Fire behaviour tests for lithium-ion batteries – a literature review

Cristina Sanfeliu Meliá*[a], Anne Steen-Hansen[a,b], Gabriele Lobaccaro[a], Christoph Meraner[b]

[a]Department of Civil and Environmental Engineering (NTNU), Trondheim, Norway

[b]RISE Fire Research, Trondheim, Norway

*Corresponding author

Abstract

Large lithium-ion batteries (LIB) is a field that experienced a rapid development in the recent years. In the last decade over 30 fire incidents have globally occurred in large LIB installations [1], for instance, APS Arizona (USA) [2] and Victorian Big Battery (Australia) [3]. Although the probability of fire is very low, the consequences of a fire caused by LIB malfunction may be severe.

One major problem with LIBs is the exposure to thermal and health hazards. LIBs are composed of flammable substances and store high energy density. LIBs may start a thermal runaway (TR) process under a failure mechanism in the battery (mechanical, thermal, or electrical failure). During the TR process, the battery releases flammable and toxic gases and may start a fire or cause an explosion [4]–[6].

The knowledge of fire behavior is important for improving safety and preventing accidents involving batteries. A uniform way of performing tests and documenting fire behavior are under development. The lack of studies summarizing fire test results, including test set-up and test procedure, makes the comparison between studies difficult.

The research method consists of a systematic review of studies published in open-access databases (i.e., Scopus, ScienceDirect, and so on), with the purpose of examining the way the research on the fire behavior of LIBs has been conducted. The content has been categorized by four-phases (PRISMA method).

The work is in progess, a conclusion is that further research is needed to develop fire test conditions and good procedures for documentation of large LIB capacities (~more than 100Ah).

LIB Fire (RISE Fire Research, Norway)

Types of LIBs and fire behavior

- From a cell: jet fires during the burning of exothermic reactions, and stable combustion.
- From a module: the TR propagation into cells contributes to a variety of jet fire stages (expansion, jet fires and stable combustion). The fire is abated and extinguished after total combustion.

Cell type	LCO	NCA	NMC	LFP
Cathode active material	Lithium Cobalt Oxide	Lithium Nickel Cobalt Aluminium	Lithium Nickel Manganese Cobalt Oxide	Lithium Iron Phosphate
Nominal voltage	3.7	3.6	3.6/3.7	3.2/3.3

Research questions and Results

- ***What LIBs composition and energy capacity have been tested to fire behavior and how? What are the battery characteristics that impact fire behavior?***

LCO, NCA, NMC and LFP are cathodes that have been tested to fire. The tested LCO cathodes have small capacity (Ah), while NCA cathodes less than 50Ah, NMC and LFP cathodes are more flexible in terms of capacity, achieving up to 100Ah per cell. Battery characteristics that impact fire behavior are cell chemistry, cell capacity, SoC% and cell aging.

- ***Which experimental fire test methods under controlled conditions have been used?***

Several battery capacities have been tested in different test scales: cone calorimeter (ISO 5660-1) and Tewarson calorimeter test (ISO 12138) as bench scale, single burning item (SBI, DIN EN 13823) test as intermediate-scale and open burning HRR calorimeters and room fire tests (ISO 9705) as full-scale. Reactor heater and temperature-ramp method (Accelerating Rate Calorimeter) were found in the literature as fire test for small battery capacities (~1-3Ah).

- ***Which fire parameters have been measured?***

The most common fire parameters are measured in the tests were heat release rate, mass loss rate, surface temperature, maximum temperature, TR onset temperature and the impact of SoC% in the heat release rate. Despite that, few tests included flame temperature and radiative heat flux from the battery. The ignition method considered in the analysis of papers is thermal method. Electric heating and propane burners are common ignition methods. Electric heating includes conduction heat and radiation heat. Note that not all manuscripts show results of the described fire parameters.

