Thermal Analysis of Li-Ion Cells for Safety Simulation

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INTRODUCTION

TUM CREATE is a research programme sponsored by the Singaporean National Research Foundation (NRF). It is jointly performed by Technische Universität München (TUM, Munich) and Nanyang Technological University (NTU, Singapore), aiming at innovative technologies and future transportation concepts, that match the challenging requirements of fast growing and continuously changing tropical megacities. For electric vehicles (EV) energy storage is still a common known problem. In tropical climate conditions one of the most essential issues to consider is the thermal behaviour of the battery cell. High temperatures deplete battery lifetime significantly and are furthermore critical for battery safety [1].

Therefore, besides active cooling systems for the battery pack, the authors' approach is to make the single cells as intelligent as possible by applying different temperature monitoring and simulation techniques.

THERMAL SENSING

For getting broad information on the cell's thermal behaviour two methods are adopted: On-cell and in-cell thermal measurement. In the first step, a matrix of integrated thermal sensors is placed on both sides of a Li-Ion pouch bag cell. (cf. Figure 1 top). By comparing both, data gained from measurements with the thermal sensors and from an infrared camera, a temperature distribution model of the cell's surface is created. Identifying extreme values leads to reduction of the amount of sensors to only one or two in order to make it more applicable for usage in a whole battery pack. Applying the before created model to the sparse data then still provides a detailed image of the whole cell's temperature distribution and enables a suitable thermal on-cell monitoring for an EV's battery a pack.

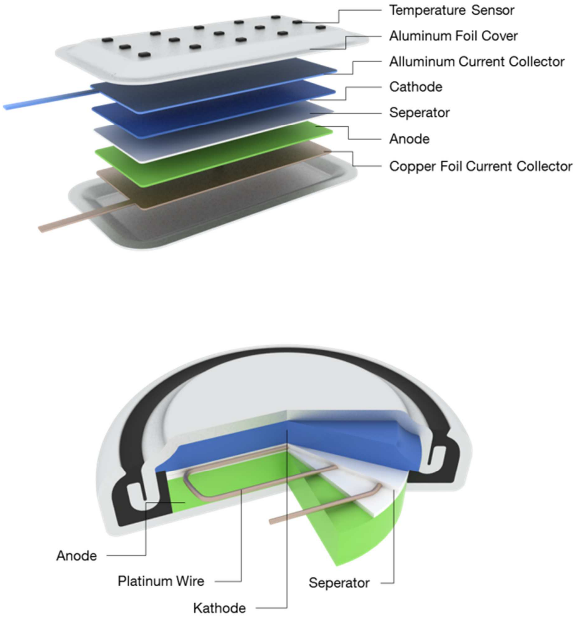

Figure 1. Configuration of a pouch bag cell with surface temperature measurement (top) and coin cell with in-cell thermal measurement using a platinum wire (bottom)

To gain knowledge about in-cell thermal behaviour as well, in the second step thermal measurements are executed in directly in a cell. In-cell and surface data are correlated to a detailed model. For a first evaluation of different sensor types coin cells are employed. Although, coin cells have a different thermal behaviour compared to pouch cells due to their different size, shape and casing material, for first investigations they are quite suitable: no cells need to be opened as they can be self-made fast and easily. Furthermore, the self-production is beneficial for investigation of different chemistries, different sensors and their way of integration.

Another advantage of coin cells for initial investigations is a similar internal design of the cells compared to pouch cells, other than for cylindrical cells: This means a layer-wise construction instead of wraps. Additionally, the existence of only one layer of electrodes helps to identify reciprocal effects between cell and sensors more directly.

One limiting factor compared to on-cell measurement for in-cell measurement is the sensor's size. To reduce the impact on cell's behaviour the thickness should not exceed the layer thickness (see Figure 2).

