COMPARISON OF FIRE SUPPRESSION MATERIALS FOR ENSURING FIRE SAFETY IN ELECTRIC COMMERCIAL VEHICLE MANUFACTURING PLANTS

by

Umit SENYUREK[a*], Kursat Can ATA[b], Cenk CELIK[b], and Hakan Serhad SOYHAN[c]

[a] Institute of Science and Technology, Kocaeli University, Kocaeli, Turkey
[b] Department of Mechanical Engineering, Kocaeli University, Kocaeli, Turkey
[c] Department of Fire Safety and Mechanical Engineering, Sakarya University, Sakarya, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI2505657S

The swift progress in electric commercial vehicle technology has significantly transformed manufacturing processes. With the rising demand for electric commercial vehicles, fire safety in manufacturing facilities has become a paramount concern. The high energy density of lithium-ion batteries, which are commonly used in electric commercial vehicles, presents unique challenges that require the deployment of efficient fire suppression systems. Thermal runaway is a critical trigger mechanism in lithium-ion batteries, where an increase in temperature can lead to a self-sustaining exothermic reaction. This phenomenon can be initiated by various factors such as overcharging, physical damage, or manufacturing defects. In a manufacturing plant, thermal runaway can occur due to improper handling, such as dropping batteries, mechanical damage during assembly, faulty battery management systems, or environmental factors like excessive heat. Once thermal runaway occurs in a single cell, it can rapidly propagate to adjacent cells, leading to a cascading failure and potential fire hazards. This can result in significant damage to equipment, production downtime, and safety risks to personnel. In severe cases, thermal runaway can cause large-scale fires, explosions, and the release of toxic gases, posing serious threats to human life and the entire facility. Therefore, understanding and mitigating thermal runaway is crucial in an electric commercial vehicle manufacturing plant to ensure operational safety and efficiency. This paper aims to compare various fire suppression materials and their effectiveness in maintaining fire safety in electric commercial vehicle manufacturing plants. By evaluating different materials, we seek to identify the most suitable options for mitigating fire risks associated with the production of electric commercial vehicles. The findings of this study will provide valuable insights for manufacturers and safety engineers in enhancing fire safety protocols and ensuring a safer working environment.

Key words: *thermal runaway, predictive maintenance, electric vehicle batteries, machine learning models, battery management system*

Introduction

Thermal runaway is a severe issue in lithium-ion batteries (LIB) due to chemical reactions leading to uncontrollable internal temperature rises, causing deformation of the SEI layer

* Corresponding authors e-mail: umitsenyurek@yahoo.com

[1], redox reactions between electrolyte-electrode [2], or reactions between electrode-binder [3]. Understanding this phenomenon requires identifying deformation scenarios of all electrodes, electrolyte, and SEI elements [4]. During thermal runaway, the temperature inside LIB can rapidly exceed 1000 °C, releasing toxic gases [5]. A common cause of thermal runaway is the melting of the polyolefin separator, causing an internal short circuit [6]. Even though electrolytes and separators are relatively light, burning these substances accounts for approximately 80% of the heat released during a fire [7]. Although some energy is dissipated as joule heat (the electrochemical energy stored in the cell), most are derived from the exothermic reduction and oxidation reactions at the electrode interfaces [8]. Thermal runaway progresses through stages. *Stage I:* safe operational temperature range, *Stage II:* onset of irreversible damage, which can be mitigated by cooling, and *Stage III:* total cell destruction, followed by rapid energy discharge. The first critical temperature is reached when the electrolyte increases internal pressure until the cell either vents or ruptures, releasing gases and reducing internal temperature. Next, the separator melts, and its micro-pores expand, leading to micro shorts between electrodes, raising the cell temperature and causing voltage instability. The second critical temperature occurs when the separator pores expand enough to cause a hard short between the anode and cathode. This rapid discharging of all stored energy and sharply increasing temperature makes thermal runaway unavoidable and leads to total cell destruction [8].

