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Thermal runaway in lithium-ion batteries: A literature review

Mechanisms, causes, and modelling

Department of Materials and Mechanical Engineering

Bachelor's thesis

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Lithium-ion batteries are widely used in several industries as well as critical electricity distribution infrastructure due to the well-established process and their energy density, which ranks highly in relation to other battery technologies. However, there are risks involved in large-scale applications, particularly thermal runaway. This thesis examines the mechanisms and causes of thermal runaway, with a focus on the modelling of the thermal runaway process. It covers the main triggering factors and key stages of the process, along with experimental methods used to study the phenomena and validate the developed models.

Litium-ioniakkuja käytetään monilla eri teollisuuden aloilla sekä osana kriittistä sähkönjakeluinfrastruktuuria niiden akkuteknologioiden mittakaavassa korkean energiatiheyden ja vakiintuneiden käyttömenetelmien vuoksi. Akuilla on myös riskinsä suuren mittakaavan käyttökohteissa. Näistä merkittävin on lämpökarkaaminen. Tämä tutkielma käsittelee lämpökarkaamisen syitä ja mekanismeja, painottaen lämpökarkaamisprosessin mallintamista. Se kattaa pääasialliset laukaisimet ja prosessin tärkeimmät vaiheet sekä kokeelliset menetelmät, joita käytetään ilmiön tutkimiseen sekä kehitettyjen mallinnuksien varmentamiseen.

Keywords: Thermal runaway modelling, lithium-ion batteries, thermodynamics, fluid mechanics

Disclaimer: AI tools were utilized for spell-checking only. No generative tools were utilized in the writing of this thesis.

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1 Introduction

Lithium-ion batteries are a cornerstone of modern post-industrial society. The relatively good energy density, long life span, and good energy retention rates have led to batteries being used from small, battery-powered electronics to humongous energy systems, helping to stabilize power grids that face increased volatility due to increases in environmentally dependent energy production methods. Especially, the push to modernize and electrify the automotive industry continues to increase the demand for lithium-ion batteries.

With increases in use cases and demand, operational safety has become a major focus of research. Understanding the mechanisms behind one of the major failure types of lithium-ion batteries, thermal runaway, is of increasing importance. Understanding of the mechanisms will help us to mitigate the risks of catastrophic failure of battery systems. Thermal runaway can cause fires, explosions, and releases of toxic and flammable gases. Especially risky are large energy storage systems, where failure in one battery or even in one cell can propagate through the entire system, causing major damage [1], [2].

To develop the understanding required for risk mitigation, we require both experimental data and theoretical models. Experimental data is used for both the validation of mathematical models for thermal runaway as well as to give insight into the underlying process. As the models rely on some simplifications, the experiment can also be used to determine the correct simplifications for the creation of the most effective model. As model complexity ranges from simple energy balance models all the way to complex multi-dimensional computational fluid dynamic models, it also becomes a question of which model to choose to fit your use case [1], [3], [4]. The goal of this thesis is to look into the mechanisms of thermal runaway and review the different ways it has been modelled with a focus on model accuracy in relation to efficiency.

2 Structure of Li-Ion batteries

2.1 General electrochemical structure

Lithium-ion batteries are constructed from an electrochemical pair separated by an electrolyte that allows the lithium ions to move between the anode and the cathode of the battery cell. This process is almost completely reversible, and the energy is stored in the form of chemical energy that is released as a load is connected to the battery [5]. As lithium in its elemental form is highly reactive, it is doped with other elements to improve and alter the properties of the material. As shown in Figure 1, nickel, cobalt, and manganese all affect different aspects of the battery properties, ranging from capacity and safety to charge and discharge rate. Other common enrichments include aluminium for stability, titanium for structural integrity, and magnesium to stabilize the rate of lithium-ion diffusion in the inter-slab space [6].

