Fine Tuning Thermal Controls Software for Electric Propulsion

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Thermal Controls: Introduction

Enable peak performance, low-energy modes, safety functions, health monitoring

Passenger Comfort	Propulsion System		Power Electronics
Cabin Cooling/Heating	Battery Thermal	Motor/Inverter	Charging + Compute

Cooling, Heating, Humidity Control, Auto Temp. Control

Heating, Cooling, Thermal Runway Monitoring and Prevention, Health Monitoring

Compute Nodes Cooling, OBC and Other Electronic Thermal Management

TMS Overview

Quite a bit of variety in TMS available in literature and between different products/applications!

- Passive with Fins
- Active(Fan) with Fins
- Ducted Channels

- Direct Cooling – Single/Two Phase Immersion
- Indirect Cooling – Bottom Cooling/Cold Plate
- Indirect Liquid Cooling – Side Channels
- Indirect Cooling – Cold Plate – Two Phase

- PCM Direct Contact
- PCM + Air and/or Heat Pipe
- PCM + Liquid Cooling: Hybrid

The Cell Factor!

Typical cylindrical formats and their properties are shown below

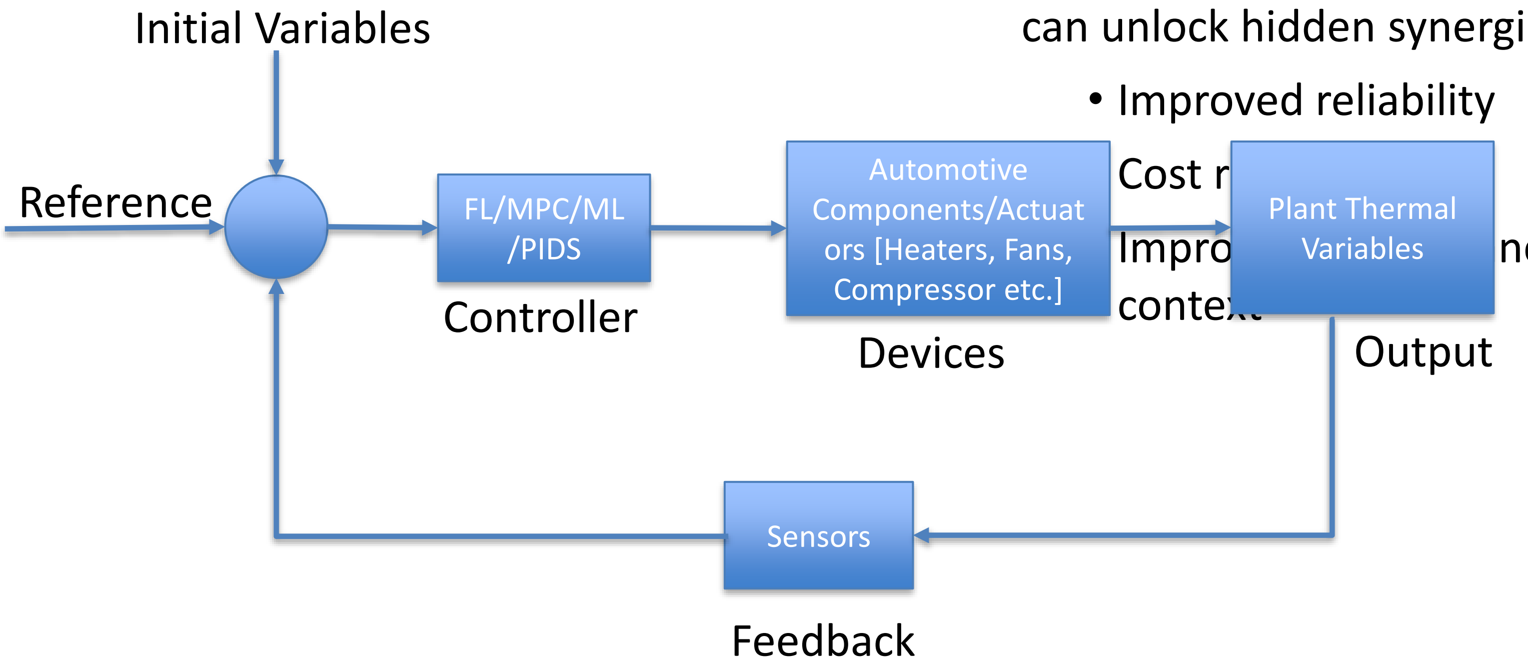
Property	NCM	NCA	LFP	LMFP
Max Continuous Charge Rate	3C	3C-5C	2C-4C* [Claimed by at least two major suppliers in 2026]	3C [2025]
Impedance [mΩ]	2.5 (4695), 11-25 (2170)	12-25 (2170), <5 (4680)	4 (4695), 7 (33140),	2.5-5
Typical Anode	Gr/Si	Gr/Si	Gr/Si	Gr/Si
Capacity [Ah]	4 - 36	3.1 – 6	3 - 23	30
Cylindrical Formats	1865, 2170, 4680, 4695	1865, 2170	4695, 46120, 33140, 3270, 2665	4695
Safety	$$	$$	$$$	$$$

