TOWARD FIRE DYNAMICS SIMULATIONS OF THERMAL RUNAWAY PROPAGATION IN BATTERY ENERGY STORAGE SYSTEMS

DANYAL MOHADDES[1], YI WANG[2],
[1]*FM, Research Division, danyal.mohaddes@fm.com*
[2]*FM, Research Division, yi.wang@fm.com*

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Introduction

Battery Energy Storage Systems (BESS) are a prevalent and growing means of stabilizing power grids with high penetration of intermittent renewable energy sources [1]. BESS typically rely on lithium-ion batteries (LIBs) as their basic building block. LIBs are packed together in an enclosure to form a module. Multiple modules are assembled into a rack, and these racks are housed within a container to form one of many units in a BESS. LIBs pose a safety hazard if abused thermally, mechanically or electrically due to a failure mechanism known as thermal runaway (TR) [2]. TR is a localized breakdown of the LIB internal structure, causing exothermic chemical reactions that lead to a propagating reacting front within the LIB. It further results in the production of large quantities of flammable gas, which increase the LIB's internal pressure and lead to its rupture, releasing the flammable gas.This rapid self-heating thermally abuses neighboring LIBs within a module, driving them into TR, initiating a cell-to-cell cascade known as TR propagation (TRP). Since the LIBs are enclosed within a module, the large volume of vented gas produced by TRP is driven out of vents and openings on the module body [3], whereupon it mixes with ambient air and poses a fire and explosion hazard. Fire dynamics thus come into play at the module scale, due to the potential for flame heating of the module exterior by a vented gas-fueled fire. To this end, the present study will discuss recent model developments and their implementation in an OpenFOAM solver at the module scale, toward building a predictive capability for analyzing and predicting rack and unit-scale TRP events and associated fire dynamics.

Methodology

The developments we consider in this work utilize FireFOAM, an LES solver in the OpenFOAM family developed originally at FM [4] for simulation of fire dynamics and fire suppression. FireFOAM is capable of simulating complex fire scenarios, handling the coupled physics arising from gaseous flows and combustion, water sprays, films, radiation and solid-phase pyrolysis. FM maintains a branch of FireFOAM with specific capabilities for handling practical fire scenarios [5].

In this work, we implemented TRP as a region model derived from the base pyrolysis model within FireFOAM. In particular, our implementation targets recent module-scale [3] and rack-scale [6] TRP fire dynamics experiments conducted at FM using large pouch-format Li-NMC532 (nickel-manganese-cobalt oxide)-graphite cells. The mathematical formulation of the TRP model is based on our earlier work [7] and is only described at a high level here. The thermo-chemical behavior of each LIB is described by one-dimensional reaction-diffusion equations for mass, energy and species to consider multi-species reactions and mass loss due to venting. A one-dimensional treatment is reasonable due to the high in-plane thermal conductivity of pouch-format LIBs, and thermal and kinetic parameters are obtained via parameter optimization against single-cell experiments [7]. To analyze TRP, we apply an inter-cell thermal resistance as a boundary condition between LIBs, the value for which we infer from the module-scale experimental data [3], and assemble a stack of LIBs as a single object representing a module within the region model. We include treatments for the coupled boundary condition such that vented gas exits the module at physically realistic locations based on the module geometry. The experiments use a torch to ensure the vented gas burns to permit studying of the fire dynamics, and thus we likewise assume that all vented gas burns in the ambient air.

Results

Here we show a sample of the results to be presented at the Workshop. The geometry considered is based on two-module TRP tests conducted at FM [3] with twelve LIBs per module. Each module is a rectangular prism with dimensions

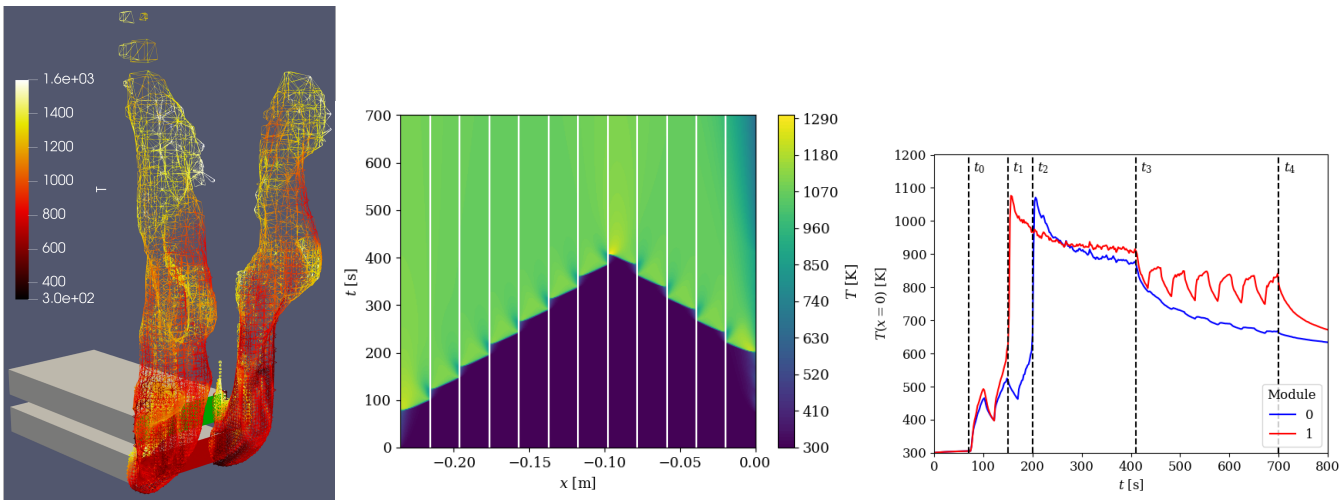

Figure 1: Left: Snapshot at a time $t_2 < t < t_3$, showing the stoichiometric isosurface; Center: Space-time evolution of temperature in Module 0, with white lines showing boundaries between LIBs; Right: Coupled boundary temperature over time.

$0.85\,\text{m} \times 0.45\,\text{m} \times 0.11\,\text{m}$. The lower module, denoted Module 0, is located $1.1\,\text{m}$ above the ground, and Module 1 is located $0.055\,\text{m}$ above Module 0.

The simulation begins by heating the non-coupled boundary of Module 0 to TR, which induces TRP at $t = t_0$, where times are marked by vertical lines in the right subfigure. The left subfigure shows an instantaneous snapshot from the simulation, showing that the vented gas burns in two turbulent, buoyant plumes due to the presence of vent holes on either side of each module. The fire imposes a heat flux on the coupled boundary of both modules, increasing their temperature, as shown in the right subfigure. This initiates a second TRP front in Module 0 at t_1 and a third in Module 1 at t_2. The bi-directional progression of TRP in Module 0 is shown in the center subfigure. TRP completes in Module 0 and Module 1 at t_3 and t_4, respectively. The fire is thus largest for $t_2 < t < t_3$, when there are three TRP fronts propagating simultaneously; the snapshot shown in the left subfigure corresponds to this time period. These results are phenomenologically in agreement with the experimental results [3], and further analysis of the simulation results, along with comparisons to experimental data, will be provided during the Workshop presentation.

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