Equation (1) details the thermal model, which considers heat accumulation, radiative heat transfer, convective heat transfer, and heat generation.

$$C_p m_{\text{cell}} \frac{\partial T_{\text{cell}}}{\partial t} = \dot{Q}_{\text{cell}} - A_{\text{cell}} \in \sigma (T_{\text{ambient}}^4 - T_{\text{cell}}^4) - A_{\text{cell}} h (T_{\text{ambient}} - T_{\text{cell}}) \tag{1}$$

where Cp is the specific heat capacity, m_{cell} – the initial mass, T_{cell} – the cell temperature, $\dot{Q}_{\text{cell}}$ – the heat generated during thermal runaway (TR), A_{cell} – the cell surface area, $\in$ – the emissivity, σ – the Stefan-Boltzmann constant, T_{ambient} – the ambient temperature, and h – the convective heat transfer coefficient. The model is valid if the Biot number is less than 0.1, as per:

$$\text{Bi} = \frac{hL_{\text{c}}}{k} < 0.1 \tag{2}$$

where h is the heat transfer convection coefficient, L_{c} – the length of the cell, and k – the thermal conductivity. This situation allows the partial differential in eq. (1) to be simplified to an ordinary differential $(\text{d}T_{\text{cell}})/\text{d}t$.

Research shows that most heat generated during a thermal runaway comes from side reactions involving the SEI, electrodes, and electrolyte, with only a small contribution from the cell stored electrochemical energy. Heat generation is defined by:

$$\dot{Q}_{\text{cell}} = \dot{Q}_{\text{SEI}} + \dot{Q}_{\text{P-ele}} + \dot{Q}_{\text{N-ele}} + \dot{Q}_{\text{ele}} + \dot{Q}_{\text{ISC}} \tag{3}$$

where $\dot{Q}_{\text{SEI}}$ is the heat from SEI decomposition, $\dot{Q}_{\text{P-ele}}$ – the heat from the reactions between cathode and electrolyte, $\dot{Q}_{\text{N-ele}}$ – the heat from the reactions between anode and electrolyte, $\dot{Q}_{\text{ele}}$ – the heat from electrolyte decomposition, and $\dot{Q}_{\text{ISC}}$ – the heat from internal short circuit during thermal runaway [7].

Studies focus on improving safety measures to prevent thermal runaway in LIB, especially in applications like EV, addressing gaps in understanding fire hazards, ignition times, and heat release. Preventive strategies include methods to stop runaway initiation, mitigate severity, and enhance firefighting techniques. Future efforts should prioritize developing cost-effective safety measures, additives with minimal impact on performance, and advanced suppressants for multi-class fires, while integrating thermal runaway retardants in LIB design. Integrating fire extinguishing agents into capsules also can enhance safety and reduce EV complexity and cost. Simplifying capsule preparation processes and reducing costs are crucial for practical implementation. They may enable advanced functionalities like self-extinguishing and self-healing, contributing to safer and more sustainable EV and addressing global climate change [9]. The EV production facilities consist of manufacturing stages such as body shops, welding shops, paint shops, and vehicle assembly lines [10, 11]. The EV LIB are either externally sourced, ready-made, or assembled in a dedicated area [12, 13]. The area where LIB are assembled poses a significant fire risk [14, 15]. Therefore, rapid intervention in the event of a LIB fire is necessary for swift cessation of thermal runaway reactions, prevention of the spread of the reaction to neighbouring LIB, and rapid removal of heat from the environment [16, 17]. To achieve this, EV manufacturers equip their facilities with advanced fire suppression systems, such as automated water mist systems and specialized extinguishing agents tailored for LIB fires [18, 19]. Understanding LIB health monitoring and early detection of potential issues through intelligent sensor technology is crucial in preventing catastrophic incidents [20, 21]. Collaborative efforts between manufacturers, regulators, and research institutions are essential for continuously improving fire safety protocols and staying ahead of evolving risks in EV production [22, 23].

The selection of fire suppression materials in this study was based on their accessibility and availability to both firefighting teams and company fire suppression crews. Ensuring that these materials are readily accessible and can be effectively utilized in emergency situations is crucial for maintaining fire safety in electric commercial vehicle manufacturing plants.

