MATLAB EXPO

5月28日, 2024 | 北京

考虑电热特性的电池组建模

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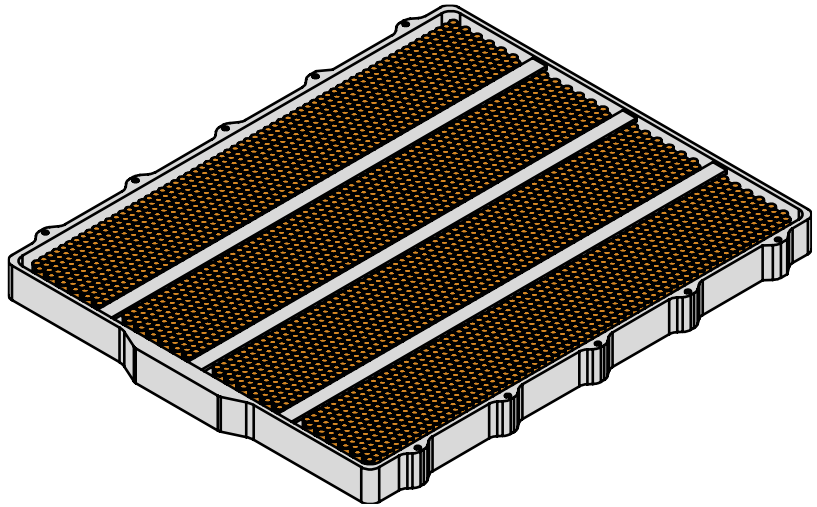
MathWorks

为什么探索电池包电热特性建模

电池包温度监测的重要性

- 电池包是很多固定和移动设备应用的核心
  - 能量存储
  - 价格昂贵
- 锂离子电池的性能受其温度的影响很大

电阻增加
容量下降



电池老化
热失控

为什么探索电池包电热特性建模

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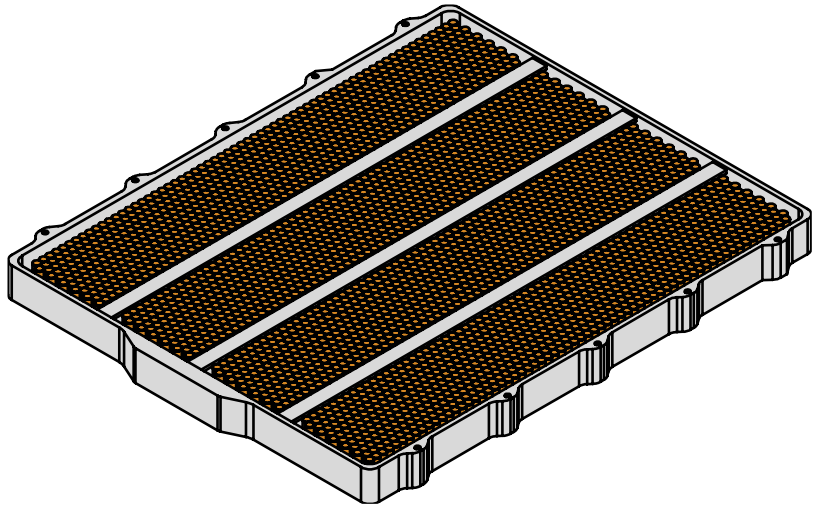


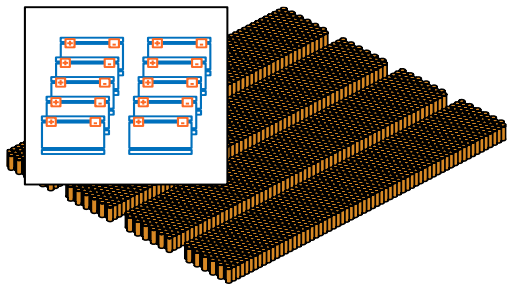
电池老化
热失控

- 电池热管理确保电池在安全的温度范围内运行
- **电热仿真**是热管理的一个强大的系统匹配和部件选型设计工具
- 创建详细的电热模型是一项具有**挑战性的任务**

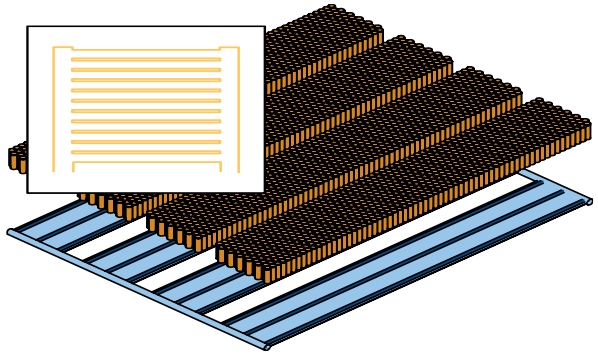
主要内容
仿真电热行为

今天旨在分享如何用Simscape Battery：

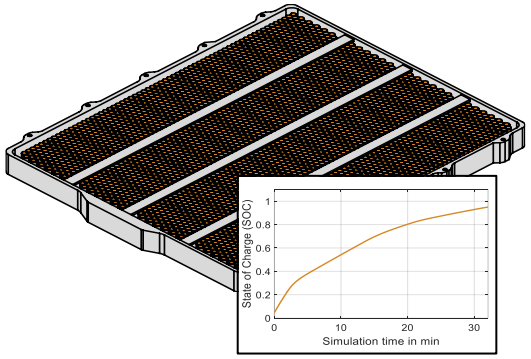
1. 考虑电热特性的电池包建模



2. 液冷系统建模

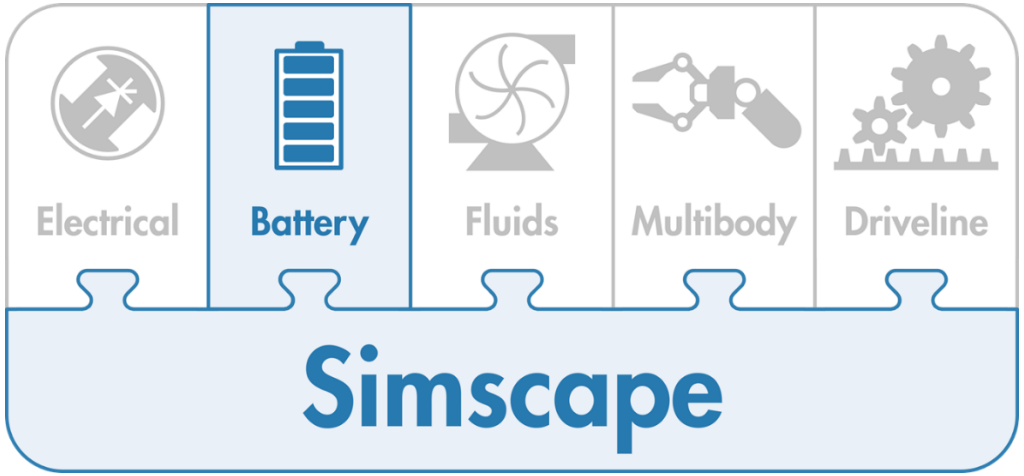


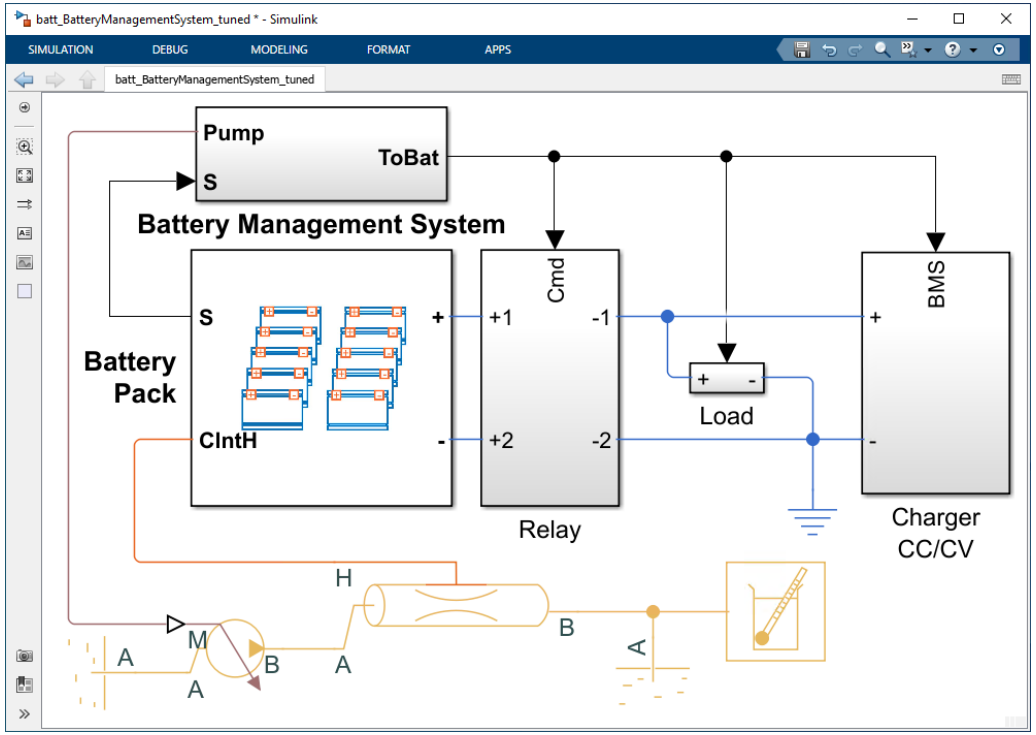
3. 快充工况下仿真测试电池包行为



Simscape Battery是什么？
概述

- Simscape的附加产品
- 设计和仿真电池和储能系统：
  - 电池单体电热行为
  - 电池包设计
  - 电池管理系统(BMS)
- 使用 Simscape Battery
  - 仿真测试电池包满足电热性能设计需求
  - 仿真测试BMS算法

