Energy storage system safety in electrified vehicles

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ABSTRACT
The environmental challenges with CO_2 emissions and a diminishing oil reserve drive the need of a broad introduction of electrified vehicles. The relatively new lithium-ion battery technology offers batteries with increased energy and power densities. Li-ion technology requires a monitoring system since its safety window is lower than many other battery technologies. In an energy storage system for electrified vehicles safety aspects thus have to be taken into serious consideration. In this paper fire as a consequence of malfunction or abuse of the energy storage system is discussed.

KEYWORDS: energy storage system, electrified vehicle, lithium-ion, battery, safety, thermal runaway, fire

INTRODUCTION

An electrified vehicle has a traction system which can be either pure electric or a combination of electric and some other source (e.g. fossil fuel). New battery technologies, e.g. lithium-ion, makes it possible to build electric vehicles (EV) and plug-in hybrid vehicles (PHEV) with acceptable driving range with zero emissions. The Li-ion cells offer high energy and power densities and are constructed with advanced materials. There are however, still aspects to consider for these new technologies and electrified vehicles. A drawback is that the window of stability is relatively small (both regarding temperature and voltage region) and the lithium-ion cell materials are volatile and flammable. Safety is thus an important issue due to the combination of the reactive nature of the cell materials and the presence of hazardous voltages in the vehicle.

LITHIUM-ION BASICS AND THERMAL EVENTS

Lithium-ion cell technologies have been used for more than 10 years in consumer products, such as laptop computers and mobile phones. During the years, there have been fire incidents with these batteries. The last 5 years, reports have been made regarding battery fire incidents in e.g. laptops, iPods, cargo planes and electric vehicles [1].

Lithium-ion cells consists of different layers, essentially; anode, separator, cathode and electrolyte.
The electrolyte consists of organic solvents, lithium salt and additives. The electrolyte recipe is every cell manufacturer's secret, especially regarding the additives. The organic solvents, e.g. ethylene carbonate (EC) and dimethyl carbonate (DMC) are flammable. Lithium is a reactive metal while the lithium-ion is more stable. Lithium metal can however be formed during normal and abusive use.

Under abuse or malfunction conditions, the lithium-ion cell temperature can increase. If the temperature reaches typically 120-150 °C, exothermic reactions within the cell starts. The exothermic reactions will further increase the temperature, which could start additional exothermal reactions. If the overall cell reaction creates a rapid temperature increase, it could result in a so called thermal runaway, which could consist of one of or a combination of the following; rapid gas release, electrolyte leakage, fire, rapid disassembling/explosion.

Figure 1 shows an overview of the potential chain of events for a thermal runaway. On the left side in the figure, the sources of a cell temperature increase are shown. Furthermore, one cell could affect the adjacent cells. In a worst-case scenario the thermal events from one of several cells could spread and affect the complete energy storage system.

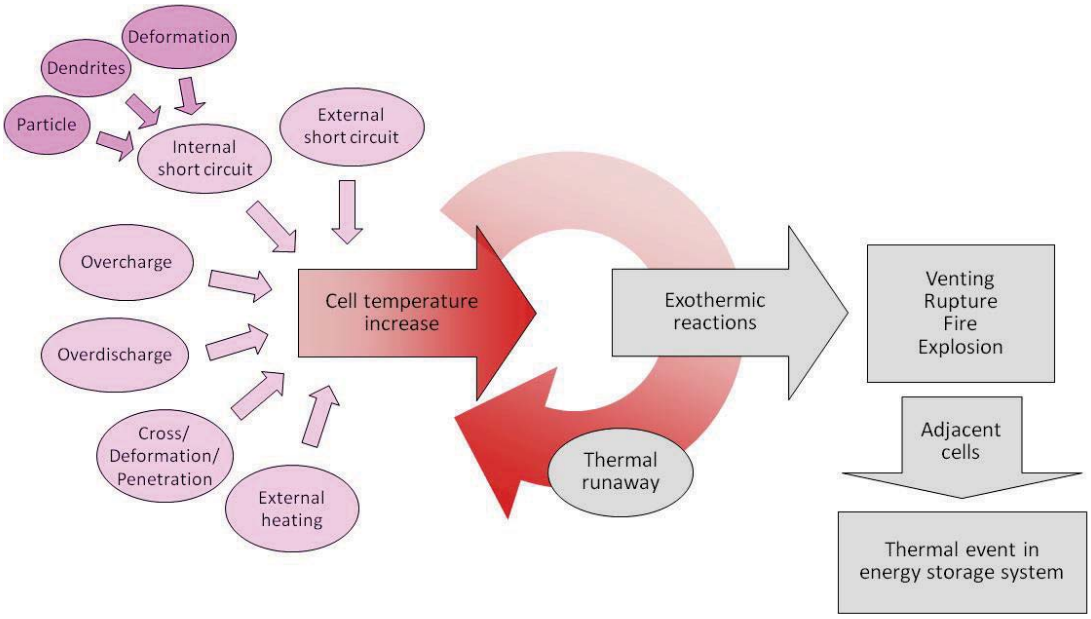

Figure 1. Potential chain of events for a thermal event on the cell level developing to system level.

