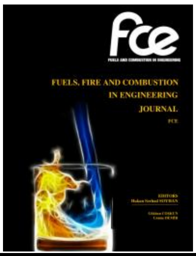
Mühendislikte Yakıtlar, Yangın ve Yanma Dergisi, 10(1):21-27,2022

MÜHENDİSLİKTE YAKITLAR, YANGIN VE YANMA DERGİSİ
FUELS, FIRE AND COMBUSTION IN ENGINEERING JOURNAL

eISSN: 2564-6435
Dergi sayfası: http://dergipark.gov.tr/fce

Geliş/Received
06.01.2022
Kabul/Accepted
11.04.2022

Doi: 10.52702/fce.1054263



Elektrikli Araçlarda Batarya Kaynaklı Yangınlar

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ÖZ

Günümüzde global olarak egzos emisyonlarının düşürülmesi eğilimi ile temiz enerji kaynaklarına olan talebin artması, bir çok araç üreticisinin elektrikli araçları geliştirmesi sürecini başlatmıştır. Seri üretimi göreceli olarak yeni olan elektrikli araçlara günümüzde yollarda her geçen gün daha fazla karşılaşmaya başladık. Kullanımı yaygınlaşan elektrikli araçlarda karşılaşılan en yaygın acil durumlardan biri olan yangınların müdahale yöntemlerinin içten yanmalı motorlu araçlara göre yangınların oluşumu ve söndürme mekanizmasının farklılıklar göstermektedir. Bu çalışmada, elektrikli araçlarda karşılaşılan yangınların en temel oluşum yeri olan bataryalarda, termal kaçak oluşum mekanizmasının sebepleri incelenecek, oluşabilecek yangına müdahale yöntemleri hakkında bilgiler irdelenecektir. Buradan çıkan sonuçlar vasıtasıyla elektrikli ve yarı elektrikli (hibrit) araçlarda uygulanma ihtimalleri irdelenecektir.

Anahtar Kelimeler: Elektrikli araç, Lityum-iyon pil, termal kaçak,

Battery Caused Fires in Electric Vehicles

ABSTRACT

Nowadays, the global trend of reducing exhaust emissions and the increasing the demand for clean energy sources have initiated the development of electric vehicles by many vehicle manufacturers. We are starting to encounter electric vehicles, whose mass production is relatively new, on the roads more and more every day. Fire response methods, which are one of the most common emergencies encountered in electric vehicles, which are widely used, differently in the extinguishing agent and extinguishing methods of fires compared to gasoline or diesel engine vehicles. In this study, the causes of the thermal leak formation mechanism in batteries, which are the most basic place of fires encountered in electric vehicles, will be examined, and information on the methods of intervention to the fire that may occur will be examined. By means of the results obtained from here, the possibilities of application in electric and semi-electric (hybrid) vehicles will be discussed.

Keywords: Electric vehicle, Lithium-ion battery, thermal runaway,

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1. INTRODUCTION

Although it is stated that the modeling of the first electric vehicle was developed by different people, the earliest model of an electric vehicle made by a Hungarian in 1828 by Ányos Jedlik. The earliest electric powered vehicle introduced by Robert Anderson at 1839 after seven years study [1]. The first electric model vehicle powered by a non-rechargeable battery was produced by the Dutch Professor Stratingh in 1835 [2]. Since the batteries, which are the energy source of electric vehicles, do not allow long range and are not refillable, and have a short range compared to internal combustion vehicles, mass production of electric vehicles has a slow period for a long time, and came up again with the rapid development of battery technologies.

Today, with the increase the demand to clean energy, new dangers appeared by electric vehicles which are also carefully should be studied for proper precautions . One of the most important of them is the fire hazard arising from the battery technology used.

Published fire statistics of USA fires (between 2003-2007) shows us the average of all fire teams' intervention to vehicle fires are yearly about 287.000 fires. The results of the these fires causes; 480 people life, about 1,500 people injuries with $ 1.300.000 direct financial loss [3].