The probability of LIB fires in EV production facilities can be evaluated by considering three primary triggering scenarios: mechanical damage to LIB cells during handling or assembly can lead to electrolyte leakage and subsequent ignition, thermal runaway due to internal short circuits or overcharging poses a significant risk, and manufacturing defects in LIB components, such as separator misalignment or electrode contamination, may compromise LIB structure integrity and increase the likelihood of thermal runaway [24-26]. Understanding these triggering mechanisms is essential for implementing preventive measures and ensuring the safety of EV production facilities. The detailed descriptions of these primary scenarios are discussed further in the paper.

Short circuit: The formation of short circuits due to dust or dirt during the initial charging and rework processes involving recharging may lead to fires during LIB assembly [26, 27].

Experiment design

This study involved conducting fire risk experiments on a lithium-ion bus battery with a capacity of 75.2 kWh. The battery was positioned on a specially designed table above a water-filled pool. The fire was ignited by heating wooden blocks located at the base of the battery using LPG. The experiments were carried out at the fire station, fig. 1.

Battery

The battery used in this study is a Proterra BE40 model lithium-ion bus battery. The battery is notable for its high energy density and long-lasting performance. The NMC 811 chemistry, with its high nickel content, enhances energy density, while the manganese and cobalt oxide components ensure the battery stability and safety. The cylindrical cell type

Figure 1. Battery on experiment table and fire start

increases the battery mechanical durability and its modular design facilitates maintenance and repair processes. The battery liquid cooling system maintains performance even under high-temperature conditions. The IP67 protection rating guarantees the battery resistance to dust and water. These features enable the battery to be used safely and efficiently in commercial vehicles. The LIB specifications used in the experiments given in tab. 1.

Table 1. The LIB specifications

Feature	Value
Brand	Proterra
Model	BE40
Nominal energy	75.2 kWh
Physical eimensions	Length: 2809.0 mm, width: 628.0 mm, height: 177.0 mm
Weight	500 kg
Battery chemistry	NMC 811 (lithium, 80% nickel, 10% manganese, 10% cobalt oxide)
Cell type	Cylindrical
Number of modules	16
Number of cells	2800
Nominal voltage	650 V
Maximum charge current	200 A
Operating temperature range	–20 °C to 60 °C
Cooling system	Liquid cooling
Protection class	IP67

Extinguishing material

– The ABC class dry chemical extinguisher contains monoammonium phosphate, interrupts chemical reactions, effective for various fire types. The composition of material is given in tab. 2.

Table 2. Dry chemical extinguisher material composition

Material	CAS No	Volume [%]
Ammonium phosphate monobasic	7722-76-1	95

– Lithium battery fire suppression solution (Pure Anti Fire Ev4) uses aqueous vermiculite dispersion to cool and inhibit chemical reactions, environmentally friendly. The composition of material is given in tab. 3.

Table 3. Pure anti fire extinguisher material composition

Material	CAS No	Volume [%]
Water	7732-18-5	98
Disodium metasilicate	6834-92-0	1
Boric acid, disodium salt	1330-43-4	1

– Lithium battery fire suppression gel (Lith Ex – pressurized extinguisher). The lithium battery fire suppression gel forms a non-combustible barrier that effectively cools and inhibits chemical reactions during lithium battery fires. Utilizing aqueous vermiculite dispersion (AVD), it creates a protective layer over the fire source, preventing oxygen from fueling the flames. The vermiculite platelets encapsulate the fuel source, significantly reducing the risk of re-ignition. The composition of material is given in tab. 4.

Table 4. Lith Ex – pressurized extinguisher material composition

Component	Percentage [%]	CAS number
Aqueous vermiculite dispersion	75.6%	1318-00-09
Nitrogen	0.885%	7727-37-9
Helium	0.00666%	7440-59-7

– Class B foam. Designed for flammable liquid fires, forms a film layer over flames.
– Class A foam. Used for solid combustible material fires, forms a film layer over the fire.
– Dry foam (Class A). Forms a film layer, mixed with pressurized water to create foam.

The compositions of all foam materials used are given in tab. 5.