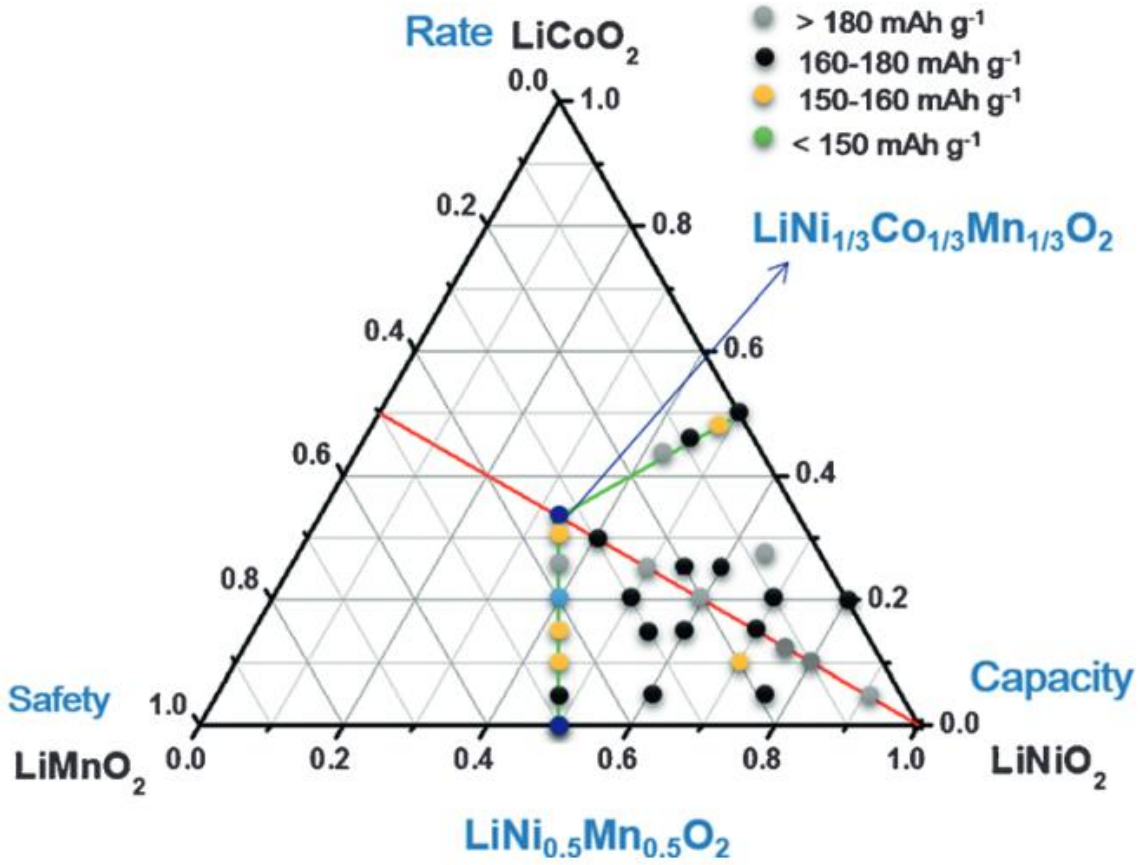

Figure 1:Compositional phase diagrams of lithium stoichiometric-layered transition-metal oxide: LiCoO2-LiNiO2LiMnO2. The positions indicated by dots represent the described LiNi1-x-yCoxMnyO2 materials [6].

2.2 Battery construction

The vast majority of Li-Ion cells are circular, tube-like constructions. Within the tube, the cathode, anode, and the separating membrane are wrapped around a so-called jelly roll [7]. Most of the lithium-ion batteries in production today consist of smaller battery cells, even in high-power and high-performance applications like cars. Large electric vehicle (EV) batteries comprise a large number of battery cells, all of which are made up of jelly rolls. The cells that encase the jelly rolls are arranged in battery modules, which act as outer casings for the individual cells, making it easier and safer to replace the batteries [7], [8]. The different construction methods of individual cells can be seen in Figure 2.

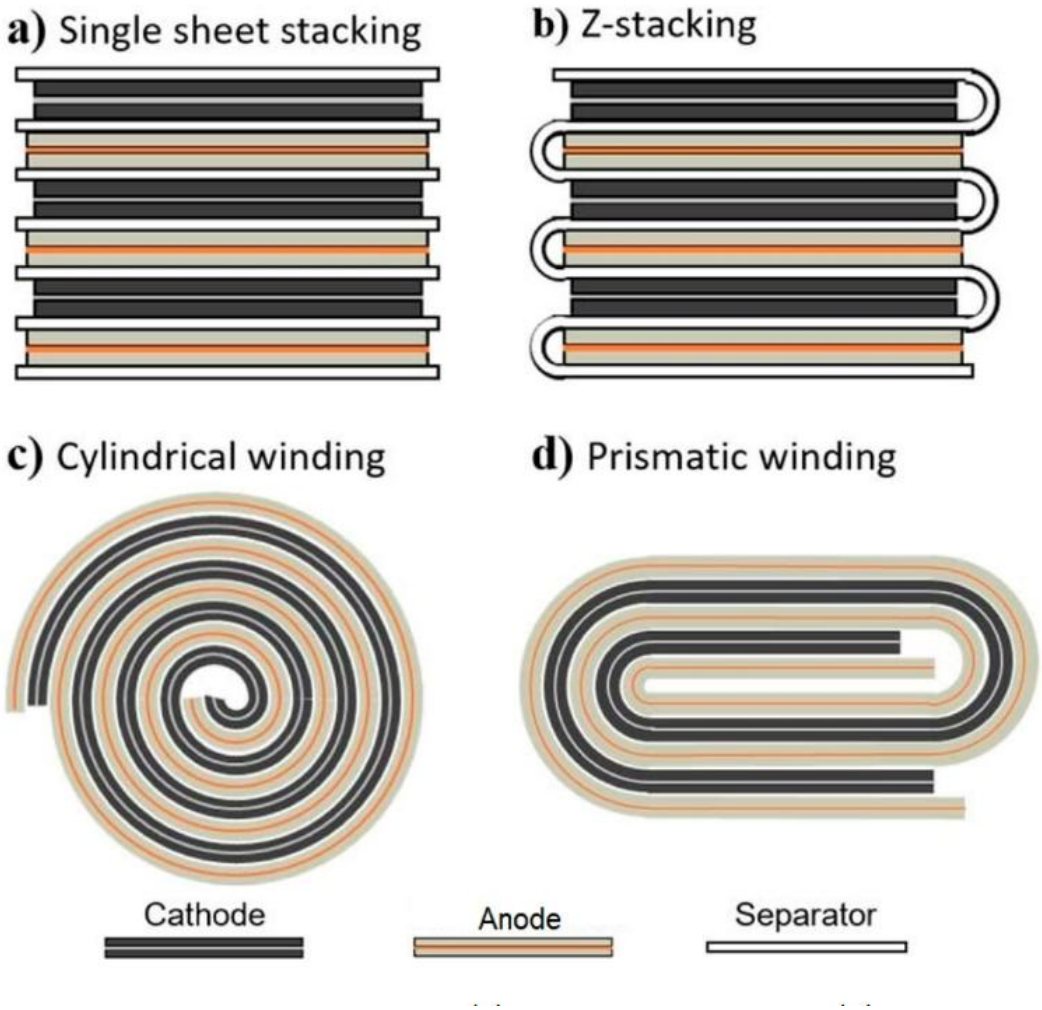

Figure 2: Schematic showing four typical types of Li metal battery manufacturing processes. (a) Single sheet stacking; (b) Z-stacking; (c) cylindrical winding, and (d) prismatic winding [9].