LI-ION FOR AUTOMOTIVE USE

The conditions and requirements put on lithium-ion batteries in automotive applications are different from those in consumer electronics. Basically, Li-ion batteries for consumer products do not meet the needs of the automotive industry. The safety aspects, which are discussed in this paper, are just one on many aspects which must be considered in a different perspective.

In order to meet the demand of the automotive industry, new lithium-ion battery materials have been developed. Lithium iron phosphate (LFP) is a more stable cathode material than the mainly cobalt-based lithium oxides that are commonly used in consumer Li-ion batteries. Researchers has also developed other electrode materials, for example mixed cobalt with other materials (e.g. Ni, Mn, Al) in order to improve safety and other aspects (e.g. life time, energy and power densities) [2].

The cell design, both chemical and mechanical, affects safety. The cell manufacturer can influence the electrolyte composition and its additives [3], e.g. flame retardants, redox shuttles and gas release controller. The selection of the active electrode materials (anode and cathode) also affects the thermal runaway and its onset temperature. The mechanical packaging, e.g. cylindrical, soft or hard prismatic can or pouch prismatic, also affects the cell behavior during a thermal event. For example, a cylindrical cell could build up a much higher pressure than a pouch cell. There can be both positive and negative aspects on each cell packaging. For example, with a cylindrical cell it can be easier to control the venting direction. There are thus a number of safety mechanisms that can be included into a lithium-ion cell construction, by its manufacturer [4].

Lithium-ion batteries for automotive use have shown an increased safety regarding fire and explosion. Therefore, the focus of the lithium-ion safety have drawn more and more towards the safety aspects of released gases and smoke, as well as other electrical aspects, e.g. electromagnetic compatibility (EMC).

EXPERIMENTAL

In order to experimentally study thermal runaways in lithium-ion cells three cells of size 18650 were thermally abused in a thermostated oven. Two of the cells were standard laptop batteries from Samsung and Sanyo with unknown cathode composition, most likely cobalt mixed oxides. The third

18650 cell was manufactured by K2 Energy and had a lithium iron phosphate (LFP) cathode. The cell was fastened on a brick and centrally placed inside the oven. The oven was equipped with a fan system to circulate the air to achieve a uniform temperature. The cells were tested one at a time with continuous heating from ambient temperature up to the onset of thermal runaway or to max 300 °C, without any ramping or stops. Prior to the test, the cells were fully charged to 100% SOC according to each manufacturer's charging instructions. Each cell was equipped with four thermocouples, placed uniformly with two sensors on the top and two sensors on the bottom of the cell. Figure 2 shows the average cell surface temperature for the three tested cell types.

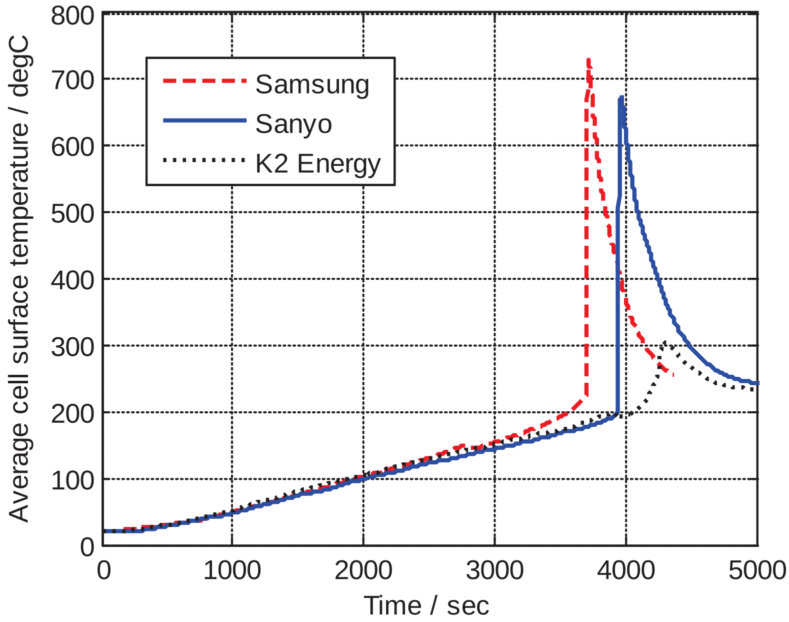

Figure 2. Temperature development for three 18650 lithium-ion cells during thermal abuse tests.