- Higher charge rate may require faster heat dissipation and may require non-traditional TMS or Controls to enable higher reliability and safety

Thermal Controls Loop: A Simple Example

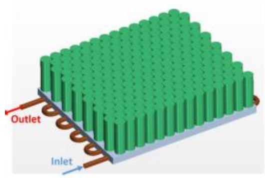
Simple controls loop with feedback

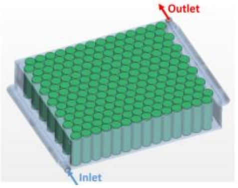
- Control scheme closely matching physical behavior can unlock hidden synergies in the system
  - Improved reliability
  - Cost r
  - Impro nce depending on the contex



Thermal Controls: Does Physics Matter?

Thermal Controls Architecture must adapt to match TMS Physics

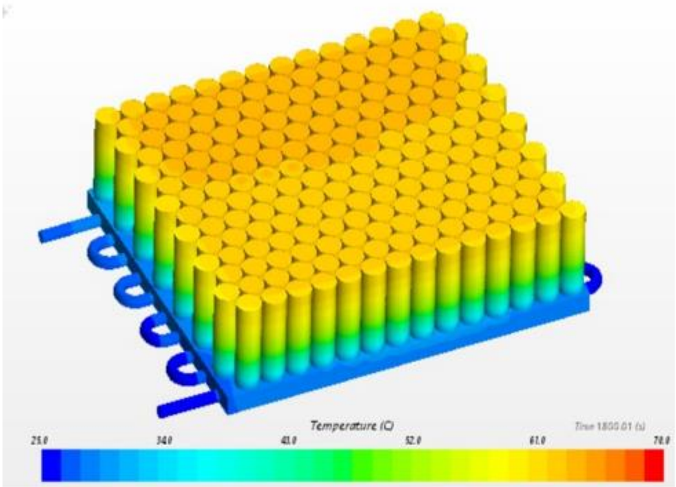




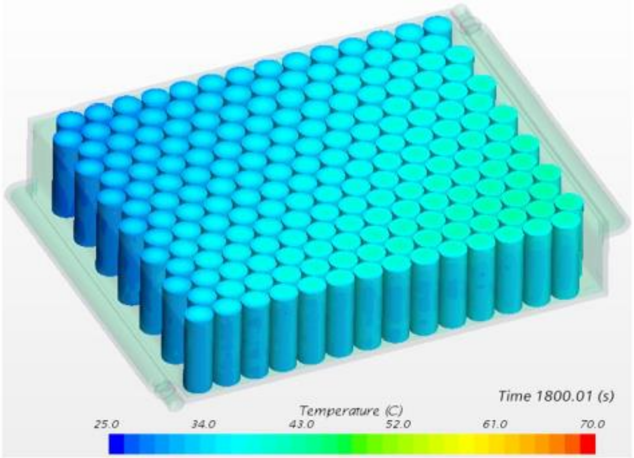
- Indirect liquid cooling
  - Bottom cooling with 2170FF Li-ion cells
  - Higher battery max and average temperatures
  - Lower temperature gradient across the module
  - Large temperature gradient along the length of cell
  - Smaller average-temperature gradient radially

