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Fire Spread due to Thermal Runaway in a Lithium-ion Battery Cell

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ABSTRACT

The risk of spreading of fire between Lithium-ion battery cells is assessed using Finite-Element (FE) modelling of the heat transfer initiated by a thermal runaway. The results are contrasted to experimental data where the heat release rate (HRR) is utilized as an input to the simulation. It is found that the temperature increase in a neighbouring cell can be quantitatively estimated during the early stages of the fire taking into account the anisotropic thermal conductivity of the cells.

KEYWORDS: Lithium-ion battery, thermal simulations, fire test

INTRODUCTION

The thermal environment of lithium-ion battery cells is of interest since it is known that a thermal runaway may propagate to neighboring cells causing further spreading, e.g. the thermal runaway in a lithium-ion cell produces a significant amount of thermal energy that easily may cause thermal runaways in neighboring cells. The thermal runaway is caused by exothermic reactions in the lithium-ion cell that will further increase the temperature resulting in a rapid temperature increase that is very difficult to directly control by e.g. cooling. Along with the thermal runaway a number of hazardous events may happen such as rapid gas release, electrolyte leakage, fire and rapid disassembling/explosion [1].

To understand and avoid fire spreading it is of high interest to assess the impact on a neighboring cell of the cell undergoing thermal runaway. In this work simulations are performed as a complement to previous experimental work where temperatures at key locations between and around the battery cells have been monitored. In order to achieve this a simplified geometrical model has been constructed in the Finite-Element software COMSOL with homogenized battery cells in such a way that each cell is considered as one layer of material and simulated for two cases; either isotropic or anisotropic thermal conductivity in the plane and across the layers.

EXPERIMENTAL SET-UP

Fire tests on EiG ePLB-F007A 7 Ah pouch cells have been performed and some of the results in terms of toxic emissions and heat release rates are already published [2]. The tested EiG cell had a lithium-iron phosphate, $LiFePO_4$, cathode and a carbon based anode. Each of the tests consisted of five cells tightly packed together with steel wires, see Figure 1. The cell terminals (tabs) was cut-off prior the tests for all but the middle cell. In the tests the thermal runaway was initiated by a LPG burner of approximately 15 kW placed underneath the packed cells, see Figure 1. During the test temperatures between some of the cells were carefully monitored in two positions, see Figure 2. The five cells were fully charged, 100% state of charge (SOC).