- ***What are the HRR peak (kW), THR (kJ) and Max Temp. per energy capacity (Wh) for LFP and NMC cells?***

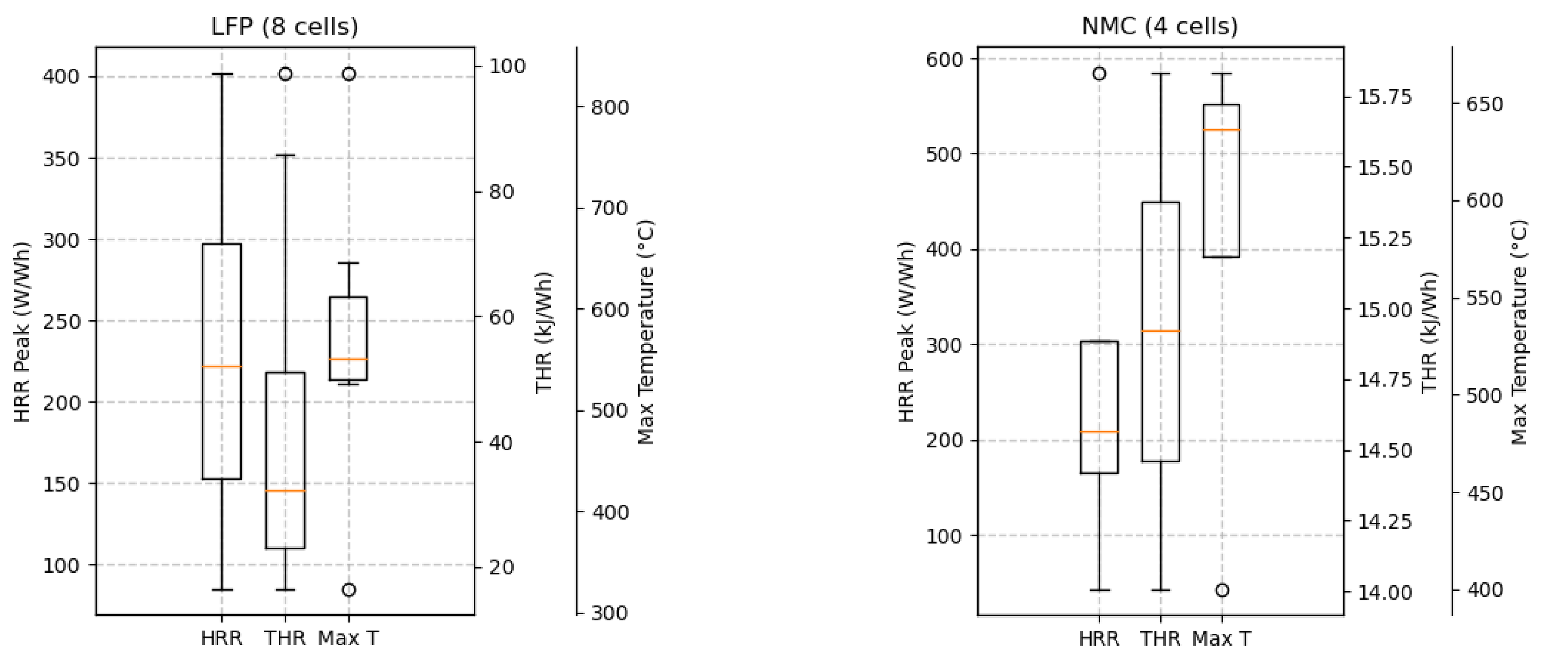

Fig 1. HRR Peak (kW), THR (kJ) and Max Temperature (C) per Energy Capacity (Wh) for LFP and NMC Cells at 100% SoC

Results of HRR peak and THR per Wh, show a range of data values. For instance, LFP cells show HRR peaks from 85 to 365 W/Wh. Large differences of kJ are also observed. NMC cells present higher HRR peaks. According to temperatures, LFP batteries have higher temperatures than NMC batteries.

