Visualisation of Thermal Propagation in Full EV Packs

Modelling the Evolution of Thermal Behaviour during Initiation and Propagation of Thermal Runaway in Lithium-Ion Batteries

Jess Cary, **Dr. Paul Christensen, Dr. Wojciech Mrozik**

ABSTRACT

This study delves into the thermal behaviour of lithium-ion battery packs used in electric vehicles (EVs). A full EV battery pack was dissected and subjected to a controlled overcharge test. The research focuses on the initiation and propagation of large-scale thermal runaway. This investigation sheds light on the complexities of thermal behaviour in EV battery packs and the importance of safety measures as thermal propagation is tracked inside the pack.

THERMAL MODEL: WHY?

Overcharging resulted in the violent ejection of flames from the pack. Following the pack expanding, the seals compromised and began venting the vapour cloud, which then ignited. Flames travelled around the corner of the pack and ignited gases venting from the main cable port and the ensuing flame travelled down the cables. The events in *(Fig. 1)* all took place within 6 seconds. Flares projected outside of the pack throughout this time as modules went into thermal runaway and the vapour clouds ignited.

- Safety Assurance: Thermal models help ensure that the battery pack's thermal behavior aligns with safety standards. By validating the model against test data, any deviations or anomalies can be identified, ensuring that safety margins are maintained. Post-test analysis using the model also helps identify potential safety hazards, such as hotspots or conditions that could lead to thermal runaway. This information is vital for developing safety protocols and mitigating risks.
- Safety Optimisation: The model has many applications in refining safety features, thermal management strategies, and emergency response protocols. This iterative process enhances the overall safety of EV battery packs. Thermal models allow for continuous safety improvement by assessing the impact of changes in battery chemistry, design, or thermal management systems. This proactive approach ensures that safety measures stay ahead of emerging risks.
- Data Validation: With temperatures in this pack reaching up to 911°C, thermal models can aid in visualising the processes happening inside the pack, that test hardware may not be able to. Comparing the modelling predictions with the actual test data helps validate the accuracy and reliability of the thermal model. Any disparities between the model and experimental results can highlight areas for improvement in the model's parameters and may highlight errors or failures during the test.
- Optimisation for Future Tests: Based on insights from the completed test, thermal models can be used to optimise the design and configuration of future tests. This can lead to more efficient and informative test setups, potentially reducing the need for additional physical tests.

THERMAL MODEL: GEOMETRY AND MESH

Delving into the visualisation and modelling aspect of the EV battery pack. The objective was to gain deeper insights into the thermal evolution inside an EV pack and perform full-scale thermal management simulations.

- The process was initiated by creating a three-dimensional (3D) model of the EV battery pack using Inventor and Fusion360. These accurately represented and visualised the physical geometry of the pack, including individual modules *(Fig.6.)*.

Multi-Scale Physics Modelling:

- For a more technical approach, ANSYS SpaceClaim was then utilized to commence the modelling process at the lowest scale, focusing on individual pouch cells. These were represented with detailed models, capturing factors such as positive and negative tabs, materials, and specification accurate dimensions *(Fig.7.)*.
- Moving up the scale, multiple battery cells were then compiled into modules. These modules were designed with the physical configuration within the EV battery pack. (22 modules had 8 cells configured in a 2(2s2p) formation, and the other 4 modules had 4 cells configured in a (2s2p) formation).
- These formed the entire battery pack, encompassing all modules and their virtual interconnections. This full model provided a realistic visual of the thermal dynamics within the EV battery pack, ensuring the simulations were based on precise representations of the physical components.

Mesh Generation:

The mesh represents the geometry of an object and discretises it into smaller elements to facilitate numerical calculations with appropriate cell, skew, boundary, zone, and other key element sizes to capture details for computational analysis (CHT of CFD specifically).

