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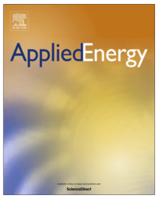

Numerical analysis of heat propagation in a battery pack using a novel technology for triggering thermal runaway

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HIGHLIGHTS

- Heat propagation during thermal runaway (TR) in a battery pack with aluminum heat sink was analyzed.
- TR in the battery pack, triggered by a novel internal short circuit device (ISCD) was modeled.
- A 2D geometry and model couplings reduce computation time significantly.
- Small air gaps and mica paper in combination with a thermally conductive matrix increase safety in battery packs.

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ABSTRACT

This paper presents a numerical model used for analyzing heat propagation as a safety feature in a custom-made battery pack. The pack uses a novel technology consisting of an internal short circuit device implanted in a cell to trigger thermal runaway. The goal of the study is to investigate the importance of wrapping cylindrical battery cells (18650 type) in a thermally and electrically insulating mica sleeve, to fix the cells in a thermally conductive aluminum heat sink. By modeling the full-scale pack using a 2D model and coupling the thermal model with an electrochemical model, good agreement with a 3D model and experimental data was found (less than 6%). The 2D modeling approach also reduces the computation time considerably (from 11 h to 25 min) compared to using a 3D model. The results showed that the air trapped between the cell and the boreholes of the heat sink provides a good insulation which reduces the temperature of the adjacent cells during thermal runaway. At the same time, a highly conductive matrix dissipates the heat throughout its thermal mass, reducing the temperature even further. It was found that for designing a safe battery pack which mitigates thermal runaway propagation, a combination of small insulating layers wrapped around the cells, and a conductive heat sink is beneficial.

1. Introduction

Li-ion battery cells are very popular battery types which can be found in nearly every application that requires energy storage [1,2]. Despite its superior properties when compared with other types of storage devices, Li-ion batteries are still susceptible to fires and explosions caused by thermal runaway [3]. The risk increases if the cells operate in high energy battery packs, where thermal runaway can propagate from one cell to another, leading to a chain reaction, popularly known as thermal runaway cascading. For this reason, it is important to investigate the safety elements and identify the key parameters that play a significant role to the temperature dynamics inside a battery pack. The design features and configurations of the battery modules depend on the application and the required gravimetric energy density; therefore studies on different designs were performed by various authors and companies.

In Ref. [4], the authors analyzed the thermal runaway propagation in rectangular cells and found that the propagation can be prevented by reducing the energy released during a short circuit. In addition to this, the risk of cascading can be decreased by improving the heat dissipation through the surfaces, and by adding an extra resistant layer between rectangular cells. In a similar numerical analysis on square pouch cells, Larsson et al. [5], found that a

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Nomenclature

Symbol	
$\dot{Q}_a$	heat rate released due to anode decomposition, W m^{-3}
$\dot{Q}_c$	heat rate released due to cathode decomposition, W m^{-3}
$\dot{Q}_{ec}$	heat rate released due to electrochemical reactions, W m^{-3}
$\dot{Q}_s$	heat rate released due to SEI decomposition, W m^{-3}
A_a	frequency factor for anode decomposition, s^{-1}
A_c	frequency factor for cathode decomposition, s^{-1}
A_{ec}	frequency factor for electrochemical reactions, s^{-1}
A_s	frequency factor for SEI decomposition, s^{-1}
C	capacity of the battery, Ah
Cp_{can}	specific heat of the steel can, J kg^{-1} K^{-1}
Cp_{mica}	specific heat of the mica paper, J kg^{-1} K^{-1}
Cp_{AL6061}	specific heat of the aluminum heat sink, J kg^{-1} K^{-1}
Cp_{jr}	specific heat of the jelly roll. J kg^{-1} K^{-1}
E_a	activation energy for anode decomposition, J
E_c	activation energy for cathode decomposition, J
E_{ec}	activation energy for the short-circuit, J
E_s	activation energy for SEI decomposition, J
h_a	enthalpy of anode decomposition reaction, J kg^{-1}
H_{cell}	height of the cell, m
h_c	enthalpy of cathode decomposition reaction, J kg^{-1}
h_{conv}	heat transfer coefficient, W m^{-2} K^{-1}
h_{ec}	heat released by the short-circuit, J
h_s	enthalpy of SEI decomposition reaction, J kg^{-1}
ISCD	internal short circuit device
k	conductivity of the domain, W m^{-1} K^{-1}
k_b	Boltzmann constant, J K^{-1}
k_{can}	thermal conductivity of the steel can, W m^{-1} K^{-1}
k_{mica}	thermal conductivity of the mica paper, W m^{-1} K^{-1}
K_{AL6061}	thermal conductivity of the aluminum heat sink, W m^{-1} K^{-1}
k_{jr}	thermal conductivity of the jelly roll, W m^{-1} K^{-1}
m_a	mass of anode, kg
m_c	mass of cathode, kg
$\boldsymbol{n}$	unit vector, -
T	temperature, °C
T_{amb}	ambient temperature, °C
T_{init}	initial temperature, °C
T_{ISCD}	melting temperature of the ISCD, °C
V	nominal voltage of the cell, V
V_{cell}	volume of the cell, m^3
x_a	fraction of Li in anode, –
x_s	fraction of Li in the SEI, –
z	dimensionless measure of the SEI thickness, –
α_c	degree of conversion of cathode, –
η	efficiency factor, –
ρ_{AL6061}	density of the aluminum heat sink, kg m^{-3}
ρ_{can}	density of the steel can, kg m^{-3}
ρ_{jr}	density of the jelly roll, kg m^{-3}
ρ_{mica}	density of the mica paper, kg m^{-3}
σ	Stefan-Boltzman constant, W m^{-2} K^{-4}