All cells vented and got into thermal runaway. The cells from Samsung and Sanyo with the cobalt mixed oxide showed a very rapid temperature increase at the onset of thermal runaway. The LFP based cell from K2 Energy also entered thermal runaway but with a more modest temperature increase. Both Samsung and Sanyo cells started to burn during the thermal runaway while the K2 Energy cell did not burn. Table 1 shows basic cell data and extracted thermal runaway results where the rise time is the time between the onset and peak temperature of the runaway. The temperature rise is the difference between onset and peak temperatures of the runaway and the temperature rise rate is the ratio between temperature rise and rise time. As seen from the results the cell with the LFP cathode demonstrates a more safety performance than the laptop cells with a lower temperature rise rate and no fire.

Table 1. Basic data for tested cells and extracted results from the thermal runaway.

Cell type	Cell data		Thermal runaway results			
	Nom voltage (V)	**Nom capacity (Ah)**	**Onset temperature (°C)**	**Temperature rise (°C)**	**Rise time (sec)**	**Temperature rise rate (°C/sec)**
Samsung ICR18650-24F	3.6	2.4	227	503	20	25.2
Sanyo UR18650F	3.7	2.2	198	477	26	18.3
K2 Energy LFP18650E	3.2	1.25	213	91	157	0.6

LITHIUM-ION BATTERY FIRE DEVELOPMENT

When discussing fire in an energy storage system, two main fire types should be considered. The first type is the reaction within the lithium-ion cell material itself, that is, reactions between electrolyte and electrodes. The special properties in this case are; an accelerated process due to exothermic reactions and self-supply of oxygen due to oxygen released by the reactions itself. Therefore, this fire is difficult to control and extinguish. In theory, the thermal runaway reactions could be stopped by cooling the cell below the onset temperature of the reaction. In practice, as seen in Figure 2, the temperature development is so rapid that simultaneous cooling is difficult to achieve after the onset of the thermal runaway, a more viable option is to make sure that the onset temperature is not reached.

The second type is a more traditional fire, that is, a fire which requires oxygen from its surroundings. It could be fires in e.g. plastics, cables and housing inside the energy storage system as well as in parts of the cell. Free electrolyte from cells or fire in plastic insulation and separator on a cell-level may be part of this type of fire. Furthermore, a fire of the first type, involving a thermal runaway inside a cell could start a fire of the second type, and vice versa.

The design of the energy storage system is important in order to make it possible to stop or retard additional cells from going into thermal runaway. As always with batteries, adding additional safety is a compromise that adds negative consequences, e.g. adds weight, volume and costs to the system. However, the access of fire fighting media to be applied on the cell surfaces inside an energy storage system is usually very limited due to the packaging design of energy storage systems and electrified vehicles. A lithium-ion cell which undergoes thermal runaway or other severe conditions (e.g. overtemperature) will react with swelling and could release gases, smoke and particles. The gases released during cell venting are flammable and could thereby be ignited by a spark in the vicinity. Regarding the electrified vehicle and the integration on the energy storage systems as well as the hazardous voltage systems in the vehicle, the design for crash safety is vital.

THE OVERALL SAFETY OF THE ENERGY STORAGE SYSTEM

The overall safety of a complete electric vehicle and energy storage system will not only be a function of the cell safety but also of many other parameters on the system level. The battery management system (BMS) is very important in order to e.g. monitor and prohibit critical situations, alerting the driver in case of a thermal event, activate potential available counter-actions and controlling the shut-down procedure of the system, which should be constructed under consideration of the complete safety of the electrified vehicle. The cooling system and the mechanical housing and structures are other important parameters. The positioning of the cells within the battery pack is also essential, and should e.g. consider cell venting properties.

In order to obtain a safe system, all components and its properties must be considered. One of the key design parameters to understand when designing an energy storage system for electrified vehicles are the mechanisms for spreading of gases, smoke, fire and heat from components (e.g. battery cells) to battery system and to the complete electrified vehicle.

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