Extended Abstract

Modelling and Control for Hybrid Cooling of Lithium-ion Batteries

Lithium-ion batteries are essential for clean energy storage, but their performance, safety, and lifespan depend on effective thermal management. If a battery gets too hot, it can degrade faster or, in extreme cases, enter thermal runaway. On the other hand, cooling methods must be efficient and well-balanced, not just in reducing overall temperature but also in ensuring an even temperature distribution across the battery.

Current battery cooling methods typically focus on either cooling the surface of the battery or cooling the tabs (electrical terminals). Each method has its strengths—tab cooling provides more uniform temperature distribution due to higher thermal conductivity, while surface cooling removes heat more efficiently due to a larger contact area. However, most cooling strategies use one or the other, missing out on the potential benefits of combining both. This study proposes a novel thermal model and control strategy that optimally integrates tab and surface cooling, ensuring better thermal performance than conventional methods.

A control-oriented battery thermal model

To make this integration possible, a library of control-oriented reduced-order thermal models, characterised by different number of states, is developed using the Spectral-Galerkin method with Chebyshev polynomials. This mathematical technique allows a complex, physics-based 2D thermal model to be simplified into a system of ordinary differential equations, making it computationally efficient. A key innovation in the proposed model is the decomposition of the temperature solution into individual cell-side components, allowing precise control over how much cooling is applied to a particular side or region of the battery. In addition, the modelling framework applies to various battery geometries, i.e., cylindrical, pouch and prismatic.

Validated on a large-format cylindrical battery cell against a high-fidelity finite element model and benchmarked against a widely used two-state thermal equivalent circuit (TEC) model under real-world driving and cooling scenarios, results show that the proposed model with four states accurately captures the two-dimensional thermal dynamics, while the one-state model significantly outperforms the widely used two-state TEC model in both accuracy and computational efficiency, achieving a 29% reduction in computation time. The TEC model fails to capture critical thermal gradients and significantly underestimates battery temperatures under highly dynamic operating conditions, making it unreliable for battery safety management.

Finding the best cooling strategy

The developed model can be effectively applied to various model-based applications. These include rapid analysis of different cooling scenarios, real-time closed-loop temperature control, and thermal optimisation of cell design. To understand how different cooling strategies perform, we analyse various cooling scenarios, including surface-only cooling (SC), bottom-tab cooling (bTC), bottom-tab + surface cooling (bTSC), bottom- and top-tab cooling (btTC), and all-tab + surface cooling (aTSC). Each of these methods is assessed based on how well it lowers the average temperature and temperature gradients across the battery cell. One key takeaway is that no single cooling method is perfect—each one comes with trade-offs. These performance trade-offs necessitate the selection of a scenario to satisfy application-specific requirements. In this regard, an interesting question is: Which cooling scenario produces the lowest thermal gradient while maintaining a fixed average temperature? To answer this question and demonstrate the application of our developed battery thermal model, we implement a simple feedback control strategy based on multiple proportional-integral (PI) controllers. The results show that btTC provides the most uniform temperature distribution, effectively reducing hot spots in the battery.

Does battery shape matter?
The dimensions of a battery cell are crucial in determining its thermal properties. Therefore, it is necessary to understand the impact of geometric parameters for optimised cell design. A dimension perturbation analysis was carried out to examine the impact of the length-to-radius ratio on the cooling efficiency of cylindrical batteries. Findings show that shorter, bulkier battery cells offer better heat dissipation than taller, slimmer designs. Among commercially available cylindrical cells, the Tesla 4680 performs best, while the 18650 format is less thermally efficient. This suggests that current battery form factors may not be fully optimised for heat management.

A smarter approach: Model predictive cooling control
To optimise battery cooling, this study formulates the integration of tab and surface cooling as an optimal control problem and solves it within the model predictive control (MPC) framework. This strategy enables real-time, dynamic adjustments of cooling power based on battery temperature changes, ensuring that cooling is applied only where and when it's needed. The proposed MPC strategy is evaluated against conventional side-only and base-only cooling under a real-world driving condition. Results show that the proposed MPC can effectively minimise both the average temperature rise and thermal gradients within the cell and demonstrates superior thermal performance compared to the conventional cooling methods.

Why this matters
This study proposes a more accurate, computationally efficient, and flexible thermal model that can replace conventional TEC models in battery management systems. The ability to independently regulate cooling at different battery surfaces allows for more precise and targeted cooling, leading to improved battery safety, longer lifespan, and better overall performance. The findings also emphasise that battery cell geometry plays a critical role in heat dissipation, highlighting the need for optimised geometries in future battery designs.

The MPC-based cooling strategy represents a major leap forward in thermal management, offering real-time, intelligent control of coolant distribution that outperforms traditional cooling methods. By maintaining lower and more uniform temperatures, this strategy reduces battery degradation, prevents overheating risks, and enhances efficiency, making batteries safer and more durable for long-term use.