Table 5. Foam extinguisher materials composition

Foam Type	CAS Number	Content ratio [%]
Class B foam	68131-39-5	3% for hydrocarbons, 6% for polar solvents
Class A foam	7732-18-5	0.1-1.0%
Class A foam (dry)	9003-11-6	0.1-1.0%
Protein foam	9000-70-8	3%

– The F-500 suppression agent. Rapidly cools and encapsulates combustible materials, uses microencapsulation technology. The agent works by altering the composition of water droplets, creating spherical micelles that encapsulate and isolate fuel sources, thereby preventing re-ignition. The composition of material is given in tab. 6.

Table 6. The F-500 extinguisher materials composition

Component	Percentage [%]	CAS Number
Water	98	7732-18-5
F-500 Encapsulator agent	2	Not available

– Protein foam. Effective for petroleum fires, covers fuel surface to control flames.
– Carbon dioxide (CO_2) extinguisher. Displaces oxygen and cools the fire. Safe for electrical fires, leaves no residue. The composition of material is given in tab. 7.

Table 7. The CO_2 extinguisher material composition

Material	CAS No	Volume [%]
Carbon dioxide	124-38-9	100

– Water.

Experiment

A single 5 kg CO_2 extinguisher was used for 20 seconds. The fire oxygen source was cut off, but internal chemical reactions continued, indicating the need for additional measures to fully suppress the fire. The CO_2 extinguishers are effective in displacing oxygen, which is crucial for combustion, but they do not cool the fire or prevent re-ignition if the heat source remains. Initial temperature was reduced by approximately 150 °C, but hotspots remained due to ongoing chemical reactions, fig. 2.

Figure 2. Battery fire test view under thermal camera

Three 6 kg dry chemical extinguishers were deployed for 30 seconds. These extinguishers effectively halted the chemical reactions of the fire, yet thermal runaway persisted, highlighting the limitations of dry chemical agents in certain fire scenarios. Dry chemical extinguishers work by interrupting the chemical reaction of the fire tetrahedron, but they may not be sufficient for fires involving materials that can reignite from residual heat. Temperature reduction was around 200 °C, but thermal runaway was observed, indicating insufficient cooling.

Two 12 kg and two 6 kg units of Pure Anti Fire Ev4 were used for 1.5 minutes. This solution demonstrated superior effectiveness by rapidly cooling the fire and halting chemical reactions. Its performance was notably better compared to other extinguishers, suggesting its potential as a preferred choice for lithium battery fires. The cooling effect is particularly important in preventing thermal runaway in battery fires. Achieved a significant temperature drop of 300 °C, effectively preventing thermal runaway and re-ignition.

A single 25 kg unit of Lith Ex- pressurized extinguisher was used for 4 minutes. This extinguisher rapidly cooled the fire and halted chemical reactions, proving to be a robust solution for lithium battery fires. The extended application time and substantial quantity of extinguishing agent contributed to its effectiveness. Achieved a temperature reduction of 350 °C, effectively halting chemical reactions and cooling the fire.

The 1616 L of water and 50 L of foam concentrate were mixed at a 3% ratio and applied at 8 bar pressure for 3 minutes. This mixture formed a film layer on the surface of the fire, yet it was unable to fully extinguish the fire, indicating the need for more potent extinguishing agents. Class B foams are designed to form a barrier between the fuel and the air, but their effectiveness can be limited by the type and intensity of the fire. Reduced temperature by 250 °C, but hotspots persisted, indicating the need for additional cooling measures.

The 646 L of water and 20 L of foam concentrate were mixed at a 3% ratio and applied at 8 bar pressure for 1.5 minutes. Similar to the previous foam application, a film layer was formed, but complete extinguishment was not achieved. Class A foams are effective for ordinary combustibles, but may not be sufficient for fires involving flammable liquids or gases. Achieved a temperature drop of 200 °C, but was insufficient for complete extinguishment.

The 10 L of foam concentrate were applied at 8 bar pressure for 1.5 minutes. This application resulted in a film layer on the fire surface, yet the fire persisted, demonstrating the limitations of dry foam in certain fire conditions. Dry foam can be effective in smothering fires, but may not address underlying heat sources. Reduced temperature by 150 °C, but internal heat sources remained active.