Amidst concern of battery cooling in the face of rising energy densities of modern Li-Ion batteries, another group of battery cells has been developed using prismatic casings. The internal structure largely mimics that of a cylindrical battery, only with the distinct difference in the shape of the jelly roll [3], [10]. This construction has been seen to improve cooling capabilities, especially under forced convection, due in part to the cell shape allowing better flow of the cooling medium through the battery, as seen in Figure 3 [11].

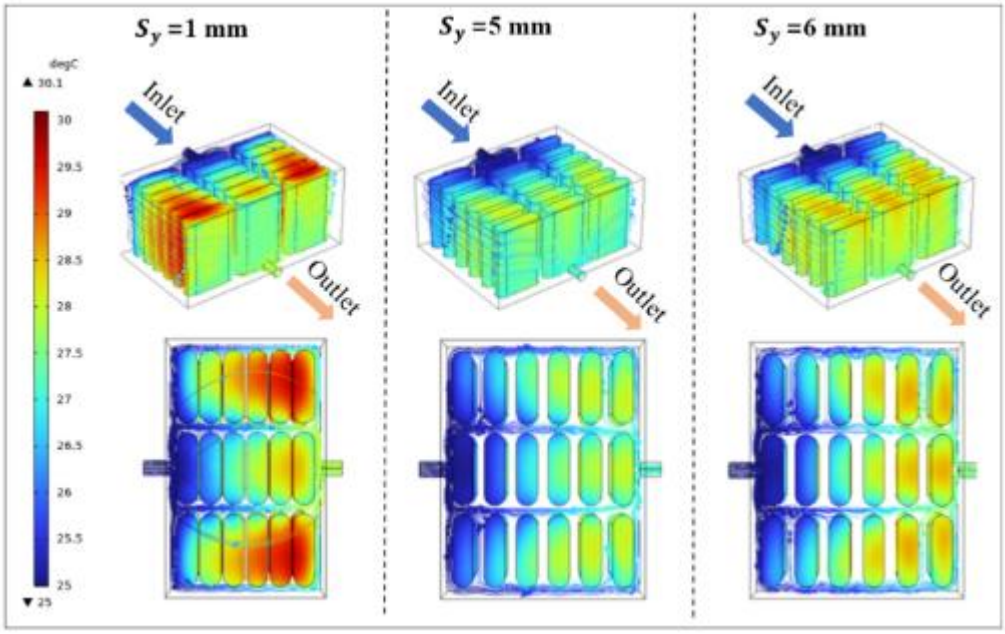

Figure 3: Streamlines of the cooling channel upon completion of battery discharge for different longitudinal distances [11].

As shown in a study by Feng et al. [10] and Alkheder et al. [4], the operating temperature of the batteries is a major contributor not only to battery performance and longevity, but also a considerable addition to the risk of thermal runaway unless properly managed. Prismatic cells combine the ease of manufacturing, installation, and replacement of cylindrical cells while only slightly sacrificing energy density. In return, the cooling capabilities of the batteries are significantly improved, resulting in longer lifespans and better energy efficiency [4], [11], [12].

3 Thermal runaway

3.1 Thermal runaway process

Thermal runaway is an abnormal process within a Li-Ion battery, where the temperature of the cell rises uncontrollably due to exothermic reactions within the battery cell [2]. A cell is considered to be in a state of thermal runaway when the heat generation rate rises above the heat dissipation rate of the battery cell. Larger battery cells suffer from increased risk of thermal runaway due to their poor ratio of stored energy to surface area [2], [10]. As found by Kong et al. [13], Li-Ion batteries start experiencing irreversible damage when the internal temperature reaches 130 ºC. The onset temperature or thermal runaway is considered to be around 260 ºC, depending on the exact material composition of the anode, cathode, and the separator. Between 200-260 ºC, the electrolyte will start to decompose, providing additional thermal energy to the process, as the decomposition is exothermic. Upon reaching 260 ºC, the chemical reaction inside the battery reaches its final stage as the binder material starts reacting with the cathode of the cell, and the thermal runaway begins.

During the thermal runaway process, the temperature inside and outside of the battery increases due to exothermic reactions and the release of stored energy. During this, the pressure inside the battery also increases due to the rising temperature and the gases released as products of the chemical reactions happening during the runaway process [10], [13]. Most commercially available Li-Ion batteries, such as the typical 18650 cell, are equipped with an over-pressure protection system in the form of a valve or a burst disc. Critical pressure for the 18650 cell is 1,9 MPa, after which the internal pressure rapidly drops. This venting, however, has a very negligible effect on the temperature of the cell as seen in Figure 4 [13].