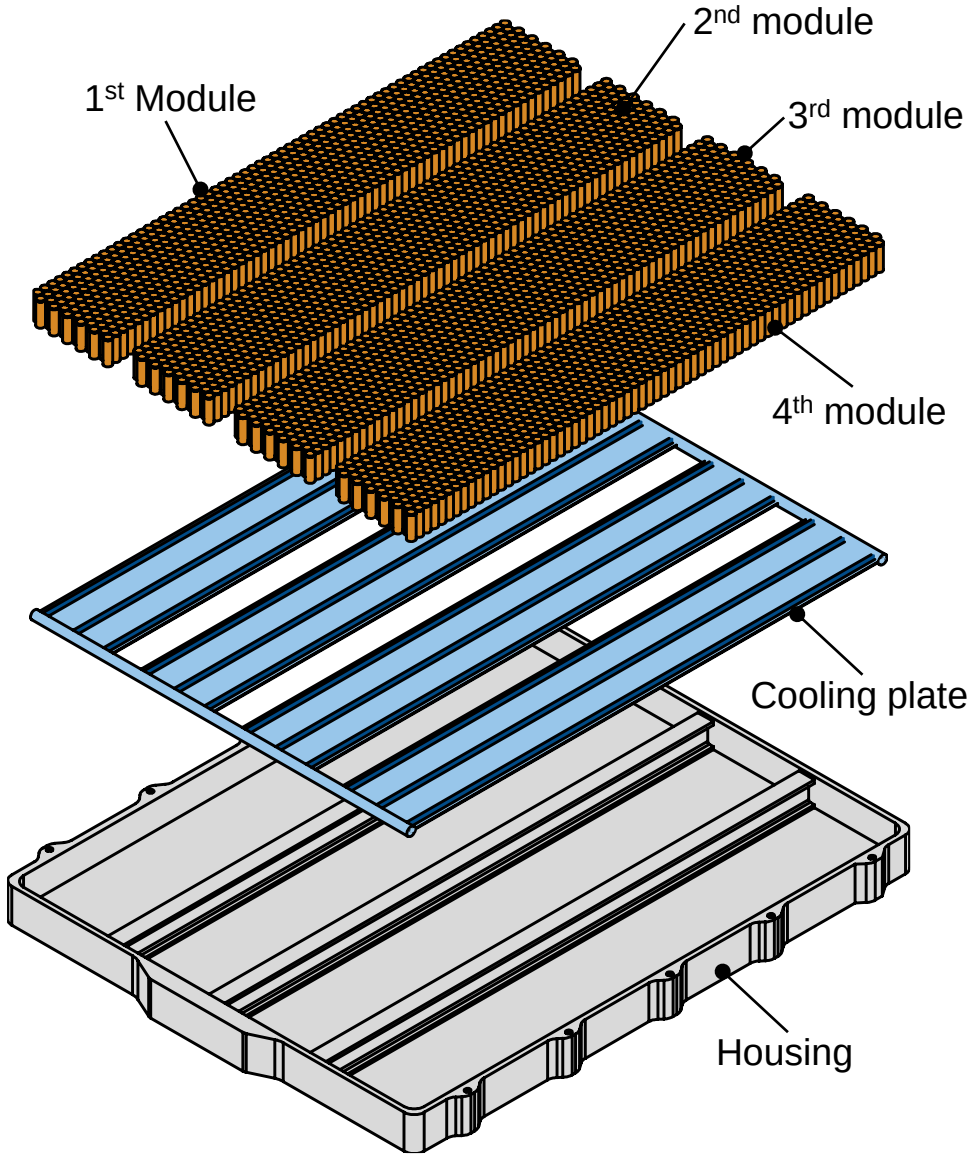




测试电池包的能力

本次探讨基于的电池包

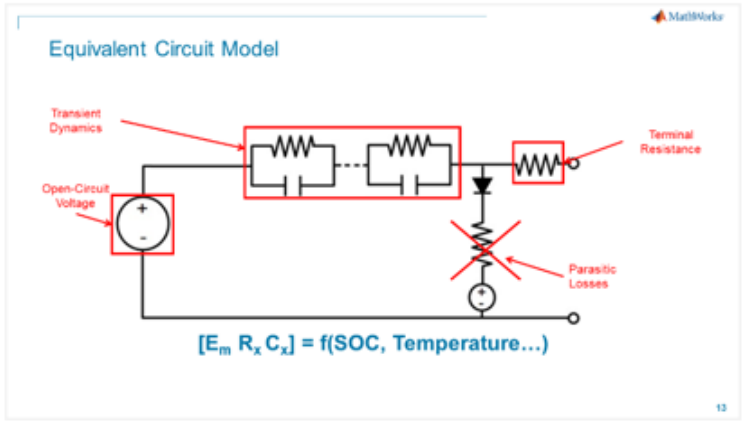
- 待电热特性建模的电池：
  - 3072 个圆柱电池
  - 串并联方案：96s32p
  - 电池分为4个模组
  - 装机容量: 50 kWh
- 摘自某中型电动轿车的优化研究(400公里续航里程）



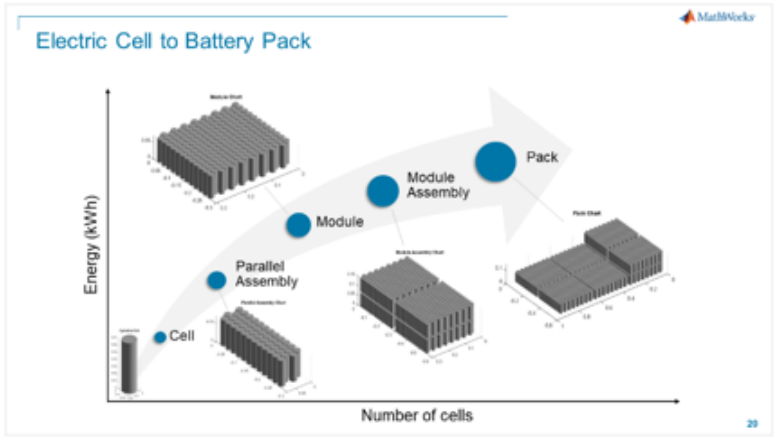
» MAC 2022: Fulfill Range, Acceleration, and Cost Targets Using Battery Sizing