Another statics (the year of 2021) which figure gives us sold vehicle and their fire cases and published by Bureau of Transportation Statistics of USA (BTS), and Government Recall Bureo of USA. According to the reports, it is broke down fires of vehicle by their type as hybrid, gasoline, and pure electric types, the results compared with the sales data. The data is prepared for each 100.000 vehicle as a unit. It has been underlined by the reporters that hybrid vehicles are actually have more fires per 100.000 vehicle sales. According to the report, the fires per unit;

At hybrid vehicles 3,474 % per unit,

At gasoline vehicles has 1,529 % per unit,

At pure electric vehicles has 0,025 % per unit,

It is important here, the fires at hybrid cars 2.2 times more than the gasoline cars' fires, but electric vehicles is less as it can be ignored. But the sales of the fully electric vehicles is in increasing trend, so the statics can be change following years.

According to International Energy Agency (IEA); last year, electric vehicle sales increased at all around the world and sold more than 10 million. One another report underlined us, at Europe electric car sales overtook China electric car sales , and registered in Europe to 1.4 million, while in China increased their sales to 1.2 million.

Today, the battery technologies which are using at electric vehicle is wide, the difference range of nominal voltages (V) and energy densities (Wh/kg) caused various types of batteries. The researches and developments on technologies still continue. The most usage types of batteries which are using in electric vehicle are given in Table 1 [4].

Table 1 Types of Batteries using in Electric Vehicles [4]

Battery Types	Nominal Voltage (V)	Energy Density (Wh/kg)	Cycle Life (#)	Memory Affect	Working Temperature
Pb-acid	2	35	1000	Not Available	-15, +50
NiCd	1,2	50-80	2000	Available	-20, +50
NiMH	1,2	70-95	<3000	Rare	-20, +60
Zebra	2,6	90-120	>1200	Not Available	+245, +350
Li-ion	3,6	118-250	2000	Not Available	-20, +60
LiPo	3,7	130-225	>1200	Not Available	-20, +60
$LiFePO_4$	3,2	120	>2000	Not Available	-45, +70
Zn-air	1,65	460	200	Not Available	-10, +55
Li-S	2,5	350-650	300	Not Available	-60, +60
Li-air	2,9	1300-2000	100	Not Available	-10, +70

1.1. Common Types of Batteries

(1) Lead-Acid Battery: They are commonly using in vehicles as starting the ignition, lighting, radio, and for other electrical needs. At the beginning period of the electric vehicles this type of batteries used. It is cheap however the battery is too heavy and not provide enough range for electric vehicle on road [5]. The earliest and one of the succesful type of batteries are Lead-acid type, because of that it is the widest type which is using at vehicles. The lead-acid batteries basic elements are; anode is lead (Pb), and the cathode is lead dioxide (PbO_2). Sulphuric acid (H_2SO_4) is acting as the electrolyde liquid. These type of batteries has some advantages with some disadvantages. The most common advantages are; high discharge current, lower self-discharge, cheap and does not have a memory effect. Their disadvantages are more than their advantages as; low rated voltage and low energy density. When they are not used, the battery life is reducing [4].

(2) Nicel-Cadminium (NiCd) Battery: These type of batteries has some advantages when we

compare with NiMH batteries, such as longer expire life and more easy tolerate the discharging disadvantage. When they compared with lead-acid type batteries, they have weight advantage. However, the disadvantages are; low relative electrical capacity, and when they are forcing quick charge or deep discharge they can be melted or starts to burn. They have another disadvantage is the repetitive charging which is not waiting completely discharging of the battery may cause the memory problem [5].

(3) Nickle-Metal-Hydrite (NiMH) Battery: Nowadays these are one of the mostly using battery types at electric vehicles. Because of it is ability to energy absorption they are widely using at hybrid vehicle, some features are better than lead-acid type batteries, such as: longer life cycle, lighter, higher self discharge rate, faster power delivery. But at the other hand, repeatative quick discharges may reduce the battery's life with high load in order to get rapid power requirement. Because of these reasons, the usage of this type of battery is more proper for hybrid vehicles [5].