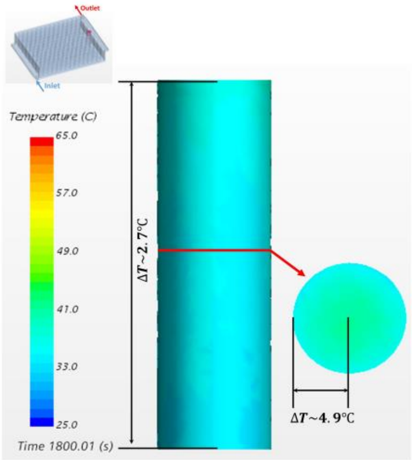
- Direct liquid cooling
  - Immersion cooling with 2170FF Li-ion
  - Lower battery max and average temperatures
  - Higher temperature gradient across the module due to lower dielectric-fluid thermal properties
  - Lower temperature gradient along the length of cell
  - Higher average-temperature gradient radially

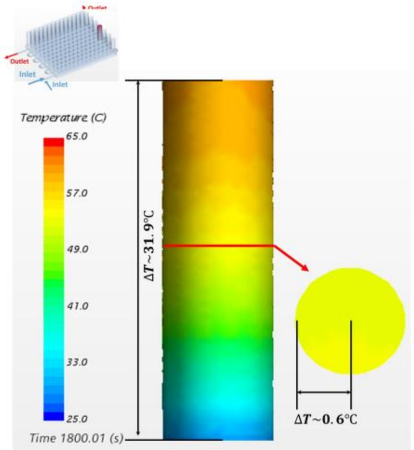
12-minute charge case



Bottom Cooling





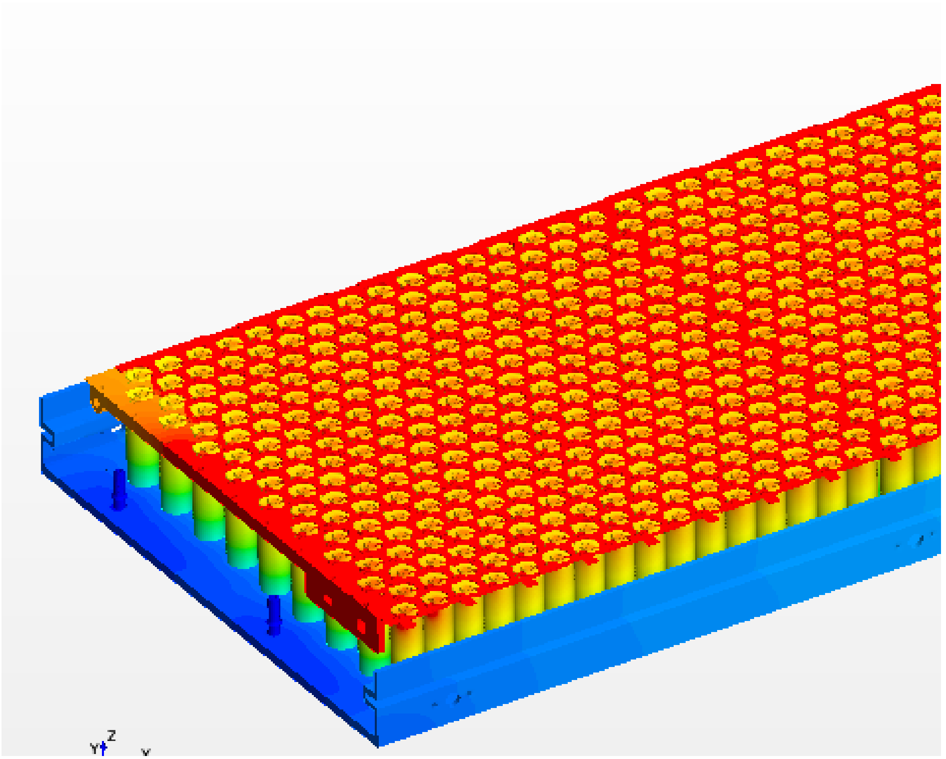


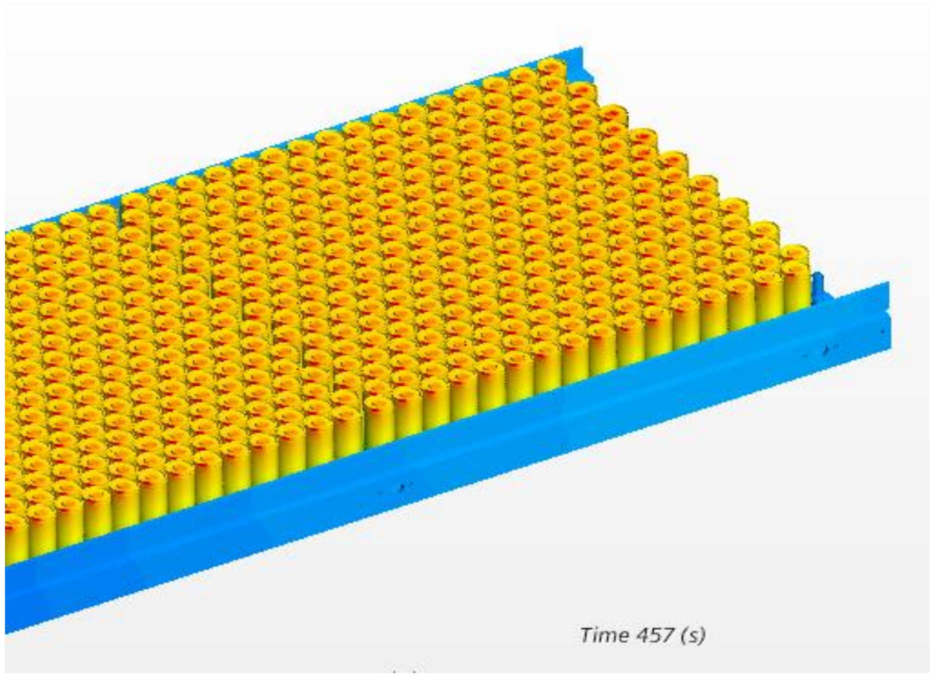
Immersion Cooling

