Comprehensive review on hazards related to lithium-ion batteries technology

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Abstract: With the recent developments on renewable energies, the capacity for energy storage represents a growing area for improvement. Rechargeable batteries have been recently improved in terms of durability, energy density, size and volume. Lithium-ion batteries represent one of the best examples of improvement of energy storage technologies; these have been widely used in a diverse field of applications, from common electronic devices used by millions of people around the world to electric and hybrid vehicles as alternative for conventional fuel-based transportation. Research on the improvement of the design of lithium-ion batteries is constantly on-going and new materials are being investigated in order to improve the quality of the batteries in terms of efficiency and charge cycles. However, lithium-ion batteries represent considerable hazards to customers as demonstrated by a series of significant incidents that have occurred in different battery cells involving overheating, fires and explosions in different devices.

Due to the exposure of these batteries, risks related to thermal runaway phenomena are presented propose different approaches to follow in order to investigate causes, prevention measures and design changes to prevent these types of incidents. Thus, a comprehensive presentation of the current status of the safety research on lithium/ion batteries thermal runaway is presented. An overview of the possible promoters for the thermal event is presented by studying the kinetic characteristics of the phenomena as well as the different possible approaches to study this phenomenon such as molecular simulations to understand mechanisms and proposes related decomposition paths.

Keywords: lithium-ion batteries, thermal runaway, hazards, incidents, safety.

Introduction

Lithium ion batteries nowadays constitute one of the most important fields of study in different areas, from electrochemical application to environmental and energy resources for diverse applications. The importance of this technology lies mainly on the increasing need of the energy storage capacity. This aspect has been identified as the weakest point in the current energy domain due to the need of having cost-effective, safe and long-life storage systems (Ibrahimet al. 2008). The integration of these characteristics has allowed lithium-ion batteries to become remarkably used in many kinds of electronic appliances from portable devices including cellphones, laptops, gps, tablets, up to electric and hybrid transportations such as vehicles and airplanes. This fact has both benefits and concerns and are now of great interest for the industry.

Besides, lithium-ion batteries have established an important domain by themselves. When compared to different battery systems used both currently and during their development, lithium-ion batteries are comparably a better resource as secondary battery systems with high capabilities of energy storage capacity in terms of durability, energy density and low cost among others. For instance, comparing the values for energy density of lithium-ion batteries with those of lead-acid or Nickel-Cadmium batteries, the characteristics of lithium-ion batteries ($\sim$150W h kg^{-1} and$\sim$300 W h L^{-1}, respectively) are significantly greater than the others ($\sim$50 W h kg^{-1} and $\sim$100 W h L^{-1}); which accordingly means: lighter weight and smaller size for lithium-ion batteries (Escobar-Hernandez et al. 2016).

Even though lithium-ion batteries technology has been evidenced to be significantly more efficient than other technologies in terms of performance, numerous cases have been recently reported to involve overheating, smoke, fire and explosions in multiple applications. It is important to notice that heating has been an issue common issue with batteries since their creation is due to the generation of heat and the transformation of from chemical to electrical. However, the case numbers of overheating (where the generated heat is higher than the heat dissipated to the environment, also known as thermal runaway), are undesired and they have been increasing in recent years. This could be related to malfunctions and manufacturing defects in the batteries. No matter what's the source of these incidents, which are more frequently observed due to the constant increase in lithium-ion batteries use. Those, cases are of great concern and such examples are found in a daily basis.

The most significant and recent case, was the global recall of Samsung of its Galaxy Note 7 smartphone, with outcomes up to one billion dollars (Forbes 2016). The issues affected customer safety because of the phones catching fire or exploding during charging cycles under normal conditions (BBC, 2016). Actually, this is not a novelty for smartphones; in previous Samsung and Apple models, the batteries have already been pointed as cause of the fires. Moreover, other battery related incidents have had important significance as well, especially in aviation and vehicle industry. The first group has brought the attention of aviation agencies such as the U.S. Federal Aviation Administration, which has developed a public database of reports regarding associated incidents in cargo and passenger planes involving lithium-ion batteries failures including smoke, fire, extreme heat or explosion.