- ***What are the instrumentation methods for gas analysis? What gases have been measured?***

Reference	Cell type, Capacity	Gas Analysis Instrumentation	Gases
Peng et al. (2019)	LFP, 60Ah	Paramagnetic, NDIR, FTIR	CO, HF, SO_2, NO_2, NO, HCl
Liu et al. (2021)	LFP, 243Ah	Paramagnetic, NDIR, FTIR	CO, CO_2, H_2, CH_4, HF
Mao et al. (2021)	LFP, 325Ah	Paramagnetic, NDIR	CO_2, CO
Peiyan et al. (2022)	LFP, 60Ah	Paramagnetic, NDIR, FTIR	CO, CO_2, H_2, HF
Huang et al. (2015)	NMC, 50Ah	Paramagnetic, FTIR	CH_4, C_2H_4, C_3H_6, CO, SO_2
Liu et al. (2022)	NMC, 117Ah	Paramagnetic, NDIR, FTIR	CO_2, H_2, CH_4, C_2H_4, CO, HF

Conclusions

The maximum battery capacity that has been founded in the studies is for a 117Ah NMC cell and a 325 Ah LFP cell. Battery capacity determines the calorimeter scale for measuring HRR of the battery. The method of testing fire might provide different results for the same battery chemistry and type.

In terms of gases, release of hydrogen fluoride (HF) has been studied for several battery capacities and chemical battery compositions during TR process. Other toxic gases such as nitrogen oxides and sulfur oxides and a combination of hydrogen with chlorine and fluorine have rarely been studied for large battery capacities (up to 100Ah).

References

[1] J. Conzen, S. Lakshmipathy, A. Kapahi, S. Kraft, and M. DiDomizio, "Lithium ion battery energy storage systems (BESS) hazards," *J. Loss Prev. Process Ind.*, vol. 81, p. 104932, Feb. 2023, doi: 10.1016/j.jlp.2022.104932.

[2] D. Hill, *McMicken Battery Energy Storage System Event: Technical Analysis and Recommendations*. DNV GL Energy Insights USA, Incorporated, 2020.

[3] A. Blum, T. Benson, P. Rogers, C. Grant, and G. Hough, "Victorian Big Battery Fire July 30 2021: Report of Technical Findings," 2022.

[4] Q. Wang, B. Mao, S. I. Stoliarov, and J. Sun, "A review of lithium ion battery failure mechanisms and fire prevention strategies," *Prog. Energy Combust. Sci.*, vol. 73, pp. 95–131, Jul. 2019, doi: 10.1016/j.pecs.2019.03.002.

[5] J. Sun, B. Mao, and Q. Wang, "Progress on the research of fire behavior and fire protection of lithium ion battery," *Fire Saf. J.*, vol. 120, p. 103119, Mar. 2021, doi:10.1016/j.firesaf.2020.103119.

[6] P. Sun, R. Bisschop, H. Niu, and X. Huang, "A Review of Battery Fires in Electric Vehicles," *Fire Technol.*, vol. 56, no. 4, pp. 1361–1410, Jul. 2020, doi: 10.1007/s10694-019-00944-3.

Acknowledgements - Project Founding and Collaborations

This literature review is part of a PhD named Fire Safe, Sustainable Solutions for Energy Systems in Buildings. PhD candidate is the main author of the poster. The project includes study of cell, module and unit level fire tests. The project is funded through Green2050 - Centre for Green Shift in the Built Environment, hosted by Department of Civil and Environmental Engineering, NTNU. Collaboration with SafeBESS project – Technology and building design for safe operation of battery energy storage systems, led by SINTEF. Collaboration with research groups in fire tests of batteries (RISE Fire Research, Norway and RISE, Sweden).

FRIC FIRE RESEARCH & INNOVATION CENTRE

green 2050

NTNU | Norwegian University of Science and Technology