* Reference: Dubey et al. "Direct Comparison of Immersion and Cold-Plate Cooling for Automotive Li-Ion Battery Modules

Zooming into Thermal Gradients in a Typical Module

Temperature field showing hotspots and gradients along the dimensions





Zooming into Thermal Gradients on a Pouch Cell

Thermal gradients for two different types of cooling at single-cell level

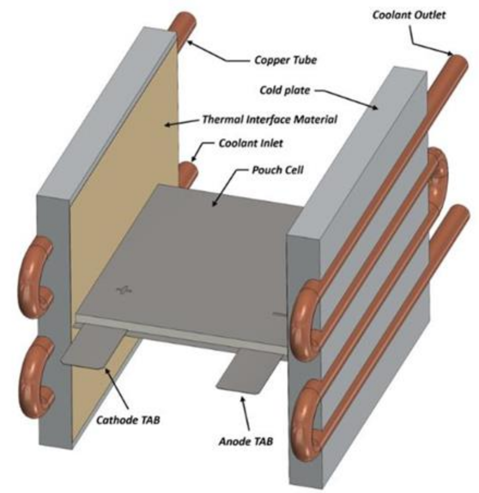
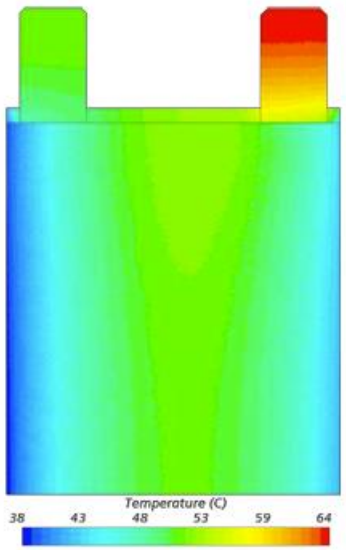


FIGURE 1 DOUBLE-SIDED COOLING CONFIGURATION



Temperature Contours at
5C Discharge

Ref: Bakhshi et al.