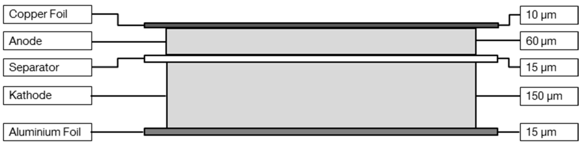

Figure 2. Proportions of the cell layers (cf. [1])

While for on-cell measurement platinum RTD sensors or integrated temperature sensors are a good choice due to their stability, reproducibility and linearity in the required temperature range, their thickness between approximately 200µm and 500µm is very inappropriate. To maintain the good characteristics therefore in the first experiments a platinum wire is used. The available diameters are in the micrometre range. Additionally, the higher redox potential between platinum and lithium (4.25 V) compared to the cell voltage (ca. 3.8 V) avoids electro-chemical side reactions. Compared to a platinum foil a wire has the advantage of covering as small space as possible in the cell and therefore has less impact on the cell's ion flow. Placed between a double layered separator the platinum wire is electrically isolated against the electrodes' active materials (cf. Figure 1).

Once the sensors are placed on the cell's surface as well as in the cell different charging and discharging cycles combined with different climate conditions are applied to the cell and thermal data are collected.

THERMAL SIMULATION

Using both surface and in-cell data helps to create three-dimensional temperature models. These allow battery safety simulation and thus improve the understanding of battery characteristics during abuse operation. Multiphysic models able to describe hazards, such as short circuit, overcharge, overdischarge, thermal abuse, crash or nail penetration need to be developed.

For thermal simulation, electrochemical models, e.g. the one described by [2], are coupled to an energy balance for each arbitrary control volume [3]:

$$\rho c_p \frac{\partial T}{\partial t} = -k\Delta T + S \qquad (1)$$

where ρ [g/cm^3] is the density, c_p [J/(gK)] the heat capacity, T [K] the temperature, t [s] the time and k [W/(cmK)] the thermal conductivity. The energy balance in (1) states the dependency of the temporal change of stored thermal energy $\rho c_p \frac{\partial T}{\partial t}$ on the difference of heat generation S [W/cm^3] and heat conduction $k\Delta T$ (cf. Figure 3). Heat conduction is assumed to dominate internal heat transport in the system [4]. The heat generation term can be estimated based on various losses in the cell:

$$S = S_{joul} + S_{rev} + S_{abuse} + \cdots \qquad (2)$$

The irreversible heat S_{joul} is the deviation from the actual to the equilibrium potential in each control volume and S_{rev} the reversible standard operation heat arising from entropic effects. For Li-Ion cells S_{abuse} sums up the volumetric heat originated from different cell component reactions at increasing temperatures, e.g. the highly exothermic reduction of positive active material with the electrolyte (S_{pe}) [5].

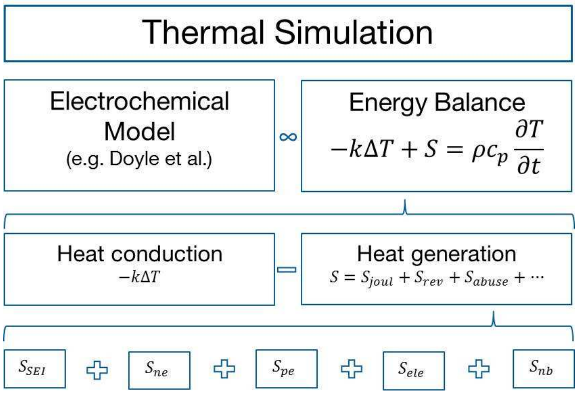

Figure 3. Overview Battery Safety Simulation

Once a standard thermal model of a single cell is established, heat sources describing different safety hazards can easily be added. In a second phase other physical characteristics, e.g. electrical aspects, need to be considered. Under abuse operation the defining thermal model parameters can change. The cell might inflate during thermal runaway, for example. Therefore safety simulation of Li-ion Cells is a highly complex problem. Diverse model solutions and solver shall be compared to and validated with the data gained from thermal sensing.

SUMMARY

The overall target is to minimize safety risks, while reducing time to market and costs of newly developed Li-Ion cells. Additionally, a single cell becomes as intelligent and independent as possible, such that the complexity of battery management systems is reduced and therewith safety for cell transportation will increase. Here feasible numerical simulation of thermal behaviour can be a technical breakthrough. Surface temperature and in-cell measurement data are used to verify simulation results and optimize the battery operation regime for temperature management. A functional thermal management system is essential for use in electric vehicles to provide safe and reliable screening and control.

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