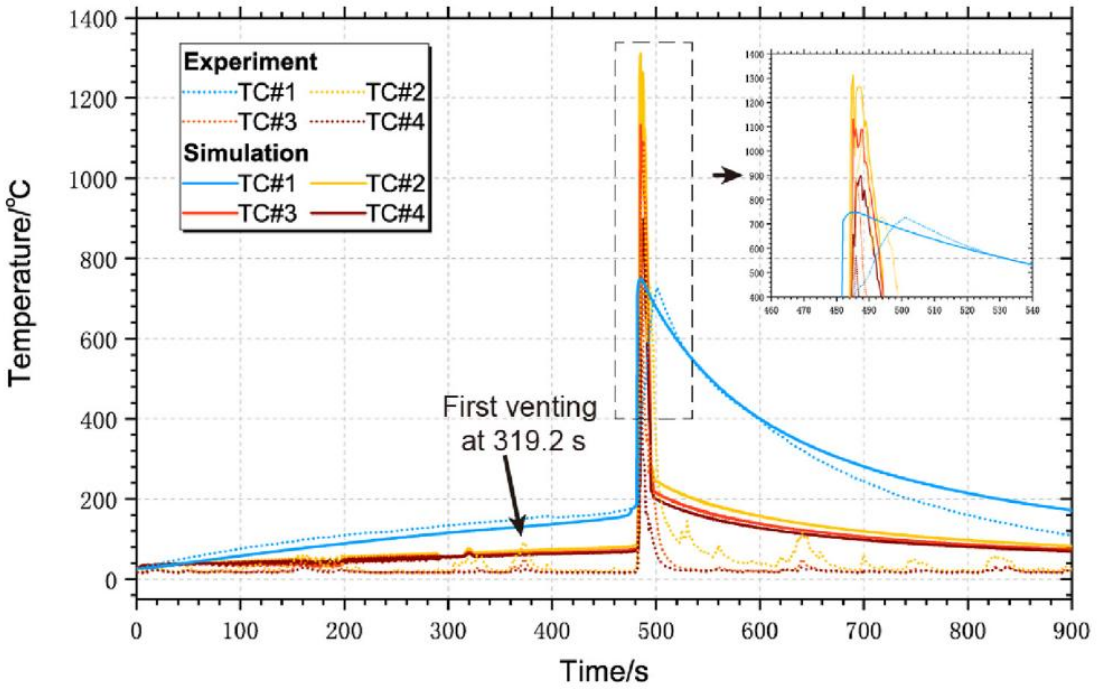

Figure 4: Comparison of the measured and predicted temperature of the cell surface and flame for the NCA cell with 75% state of charge [13].

In a study regarding the thermal runaway propagation within the battery, Chen et al. [8] stated that unless a certain triggering temperature is reached within the battery, the thermal runaway does not start to spread. According to the research of Chen et al. [14], during a normal galvanostatic charge-discharge procedure under natural convection, the surface temperature of the cell doesn't exceed 360 K. This doesn't cross the threshold of 260 ºC or 533,15 K that is required for the battery to be in a state of thermal runaway [13]. However, considering large capacity batteries consisting of hundreds or thousands of individual cells, inadequate cooling could result in a high enough temperature to result in a thermal runaway process that spreads throughout the battery. This propagation is found to speed up as it advances, only making the reaction more dangerous and difficult to stop or contain [8], [10].

3.2 Overheating

As thermal runaway is a process inherently tied to temperature, overheating the battery by various means is an intuitive way of setting off the process of thermal runaway. The battery cells undergoing galvanostatic charge-discharge cycles produce heat that is dissipated from the cell to the surroundings via several heat transfer methods, such as conduction, convection, and radiation [8], [14]. Studies using accelerating rate calorimetry by Galushkin et al. [15] and Feng et al. [10] show the thermal runaway process behaving very similarly regardless of whether the heat source is internal or external. Once the process is triggered by the temperature rising over 260 ºC, it becomes self-sustaining and uncontrollable. As shown in Figure 5, after the start of thermal runaway, the temperature increases rapidly, reaching up to 1000 ºC due to the strong and self-sustaining exothermal reactions [1], [10]. The exothermal chemical processes were explained in detail by Nie et al. [1] and they show that the process produces combustible gases, such as hydrogen (H_2), ethylene (C_2H_4), acetylene (C_2H_2) and fluoroethane (C_2H_5F)[1], [16].

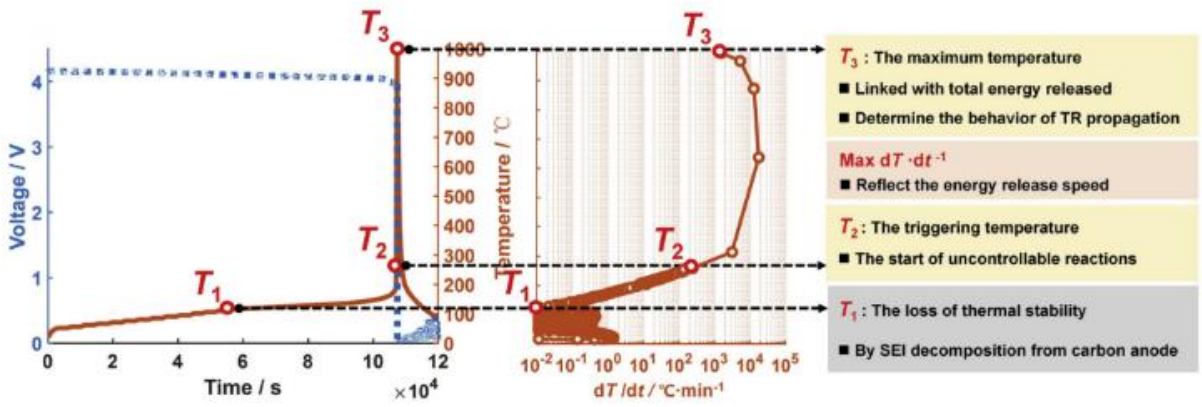

Figure 5:The key temperature nodes in the thermal runaway process [1]

3.3 Physical and electrical abuse

Abusing the battery cells either physically or electrically is a way that the thermal runaway process can be triggered. Regardless of the type, abuse of the cell increases the internal temperature of the cell by either short-circuiting the battery, exposing reactive materials, or interfering with the normal electrochemical operation of the battery [1], [2], [15].