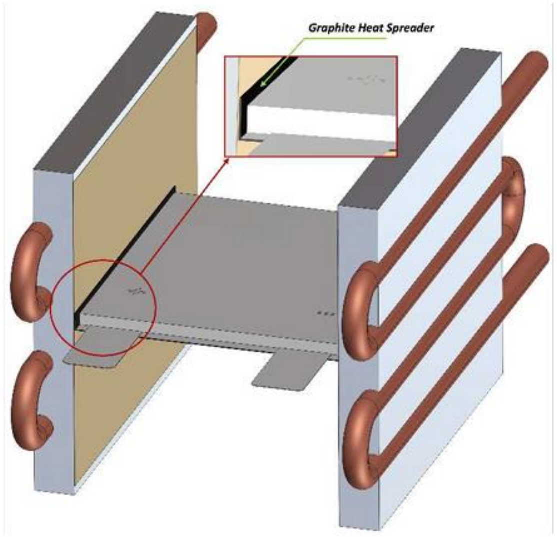
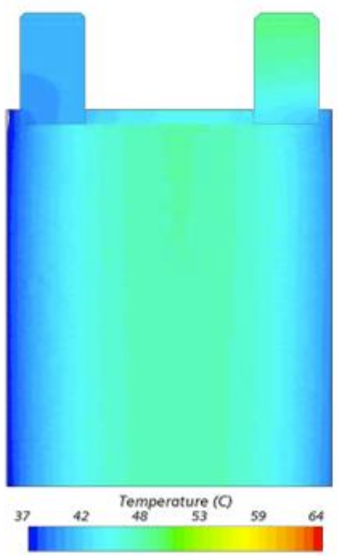


FIGURE 2 HYBRID COOLING CONFIGURATION

Temperature Contours at
5C Discharge

Ref: Bakhshi et al.



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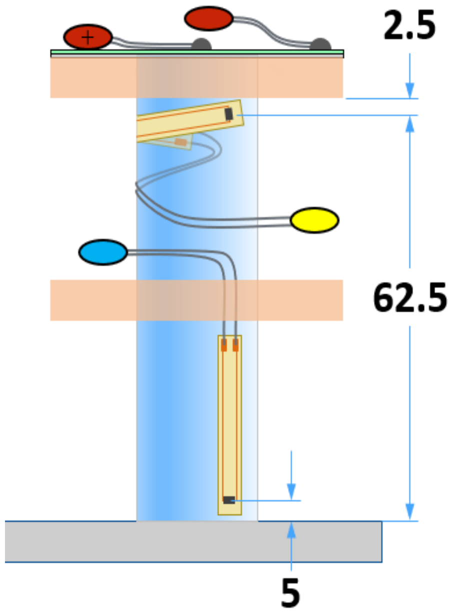
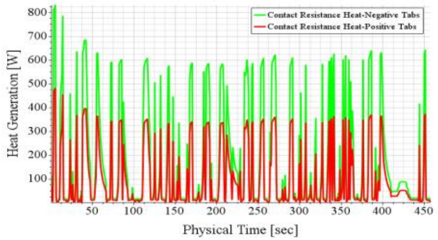
Sensor Data



- For a measurement-based system, control is as *good* as the sensor data
  - Smart installation of temperature sensors may help avoid failures
  - Gradient measurement in a few critical locations alleviates concerns



Gradient Calculator

Other Sensor Data

Fusion/State Estimator

Expensive!