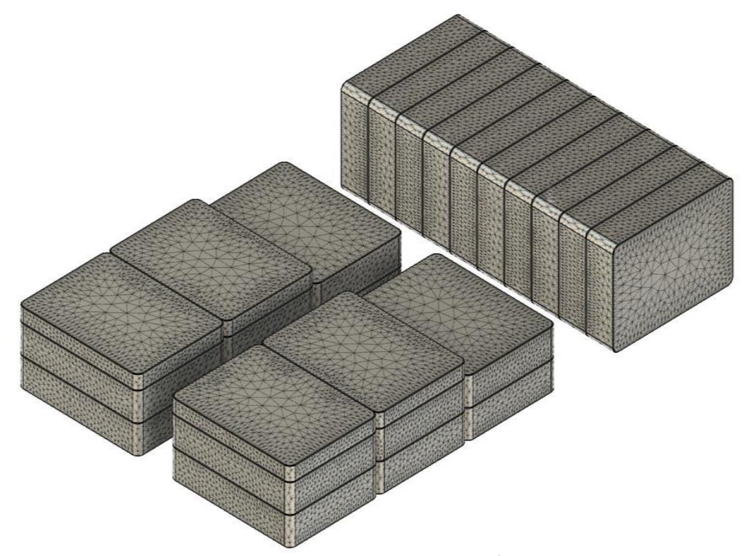

Fig.6. CAD Model and Mesh of the Full EV Pack with Individual Modules

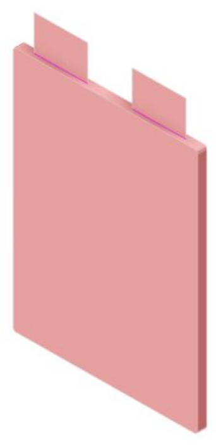

Fig.7. Cell Geometry with Negative and Positive Tabs

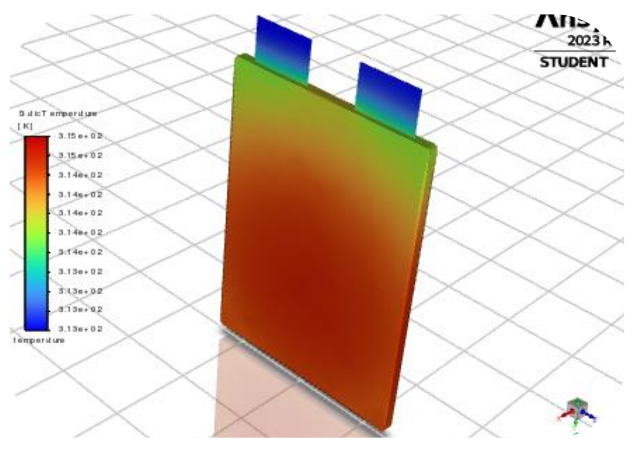

Fig.8. Temperature Contours on a Battery Cell using CHT Analysis

THERMAL MODEL: CONJUGATE HEAT TRANSFER APPROACH

- Implementing the Conjugate Heat Transfer (CHT) approach, this method accurately predict temperature variations within the solid battery components and in the surrounding fluid (air). This is critical for understanding how heat propagates and accumulates in different regions of the battery pack, thus providing an accurate visualisation.
- Incorporating the data from the overcharge test, including voltage, current, temperature, and time; the boundary conditions for the simulation can be defined including the initial temperature of the battery pack, heat transfer coefficients, and any external environmental conditions.
- Calibrating the model to match the experimental data by adjusting parameters like thermal conductivity and heat generation rates allows for realistic interpretations of the temperature contours.
- The results can be visualised in a variety of ways, e.g., by creating temperature contours *(Fig.8.)* and temperature vs. time plots *(Fig.9.)*.
- CHT models are optimal for transient analysis, which are crucial for capturing overcharge scenarios, where temperature changes rapidly over time.

SafeBatt is focused on battery safety, and accurate temperature predictions are essential for assessing the risk of thermal runaway or violent reactions. CHT models allow for a comprehensive analysis of temperature distributions, helping to identify potential hotspots, areas of concern, and implement preventative measures.