从单体到电池包建模，电热特性分析

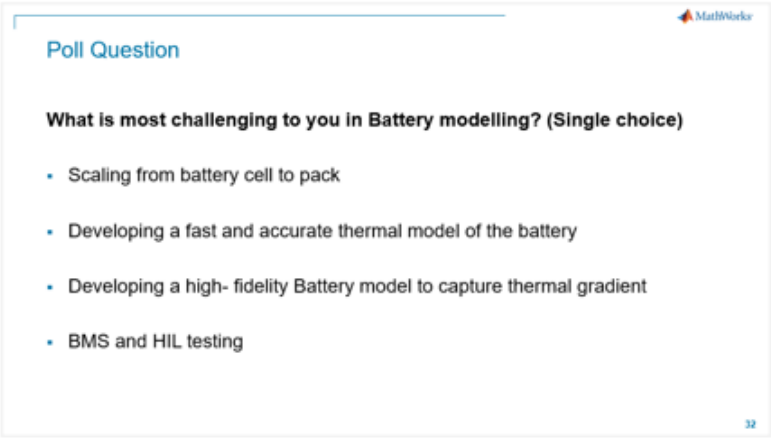
1. 单体建模



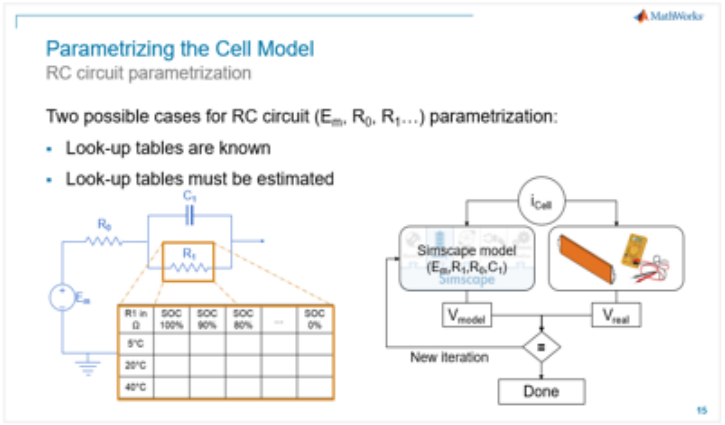
3. 电池包设计



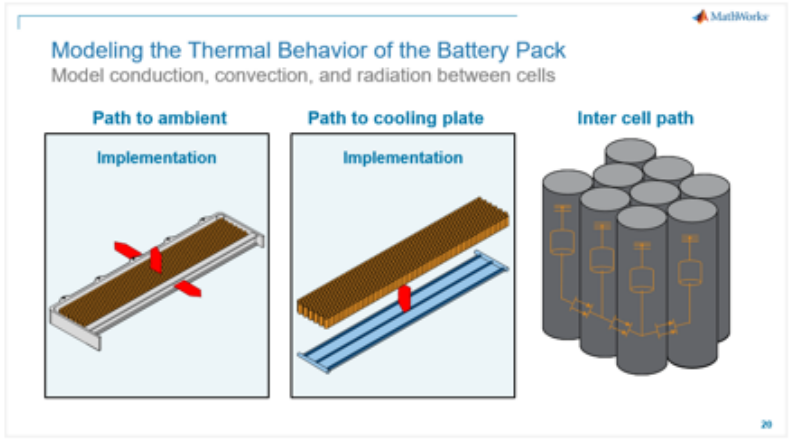
5. 模型精度



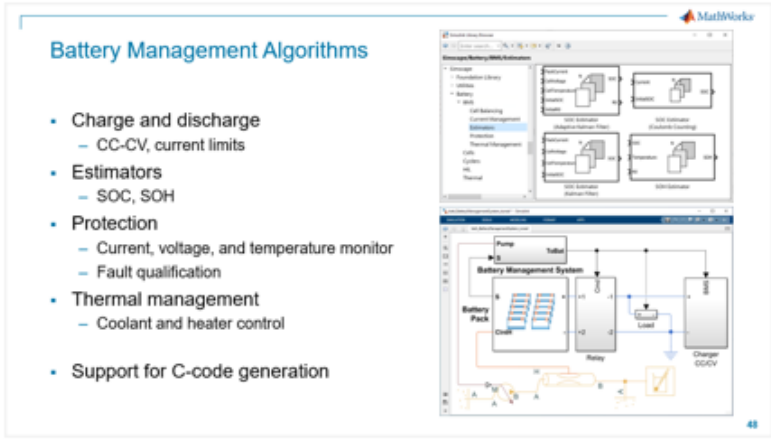
2单体参数标定



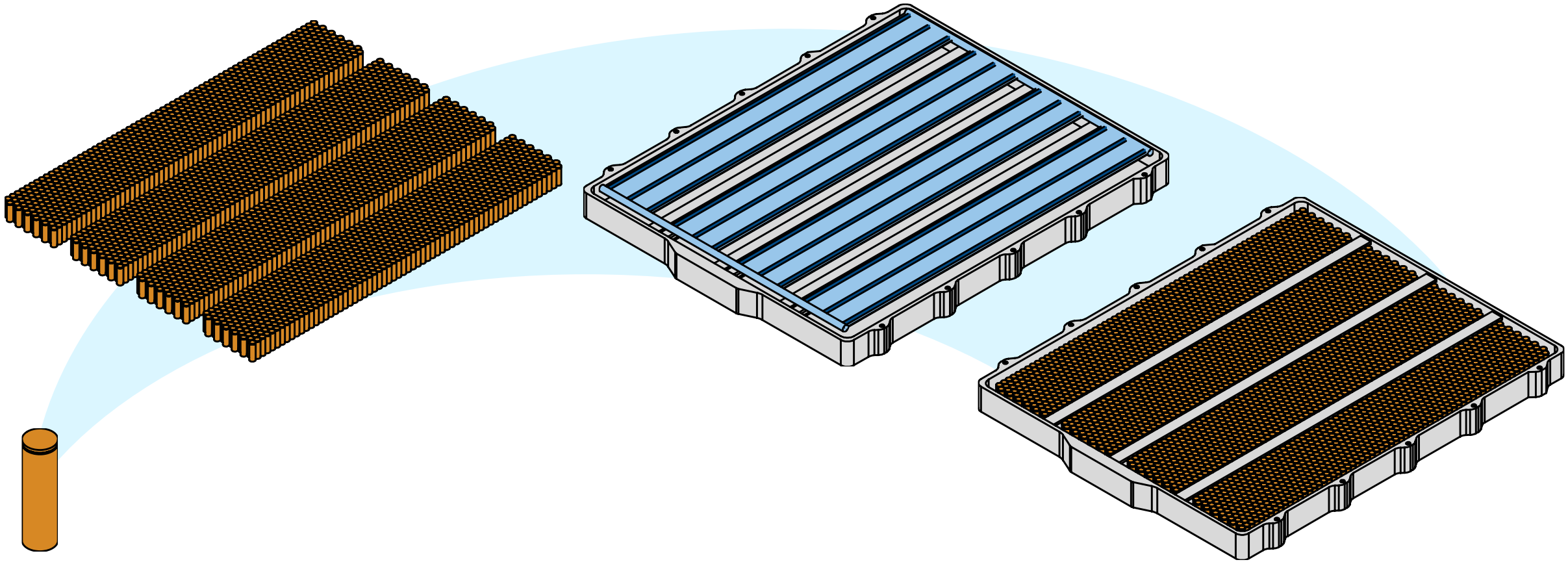
4. 热管理系统设计



6. BMS及其HIL测试

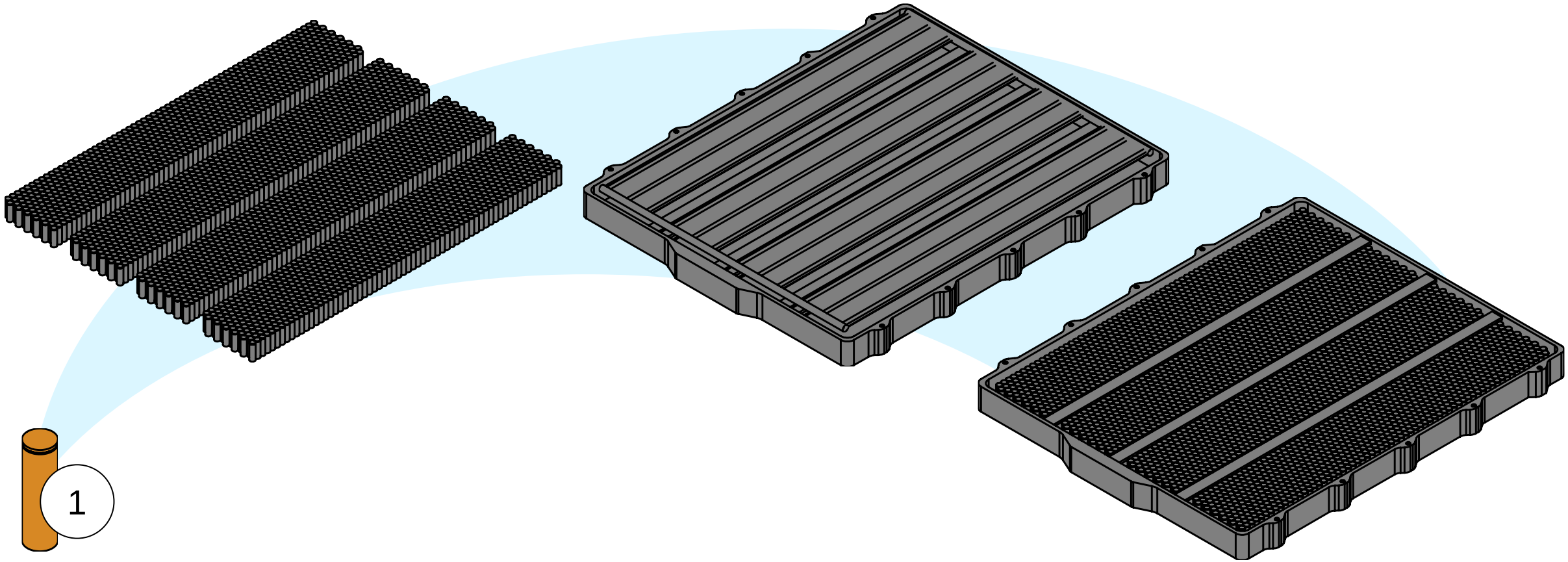


从单体到电池包的快速建模



从单体到电池包的快速建模

理解单体模型



不同类型的电池模型

- 电化学模型

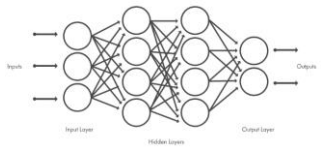
Simscape Battery: Battery Single Particle (R2024a)
Simulink: Python Importer (R2023a)

$$\frac{\partial c}{\partial t} = D\left[\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r} - \frac{\Omega}{RT}\frac{\partial c}{\partial r}\frac{\partial \sigma_h}{\partial r} - \frac{\Omega c}{RT}\left(\frac{\partial^2 \sigma_h}{\partial r^2} + \frac{2}{r}\frac{\partial \sigma_h}{\partial r}\right)\right]$$

$$J = \frac{i_n}{F} = \frac{i_0}{F}\left\{\exp\left[\frac{(1-\beta)F}{RT}\eta\right] - \exp\left[-\frac{\beta F}{RT}\eta\right]\right\}$$

$$\nabla \cdot \left[\kappa^{eff}\nabla \overline{V}_2 + g_2 \kappa_D^{eff}\nabla\left(\ln \overline{c}_2\right)\right] + J_{V_2} = 0$$

- 数据驱动模型

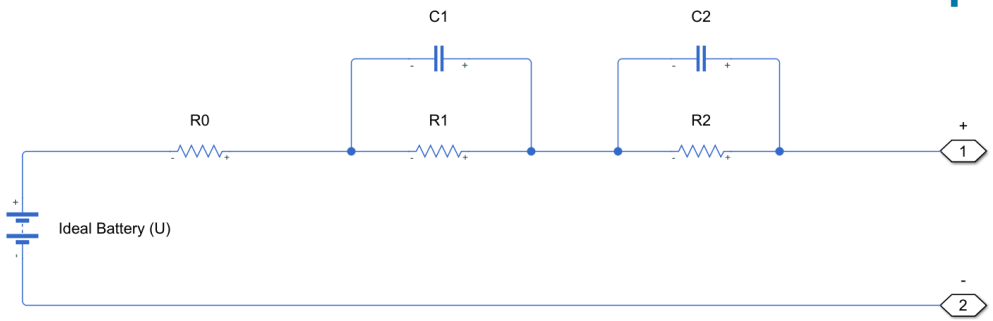


System Identification: neural state-space model

Reduced Order Modeling of Electric Vehicle Battery System Using Neural State-Space Model

- 等效电路模型 (ECM)

Simscape Battery: Battery (Table-Based)
Simscape Battery: Battery Equivalent Circuit (R2023b)