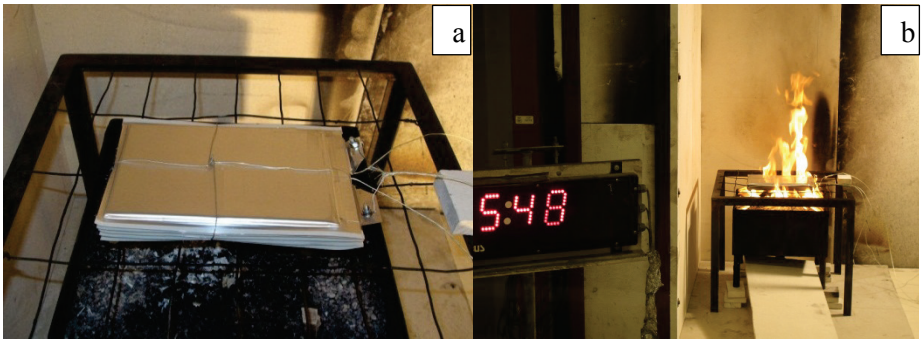

Figure 1 *Photographs before (a) and during test (b).*

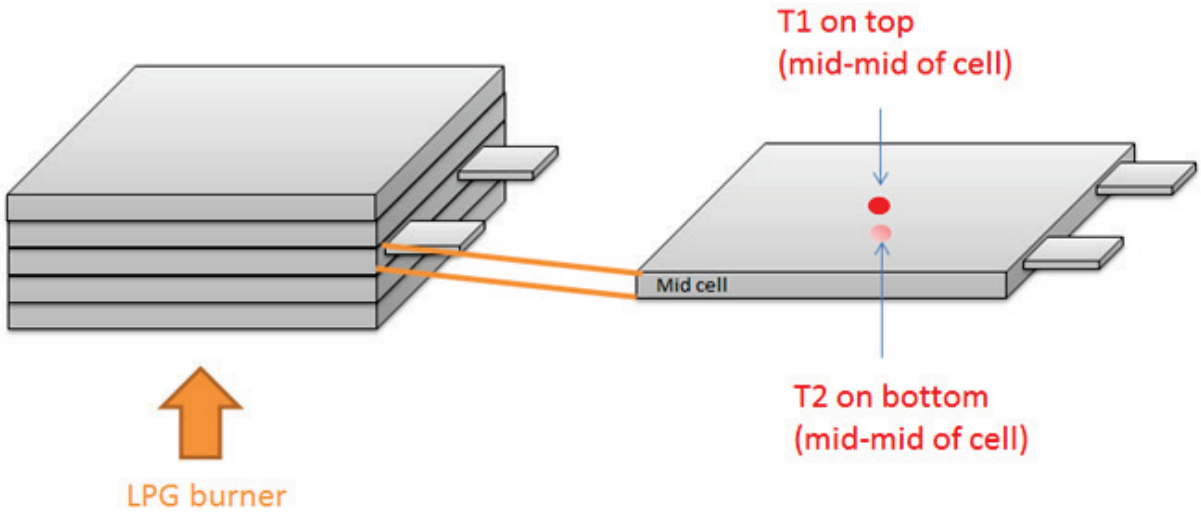

Figure 2 *Schematic illustrations of the test setup showing the placement of two thermocouples, T1 and T2.*

The resulting HRR have been reproduced in Figure 3 for completeness as it is used as an input into the numerical work presented below. In Figure 3-4, the burner is started after 120 seconds. It is interesting to note that in Figure 3 five distinct peaks are visible signifying the thermal runaway of the five different cells in the pack. In the simulations, results obtained from the first peak will be used.

NUMERICAL DETERMINATION OF THE TEMPERATURE FIELD

In addition to using the HRR measurements, the temperatures between the cells in a battery pack of five cells are computed. The EiG cell has a pouch packaging which has a multilayered repeatable structure; negative current collector of copper, anode, separator, cathode, positive current collector of aluminum; where the thermal physical parameters vary significantly in terms of thermal conductivity, density and specific heat along and across the cell. The purpose of the simulation work is to gain better understanding under what conditions a fire is spreading between cells and thus also when there is a risk of cascading thermal runaways. It is assumed that a simple temperature condition is what initiates a thermal runaway where the limit is somewhere above 120 ˚C. To be able to accurately compute the temperatures in the pack shown in Figure 1 at the locations shown in Figure 2, we have constructed a simplified 2D geometrical model similar to that of Figure 2. In the model the battery cells are in the same ambient conditions (T_0=28˚C) as the surrounding in the experiment and are assumed to always be in perfect contact to each other although this may be rather far from the actual situation when a thermal runaway is well underway and the cell pouch is prone to swelling, which also was observed during the experimental tests. However, the steel wires partly inhibited the swelling.

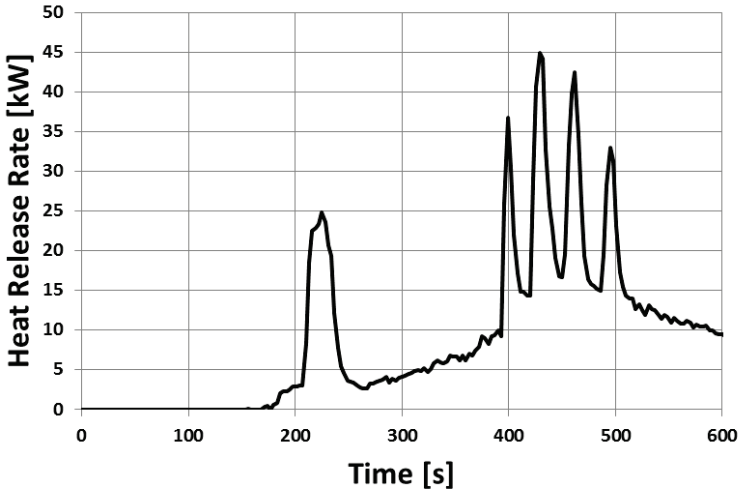

Figure 3 *Heat release rates from fire test of EiG F007 cells where 5 cells are exposed to a LPG burner (the power of the burner has been subtracted from the graph).*

The ambient conditions give the proper boundary conditions for the thermal exchange between the cells and the surroundings by conduction, convection and radiation. The model is built in the multi-physics software COMSOL suitable for studying heat transfer problems. In the model the five cells have been implemented where bulk values of the density, specific heat and thermal conductivity is specified. The COMSOL software solves the heat transport taking into account heat conduction and radiation as well as solving for the Navier-Stokes equations to assess the convection around the cells coming from the fluid movement of air around the cells. The software is Finite-Element (FE) code and we have assumed that the Reynolds number is small such that turbulent fluctuations can be neglected. The model consists of around 10000 elements to have sufficient convergence and accuracy. The model takes about 10 minutes on an ordinary personal computer. In order to have reliable results, good input data are needed and values of the density, specific heat and thermal conductivity were in this case estimated from Spotnitz and Franklin [3] and Wu, Xiao and Huang [4]. Ideally, careful measurements of these quantities at elevated temperatures are needed but difficult to obtain. Here the values of density, ρ=1895 kg/m^3 and specific heat capacity, C_p=700 J/(kgK) have been used throughout the temperature range. The heat conductivity coefficient, k, was varied in the simulations since the structure of the battery cell allows for this value to be highly anisotropic. The first peak in the HRR measurement in Figure 3 is used as a heat source and it is assumed that the thermal energy is deposited homogenously into the bottom cell.