(4) Lithium Ion (Li-ion) Battery: The positive electrode of the battery is lithium metal oxides. Compare with other materials; their advantages are low toxicity level, high capacity and cheap to procure. For these reasons, Lithium manganese oxide ($LiMn_2O_2$), Lithium nickel oxide ($LiNiO_2$), Lithium cobalt oxide ($LiCoO_2$) are the most common oxides that using in lithium-ion batteries. The technology has different features if we may compare with nickel material base battery technologies; these have a higher nominal voltage and higher energy density [4].

(5) Lithium - Ion Polymer (LiPo) Battery: Their features nearly similar with lithium-ion batteries. The only change point is; the electrolyte is polymer material in lithium-ion polymer batteries. Polymer electrolyte material specific electrical conductivity is higher than alternative organic electrolyte liquids. And it is allows production of lithium polymer batteries more easily, in different ways [4].

(6) Lithium Iron Phosphate Battery (**$LiFePO_4$**): These are other type of lithium-based batteries. Positive electrode material is lithium iron phosphate. The advantages of them; first of all the energy density is high, and cycle rate is high and it is more secure. At the other hand, the disadvantage of this type; lower performance displays when we compare with lithium-ion batteries [4].

(7) Lithium and Sulphide (Li-S) Battery: These are batteries that use sulphur as the cathode material, and one of the lithium-based battery groups. The advantage of this type of batteries; their energy density is relatively high, with high charging efficiency, but their disadvantage is low cell voltage with average cycle life [4].

Nowadays lithium-ion is the most using type of batteries in electric vehicles. The reason of it, their energy density relatively higher and the power per mass battery unit is also higher than some other types. The developments on this battery type is focusing on reducing their weight and dimensions, and by thus creating competitive prices [6].

1.2. Work Mechanism of Lithium Ion Batteries

The battery is becoming these parts; (a) cathode, (b) anode, (c) separator, (d) electrolyte, and (e) positive-negative current collectors. The simplest expression to its energy generation mechanism is; both two electrodes (anode, and cathode) are hosting the lithium ions (Li+). Lithium ions moves from anode to cathode while the energy is needed (discharge) and lithium ions moves opposite direction while the battery needs charge, it is shown in Figure 1. During the charge and discharge processes the lithium ions are enters into host materials. The D Class fire extinguishing agents are not proper to control the Li-Io battery fire when the battery catch fire because of a mechanical abuse, external heat or an internal fault. The reason of that is there is no free lithium metal within a lithium ion cell left [7].

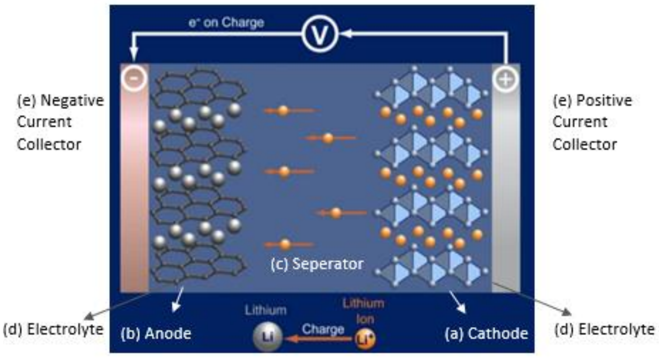

Figure 1 Lithium-ion cell during charging/discharge [7]

Some researches on lithium-ion which done by John Goodenough, M. Stanley Whittingham, Rachid Yazami and Koichi Mizushima conduce to the first prototype battery created by Akira Yoshino in 1985 [8]. After these improvements, in

1991 first mercantile lithium-ion battery was presented by Yoshio Nishi at Sony company [9].

1.3. Avantages and Disavantages of Lithium Ion Batteries

Many types of lithium-ion batteries in use, each one has different characteristics, but vehicle manufacturers are focused on excellent long life. If we compared with other battery types that in use , lithium-ion has many advantages. For example, its specific energy much more than others (140 Wh/kg) and energy density is also higher than others, this specific characteristics makes them proper for battery electric vehicles. Lithium-ion batteries are also good for capability holding energy, and much lower self-discharge rate (5% per month) than NiMH batteries. At the other hand the disadvantages of lithium-ion batteries can not be ignored. If we compare with other batteries these type of batteries are very expensive, and the most important disadvantage is they have significant safety concerns when they overcharge and overheating. Lithium-ion may cause a thermal runaway that can trigger vehicle fires, explosions, high energy and toxic gas release [10].