Physical abuse is typically in the form of crushing or piercing. This damages the structural integrity of the cell, causing separator damage and cracks or holes in the outer casing, exposing the material to the surrounding medium. Separator damage can bring the anode and cathode into direct contact, creating a short-circuit or, at the very least, disrupting the internal chemistry of the cell. A damaged outer casing, on the other hand, can expose lithium, which is a highly reactive element. This exposure to air or water causes a strong reaction with a resulting large temperature spike or even an explosion [15], [17].

Operating the battery outside its intended limits is referred to as electronic abuse. Most typically, this is in the form of overcharging, overdischarging, overvoltage, or a higher-than-intended current throughput. From a thermal runaway point, overcharging is the most dangerous as it destabilizes the cathode in the cell and can cause lithium plating to form on the anode, as seen in Figure 6. The change in electrochemical structure can lead to degradation, thermal instability, and premature failure [1], [2], [10].

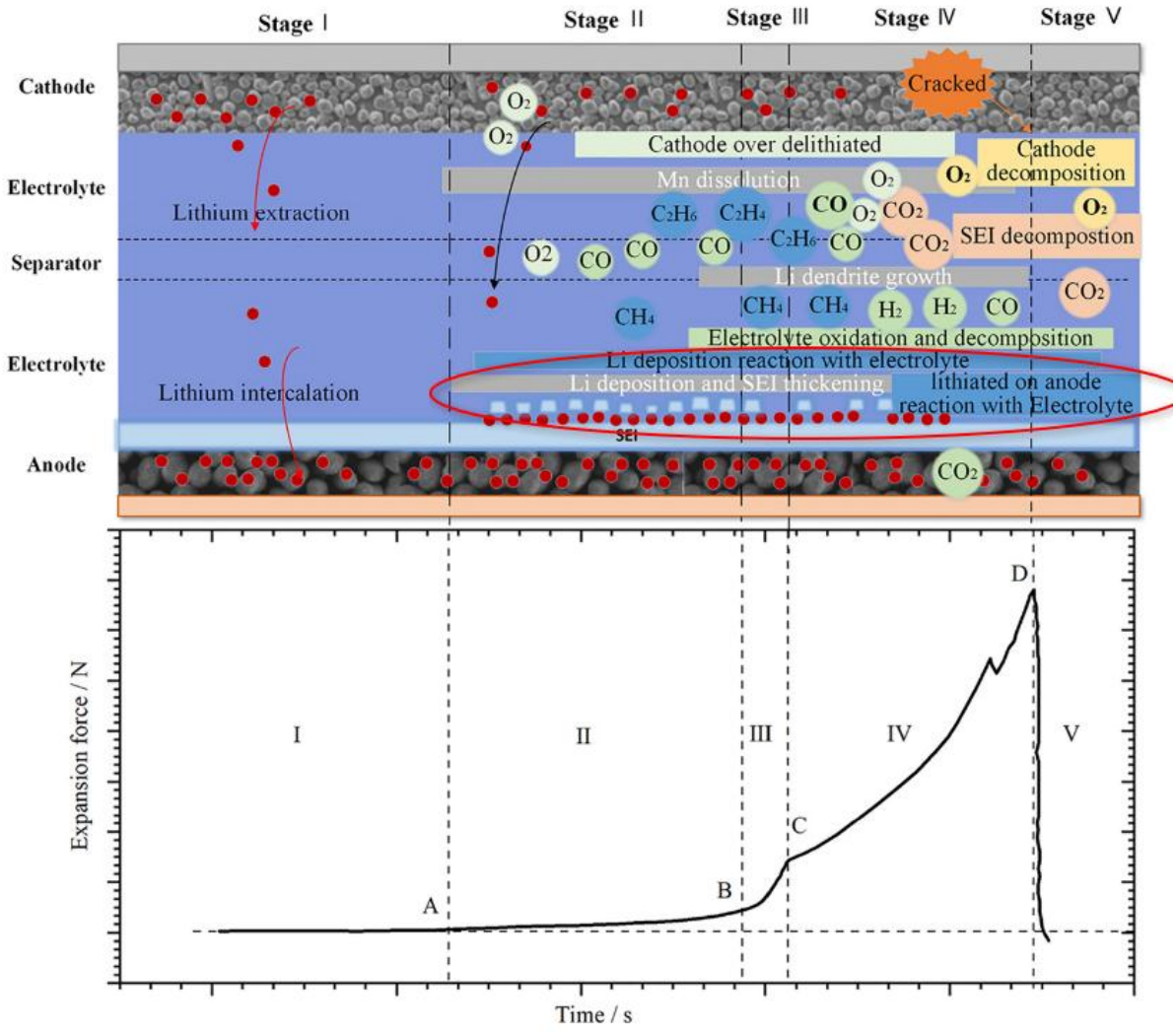

Figure 6: The evolution mechanism of expansion force at each stage during the whole overcharging process, adapted from [18].

3.4 Internal or external short-circuit

Short-circuiting a lithium-ion battery results in a high likelihood of a thermal runaway reaction. Whether internal or external, the short-circuit results in a huge increase in current as the entire potential of the battery is released through the newly formed conductor. This sudden current surge heats the battery massively, making thermal runaway very likely [1].

For short-circuits to happen within the battery, there must either be a manufacturing defect, external abuse, or internal damage through aging. Internal short-circuits happen when the separator between the anode and cathode is damaged, connecting the electrodes directly. This opens a new low-resistance path for the electricity to run through, heating the area locally. The concentrated nature of the heat source puts it at a high risk of reaching the temperature threshold of thermal runaway, resulting in the uncontrollable reactions presented in chapter 3.2 [1], [15].

