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An Open Source Design Exploration Tool for Battery and Coolant Configuration

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***Abstract*—Ensuring both electrical performance and effective thermal management in large-scale battery packs is a critical challenge for next-generation electric mobility and energy storage systems. Current modeling approaches often rely on rigid configurations or computationally expensive CFD simulations, limiting their use in early design stages. This work introduces a modular, compositional framework that enables the dynamic construction of battery packs of arbitrary size, where each cell is modeled individually with coupled electrical and thermal dynamics. The framework integrates a configurable liquid cooling system supporting multiple layouts and coolant types, allowing rapid evaluation of thermal management strategies under diverse operating conditions. By combining scalability, flexibility, and high computational efficiency, the proposed approach accelerates design iterations, reduces prototyping costs, and supports the development of safer and more reliable battery systems for real-world applications.**

***Index Terms*—thermal simulation, design space exploration, battery configuration, coolant, open source tool, SystemC AMS**

I. INTRODUCTION

Among the critical challenges in battery pack design, thermal management plays a crucial role in ensuring operational safety, extending battery lifetime, and maintaining performance under varying load conditions [1]. Inadequate heat dissipation can lead to uneven temperature distribution, accelerated aging, and, in extreme cases, thermal runaway events, thus making accurate thermal modeling and design exploration an essential step in the design process [2].

Current modeling approaches require sacrificing either accuracy or computational efficiency, and this trade-off limits the ability of engineers to explore multiple design alternatives quickly [3]. An additional challenge lies in the design of the cooling system itself, as its configuration significantly impacts both thermal safety and overall energy efficiency [4]. A preliminary and accurate evaluation of different cooling strategies is therefore essential to achieve an optimal balance between thermal stability and energy efficiency.

In this work, we address these challenges by providing an *automatic tool for thermal-aware battery design space exploration*. The goal is to support the design of new battery packs for demanding applications such as automotive and heavy-duty mobility, where thermal management is a key enabler for performance and safety. Moreover, predicting simultaneously thermal and electrical behavior under various operating conditions is crucial for ensuring reliability and optimizing system integration.

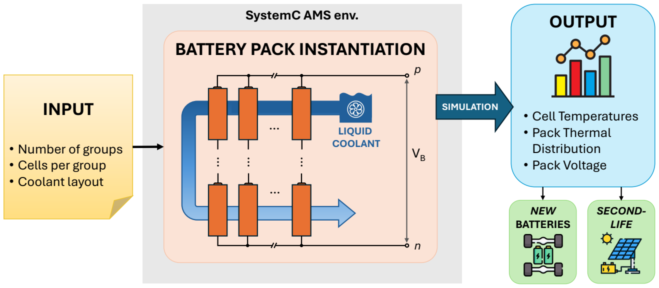

Fig. 1: Overview of the compositional battery-pack framework.

II. PROPOSED THERMAL MODEL

A. *Cell and coolant modeling*

The single electric cell is modeled using an equivalent circuit that mimics its behavior [5], [6]. The coolant loop is modeled using a compact, network-based methodology inspired by [7]. We adopt the same principles of multi-port cavities/channels, represented by reduced-order elements and a coupled solid–fluid RC formulation, to emulate embedded channels in battery packs. By following the equivalence between the thermal and electrical domains, the coolant itself is modeled through an equivalent circuit that mimics the heat exchanges. The circuit configuration depends on the cooling topology, that is chosen at design time. Typical topologies are the “S” topology (serpentine channels between rows of cells) and the “C” topology (cooling jackets of surrounding the battery module).

B. *Automatic model generation*

An automatic tool implements a fully automated pipeline that constructs the power plus electrical model in SystemC AMS from a compact design specification. The user provides crucial data for the simulation. Fig. 2.a shows an example, configured to simulate 12 Panasonic-NCR18650 cells organized in 4 groups of 3 cells each, and an “S” shaped cooling topology. The resulting topology is shown on the right-hand side, where “bm” represents cells, and “cn” represents coolant (m = cell number; n = coolant segment). The electrical connection of cells reflects the numerical order, while the table-like notation is used to specify space proximity (necessary to model heat exchange).

The tool derives the power model of a cell starting from user inputs and from a current-voltage plot provided in the