2. LITHIUM ION BATTERY FIRE HAZARD

The most serious events that may occur in lithium-ion batteries is thermal runaway and results with torch fire, and huge amount gas and heat release [11]. Inside the lithium-ion battery, huge amount of uncontrolled heat generation happens in a short time. Failure of the cathode and anode active materials, electrolyte material, causing the lithium-ion battery to jet flame and may explode [12]. The battery thermal runaway is usually results with releasing of a huge volume of smoke, gas spreading sparks, and a jet-flame. By the time thermal runaway starts, smoke release from safety valve and may leaks from body surface of battery because of openings in body surface due to deformations. This gas consists mostly flammable and toxic gases. There is a fire risk because of these flammable gases, they could be ignited by an ignition sources such as; open fire, any sparks, and electrical arcs or may be self-ignition occur due to an improper heat balancing [13] . Released gas consists two very important toxic gases which affects human health significantly they are hydrogen fluoride (HF), and phosphorous oxyfluoride (POF_3). Because of the result history of serious incidents in industry, the toxicity of HF is well known. But at the other hand the toxicity and affects on health of the POF_3 is still researching [14].

2.1. Thermal Runaway Causes

Some abuse conditions or some failures which may trigger the thermal runaway mechanism and may results fire, explosion in lithium-ion batteries mainly listed in three categories, short circuit and charging failure could be listed under electrical failure.

Table 2 Abuse conditions and potential causes [15]

Abuse Condition		Direct Cause
(A)	Thermal	Overheat
		Extreme cold
		Fire
		Thermal shock
(B)	Mechanical	Shock
		Drop
		Penetration
		Crush
		Vibration
(C)	Short circuits	Internal
		External
(D)	Electrical failure	Overcharge
		Overdischarge

(A) Thermal failure (over heating of the battery): When the internal temperature of cells reaches between 90 ˚C and 120 ˚C range, decomposition may start and the solid electrolyte interface layer may start an exothermic reaction. Hydrocarbon electrolyte may decompose above 200 ˚C temperatures and it causes releasing excessively heat.

(B) Mechanical damage (penetration, pinching and/or bending): Because of any mechanical damage which may caused by an external accident to the lithium-ion batteries; such as a traffic accident, any direct or indirect impact to the battery or any damage during installation such as dropping the battery, it may result electrical short circuit inside the battery between anode and cathode and it may cause to electrolyte producing localised heat.

(C) Internal or external short circuits: It may cause collapsing of the separator (it is located between anode and cathode), and it allows contact the electrolyte material to cathode and anode. This can happen because of any failure conditions, or because of a manufacturing mistake.

(D) Electrical failure (excessive charging conditions): Excessive charging or deep discharging which is out of the identified charge specifications can cause plating on lithium, or creation a dendrite on the surface of anode. In the time, separator may penetrate and may contact to electrodes, and it may cause a short circuit between electrodes and a thermal runaway [15].