The 480 L of water and 20 L of foam concentrate were mixed at a 6% ratio and applied at 8 bar pressure for 2.5 minutes. Despite forming a film layer, the fire was not fully extinguished, suggesting the need for higher concentration or alternative agents. The higher concentration of foam was intended to enhance the smothering effect, but additional measures were still required. Achieved a temperature reduction of 300 °C, but additional measures were required for complete extinguishment.

The 485 L of water and 15 L of foam concentrate were mixed at a 3% ratio and applied at 8 bar pressure for 2.5 minutes. The film layer formed was insufficient for complete extinguishment, indicating the need for more effective solutions. Protein foams are known for their stability and heat resistance, but may not be adequate for all fire types. Reduced temperature by 250 °C, but was insufficient for complete extinguishment.

The 2000 L of water were applied at 8 bar pressure for 7 minutes. The fire was cooled, and the oxygen source was cut off, yet complete extinguishment was not achieved, highlighting the challenges in suppressing fires with water alone. Water is effective for cooling and reducing oxygen, but may not be sufficient for fires involving flammable liquids or electrical equipment. Achieved a temperature drop of 200 °C, but hotspots and potential for re-ignition remained.

These observations underscore the importance of selecting appropriate extinguishing agents based on the specific fire scenario, as well as the potential need for combining multiple methods to achieve complete fire suppression. Understanding the properties and limitations of each extinguishing agent is crucial for effective fire management and safety. The damage caused by the tests is shown in fig. 3.

Figure 3. structural damage after the experiment and extinguishing operations performed during fire extinguishing

Results

The drill yielded valuable insights into the difficulties of extinguishing lithium-ion battery fires and the efficacy of different extinguishing agents. The main findings and observations are summarized.

Thermal runaway and fire behavior. Lithium-ion batteries exhibited rapid temperature increases due to thermal runaway, resulting in smoke, flames, and explosions. This underscores the inherent fire risks associated with these batteries.

Gas emissions. The fire released toxic and flammable gases, including hydrogen cyanide (HCN) and carbon monoxide (CO), posing serious health risks to firefighting personnel. Proper respiratory protection and monitoring equipment are essential during fire response.

Effectiveness of extinguishing agents. Among the 10 different extinguishing agents tested, the lithium battery fire suppression and cooling solution (Pure Anti Fire Ev4) demonstrated superior effectiveness. However, complete extinguishment was not achieved due to the structural characteristics of the battery, indicating the need for further research and development.

Structural damage and fire spread. The high temperatures caused significant deformation and perforation of the battery casing. Ejected cells and battery parts spread up to 15-20 m, increasing the risk of secondary fires. Observations during the drill noted severe damage to the battery casing, with cells and parts being ejected forcefully, underscoring the potential for secondary ignition and the importance of maintaining a safe perimeter.

Cooling and safety measures, Immersing the battery in a water pool was effective for cooling but required a prolonged duration (23 hours) to ensure safety. Proper personal protective equipment (PPE) is essential for firefighting teams due to the emission of toxic gases. The drill demonstrated that while water immersion is effective, it necessitates extended periods to fully neutralize the fire risk, highlighting the importance of continuous monitoring and safety protocols. The comparison of extinguishing agents is provided in the tab. 8.

Table 8. Comprasion of the extinguishing materials used in experiments

Fire suppression material	Application time	Temperature reduction [°C]	Thermal runaway stopped	Re-ignition risk	Other observations
CO_2 extinguisher	20 seconds	150	No	High	Internal reactions continued
Dry chemical extinguisher	30 seconds	200	No	Medium	Thermal runaway persisted
Pure Anti Fire Ev4	1.5 minutes	300	Yes	Low	Most effective cooling and reaction stopping
Lith Ex- pressurized extinguisher	4 minutes	350	Yes	Low	Chemical reactions halted
Water and foam mixture (3%)	3 minutes	250	No	Medium	Hotspots remained
Water and foam mixture (6%)	2.5 minutes	300	No	Medium	Additional measures required
Water (2000 L)	7 minutes	200	No	Re-ignition risk	Other observations

Training and collaboration. The drill provided valuable training and technical data for both Municipality Fire Department and electrical commercial vehicles (ECV) producer company. Regular drills are crucial for enhancing the knowledge and experience of firefighting teams, enabling them to develop more effective response strategies for lithium-ion battery fires. The collaborative effort during the drill emphasized the need for ongoing training and data collection to refine firefighting techniques and improve safety measures.