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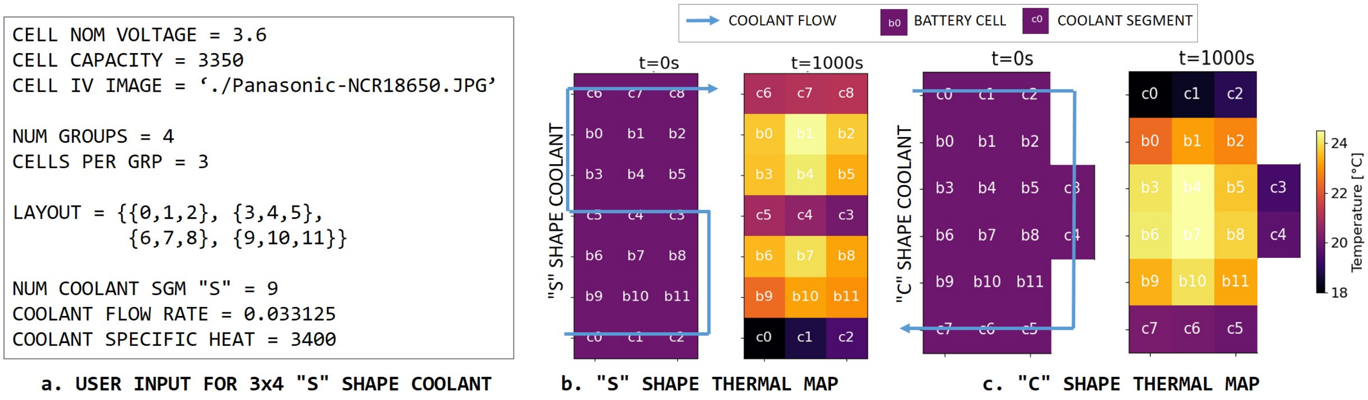

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CELL NOM VOLTAGE = 3.6
CELL CAPACITY = 3350
CELL IV IMAGE = './Panasonic-NCR18650.JPG'

NUM GROUPS = 4
CELLS PER GRP = 3

LAYOUT = {{0,1,2}, {3,4,5},
          {6,7,8}, {9,10,11}}

NUM COOLANT SGM "S" = 9
COOLANT FLOW RATE = 0.033125
COOLANT SPECIFIC HEAT = 3400
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a. USER INPUT FOR 3x4 "S" SHAPE COOLANT **b. "S" SHAPE THERMAL MAP** **c. "C" SHAPE THERMAL MAP**

Fig. 2: Application to a 4×3 configuration: user input (a), topology and thermal map with "S" shape (b) and "C" shape coolant.

TABLE I: Simulation results.

Pack configuration	Simulated time (s)	Discharge current (A)	Coolant shape	Simulation time (s)	SystemC AMS primitives	Avg. cell temperature (°C)
3×4 (12 cells)	730	32	S C	1.078 1.243	279 274	26.5 27.1
8×5 (40 cells)	1,220	48	S C	7.069 6.344	891 846	25.1 27.2
74×6 (444 cells)	1,740	500	S C	116.866 78.107	9,722 8,827	21.9 24.2

datasheet, by re-implementing the methodology in [8]. The tool then generates the electrical connection (following the series-of-parallel (SOP) paradigm) and thermal connection (reflecting space proximity). The coolant is then generated from user input and connected to the corresponding battery cells nodes, which concludes the last step of the battery pack model creation.

C. SystemC AMS implementation

The SystemC AMS implementation is realized by mapping each circuit element to the corresponding ELN primitive and wrapping it with TDF interfaces for efficiency, as proposed in other works for energy system simulation [9]–[11].

III. EXPERIMENTAL RESULTS

For the experimental application, we use the Panasonic NCR18650B cell [12]. Experiments were conducted with a fixed time step of 0.5 seconds to standardize the measurement, and the simulations were performed on an Ubuntu 24 VM (3 cores at 3 GHz, 8 GB RAM).

Table I reports the simulation results for three different sizes and for both the "S" shape and the "C" shape coolant as part of a design space exploration. Fig. 2.b-c provide a pictorial representation of the simulation output, by showing the topology and the thermal map after 1,000s of simulated time of a 4×3 configuration with "S" shape coolant (Fig. 2.b, reflecting the user specification in Fig. 2.a.) and "C" shape coolant (to show a design exploration). While using the "C" shape configuration, cells closest to the coolant maintain a lower temperature, while cells in the center and on the left are hotter. With the "S" shape configuration instead, cells tend to have an overall lower temperature due to the coolant path that separates cell groups (average cell temperature after 730s of simulated time is 0.6°C lower). This allows to intuitively see that the "S" shape coolant is more effective in cooling the cells and preserving their operation, despite the higher technical complexity implied by increased pumping power and potentially more robust manifolds.

Table I shows that the number of instantiated SystemC AMS primitives varies with the size of the simulated configuration and with the coolant configuration, as a different number of SystemC AMS primitives are requested[1]. Intuitively, simulation time is proportional to the simulated time and the number of primitives, and the initial instantiation cost for creating and connecting a battery pack does not significantly impact it. Additionally, the simulation time is significantly lower than the simulated time in all configurations. A 30-minute-long configuration can be easily evaluated with less than 10 seconds per configuration, thereby highlighting the effectiveness of the proposed tool for design space exploration.

IV. CONCLUSIONS

This work showed that different refrigerant solutions can significantly alter the operation of a battery pack, and that the proposed automatic tool may aid in the design phase by facilitating "what if" analysis and exploration of alternative configurations. Future works will include the implementation of other architectures, such as parallel-of-series, and the support of aging and fault simulation.

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[1] Each battery cell requires the instantiation of 2 capacitors, 2 resistors, 2 current sources and 1 voltage source; each coolant segment requires 1 current source, 1 capacitor and 2 resistors, plus one voltage source.

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