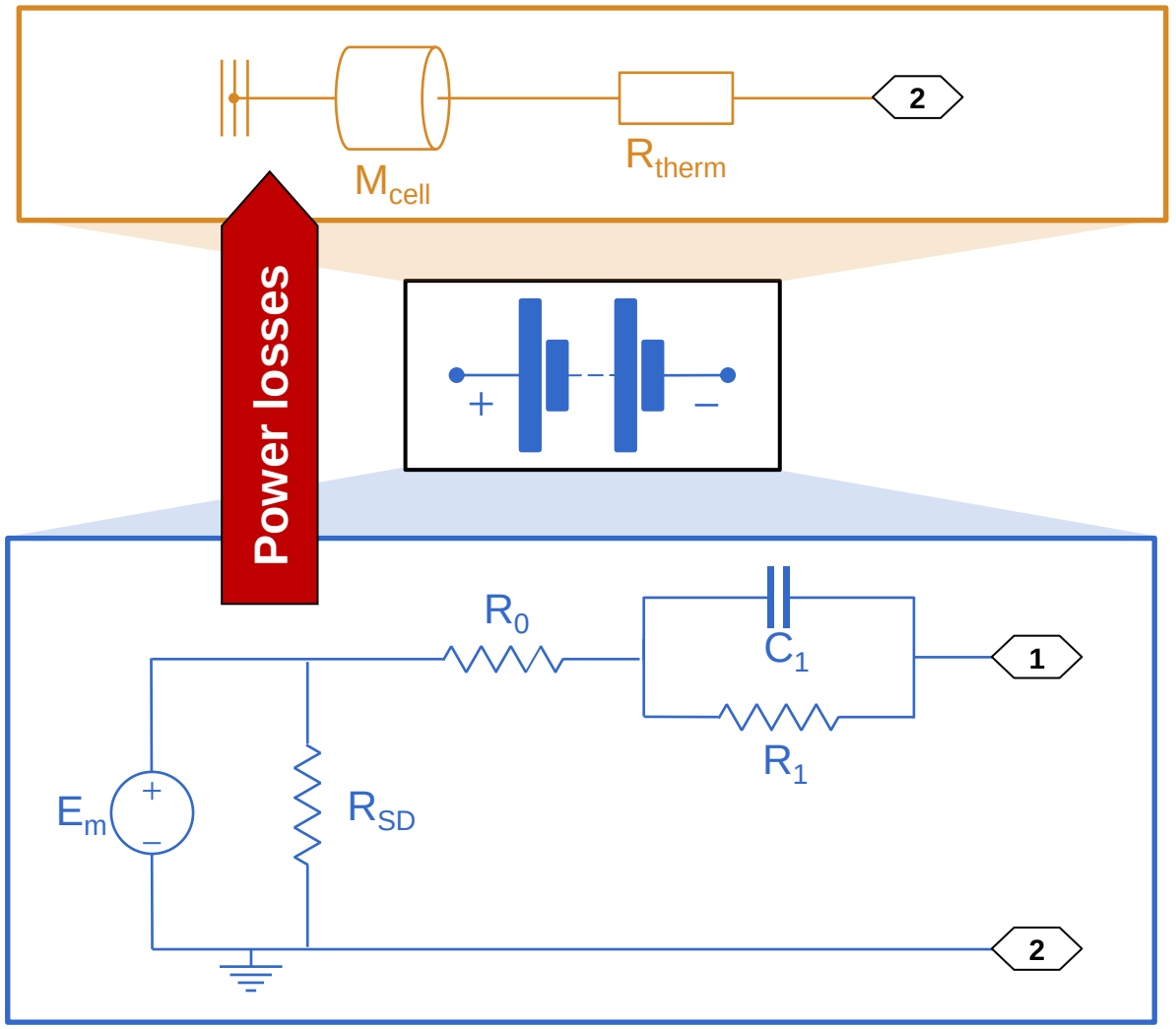


Lumped thermal model

理解单体模型

多学科物理模型

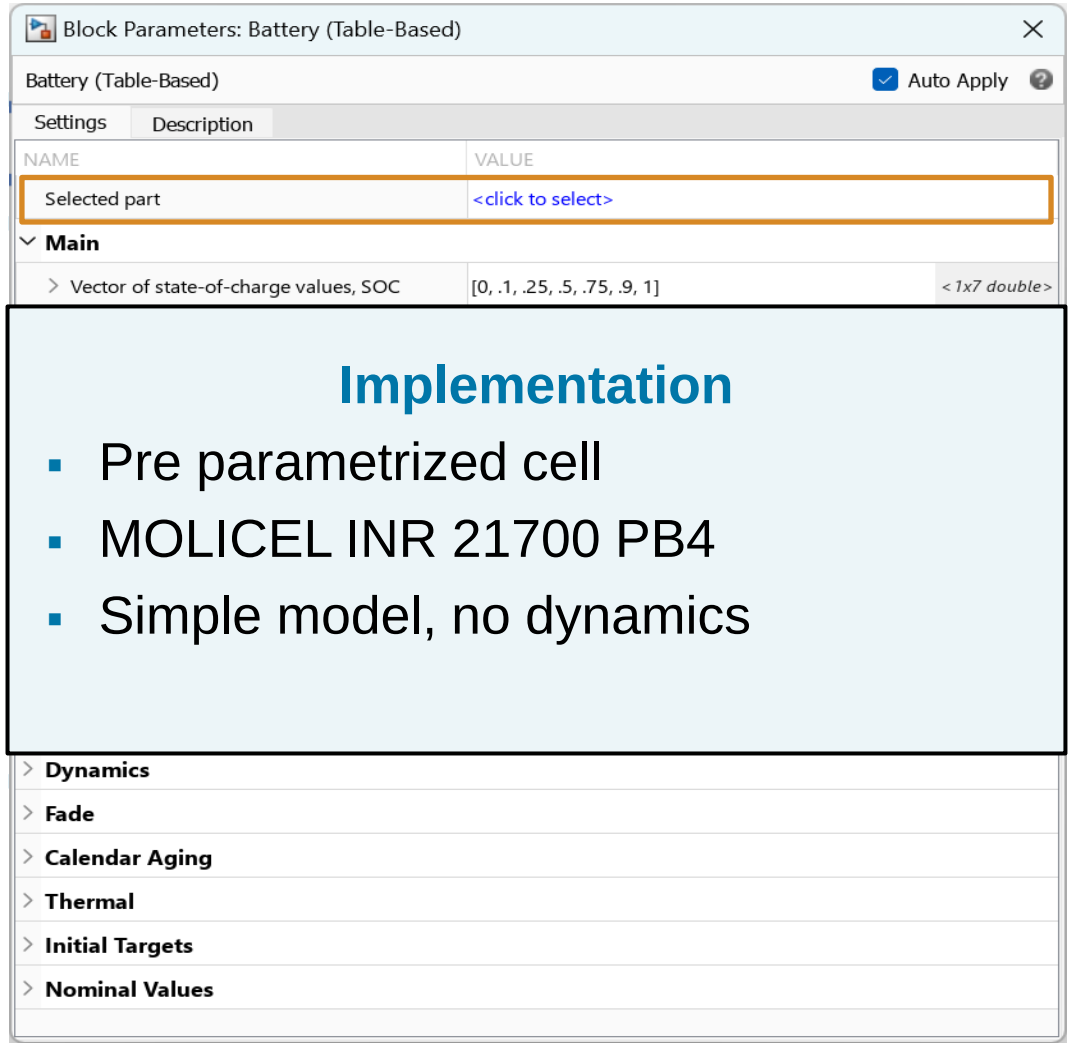
- 多学科物理模型
- 电特性单体模型
  - RC等效电路描述的单体模型
  - 不同精度模型选择
- 单体集总热模型
- 功率损失来自欧姆损失的计算



» Battery (Table-Based)

理解单体模型

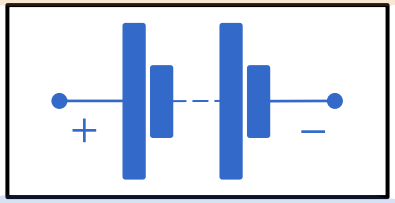
多学科物理模型



Implementation

- Pre parametrized cell
- MOLICEL INR 21700 PB4
- Simple model, no dynamics

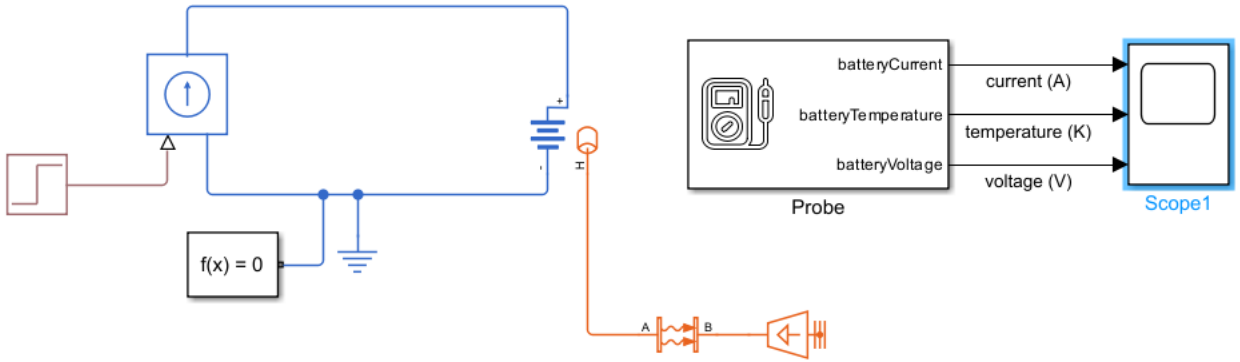
```
    nodes
      H = foundation.thermal.thermal;
      p = foundation.electrical.electrical;
      n = foundation.electrical.electrical;
    end

    equations
      % Implement custom equations here
    end
  end
```

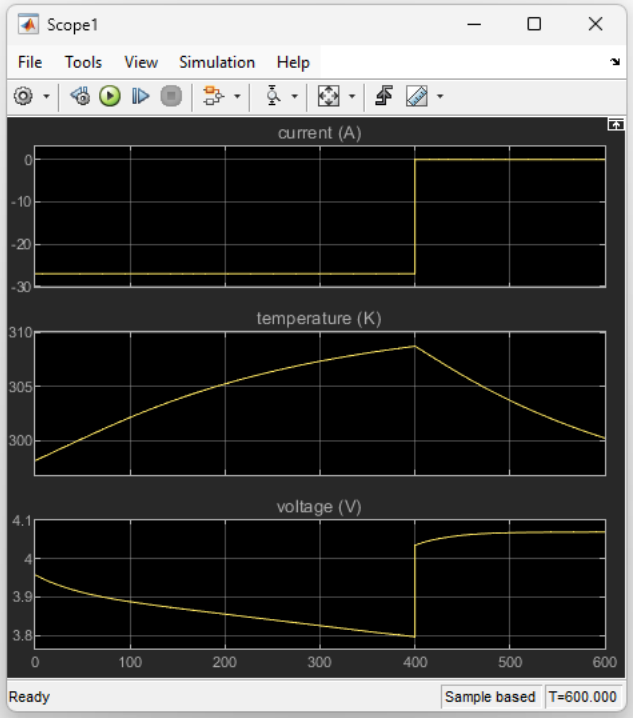



```
component (Propagation = blocks) Custom_Cell
    % Custom cell
    % Add description here
  parameters
    % Assign custom parameters
  end

  variables
    % Assign Custom variables
  end

  outputs
    % Assign custom outputs
  end

  nodes
    H = foundation.thermal.thermal;
    p = foundation.electrical.electrical;
    n = foundation.electrical.electrical;
  end

  equations
    % Implement custom equations here
  end
end
```

» Battery (Table-Based)

单体模型示例

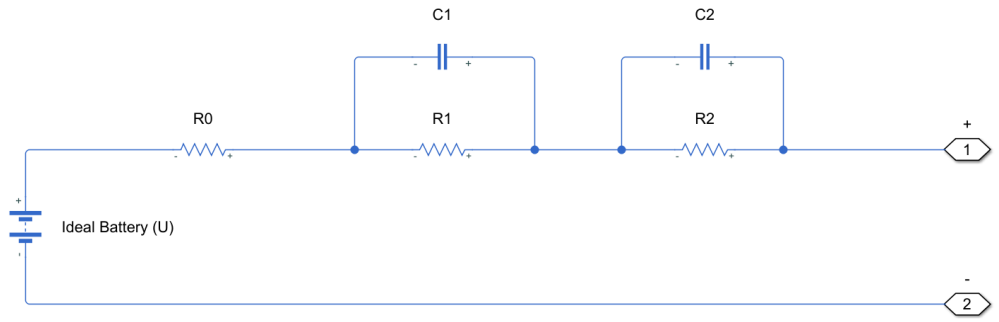

f(x) = 0
batteryCurrent
batteryTemperature
batteryVoltage
Probe
current (A)
temperature (K)
voltage (V)
Scope1
A
B