External short circuits pose a significantly lower risk compared to internal ones due to being easier to detect and protect against. Rapid discharging of the battery causes constant high current, leading to Joule heating, which increases the temperature of the battery. Being outside the cell, fuses and safety cut-off switches can be used to reduce the risk of external short circuits leading to thermal runaway [17].

Both cases of short circuits can create the temperature-induced positive feedback loop typical of thermal runaway. Failure to stop the loop or to isolate the affected cell can lead to catastrophic results as the thermal runaway propagates to other cells, resulting in further damage [17], [19].

3.5 Empirical study methods of thermal runaway causes

One of the commonly used methods for studying thermal runaway is called accelerating rate calorimetry or ARC. It is used to study the battery's thermal behaviour under external heating in a nearly adiabatic environment. Experiments by Galushkin et al. [15] and Feng et al. [10] used ARC to determine the onset temperature of thermal runaway. Their studies also helped to determine more accurately when different stages of thermal runaway were underway. ARC excels in energy balance testing, quantification of energy release, and pinpointing temperature thresholds [14], [15].

Another calorimetric study approach involves the use of copper slug calorimetry. As demonstrated by Liu et al. [19], it can be used to determine the total released energy during a thermal runaway process. These heat values are vital for simpler modelling approaches, as they allow for fairly precise approximations of energy release without intensive calculations and simulations, when the battery's chemical composition is known, as it is the largest factor in combination with state of charge to the amount of released energy [2], [19].

To understand abuse-related reactions, a controlled abuse test is conducted. This can include physical abuse, such as the test conducted by Nie et al. [1] where several different methods of physical such as bending, piercing and compression were tested, to tests overcharging the cells to the point of failure, like the one conducted by Golubkov et al. [2] Abuse tests are vital for the understanding of different risk factors inherently linked with especially the automotive applications of lithium-ion batteries, where collisions and improper charging practices can cause damage to the cells.

4 Thermal runaway modelling

4.1 Modelling aspects

4.1.1 Thermodynamics

Heat generation is the oldest studied aspect of hermal runaway and Li-Ion batteries in general. The entire process relies on the conservation of energy. In cases with negligible fluid motion, the equation for energy conservation is as follows: $\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{gen}$ [20]. Liu et al. [19] presented a model to quantify the thermal energy released during thermal runaway of 18650 cells using copper slug battery calorimetry. This research started to give insight into the exothermic reactions happening during the thermal runaway process. The reactions are typically modelled using Arrhenius kinetics, which are thermally accelerated. As seen from the equation for Arrhenius kinetics for decomposition, $r_i = A_i * \exp[\left(-\frac{E_a}{RT}\right) f(\alpha_i)]$ [16], the acceleration of the reactions is exponential [17]. This is at the very core of the reasons why thermal runaway becomes self-sustaining: the decomposition generates heat, which accelerates the reaction, which creates a feedback loop accelerating the reaction until complete failure is reached [17], [19].

Studies by Liu et al. [19] and Nie et al. [1] suggest a total energy release rate of up to 10 kJ per cell during a thermal runaway process. As the onset of thermal runaway is usually considered as the moment when the heat generation exceeds the heat dissipation capacity, it is clear that heat transfer from the battery is very important to thermal runaway modelling. As the heat transfer is mainly convective, it can be calculated with the following equation: $Q_{conv} = hA\left(T_{cell} - T_{fluid}\right)$ [11]. The heat transfer from the battery to the surrounding medium, as well as the internal temperature gradient of the battery, was studied by Feng et al. [10] and was found to include large differences depending on battery type and reactions taking place within the battery.

4.1.2 Fluid dynamics

Fluid dynamic modelling of thermal runaway consists of two main considerations. Firstly, there is cooling of the battery using either air or a liquid coolant. Focusing on the

thermal management of the battery, this focus on the fluid dynamic side is almost always paired with a thermodynamic model of some sort. [11] From research by Spotnitz & Franklin [17] and Liu et al. [19], it is seen that the key coupling for a fluid dynamic model is convective heat transfer, characterized mainly by the heat transfer coefficient c_p reflecting the temperature difference between the cell and the medium it is in. The models are also simplified or only partly represented. This results in these types of models being better suited for predicting whether the thermal runaway happens or not. All the fluid dynamic models rely on the continuity equation and Navier-Stokes equation to calculate the flow patterns and characteristics [11], [12].

The other part of thermal runaway, where fluid dynamics becomes useful, is the venting of the battery and possibly following jet fire. Following the venting of gases gathered inside the cell, there happens an ignition by either pressure change-induced rise in temperature or sparking from the cell, igniting the escaping gases on fire. [1], [13] The evolution of the jet fire and the jet fire simulation can be seen in Figure 7. It should be noted that the model by Kong et al. [13] also makes some simplifications to reduce computing time, such as treating the flow as incompressible and laminar being vented from a uniform outlet.

Although jet fires are risky, especially in closed environments, they are usually not modelled in detail due to the computational expense. For example, models by Zeng et al. [12] and Zhao et al. [11] make the simplification to reduce jet fires to just an external heat source to insert into the heat generation rate equation, reducing computation time further.