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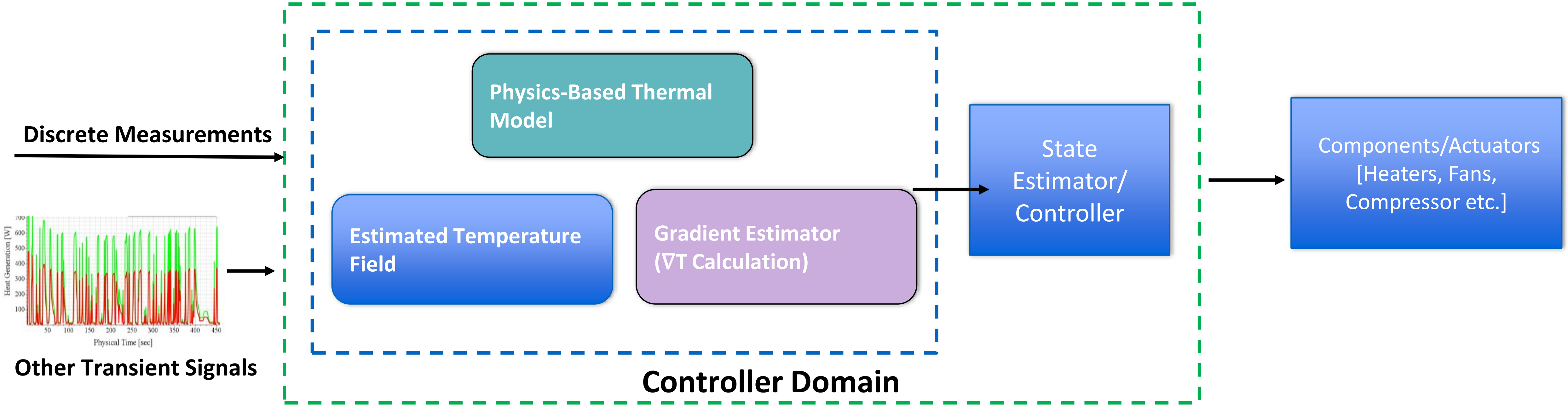

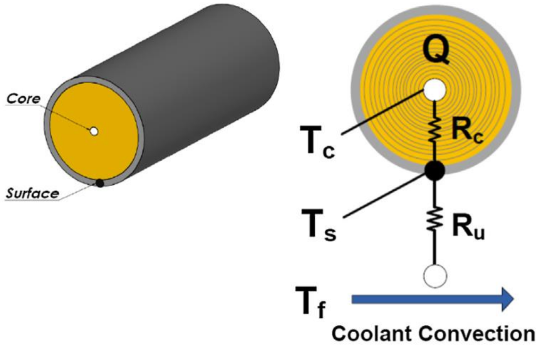

- Lumped physics-models based control system can eliminate concerns with in-adequate sensors or locations
- High quality initial feedback required
- Multiple Inputs Multiple Outputs
- High fidelity physics-based models can train ML-based controllers – training data is not insignificant

- Two-State Thermal Model for Core Temperature Prediction
  Ref: Lin et al., 2014; Park et al [shown as an example here - after all, who does not like to solve Navier Stokes equations real time on a vehicle controller!]

Summary

Battery Thermal Management: Challenges and Opportunities

- Battery thermal management systems and chemistries vary significantly depending on the application.
- Thermal gradients across battery propulsion systems can create undetected failure points, reducing the reliability of electric propulsion.
- Adding physical sensors to capture these issues is often cost-prohibitive and can introduce additional reliability concerns.

Opportunity for Innovation: Physics-Based Thermal Control Software

- Physics-based thermal control software can unlock synergies within the system, improving both safety and reliability.
- However, the high cost of computation remains a major barrier. Developing smart, simple, model-based approaches is critical to overcoming this challenge.

Cost Savings Through Virtual Sensors

- Strong cost-saving opportunity exists: real-time generation of temperature fields can enable effective use of "virtual sensors."
- Calibrated lumped models offer a practical pathway to achieving this.
- With advancements in powerful computing and hybrid algorithms combining machine learning and physics-based models, a near-complete transition to virtual thermal sensing is within reach