2.2. Fire Behaviour of Lithium Ion Battery

The experimental studies on lithium-ion batteries to understand behaviours of Thermal Runaway mechanism, and steps of the fire shown in Figure 2, There are mainly three reasons for Thermal Runaway. One of them is continuous heating and it was experimented on this study. The lithium-ion battery firstly passed through two steps; firstly electrolyte leakage realized and then after safety valve released. At the first step; the electrolytes evaporated inside of lithium-ion battery and it caused increasing the pressure inside. Increased pressure cause leaks electrolytes from the release valve. While the internal pressure increased to maximum pressure limit of safety valve, it was opened and huge amount of the toxic gas released from valve. If the process continue from that step, reactions became more stagey and causing release more toxic gases. For the single lithium-ion battery at 30% state of charge, a white gas was spread out immediately as the lithium-ion battery spend complete Thermal Runaway. Later this step, the amount of releasing smoke and toxic gas decreased and finally finished. When the condition matched, of the Thermal Runaway condition by lithium-ion battery charge stages; 30% state of charge and at 70% state of charge; at the 70 % state of charge condition spread out larger amount of smoke during Thermal Runaway. The safety valve released also liquid aluminium it was attracted to the main surface of battery. Near the safety valve, the discharged gas ignited, and a naked flame happened. The flammable gases was ignited between 500 °C and 700 °C temperature. After 28 seconds started burning, and the flame disappeared. If the battery stores more energy, it may result with more energy releasing at the stage of Thermal Runaway. Over 660 °C temperature the aluminium foils melted and under high pressure it sprayed out from the lithium-ion battery. The fire started as a jet flame and after that it turned into a steady flame. While the energy of battery was run out completely, the flame cleared away. The Thermal Runaway releases more energy when the lithium-ion battery has 70% state of charge. The main mass loss happens at battery because of the ejected molten aluminium [16].

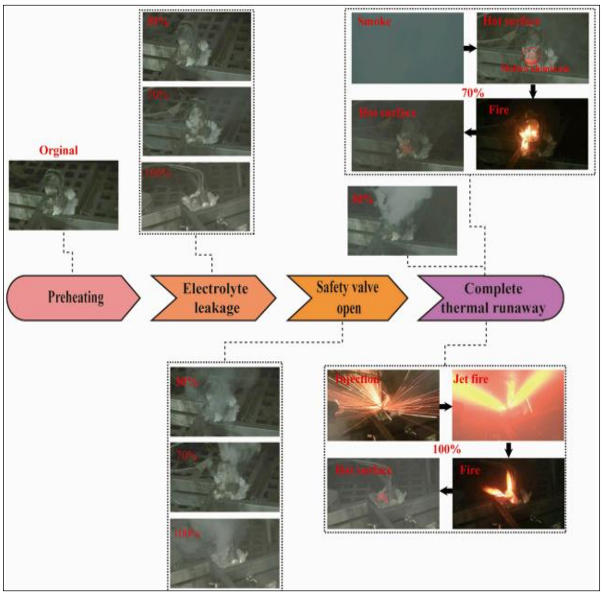

Figure 2 Thermal Runaway Behavior [16]

2.3. Fire Extinguishing Strategy

Electric car maker Tesla recommends its guide to using water instead of using foam to fight a high-voltage battery fire. It can take approximately 11,000-30,000 litres of water applied directly to the battery to completely extinguish and cool a battery fire. If water is not immediately available, using another extinguishing agents CO_2 or dry chemicals to fight the fire until water is available. Water is a key fire suppression agent.

Another important point underlined by Tesla; If the battery involves to fire, it may continue 24 hours to cool completely, re-ignition can occur, because of that the thermal imagination is important to understand if the fire is completely extinguished [17].

RESULTS

My opinion is; because of the demand on reduction of exhaust emissions, triggered the decrease usage of the petroleum based fuels. And vehicle manufacturers steered to electricity which is a clean energy source. Clean energy usage on vehicles created another problem which is storing the electricity. Because of that the importance of the batteries and their features increased. Parallelly of this development, electric vehicles rapidly started to replacing diesel and gasoline engine vehicles.

In order to solve the range problem in electric vehicles, developments in battery technology is continues at increasing speed. However, this developments also affects lithium ion batteries enormously using in home electronics today. These are started to be widely usage in automobiles due to their advantageous sides. One and maybe the most critical disadvantages of these batteries is the intense energy release in fire situations, the difficulties of extinguishing and the release of toxic gas in the combustion state, which has revealed by the internal uncontrollable heat increase. Due to its mechanism of action, it has now become an issue that needs attention for many automobile manufacturers and researchers.

To ensure the fire safety of electric vehicles;

(A) Modeling of thermal runaway mechanism,

(B) Creating an effective proactive structure that can cut off electricity when necessary, together with detection sensors,

(C) A control mechanism that can activate the reactive structure (fire extinguishing system) in cases where the uncontrollable heat increase continues as a result of a thermal runaway.

Taking these steps will be important that can reduce fire incidents in electric vehicles.

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