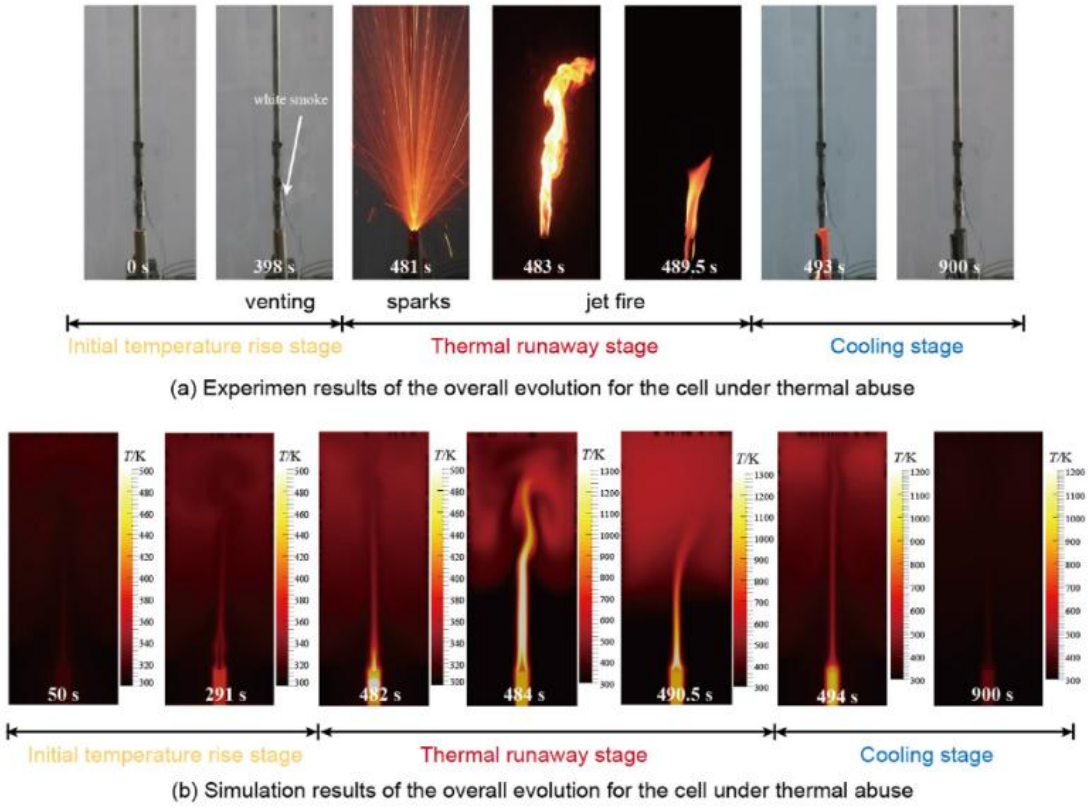

Figure 7: Comparison of the overall evolution for the cell under thermal abuse between experiments (a) and simulation (b) [13]

4.1.3 Electrochemical

Electrochemical models describe the cell's internal charge transportation, reaction kinetics, and electrode degradation. Electrochemical models typically assume homogenous electrodes and idealized kinetics represented with the Butler-Volmer-equation $j = j_0 * \{\exp\left[\frac{\alpha_a zF}{RT}\left(E - E_{eq}\right)\right] - \exp\left[\frac{\alpha_c zF}{RT}\left(E - E_{eq}\right)\right]\}$ [4]. From Butler-Volmer kinematics, the rate of electrochemical reactions, and thus heat generation, can be determined. [10], [17]

In predictive models such as the ones presented by Feng et al. [10] and Nie et al. [1], the loss of electrochemical stability can be observed via a large voltage drop and an increase in internal resistance of the battery. Due to the complexity of modelling and relatively consistent outcome, the electrochemical aspect is not typically taken into

consideration as nothing more than an additional source of heat and pressure within the cell. [4], [17]

4.2 Model frameworks

Combining different modelling aspects into coupled models to increase the accuracy of models without adding too much fidelity is the other key consideration to thermal runaway modelling. On the low end of the fidelity spectrum are simple lumped models with no consideration for flows or heat transfer. [14], [20] These models focus only on the energy of the battery, simplifying it to a single point represented by a mathematical model [20].

Moving up the fidelity spectrum, we find multidimensional models with differing amounts of simplification. These can include any combination of the submodels presented in section 4.2. As shown by Chen et al. [14], the increased complexity doesn't always mean a more accurate model. Even in their rather simple three-dimensional thermal model, the calculation time could be reduced to approximately 1/400th of the processing time of the more complex models with negligible losses in accuracy.

At the very top of the spectrum, we find the complex coupled models, including aspects of all the submodels. It is not practical to try to model the entire complex process of thermal runaway using a single model, as it would take considerable computational resources to achieve meaningful results. However, as demonstrated by models presented by Kong et al. [13] and Gambhire et al. [16], two different models can be used in tandem to calculate different parts of the process and find a sufficiently efficient solution for the accurate modelling of the entire thermal runaway process.

4.3 Boundary conditions and simplifications

Choosing the right boundary conditions and simplifications for the model is one of the most important steps in the process of developing an accurate thermal runaway model. From the simplest lumped models, like the ones presented by Liu et al. [18] and Spotnitz & Franklin [17], the boundary condition that defines the model is the

assumption of an adiabatic reaction $Q_{loss} = 0$. This means that there is no heat transfer between the boundary of the system and the outside medium, i.e., an insulated edge condition defined as $\nabla T \cdot n = 0$.

The main simplifications are: no temperature gradient in any direction, no fluid flow, a very small number, usually one, of reactions within the thermal runaway process. These simplifications are considered valid when considering smaller cell sizes or when doing a rough screening of conditions that could lead to thermal runaway [17].

