ion batteries have a high voltage, high specific energy, high energy density, and long cycle life without memory effect [8]. Thus, lithium-ion batteries are extensively applied in the electric vehicle industry. However, there are still some drawbacks, such as the high cost, as well as the security issues, which can be threatened by mechanical damage or overcharge of the batteries [6, 7].

2.2. The working principle of lithium-ion batteries

There are mainly four parts of a lithium-ion battery: the separator, electrolyte, cathode, and anode, as shown in Figure 1. The cathode is generally a transition metal oxide coated on the aluminium collector. In EV batteries, the cathode is made of $LiFePO_4$ or Li-Ni-Co-Mn-O. The anode is usually a carbon material of a graphite structure, which is coated on the copper collector. Between the anode and the cathode is the electrolyte, which is usually a kind of lithium salt dissolved in an organic solvent, playing the role of ionic conduction and electronic insulation. There is a porous polymeric separator in the electrolyte conducting lithium-ions and insulating electrons, too. It also has the function of protecting the anode and cathode from direct contact. During charging and discharging, lithium ions are inserted and removed between the atomic layers of the electrodes, conducting electricity between the cathode and anode inside the battery. In the external circuit, electricity is conducted by electrons.

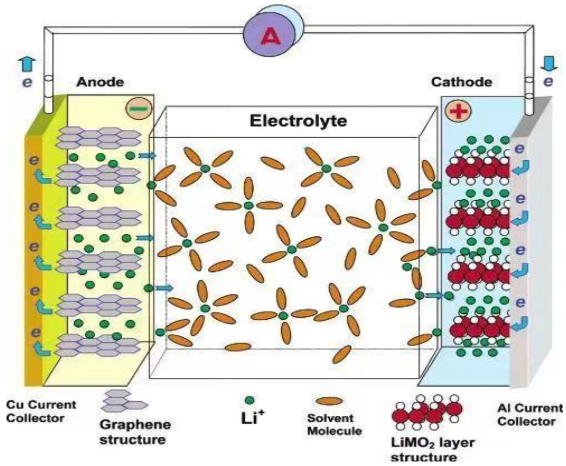

Figure 1. The structure of the lithium-ion battery [9]

3. Limitations in electric vehicles

3.1. Safety issues

The security issue of electric vehicles has risen worldwide concerns because lithium-ion batteries can become very unsafe and unstable in some conditions. Thermal runaway of EV batteries, which is caused by mechanical, electrical, and heat abuses, can easily contribute to severe fire and even explosion. A battery pack with a great many cells connected in series and/or parallel in it means not only high energy and power but also catastrophic damage when accidents happen.

In an electric vehicle, the battery is very likely to be penetrated or squeezed out of shape when a crash happens, followed by a short circuit. This leads to a sharp increase in temperature and obviously has a great potential to cause fire and explosion [7]. Moreover, the overcharge of lithium-ion batteries can cause lithium dendrite and decomposition of the electrolyte. If the lithium dendrite penetrates the separator, a short circuit will occur, which then may cause fire and explosion. As the electrolyte decomposes, oxygen as well as different kinds of flammable gases are produced, which largely increases the risk of fire [6]. In addition, such thermal runaways can also be caused by exposure to high temperatures and the failure of the thermal management system [10]. Therefore, it is vital to apply a more reliable battery in an electric vehicle in order to guarantee the safety of the owner.

3.2. Range problems

There are quite a few complaints from car owners about the limited range of the electric vehicle, however, most EV companies claim that the range of their electric vehicles is more than 500km. Some can even run as far as 700km, which is not lower than the range of internal combustion cars. This can be explained by the decrease in capacity. In an ideal situation, the number of electrons/lithium ions that migrate between the anode and cathode during charging and discharging does not change, that is, the capacity of the battery keeps constant [5]. However, in a practical situation, the number of electrons/lithium ions decreases gradually during charging and discharging, leading to a drop in capacity. This decreasing process is caused by temperature and other factors, which means the practical range of electric vehicles is lower than official data [11]. Thus, many EV owners suffer from range anxiety and are troubled by the maintenance of batteries. Instead of protecting the battery cautiously from the factors that may reduce the range of the EV, the owners of the EV would rather see an improvement in the battery capacity to increase the range.

3.3. Costly production of batteries

The high prices keep many customers away from purchasing electric vehicles and the most expensive part of an electric vehicle is its batteries. As shown in Table.1. [12], the price of an internal combustion engine is much lower than that of lithium-ion batteries. So, customers who are not very well-off would rather choose internal combustion vehicles than electric vehicles. Besides the manufacturing process, the metals contained in lithium-ion batteries, such as Co, are costly. The majority of the metals applied in lithium-ion batteries are not only expensive but also face a shortage. Without technological progress, the global amount of Copper, Zinc [13], and Cobalt [14] can last only a few decades before running out. To attract more customers to purchase electric vehicles and realise sustainable development in this industry, it is necessary to find alternatives for those rare and expensive materials.