Scope1
File
Tools
View
Simulation
Help
current (A)
temperature (K)
voltage (V)
Ready
Sample based
T=600.000

电热耦合

Heat generation

$$\dot{Q}_{\text{resistive}} = \sum_i \frac{V_i^2}{R_i} \qquad \dot{Q}_{\text{reversible}} = IT\frac{dU}{dT}$$



Lumped thermal model

$$M_{th}\dot{T} = \sum_i \frac{V_i^2}{R_i} + \dot{Q}_{\text{rev}} - \dot{Q}_{\text{diss}}$$

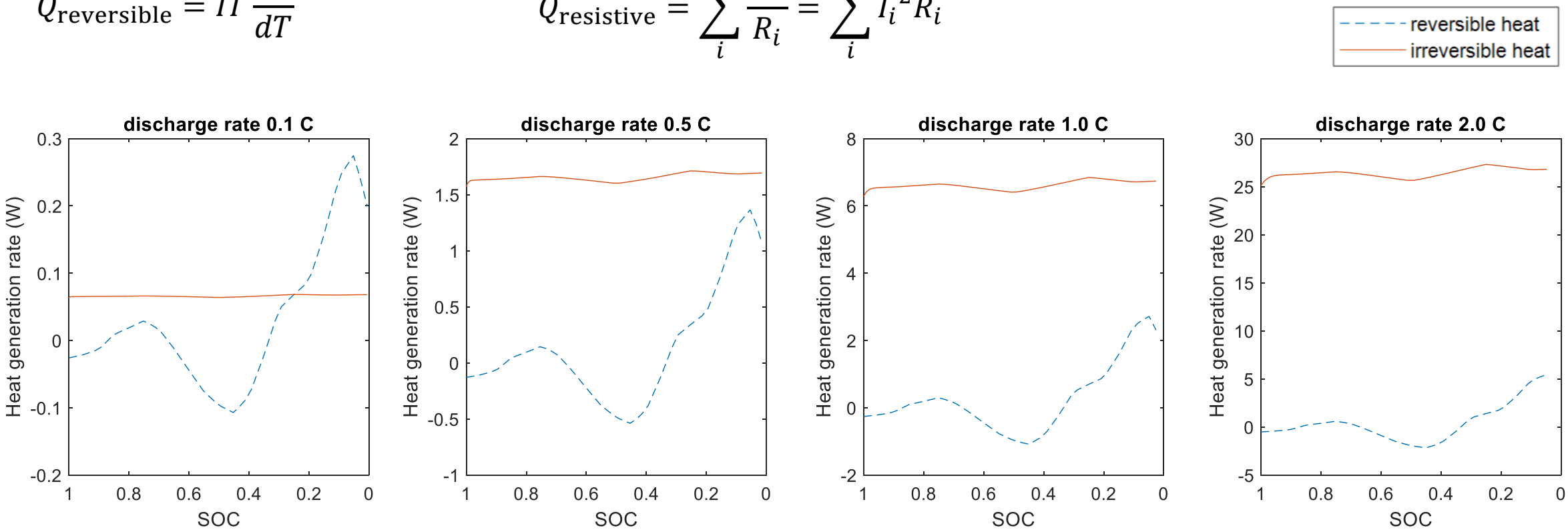
$R_i(T)$ $C_k(T)$

Temperature dependent parameters

可逆热(熵热)

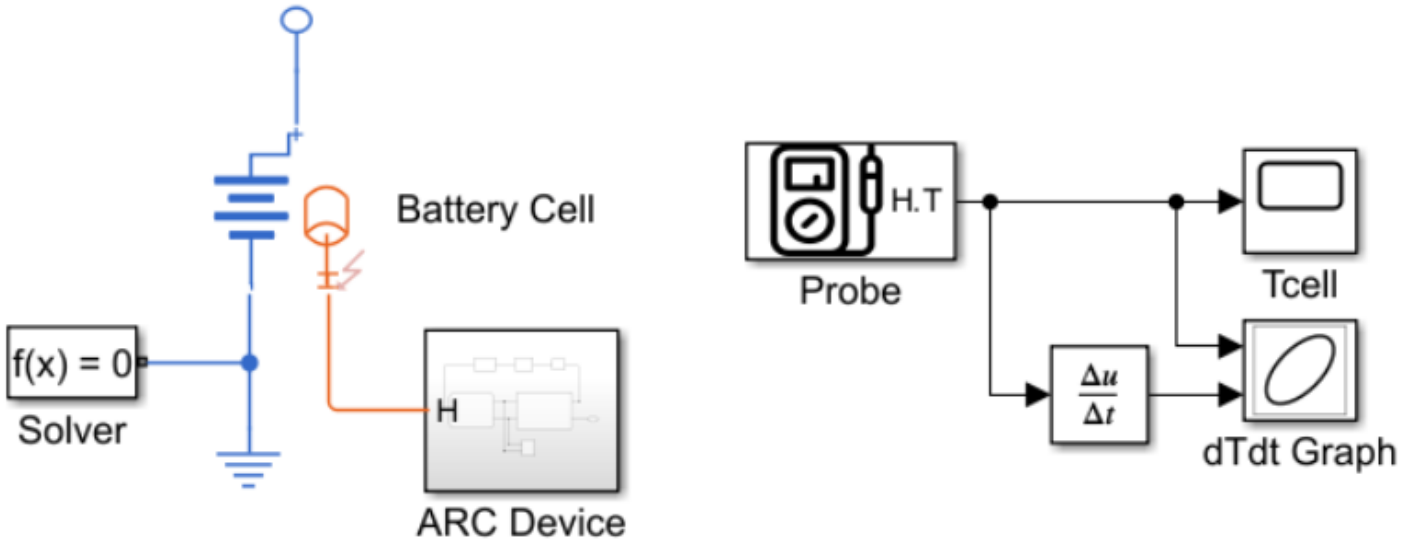
$$\dot{Q}_{\text{reversible}} = IT\frac{dU}{dT}$$

$$\dot{Q}_{\text{resistive}} = \sum_i \frac{{V_i}^2}{R_i} = \sum_i {I_i}^2 R_i$$



[Parameterize Entropic Coefficient with Measurement Protocol and Data Analysis - MATLAB & Simulink (mathworks.com)]

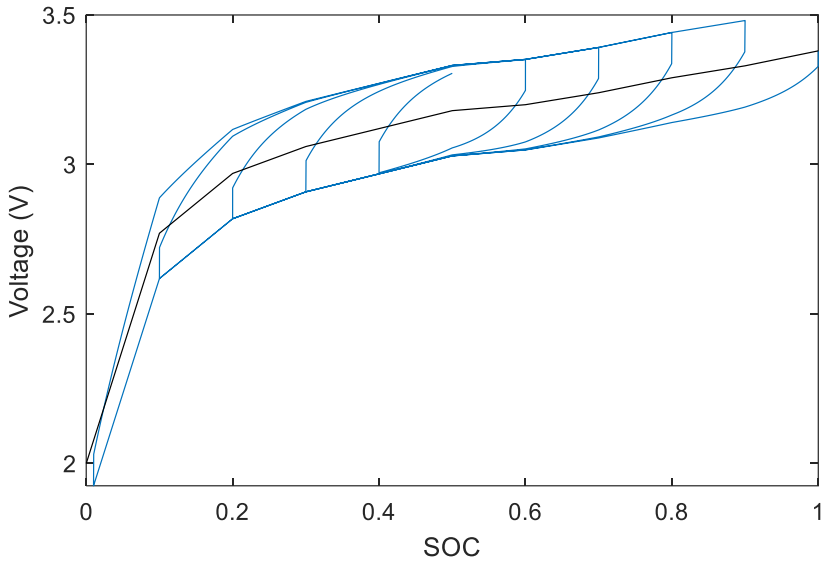
热失控故障建模

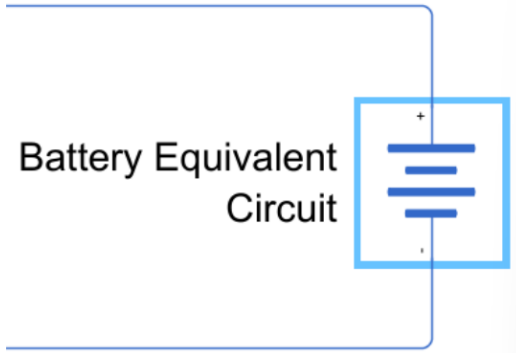


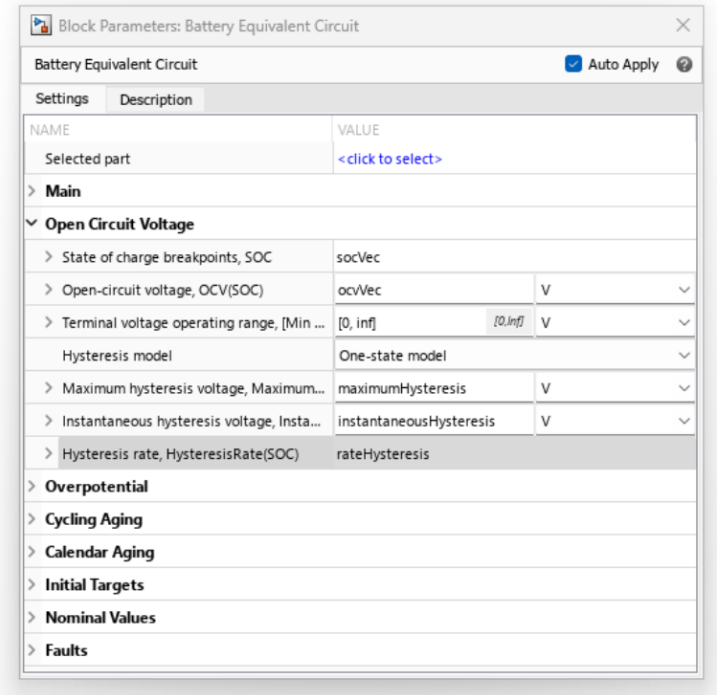
Battery model with electro-thermal dynamics and optional faults - MATLAB (mathworks.com)

Characterize Cell Thermal Runaway with Accelerating Rate Calorimetry (ARC) Test - MATLAB & Simulink (mathworks.com)