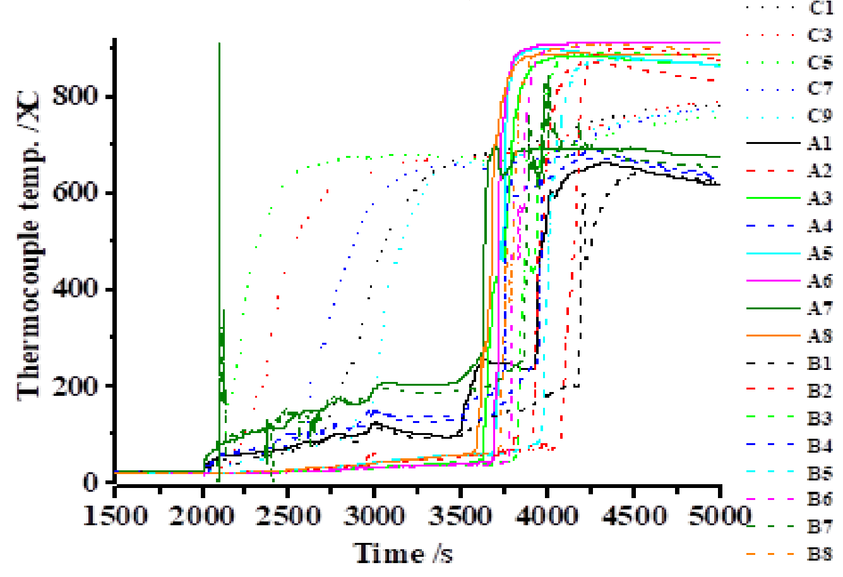

Fig.9. Graph of recorded data: thermocouple temperature against flow of time

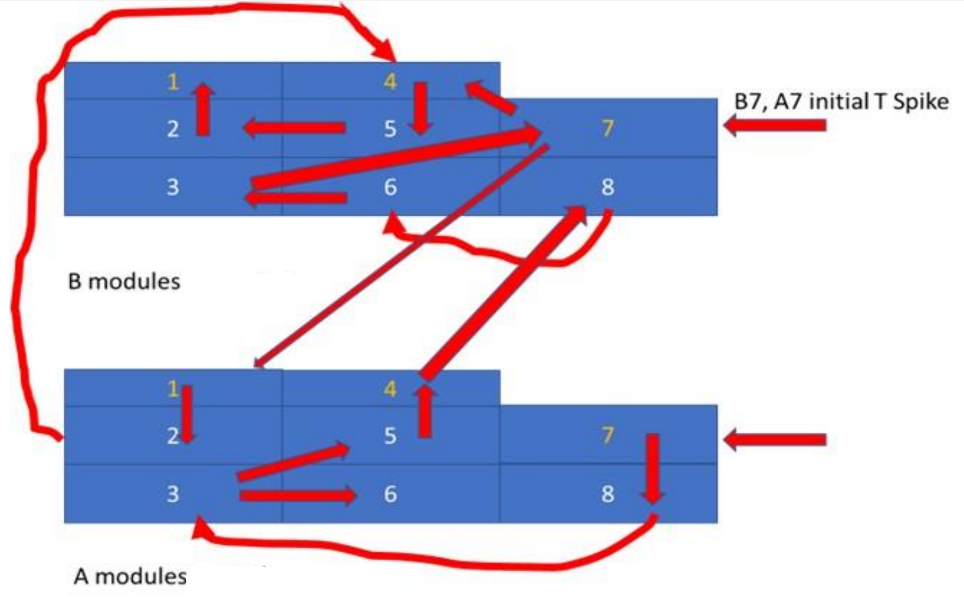

Fig.10. Order of Thermal Propagation in the Pack

MOTIVATION

- The increasing adoption of EVs necessitates a deep understanding of the safety and thermal behavior of their battery packs. Thermal runaway events in lithium-ion batteries can have catastrophic consequences, making safety paramount. This study aims to uncover the intricacies of thermal runaway initiation and propagation, providing critical insights for battery safety in EVs, specifically for large-scale applications.

Fig.1. Overcharge of the pack, resulting in thermal runaway

METHODS

- This involved the systematic disassembly of a lithium-ion battery pack, and subsequently an array of thermal measurements. Thermocouples and oxygen sensors were strategically placed within the battery pack. A single cell pair was overcharged in module C5 to initiate runaway. The thermal propagation patterns were closely monitored using an Agilent 34970A Data Acquisition unit (DAQ).
- The battery model was then created with CAD Software in a multi-scale physics application to generate an accurate cell, then meshed in a repeating pattern to form the battery module. This was then set to pattern about x- and y- units to form a full EV battery pack for use in Conjugate Heat Transfer approaches to form a visual.