Table 1. The cost of battery packs compared with internal combustion engines

Type	Price/RMB
Mini EV battery packs	30000-40000
Common EV battery packs	60000-80000
Luxury EV battery packs	170000 (Tesla Model S)
internal combustion engines	30000

3.4. Dissatisfaction with the batteries' life span

Although compared with EV batteries in the past, lithium-ion batteries nowadays arguably have a long life span, it cannot be considered long enough to satisfy the customers. As is displayed in Table. 2., the life span of lithium-ion batteries in electric vehicles is no more than ten years [12]. When life comes to an end, car owners have to change to a new battery, which is another high cost. Moreover, both high and low temperatures can have an effect on lithium-ion batteries' life span, as well as other factors, such as high charging current [16]. The inconsistency of different cells in a battery pack also contributes to the decrease in the batteries' life span [17]. It is obvious that in order to alleviate the burden of EV owners, new lithium-ion batteries with a long life span are needed.

Table 2. The cost of battery packs compared with internal combustion engines

Type of lithium-ion batteries	Circle life	Life span/y
Lithium-ion phosphate battery	3500	10
Ternary lithium battery	2000	6

4. The design of lithium-ion batteries

4.1. Improve safety

There are mainly two aspects among the approaches to making lithium-ion batteries safer. One is replacing or modifying the liquid electrolyte, which is unstable and flammable. The other is modifying the anode and cathode by coating and doping to improve their thermal stability.

The most economical and effective method to enhance the safety of lithium-ion batteries is to add some flame-retardant additives to the traditional liquid electrolyte, which has been extensively applied in industrial production. However, the additives can cause a loss of electrochemical performance [7]. In addition to additives, there are many researchers attempting to replace the liquid electrolyte with a solid one. Solid electrolytes, which include inorganic electrolytes and polymer electrolytes, have good thermal stability and can prevent internal short circuit and lithium dendrites. Generally speaking, inorganic electrolytes can provide a wide electrochemical stability window. Oxide and sulphide are mainly used as inorganic electrolytes nowadays due to their high ionic conductivity, some of which can even be higher than that of conventional electrolytes. Despite all these advantages, there are still some problems to solve, especially the interfacial resistance and mechanical stability of the solid-electrolyte interphase. Polymer electrolytes can not only enhance the safety of the battery but also be more flexible in shape with easy fabrication. However, similar interfacial problems also exist in polymer electrolytes, and the operating temperature of polymer electrolytes is narrow [18].

At present, there is not very much research on the modification of the anode. Current research mainly focuses on the modification of the cathode. ZrO_2 [19], Al_2O_3 [20] as well as non-reactive elements such as Ag [21], and C [22], have been used to coat the anode of ternary lithium-ion batteries in order that the thermal stability and capacity retention rate can be increased. Taking Ni and Al as the substitutes for Co in the cathode, the battery is also proved to have excellent thermal stability [23]. Applying an Al-ion coat to the cathode can also protect lithium-ion batteries from overcharging. Coating $AlPO_4$ on the cathode of NCM811 and Li_xCoO_2 batteries, CHO's research showed that the surface temperature of the cathode of the NCM811 and the Li_xCoO_2 batteries did not exceed 125°C and 170°C during tests at charge rates of 1C to 3C. Although a short circuit occurred when the charging voltage reached 12V at a charging rate of 3C, thermal runaway did not happen [24]. However, the process of coating and doping is so complex that it raises the difficulty and cost of production [7].

4.2. Seek for batteries with high capacity

To increase the range of electric vehicles, batteries with high capacity and energy are needed. Two new kinds of batteries have attracted a lot of attention and have been under wide investigation since the last century. One is the Li-O battery, the other is the Li-S battery.

The Li-O battery adopts the combination design of the metal lithium anode, which has the lowest electronegativity and the lightest, and the oxygen in the air as the cathode. Therefore, it has a lower weight and higher voltage than traditional lithium-ion batteries [8]. The battery has a theoretical specific energy of 13.5 kWh/kg and a specific capacity of 5000 Ah/kg. Under laboratory conditions, the specific energy is 2440Wh/kg, while the specific energy of traditional lithium-ion batteries is 110-

250Wh/kg. The reason why Li-O batteries have not been widely used in everyday life so far is that Li-O batteries have a fatal defect. The solid reaction product, lithium oxide will accumulate in the positive electrode and bloke the air diffusion, resulting in the reduction of the batteries' life span [25]. So the design of a new electrolyte system and the development of high-efficiency air electrodes are two significant issues in the future research of Li-O batteries [8]. The Li-S battery is based on the REDOX reaction between sulphur and lithium. The theoretical specific energy can reach about 2600Wh/kg and its theoretical specific capacity is 1675Ah/kg. The application of lithium metal and sulphur can not only reduce the weight of the batteries but also save costs [26]. However, during charging and discharging, soluble polysulphide will be produced at the cathode in a Li-S battery and migrate to the anode reacting with it, which is called the 'polysulphide shuttle' and reduces the efficiency and capacity of the battery. Moreover, the application of lithium metal also means lithium dendrite problems [18].