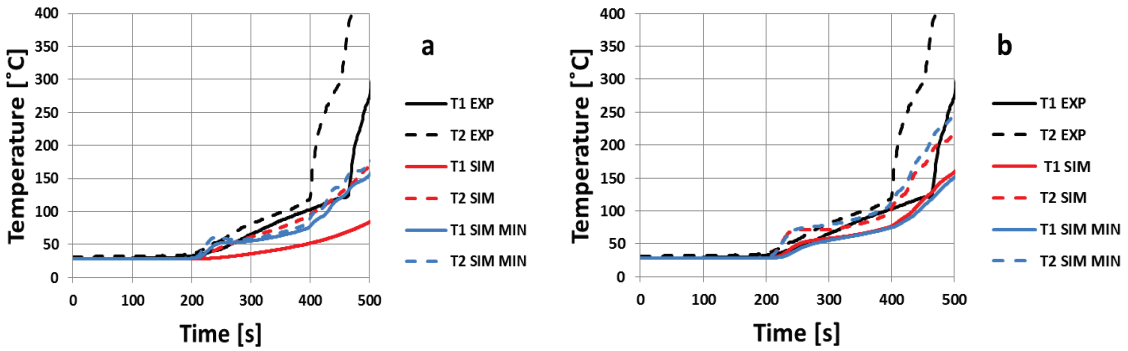

Figure 4 *A comparison of the temperatures found in the experiment and the simulations using an isotropic thermal conductivity (a) and anisotropic thermal conductivity (b).*

The simulation results are shown in Figure 4. In Figure 4a, the thermal conductivity k = 6 W/(m K) is used for T1 SIM and T2 SIM and conductivity k = 3 W/(m K) is used for T1 SIM MIN and T2 SIM MIN. In Figure 4b, the thermal conductivity k_x = 27 W/(m K) and k_z = 0.8 W/(m K) is used for T1

SIM and T2 SIM and conductivity k = 13 W/(m K) and k_z = 0.4 W/(m K) is used for T1 SIM MIN and T2 SIM MIN. A simple sensitivity study was made varying the thermal conductivity by ±50% in both the isotropic and the anisotropic cases. The results from the lower values are showed in Figure 4, however the results from the higher thermal conductivity have been omitted since they generally gave much lower values of the temperatures at the given points. It can be noted that the temperature T2 in the early stages (up to 400 s) of the fire development can be predicted to some extent by the simulation using anisotropic thermal conductivity. However, to be able to predict for longer times a temperature dependent thermal conductivity seems to be needed. Nevertheless, using the temperature condition for thermal runaway the model predicts a further thermal runaway in the adjacent cells which is corroborated in the test. Furthermore, the thermal energy released by the LPG burner is not taken into account into the thermal transfer calculations although it would yield elevated values of the temperatures in the simulation. The LPG burner was omitted in the model since it was found that the model then was prone to instabilities.

DISCUSSION AND CONCLUSIONS

The aim of the present work is to be able to quantify the conditions of battery cells neighbouring to a cell undergoing thermal runaway. The temperatures inside the closest cells determine when and if a cascade process of thermal runaways may happen. There is naturally a great interest to be able to predict and mitigate effects of single cells experiencing such an adverse event. The temperatures inside the neighbouring cell are predicted by a Finite-Element model constructed in the COMSOL software. The software solves for the Navier-Stokes fluid properties and the heat transfer within the cells. Obtaining adequate data of the battery cells is crucial for the computational model since precise measurements of these data are not available; data from the literature is used in combination with sensitivity studies of the thermal conductivity. In the first model a homogenized battery cell with isotropic thermal properties is used. However, the layout of the cell indicates that the thermal properties are indeed highly anisotropic and it is showed that this anisotropicity in the thermal conductivity is of importance. The results from the test and the simulations follow each other relatively well up to around 400 s and then the results diverge. There are several possible reasons for this discrepancy among them is that the mechanical changes, i.e. swelling of the pouch, changing the area of direct contact to the neighbouring of the cell pouches is not taken into account. Other factors such as the changes to the material compounds during thermal runaway in the cell is not considered, this changes the thermal properties of the battery cells. The thermal conductivity of the battery cell materials is most likely temperature dependent, a feature which is neglected due to the lack of knowledge of precise measured data of this quantity. To this end, the conclusion is that using rather simplified methods with accurate material data input, a cascade process of thermal runaways is possible to predict under the current situation.

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