RESULTS: OVERCHARGING ANALYSIS

- Overcharging events were meticulously scrutinized, revealing distinct voltage and temperature profiles, especially within module C5 *(Fig.3. and Fig.4.)*. These profiles can be dissected into several distinct regions *(Fig.5.)*.
- Region A was characterized by a rapid voltage increase, attributed to the internal resistance (IR) drop due to current flow. Region B displayed a gradual and sustained voltage increase, attributed to the de-intercalation of lithium ions from the NMC cathode. The inflection point, labeled C, signified the onset of lithium metal plating on the anode, a critical precursor to thermal runaway.
- Region D to E marked the voltage plateau phase, indicating the occurrence of the disproportionation reaction within the cathode, accompanied by dendrite formation a relatively slow decrease then catastrophic collapse at point F.
- Remarkably, the modules within the vertical strings exhibited a discernible order of failure: Modules 5, 3, 7, 1, and 9 succumbed to thermal runaway in this sequence.
- Notably, the battery pack showcased a discernable time delay in the propagation of heat. Our analysis revealed consistent onset temperatures for thermal runaway across the pack.
- It's worth noting that the vertical module strings yielded somewhat anomalously low Time to Thermal Runaway (TTR) values, potentially due to the placement of thermocouples and the diminished thermal conductivity inherent to pouch cells.

Chemistry	$LiNiMnCoO_2$ (NMC)
Number of cells	8
Cell capacity/Ah	56.3
Cell nominal voltage/V	3.65
Cell voltage range/V	2.5–4.2
Module capacity/Wh	1640

Fig.2. Specifications of the Battery Cell and Module

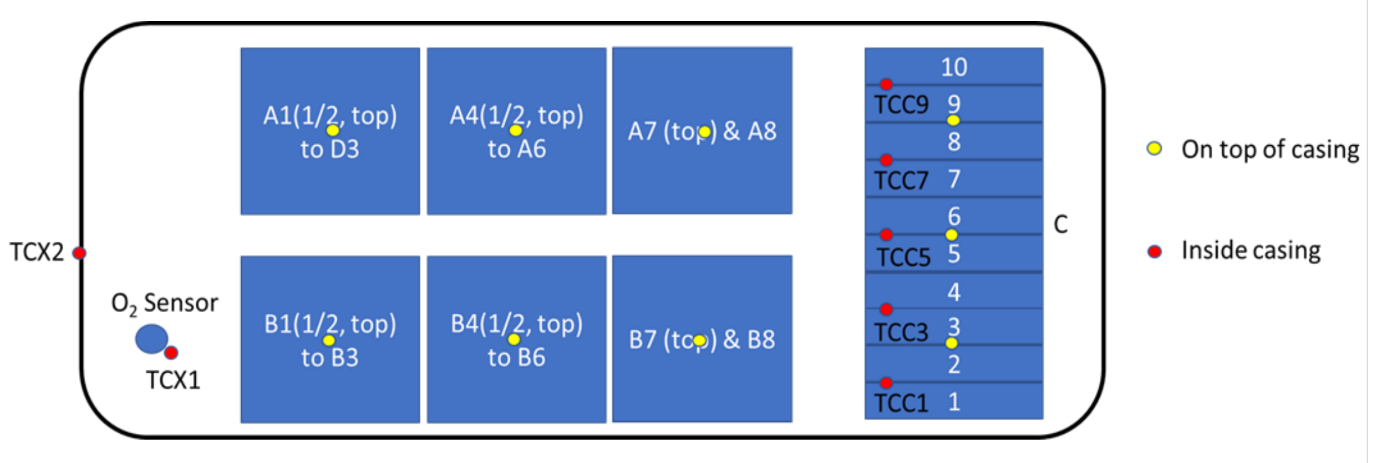

Fig.3. Top View Layout of the Modules in the Battery Pack, including Thermocouple Placements and Numbering