迟滞性







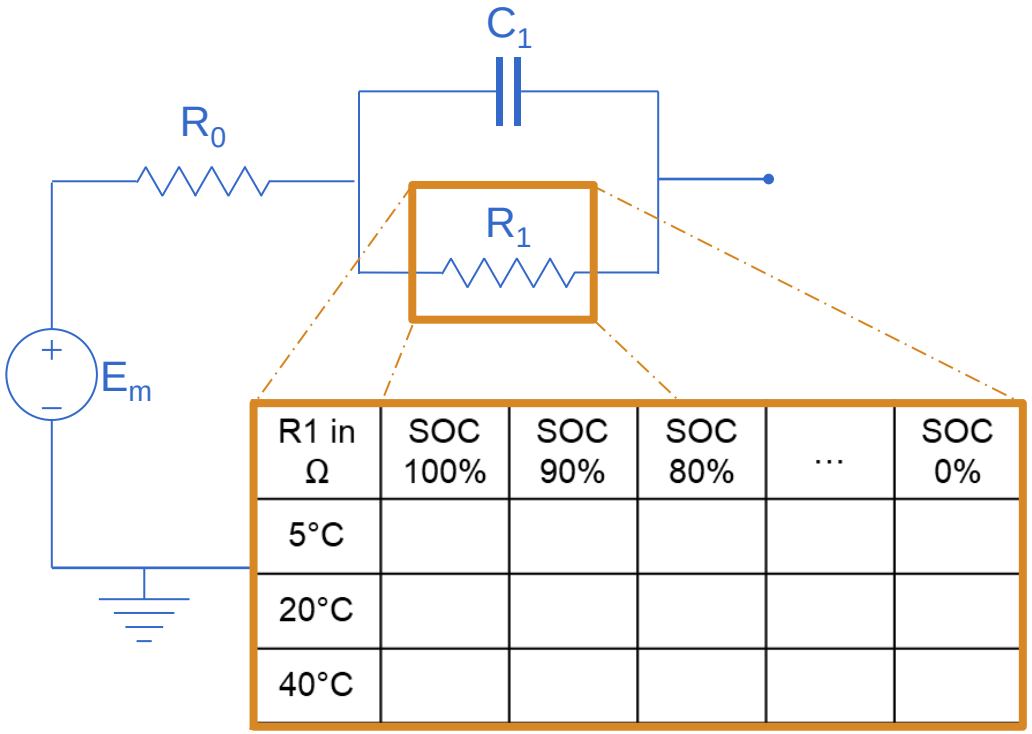
[Model Voltage Hysteresis in Battery - MATLAB & Simulink - MathWorks 中国]