As for the problems Li-S and Li-O face, the solid electrolyte mentioned before seems to be a good solution. In Li-S systems, solid electrolytes and hybrid electrolytes, which are able to prevent 'polysulphide shuttle' and lithium dendrites, have been studied in some research. In Li-O batteries, a hybrid electrolyte has been investigated to address the blockage lithium oxides cause. The hybrid electrolyte consists of an aqueous electrolyte at the cathode, an organic electrolyte at the anode, and a solid-state electrolyte membrane such as PEO or LATP between them. The aqueous electrolyte contains weak acids such as CH_3COOH, H_3PO_4, or LiH_2PO_4 to eliminate lithium oxides that can block air diffusion [18]. If the interfacial problems are solved, the application of solid electrolytes in Li-O and Li-S batteries will contribute to a surge in the stability and efficiency of these batteries. The large capacity of EV batteries and a much higher range of EVs can be expected. In addition, new carbon materials such as porous carbon aerogel, mesoporous carbon foam, and nitrogen-doped carbon nanotubes have been studied as the cathode to improve the efficiency of Li-O batteries [25].

4.3. Reduce the cost of batteries

Two approaches to reducing the cost are proposed in this paper. Firstly, Co is a kind of expensive and rare metal [13]. Reducing the use of Co in the cathode can reduce the cost. As mentioned before, replacing Co with Ni and Al, which are cheaper and more abundant than Co, can cut down the cost as well as improve thermal stability. The other approach is Li-S batteries. Compared with metal oxides, sulphur is much cheaper and more abundant around the world [26].

4.4. Extend the life span of batteries

Lithium titanate (LTO) batteries, using $Li_4Ti_5O_{12}$ as the anode and $LiFePO_3$, $LiMnO_4$, $LiNiMnO_4$, $LiCoO_2$, or ternary materials as the cathode, have almost no volume change during charging and discharging, indicating very good cycle stability. $Li_4Ti_5O_{12}$ has a much higher diffusion coefficient of lithium-ion than graphite, which can reach 2×10-8 cm^2/s, so the battery has an excellent high-rate performance. In addition, SEI film cannot form on the surface of $Li_4Ti_5O_{12}$, which avoids battery performance deterioration due to SEI film destruction. Thus, LTO batteries are safer than traditional lithium-ion batteries [27].

Except for batteries using $LiCoO_2$ as the cathode, all the other LTO batteries can reach a high cycle life of more than 10000. The LTO batteries using $LiMnO_4$ and ternary materials as the cathode can work well under both high and low temperatures. The 3Ah lithium $LiMnO_4$/ $Li_4Ti_5O_{12}$ battery developed by Norio Takami [28] et al. had a capacity retention rate of 95% when it finished 30000 cycles of 100% charging and discharging at 10C. The discharge capacity at 50C remained 94% under room temperature. Discharging at 1C under a low temperature of -40℃, and the capacity was 80% of that under room temperature. There were even no flammable gases in the $LiMnO_4$/ $Li_4Ti_5O_{12}$ battery when the temperature reached 100℃ [29]. The 20Ah ternary/ $Li_4Ti_5O_{12}$ battery that Norio Takami [28] et al. developed had almost identical discharge capacities of 8C and 1C under room temperature. Under a low temperature of -30℃, 1C discharge capacity was 80% of that under room temperature. 100% charging and discharging 6000 times at 3C, the capacity retention rate was 86%.

After 365 days of full charge storage at 25℃ and 45℃, the capacity retention rate was 88% and 73%, respectively.

However, there is the biggest disadvantage of LTO batteries. The specific energy of LTO batteries nowadays is about 50-90Wh/kg, which is quite lower than traditional lithium-ion batteries and limits their application [30]. If a breakthrough occurs in the specific energy of LTO batteries, the owners of electric vehicles will no longer be troubled by the maintenance and change of batteries.

5. Conclusions

The electric vehicle, which is energy-saving and able to provide a better driving experience than internal combustion vehicles, is faced with a series of disadvantages that limit its development and market competitiveness. Most of the limitations are related to the EV battery, lithium-ion battery. In this paper, the limitations of electric vehicles are analysed based on the characteristics and working principles of lithium-ion batteries. The limitations in the safety, range, cost, and life span of electric vehicles all result from the shortcomings of lithium-ion batteries, which keep quite a few customers from purchasing electric vehicles. In order to address these limitations, approaches to boosting the performance of lithium-ion batteries are suggested respectively in terms of safety, capacity, cost, as well as life span. Among all the new designs, Li-S batteries and LTO batteries seem the most promising. Using solid electrolytes, Li-S batteries can be very safe and cheap with a quite high capacity as long as there is a technological breakthrough in the interfacial problems of solid electrolytes. LTO batteries have excellent high rate performance, thermal stability, and a long life span. However, this kind of battery shows no advantages in the cost and energy density at present. This research provides directions for the future development of EV batteries to tackle current problems at the origin. In the future, researchers should try to design a new kind of LTO battery with high energy density and low cost, or enhance the Li-S battery's performance by applying new electrolyte technology.

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