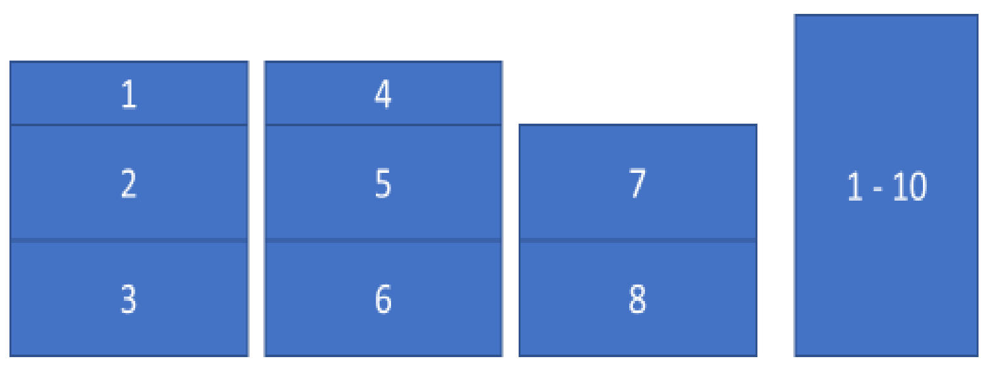

Fig.4. Side View Layout and Numbering of Modules

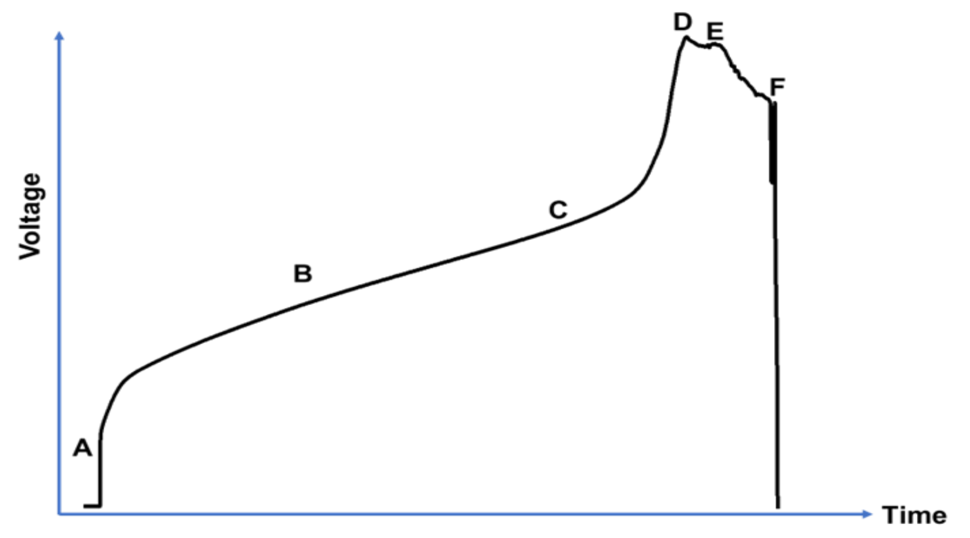

Fig.5. Generic representation of the voltage/time plot during overcharge.

IMPACT / NEXT STEPS

The recognition of the factors at play in thermal runaway phenomena bears paramount significance for enhancing the safety and reliability of lithium-ion batteries within the realm of electric vehicles. Future research should focus on optimising fire-retardant coatings, improving thermal management systems, and developing advanced safety mechanisms to mitigate thermal runaway risks in EV battery packs. These findings pave the way for safer and more efficient electric vehicles, accelerating the transition to sustainable transportation.

CONCLUSIONS

- This research venture delves into the nuanced dynamics governing the initiation and propagation of thermal runaway within lithium-ion battery packs designed for electric vehicles. The outcomes of this study underscore the pivotal role of hot gases and flames in instigating and perpetuating thermal runaway events.
- The CHT model illustrates the propagation of thermal runaway between modules based off the test data and battery specifications, demonstrating a visual representation of the order of processes *(Fig.10.)* occurring under the pack lid that may not have been visible during the tests.

INTERN BIO

Jess is studying Marine Technology with Offshore Engineering at Newcastle University.
Interested in Green Maritime Technology, Global Decarbonisation, and Offshore Renewable/Sustainable Energy Processes.

Connect with me on LinkedIn!

j.s.cary2@newcastle.ac.uk

REFERENCES

1.P. Christensen, Z. Milojevic, M.S. Wise, M. Ahmeid, P.S. Attidekou, W. Mrozik, N.A. Dickman, F. Restuccia, S.M.Lambert, P.K. Das. Thermal and mechanical abuse of electric vehicle pouch cell modules, Applied Thermal Engineering, 2021, https://doi.org/10.1016/j.applthermaleng.2021.116623
2. Zoran Milojevic, Pierrot S. Attidekou, Musbahu Muhammad, Mohamed Ahmeid, Simon Lambert, Prodip K. Das,
Influence of orientation on ageing of large-size pouch lithium-ion batteries during electric vehicle life, https://doi.org/10.1016/j.jpowsour.2021.230242.

THE FARADAY INSTITUTION
SCIENCE OF BATTERY SAFETY
SafeBatt
Newcastle University
UK Research and Innovation