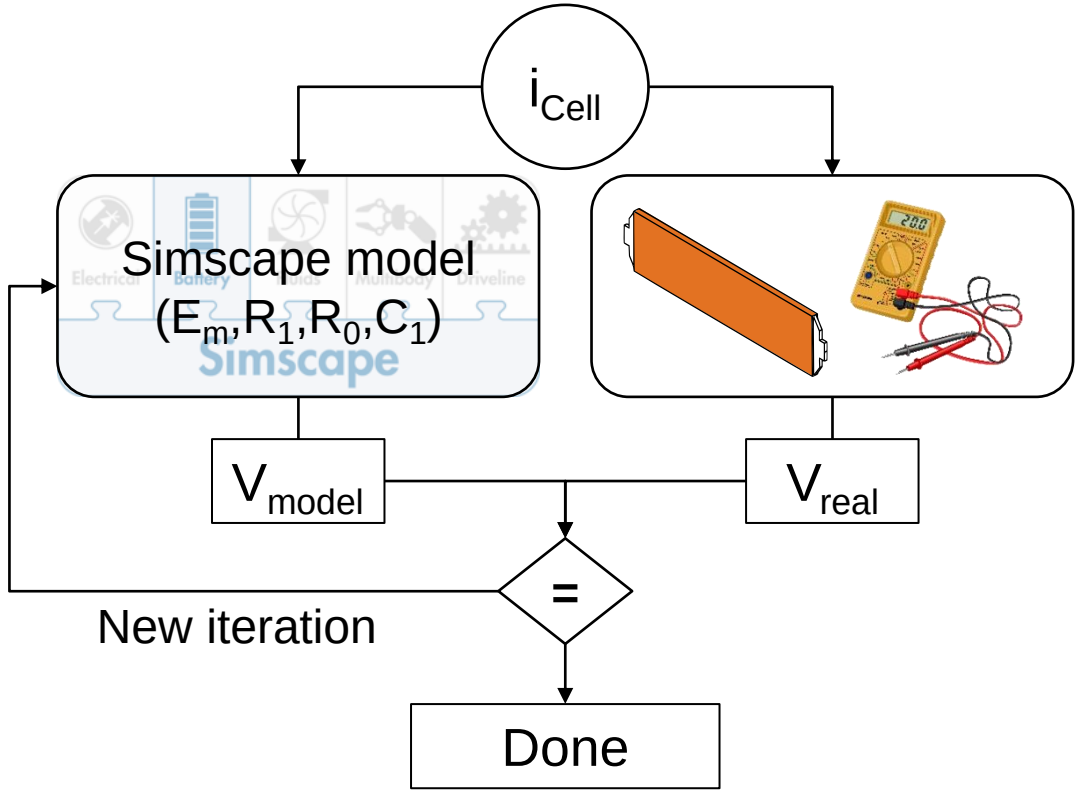
单体模型参数标定

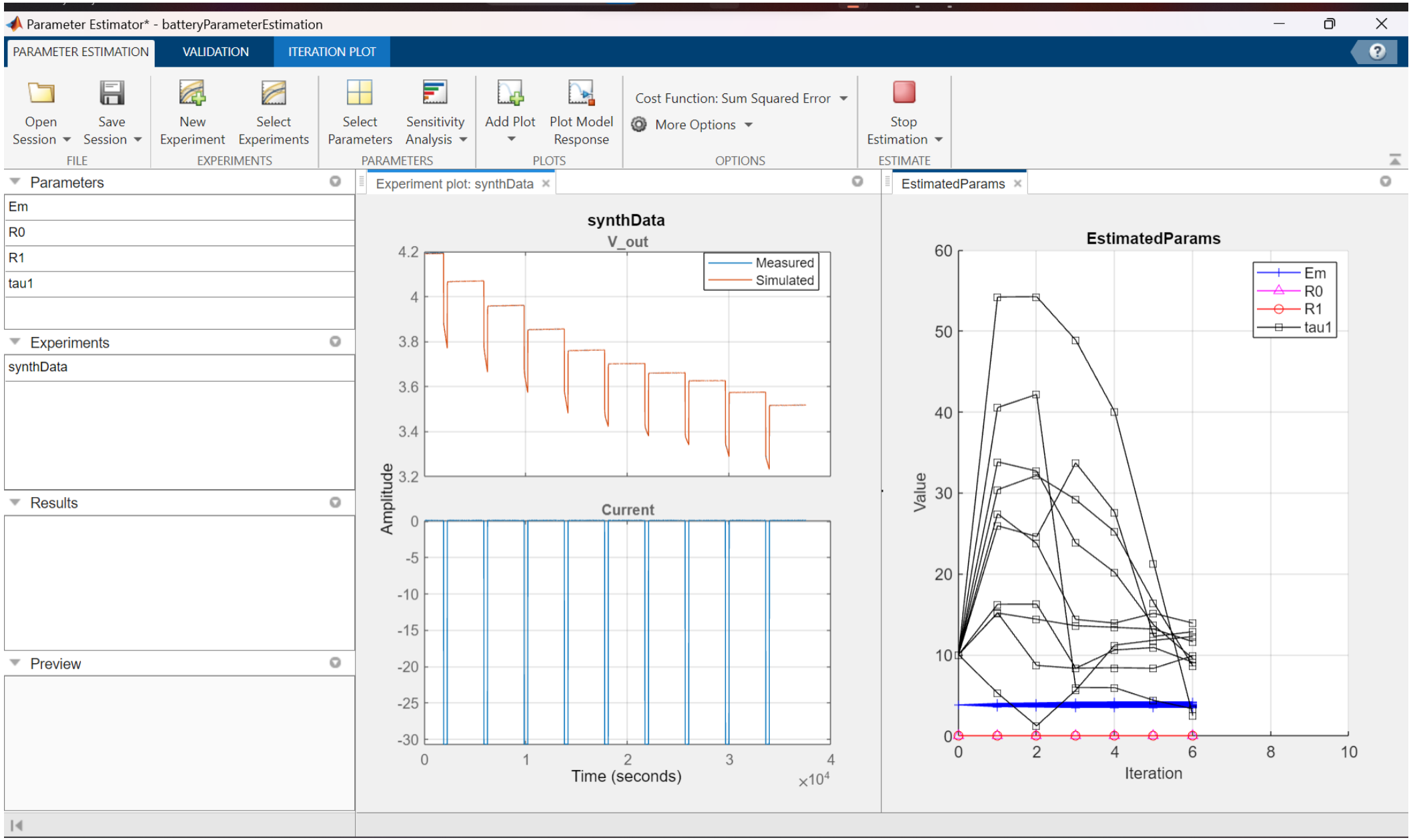
RC等效电路参数

RC (E_m, R_0, R_1…)等效电路参数标定的两种情况：

- 插值表已知
- 插值表未知，需要估计

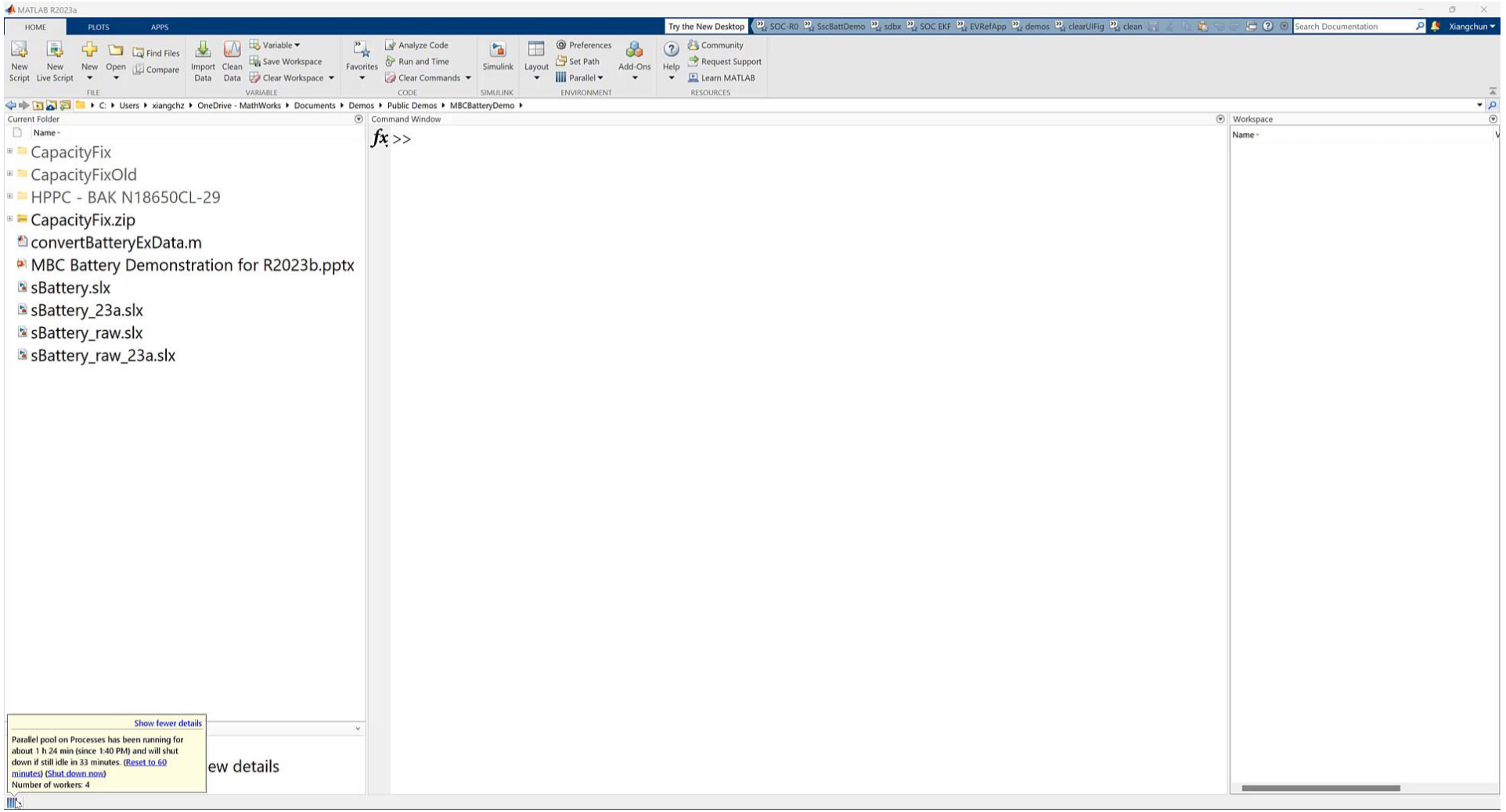






» Estimate Battery Parameters

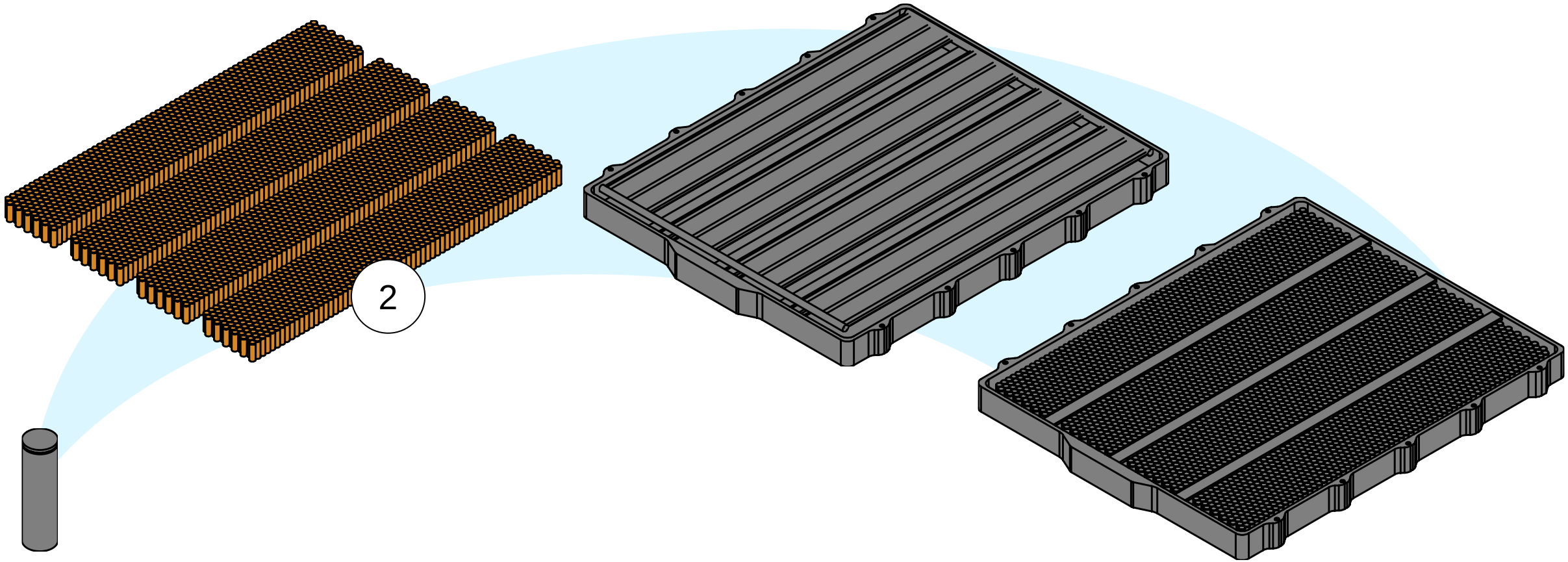
Model-Based Calibration Toolbox (MBC)
电池参数标定示例



[Characterize Battery (Table-Based) Block Parameters in CAGE - MATLAB & Simulink (mathworks.com)]