Therefore, the concerns raised by the events involving lithium-ion batteries malfunctions and fire hazards, have brought a need for further investigation on the field in order to understand the group of phenomena involved in the thermal runaway of the batteries. This need has generated intensive research work specifically on this issue. The research includes work in the electrochemical field, thermal characterization, molecular simulations, heat transfer modeling, material characterization and improvements, etc. However, there is still a lack of understanding and investigation on the current issues regarding the potential hazards related to thermal runaway cases in lithium-ion batteries. Thus, this work aims to give a comprehensive overview of the potential hazards identified in the lithium-ion batteries technology related to their safety.

Uses

The use of lithium-ion batteries is mainly concentrated in electronic portable devices, with a remarkable use in cell phones, portable computers (laptops) and other notebooks or tablets. In recent years, the use and development of lithium-ion batteries have extended to transportation advances such as Hybrid and Electric Vehicles (HEV and EV) and aviation and aerospace industry, both by using large-capacity lithium-ion batteries (Yoshio et al. 2010).

Among the electronic consumer applications, we can group several devices used in our everyday life, the production of which has increased tremendously in the last 20 years. Because of the growing use and production of portable electronics, lithium-ion batteries production and development have also increased rapidly to build a strong and focused market. Next the main applications of lithium-ion batteries for electronic devices are mentioned and brief comments on their production are made in the category of portable electronics we have: mobile phones, portable computers, tablet personal computers, electronic translators, miniature cameras, integrated circuit (IC) cards, and portable media players. Besides these general-purpose batteries classification, there are also other types of electronics such as microelectromechanical systems (MEMs) such as micromotors, small-scale scouts or drones. The last group uses microbatteries. microbatteries.

Modern car industry has a major opportunity for lithium-ion batteries. The need for electric power in cars is evident and the requirements of modern technology represent higher demands of more energy with more efficient delivery and rechargeable systems. Currently this industry is key in the fight against evident climate change due to the overwhelming quantity of emissions from car usage all over the world. Therefore, lithium-ion batteries used in this industry are highly important and need to be further developed and investigated in the different fields of applications (Wu 2015).

Some applications in this industry include: onboard electronics (e.g. guiding systems, satellite and videophones, intelligent computers, advances stereo sounds, safety airbags and lighting, etc.), Hybrid Electric Vehicles (HEV), and Electric Vehicles (EV). HEVs are designed to support Internal Combustion Engines (ICE) and to adjust their power; their appearance traces back to 1900 with a $WD hybrid version of4-Wheel Drive (4WDof an electric carriage. These reduce the conventional fuel consumption, and significantly reduce emissions of pollutants; companies with HEVs include Ford, General Motors, Lexus, Nissan, Toyota, and Chevrolet. On the other hand, EVs have a long history from the 19th century, but a temporal disappearance until the 1970s after the oil crisis lead to research on EVs. Currently EVs represent an energy alternative for transportation, because of the worrying situation of climate change and pollution worldwide. However, these cars face new challenges in the race of becoming the best alternative of transportation. These challenges include but are not limited to: safety performance during use or abuse, high energy and power density, good charging and discharge cycles and durability, and the combination of a reasonable cost with low environmental pollution during manufacturing (Wu 2015).

The use of lithium-ion batteries in military and aerospace applications is of high significance. Lithium-ion batteries are power supply to many uses for the US Armed Forces. This includes land (portable systems, vehicles, warships and communications), marine (submarines and underwater vehicles), air (Unmanned Aerial Vehicles, (UAV), drones, aircrafts), and space (satellites and space ships) (Wu 2015). It is important to mention that currently many military agencies are spending resources on research for the improvement of electrolyte/solvent systems, as well as polymer lithium-ion batteries application, in order to improve the reliability of these batteries and use them. An example is the Future Combats Systems (FCS) program initiated by the US Army for the acquisition of technologies in the fields previously mention, and the use of advanced energy storage systems, focused on lithium-ion batteries (Wu 2015).

Incidents

As mentioned earlier, incidents related to thermal runaway in lithium-ion batteries involving temperature increase, fires, and explosions, have raised concerns throughout the production and supply chain including the final consumers who rely on the use of batteries for many of their everyday activities as evidenced in the previous section. These incidents have represented losses to the different industries using lithium-ion batteries. This includes airplanes grounded from traveling due to concerns associated to lithium-ion batteries incidents, and monetary losses of millions of dollars in income to the companies. However, the prospective development of the technologies using lithium-ion batteries as power source should focus on improving safety of people when exposed to lithium-ion batteries potential hazards.