Index	
0	index representing initial condition
Calc.	calculated
can	index representing the steel can domain
EXP	experimental
ISC	internal short-circuit
jr	index representing the jelly roll domain
Meas.	measured
SEI	solid-electrolyte interface
SIM	simulation
SoC	state of charge

highly conductive firewall protects the cell better than an insulation layer between pouch cells in a pack. The authors also analyze the effect of the thickness of the firewall, indicating that a thicker conductive layer reduces the peak temperature significantly. However, the thickness increases from 5 mm to 20 mm, which add up to the total mass of the pack, reducing the energy density of the entire assembly. In an experimental analysis, Lopez et al. [6] found that by having an insulating air gap between 18650 cylindrical cells would decrease the damage caused by thermal runaway. The authors also recommend a minimum spacing of 2 mm between the cells for minimizing the chance of thermal runaway cascading. However, in such a configuration, there is the risk of sidewall ruptures and ejection of hot electrolyte and ejecta, which can propagate from cell to cell without a solid heat sink in between. Such an event was found in a similar design in Ref. [7], where the author weakened the walls of the cell to show that a manufacturer defect can lead to ejecta breaching. In the same paper, the author lists five driving factors for reducing the hazard severity when designing safe battery packs.

The above design configurations raise the question whether insulation is better than conduction, which represents an additional key guideline for battery pack design, rising the need for an investigation tool. The particular design analyzed in this paper consists of a combination of a conductive, lightweight Aluminum heat sink and electrical/thermal insulating thin layers between the cells and the heat sink. In addition to this, the cells are arranged in a hexagonal array with each cell being surrounded by at least three others. Such a pack arrangement is a novel design for improving safety in the event of a thermal runaway. The numerical model will be a tool for analyzing and optimizing the design.

In the articles presented previously [4–7], the studies were performed on parallel/linear array configurations. In Ref. [8], the authors built packs consisting of both an array of pouch cells and a triangular arrangement of cylindrical cells (18650 type). They found that due to the cylindrical geometry of the cells, the air gap between the cells and the thermal resistance protects the cells. This observation is in contrast to the findings for a rectangular pack with cells in direct contact with each other, which shows that having an insulation layer can protect the cell thermally, as also found in Ref. [6]. The authors also recommend that the cells should not be in direct contact, which means that a heat sink would be a potential alternative, as in the design analyzed in this paper. Various designs for this have been developed over the years for removing the heat from abused cells and for mitigating thermal runaway. Some designs include heat pipes [9], cooling plates [10], mini-channels [11], forced air-flow [12] etc. The main disadvantage of active thermal management is that it contains moving parts which add up to the complexity of the pack and reduce the gravimetric energy density of the pack. In addition, passive cooling, using heat sinks and phase change materials (PCM) was found to be adequate in reducing the risk of thermal runaway propagation and wall ruptures [13,14].

In a recent study, Wilke et al. [13] showed that by using a PCM composite between a matrix of 40 cells, the temperatures were