When 1D and 2D models are considered, the main boundary condition of convective heat loss applies, defined as miinus k nabla iso kirjain T pistetulo n yhtä suuri kuin h sulje auki iso kirjain T miinus iso kirjain T alaindeksi ääretön$\nabla T \cdot n = h(T - T_{\infty})$. In addition, a new boundary condition of symmetry is taken into consideration. Simplification-wise, the thermal runaway is treated as a volumetric heat source, and the material is assumed homogeneous, giving it constant values of k, ρ and c_p [4], [10].

Full fluid dynamic and conjugate heat transfer models are the most tedious and processing power-intensive models, thus there are more boundary conditions and simplifications to consider. The following specific boundary conditions are applied in works by Zhao et al. [11] and Zeng et al. [12] :

- Gas venting $p_{out} = p_{atm}$
- External convection and radiation $-k\nabla T \cdot n = h(T - T_{\infty}) + \epsilon\sigma(T^4 - T_{\infty}^4)$

When also taking into account the flow of coolant or air through the battery pack, it is also necessary to implement the boundary conditions of a no-slip wall, $u_{wall} = 0$, and conjugate heat transfer (solid to fluid) $-k_s \nabla T_s = -k_f \nabla T_f$.

Simplifications for these fluid dynamic heat transfer models consist of the assumption of laminar flow, which is found to be valid for most battery cooling solutions, constant fluid properties, a homogenous battery, and highly simplified gas generation [6], [11]. In general, most models use simplified electrochemical models as the reactions within the battery are not as relevant as the results that they produce. For the most part, it is considered acceptable to utilize empirically attained values for heat and gas generation

to keep the focus of the model in reaction kinematics and heat transfer [4], [12], [14]. Finding the right simplifications is difficult, but it can be made easier by running simulations on a very small part of the system and analysing the data from that simulation to decide what simplifications can be made.

4.4 Lumped models

Lumped models or 0D-models are the most simplified versions of thermal runaway modelling. Treating the battery as a node without spatial variation gives the advantage of modelling the thermal balance of the battery via simple energy balance equations. The reduced- order model presented by Gambhire et al. [16] couples an electrochemical and a thermal model and evaluates it against experiments with several different ambient temperatures and discharge currents. The model shows very promising results with little deviation from experimental values, while also reducing computation time from a comparably accurate model by almost a factor of 10.

This model, like lumped models typically, relies on empirically determined values of heat generation. As the models don't account for internal temperature gradients or local hotspots, they are not the most reliable way to predict thermal runaway [4], [19]. The accuracy of lumped models is also found to be lower under high discharge currents. However, their inherently low demand for computational power makes these lumped models appealing options for battery management systems and other real-time applications [4], [16], [17].

4.5 1D, 2D and 3D-models

Multidimensional models offer accuracy ranging from only a touch higher than lumped models to the very pinnacle of our current understanding of the thermal behaviour of lithium-ion batteries. Taking into account spatial variations and the battery geometry provides the tools for more accurate models while also being solvable with partial differential equations and not necessarily requiring simulations, although especially small-scale first-principle simulations are widely used in multidimensional research to

determine the possible simplifications that enable the usage of reduced order models [13], [14], [21].

1D-models excel at capturing the temperature gradient inside the battery while maintaining very manageable requirements for computing power. This can be utilized well to study and model the radial heat conduction within the battery, as was done by Chen et al. [14]. The largest shortcoming of 1D-models comes from the lack of ability to capture complex geometries and other external effects well, as that usually requires a framework far more complex [2], [14].

Modelling temperature gradients of a plane within the battery can be most efficiently done with 2D-models. While 1D-models can at best include one line on the boundary of the battery, 2D models are able to include the entire boundary layer among the selected axes. This makes it possible to both investigate temperature distribution on the surface of the cell by positioning the axis of interest on the surface, as well as allowing better models of more complex geometries like pouch cells and all types of prismatic cells. While it does require significantly more computational power and better knowledge of the materials and geometries to calculate, it is still very feasible and not overly complex, making it ideal for use cases with demand for medium to high accuracy [8], [10].

At the peak of modelling accuracy are 3D models. They capture the full temperature gradient of the battery or battery pack and can simulate everything from thermal runaway front propagation, jet fires, and gas venting events to the interactions between the cell and the cooling system. The high computational cost and the vast amount of required data of these models and simulations make them unsuited for real-time applications for now, but with the ever-increasing computational capabilities is might be feasible in the near future. [8], [11], [13].

5 Conclusions

Thermal runaway modelling is a highly complex topic with a multitude of different considerations to be made before finding the correct procedure and model for the specific use case. The main findings of this literature review are:

(1) Model demand for processing power and model accuracy are not strictly correlated. Properly determining and implementing boundary conditions and relevant simplifications will increase model accuracy, with the potential for a significantly reduced computational load.

(2) Modelling the entire thermal runaway process is not ideal for the majority of use cases. Small-scale first-principles simulations in tandem with a thorough understanding of the governing equations help direct the models for the most relevant aspects of the process regarding the case at hand.

(3) A thorough understanding of the thermal runaway process relies heavily on the mathematical models regarding the chemical reactions within the battery. Arrhenius kinematics are to be considered the base of all detailed thermal modelling, as it sets the values for both thermodynamic and fluid mechanics models.

(4) As the process is very complicated to thoroughly model, it is advisable to consider some trade-offs between accuracy and efficiency. Usually, the best course of action for any use case outside of research includes both empirical aspects and mathematical modelling.

As for most tools, these models are only as good as the way they are used. To get the best result, it is necessary to evaluate the requirements of the use case before choosing which modelling approach to use. As importantly, once the model is chosen, the effort to set the correct parameters and boundary conditions must be made to ensure accurate results every time. Future studies should continue the development and evaluation of different approaches to find the most computationally efficient models that maintain or improve the high level of accuracy reached by the work done so far.

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