One of the most concerned sectors with the incidents is the aviation industry. The focus on these issues comes from the increasing hazards introduced in air transportation, in this case by lithium-ion battery devices. Even though there is no evidence so far of incidents involving on-air explosions or fires, several cases of cargo and passenger devices are registered, as well as failures and smoke episodes in the battery electronic systems. Regarding the latter, one of the most representative incidents in the aviation industry related to lithium-ion batteries failure is discussed.

In 2013, a fire occurred on a Dreamliner Boeing 787 airplane coming from Japan in a Japan Airlines Co. flight to Logan International Airport in Boston, Massachusetts. The plane used two lithium-ion batteries in their systems to power instruments, electronics, and equipment. According to the National Transportation Safety Board (NSTB) investigation, the fire initiated after a Possible short-circuit in one of the batteries (composed by 8 different cells). Per this agency, a runaway event was the cause of the initial fire. The fire was noticed due to evidenced smoke coming from the cabin at cockpit (electronic bay specifically) at the moment the airplane was being inspected and under maintenance. The smoke was confirmed by the aircraft rescue members and firefighters to come from the power unit battery. No passengers or crew resulted injured due to the airplane was not in operation at that precise time. However, there are reports of minor injuries to one of the members of the freighters involved. As final outcome of the investigation, the NSTB among the results and recommendations of the investigation, pointed to three main points: first, flammable electrolyte mixture released was found as the potential cause for the thermal runaway phenomena in one or possibly more cells creating a domino effect and the later fire and smoke evidenced. Second, recommendations regarding regulations of the technologies implemented were issued to the US Federal Aviation Administration. Finally, additional recommendations included inspection and testing guidance to improve safety assessments. As mentioned earlier, similar incidents with other planes followed similar sequence events, however, no general conclusion regarding the specific failure in the battery has been issued yet (Singh and Waldram 2013; Escobar-Hernandez et al. 2016).

In the same way, it was described for the case of aviation, portable electronics which have evidenced fire can be considered to follow a similar trend regarding the sequence of events of the incidents. Initially, due to certain state of charge and discharge (some cases have reported recent changes of state prior the events); the electronic device starts overheating rapidly and possibly undergoes malfunction in its electronic capabilities. Later on, the battery-pack starts swelling due to internal pressure generated from gases resulting from offset reactions in the cell. Finally, the main thermal event occurs. This can follow different paths depending of the storage and ambient conditions; it can either start a fire due to the high temperature and the exposure of the electrolyte mixture to air (i.e. researches have pointed to the high instability of lithium electrolyte salts (Wang et al. 2012)), and combined with organic material from both the anode layers and the electrolyte solvent mixtures (i.e. typically organic carbonates such as ethylene and propylene carbonate depending on the specific application); or the smoke continuous due to the high rate of production of gases and vapors from the combination explained, and then explode as the pressure generated is released, no presence of fire is necessarily evidence in this case.

The events explained have finally resulted in thousands of cases of burning phones (as the famous and recent case of the Samsung Galaxy Note 7 which had to be recalled worldwide by the company) or even in serious burns to consumers. This is one of the reason to take lithium-ion batteries as a hot topic in research due to the rapid impact this kind of events have in society nowadays due to the exposure of the population to the latent hazard. Figure 1 shows evidence of the events presented.

Figure 1 lithium-ion batteries fire and explosion incidents. (a) Samsung Galaxy Note 7 (2016)). (b)Electric Cars after fire in 2010 (Marlair and Lisbona 2012). (c) Samsung Galaxy S3 (Grabet 2013).

Potential Hazards Identified

Considering the information collected and the analysis of the incidents previously studied, it is important to identify certain hazards associated to lithium-ion batteries. Existing characteristics of these batteries represent potential hazards due to different factors from both manufacture and use. Among these factors, we can group: incompatibility of the materials within the battery compartments, aging and use-related damages (abuse conditions), storage and packing, lack of safety measures such as cooling or isolation, and transport-related issues. In this section, we will aim to identify the potential hazards associated with these factors and the possible consequences derived from the incident and associated with the hazards.

The hazards identified can be classified in two main groups according to the impact on the population. These groups are: 1) Human health hazards, and 2) overheating, fire and explosion hazards. The first group comprises the effects of the battery runaway on human health resulting during or after a battery presents malfunction or abuse. This could be by acute direct contact or exposure to the battery or battery generated chemical products, or derived from constant contact with the battery.

The second is related to the consequences of the abrupt rise of the battery temperature; presented as thermal runaway phenomena, together with the direct subsequent effects after personal exposure.