These findings form a critical foundation for evaluating and improving the methods and materials used in extinguishing lithium-ion battery fires. Future similar studies will contribute to advancing fire safety knowledge and practices, ensuring better preparedness and response strategies for such complex fire scenarios.

Conclusion

The lithium-ion battery fire experiment offered crucial insights into the behavior of battery fires and the effectiveness of various extinguishing agents. The key lessons learned are summarized.

Thermal runaway and fire behavior. Lithium-ion batteries can reach temperatures exceeding 700 °C when exposed to external heat sources, leading to thermal runaway characterized by noise, smoke, sudden flames, and explosions. Early detection and intervention are vital to prevent severe fire incidents.

Gas emissions. The fire releases toxic and flammable gases, including hydrogen cyanide (HCN) and carbon monoxide (CO). These gases pose significant health risks to firefighting personnel, necessitating the use of proper respiratory protection and gas monitoring equipment during fire response.

Effectiveness of extinguishing agents. Among the various extinguishing agents tested, the lithium battery fire suppression and cooling solution (Pure Anti Fire Ev4) was found to be more effective. However, complete extinguishment was not achieved due to the structural characteristics of the battery. This highlights the need for further research and development of more effective extinguishing agents for lithium-ion battery fires.

Structural damage and fire spread. High temperatures caused significant deformation and perforation of the battery casing, with ejected cells and battery parts spreading up to 15-20 m. This indicates the potential for secondary fires and the importance of maintaining a safe perimeter around the fire scene.

Cooling and safety measures. Immersing the battery in a water pool was effective for cooling but required a prolonged duration (23 hours) to ensure safety. Continuous monitoring and the use of proper PPE are essential to protect firefighting teams from toxic gas emissions and high temperatures.

Thermal imaging and monitoring. Thermal cameras are crucial for accurately monitoring the temperature and identifying hotspots during fire response. Regular thermal imaging checks should be conducted from multiple angles to ensure comprehensive monitoring of the fire progression.

By addressing these areas, commercial vehicle and battery manufacturers can enhance the safety and reliability of their products, reduce the risk of fire incidents, and improve their overall response to lithium-ion battery fires.

References

[1] Adams, R. A., *et al*., Mechanistic Elucidation of Thermal Runaway in Potassium-Ion Batteries, *Journal of Power Sources, 375* (2018), Jan., 131-137
[2] Chen, J., *et al.,* Designing an Intrinsically Safe Organic Electrolyte for Rechargeable Batteries, *Energy Storage Materials, 31* (2020), Oct., 382-400
[3] Park, S.-Y., *et al.,* Observation and Modeling of the Thermal Runaway of High-Capacity Pouch Cells due to an Internal Short Induced by an Indenter, *Journal of Energy Storage, 72* (2023), 108518
[4] Duan, J., *et al.,* Building Safe Lithium-Ion Batteries for Electric Vehicles: A Review, *Electrochemical Energy Reviews, 3* (2020), Dec., pp, 1-42
[5] Golubkov, A. W., *et al.,* Thermal Runaway of Commercial 18650 Li-Ion Batteries with LFP and NCA Cathodes – Impact of State of Charge and Overcharge, *RSC Advances, 5* (2015), 70, pp. 57171-57186
[6] Wang, E., *et al.,* Safety Assessment of Polyolefin and Nonwoven Separators Used in Lithium-Ion Batteries, *Journal of Power Sources, 461* (2020), 228148
[7] Ghiji, M., *et al.,* A Review of Lithium-Ion Battery Fire Suppression, *Energies, 13* (2020), 19, 5117
[8] Sorensen, A., *et al.,* A Study of Thermal Runaway Mechanisms in Lithium-Ion Batteries and Predictive Numerical Modeling Techniques, *Batteries, 10* (2024), 4, 116