Regarding the effect on health, it is a fact that lithium-ion batteries from within are composed by certain chemical compounds that are toxic to some degree. Early concerns (Archuleta 1995) on the toxicity of some of the materials used in the battery manufactory industry involved the acute inhalation exposure with the potential to cause irritation in the respiratory tract, skin and eyes associated to organic solvents used such as Propylene Carbonate, Ethylene Carbonate, and Diethylene Carbonate. Regarding lithium salts used as electrolytes, the study reported irritant effects in the respiratory track when released for $LiPF_6$ and derived fluoro-organic compounds. According to studies performed about reactions between battery electrolytes and cathode, some compounds posing toxic hazards in humans can be formed at moderate temperatures around $80^{o}C$. According to Hammami et al. (2003), who studied the formation of toxic fluoro-organic compounds after abnormal behavior of the batteries.

The overheating phenomenon in lithium-ion batteries has been investigated under the thermal runaway events evidenced. This phenomenon has been widely studied by different researchers using different laboratory/calorimetry techniques and computational studies, to explain the causes of the heat generation. In this work, we present an analysis of the runaway system and its characteristics. First, it is important to mention that the composition and temperature of the bulk material can be assumed uniform, since due to the system itself and to the rapid increase in the temperature, the temperature of the overall system increases rapidly making the difference homogenous for the purposed of the analysis (Escobar-Hernandez et al. 2016).

A series of initiation events can be used to determine the state of the homogeneous thermal runaway in lithium-ion batteries systems leading to a fire hazard. The first event is the loss of cooling capacity normally evidenced after a decrease of the heat exchange area that is dominated in the battery system by the thermal contraction or material wear due to aging and/or use of the battery. External heating is taken as well as initiation event, either because of abuse conditions or because it can be present at some point, here, cases involving fires are dominated by cell exposure to high environmental temperature, causing a high heat transfer due to, for instance, excessive stacking in battery storage sites. Other important events to consider are the incompatibly of the materials and the intermediate reactant accumulation. Different researchers have studied the behavior of selected lithium-ion batteries compounds under different circumstances and combinations. Moreover, the deviation of deviations resulting from lithium-ion battery incompatibilities is associated with the incorrect introduction of a controlling reactant or the mixture of incompatible reactants in a chemical system. This is described by the undesired contact among different compounds within the battery due to rupture of one of the separating layers (i.e. Solid Electrolyte Interphase layer) which can be combined with the accumulation of unstable intercalated material resultant from the ion transport. This is a key point given the high reactivity of the lithium compounds present in the batteries. Finally, the initiation events that in addition can be related to lithium-ion batteries potential runaway hazard are extended reaction time and segregation of unstable phases. The first one associated with an extended residence time of the compounds represented by the decreased ion transport and unstable intermediate compounds increase in residence time. The last one associated to loss of reactants contact and derived of the battery failure or stop of the normal operation reactions (Escobar-Hernandez et al. 2016).

Finally, an important point to highlight is the high potential to harm that lithium-ion batteries possess. The fire and health hazards are not only derived from malfunctions or abuse conditions, but as seen in the incompatibilities of the compounds; there is an evident lack of an inherently safer design applied from the manufactory stage or earlier in order to prevent the existing hazards.

Conclusions

Regarding the analysis of the thermal runaway phenomena as the prominent fire hazard identified in lithium-ion batteries, incompatibility of the materials was found to be an important component contributing to the safety state of the batteries and related devices using them. Even though lithium-ion transport has shown to be significantly more efficient in comparison with similar battery technologies, the compounds used have shown high instability and runaway reactions leading to fire hazards as described.

About the incidents reported and the sequence of events described for the different cases, we conclude that even though incident investigations have been conducted thoroughly by the Aviation industry, and safety measures have been taken in different application, as the case of portable devices recall, a deeper understanding of the overall phenomena involved in the failure and thermal runaway events in lithium-ion batteries is still needed. This is done in order to formulate new solutions to the design of the batteries for specific applications, as well as to define safety barriers that can be implemented to the different applications following selected scenarios and applications.

In conclusion, technologies for energy storage are a key point in the chain of necessary changes that industry needs to make to counteract the evident effect of climate change. Thus, lithium-ion batteries represent one of the most important links in the development of future energy technologies including its storage. However, enlaced with their development, risk reduction should form an essential and priority design variable.

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