[9] Gao, Z., *et al.,* Bioinspired Thermal Runaway Retardant Capsules for Improved Safety and Electrochemical Performance in Lithium-Ion Batteries, *Advanced Science, 9* (2022), 2103796
[10] Zhang, L., *et al.,* Matching and Optimization Design of Electric Drive Assembly Mounting System of Electric Vehicle, SAE Technical Paper 2023-01-7002, 2023
[11] Kethareswaran, V., & Moulik, S., Electric Vehicles and the Burning Question: Reasons, Risks, Ramifications and Remedies – An Indian Perspective, *Fire Technology, 59* (2023), June, pp. 2189-2201
[12] Sun, P., *et al.,* A Review of Battery Fires in Electric Vehicles, *Fire Technology, 56* (2020), Jan., pp. 1361-1410
[13] Battke, B., *et al.,* A Review and Probabilistic Model of Lifecycle Costs of Stationary Batteries in Multiple Applications, *Renewable and Sustainable Energy Reviews, 25* (2013), Sept., pp. 240-250
[14] Hassan, M. K., *et al.,* Fire Incidents, Trends, and Risk Mitigation Framework of Electrical Vehicle Cars in Australia, *Fire, 6* (2023), 8, 325
[15] Li, H., *et al.,* Full-Scale Experimental Study on the Combustion Behavior of Lithium Ion Battery Pack Used for Electric Vehicle, *Fire Technology, 56* (2020), 6, pp. 2545-2564
[16] Zhang, G., *et al.,* Study on the Suppression Effect of Cryogenic Cooling on Thermal Runaway of Ternary Lithium-Ion Batteries, *Fire, 5* (2022), 6, 182
[17] Bisschop, R., *et al.,* Handling Lithium-Ion Batteries in Electric Vehicles: Preventing and Recovering from Hazardous Events, *Fire Technology, 56* (2020), Sept., pp. 2671-2694
[18] Wang, K., *et al.,* Early Warning Method and Fire Extinguishing Technology of Lithium-Ion Battery Thermal Runaway: A Review, *Energies, 16* (2023), 7, 2960
[19] Liu, K., *et al.,* Materials for Lithium-Ion Battery Safety, Science Advances, 4 (2018), eaas9820
[20] Cai, T., *et al.,* Early Detection for Li-Ion Batteries Thermal Runaway Based on Gas Sensing, *ECS Transactions, 89* (2019), 1, 85
[21] Han, Y., *et al.,* Application of an NDIR Sensor System Developed for Early Thermal Runaway Warning of Automotive Batteries, *Energies, 16* (2023), 9, 3620
[22] Yu, X., *et al.,* Sustainable Collaborative Innovation between Research Institutions and Seed Enterprises in China, *Sustainability, 12* (2023), 2, 624
[23] Hassan, M. K., *et al.,* Fire Incidents, Trends, and Risk Mitigation Framework of Electrical Vehicle Cars in Australia, *Fire, 6* (2023), 8, 325
[24] Kethareswaran, V., Moulik, S., Electric Vehicles and the Burning Question: Reasons, Risks, Ramifications and Remedies – An Indian Perspective, *Fire Technology, 59* (2023), June, pp. 2189-2201
[25] Tran, M.-K., *et al.,* A Review of Lithium-Ion Battery Thermal Runaway Modeling and Diagnosis Approaches, *Processes, 10* (2022), 6, 1192
[26] Lai, X., *et al.,* A Review of Lithium-Ion Battery Failure Hazards: Test Standards, Accident Analysis, and Safety Suggestions, *Batteries, 8* (2022), 11, 248
[27] Senyurek, U., *et al.,* Battery Caused Fires in Electric Vehicles*, Uluslararası Yakıtlar Yanma Ve Yangın Dergisi, 10* (2022), 1, pp. 21-27

Paper submitted: April 23, 2023
Paper revised: May 11, 2023
Paper accepted: May 28, 2023