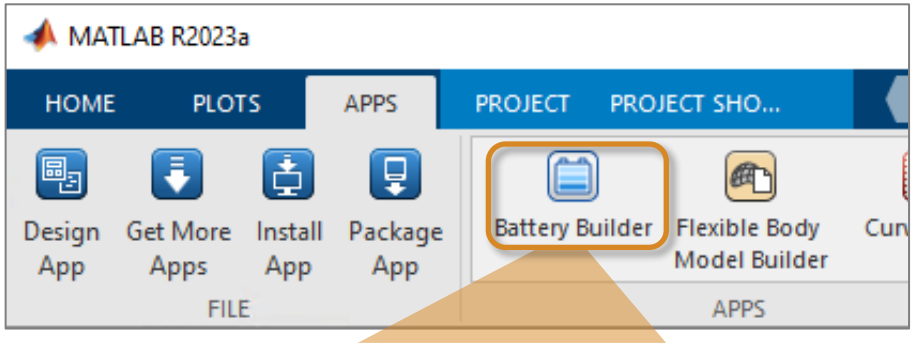
使用Battery Builder app快速实现从单体到电池包的建模

从单体到电池包



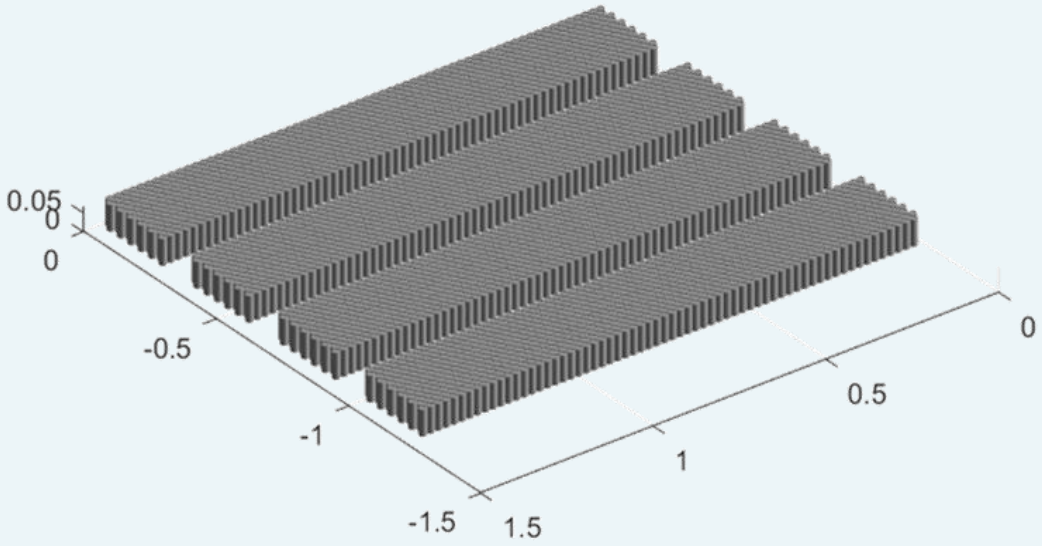
几分钟实现电池包建模

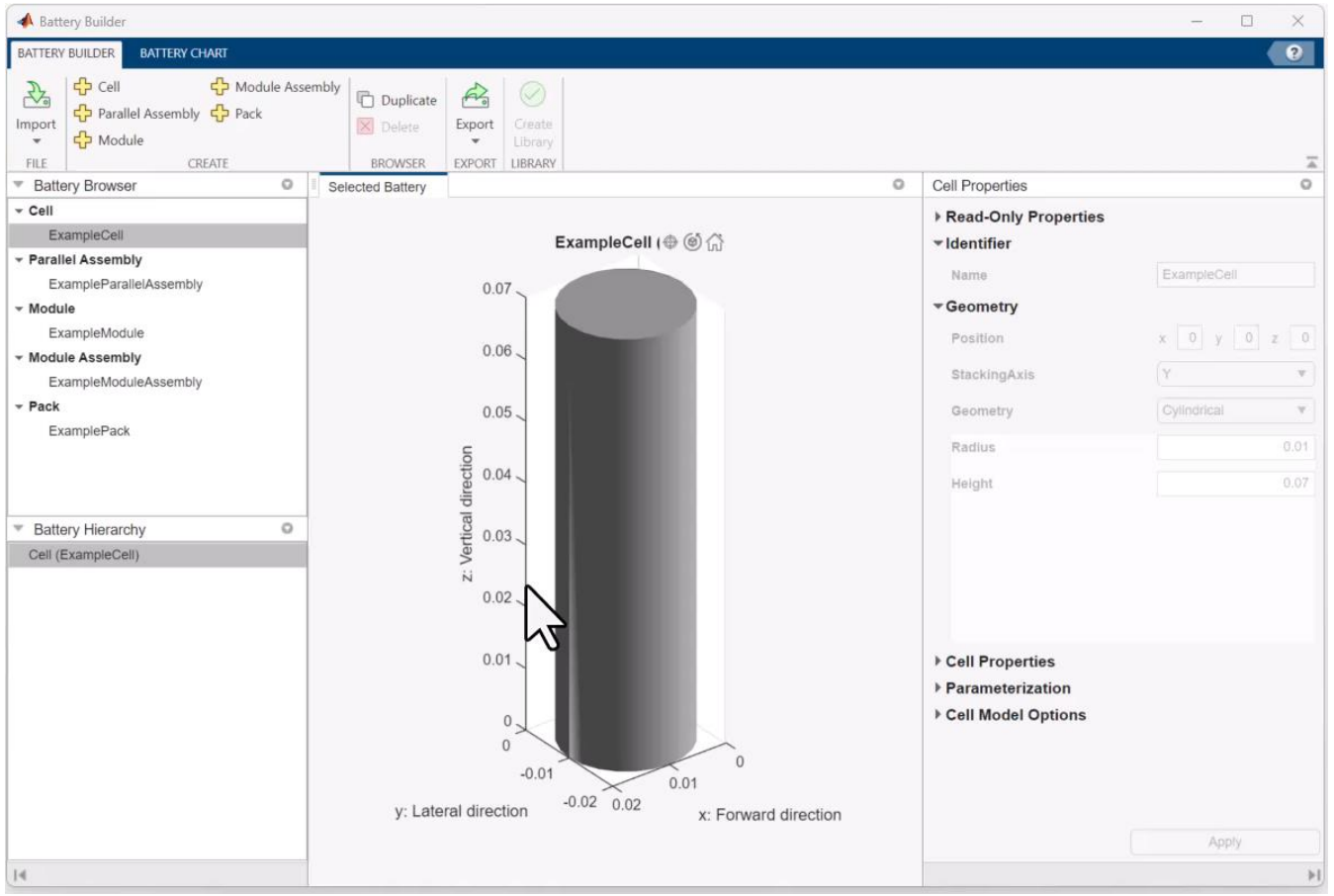
使用Battery Builder App



Implementation

- 3072 cells disposed on four modules
- Electrical scheme 96s32p



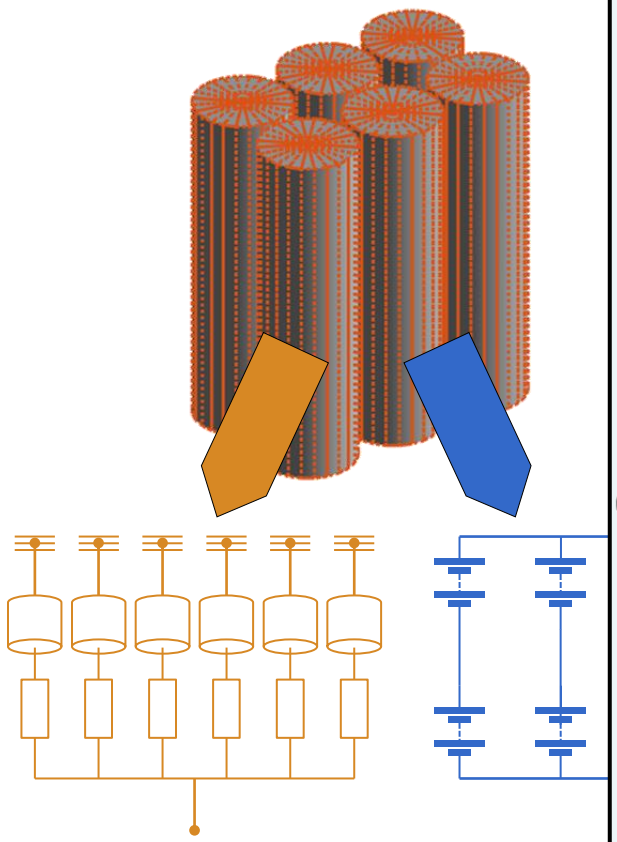


» Battery Builder

平衡仿真速度和精度

选择合适的电池包模型精度

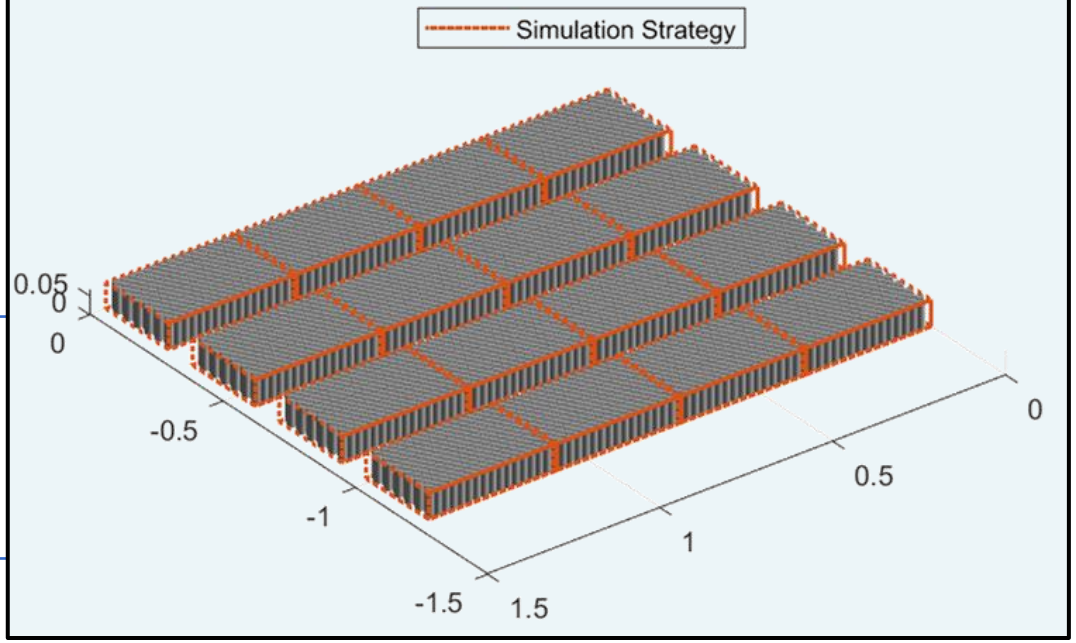
Detailed



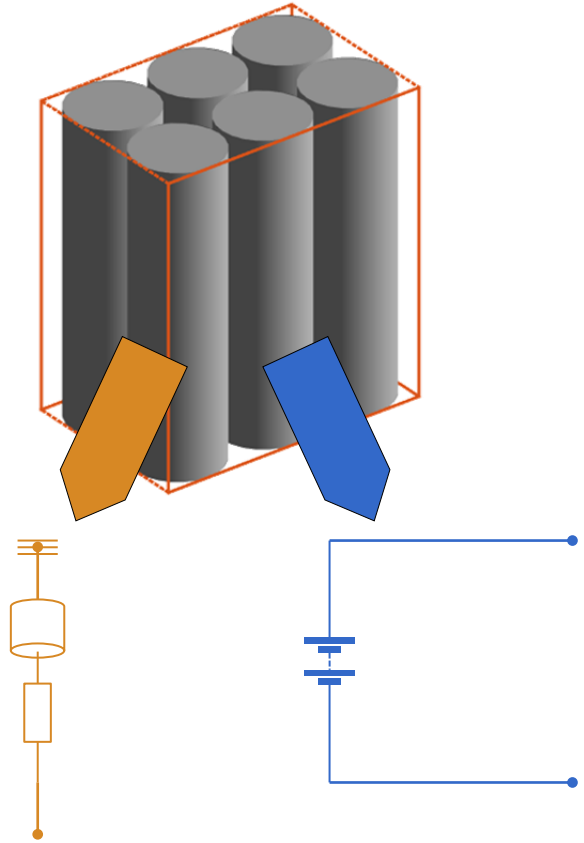
Grouped

Implementation

Selected a *Grouped* model resolution by dividing each module in four cell groups.

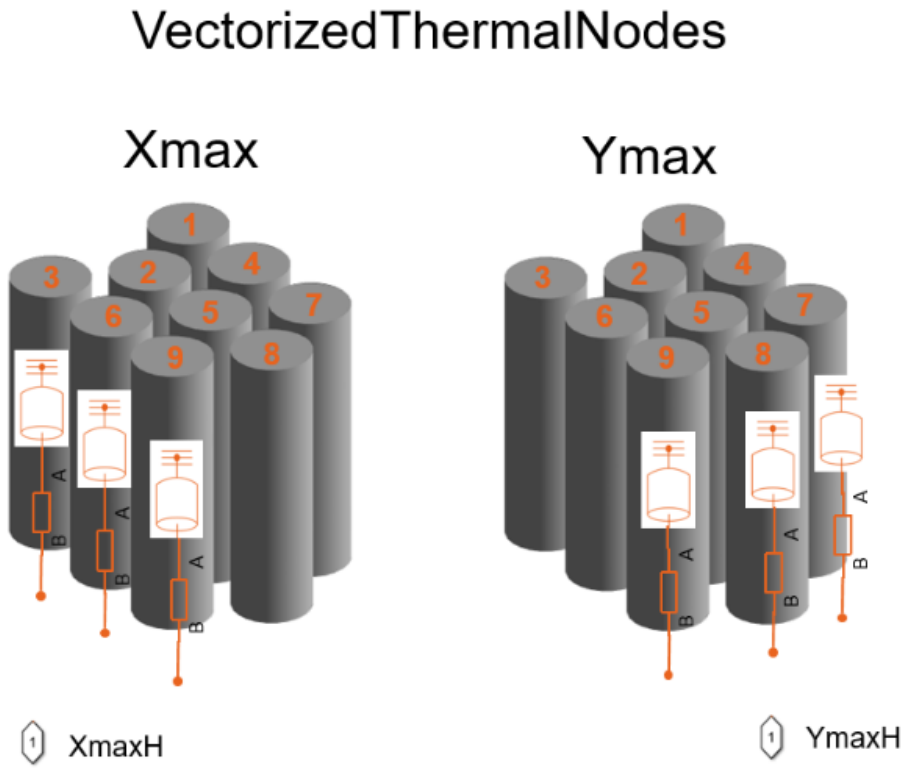


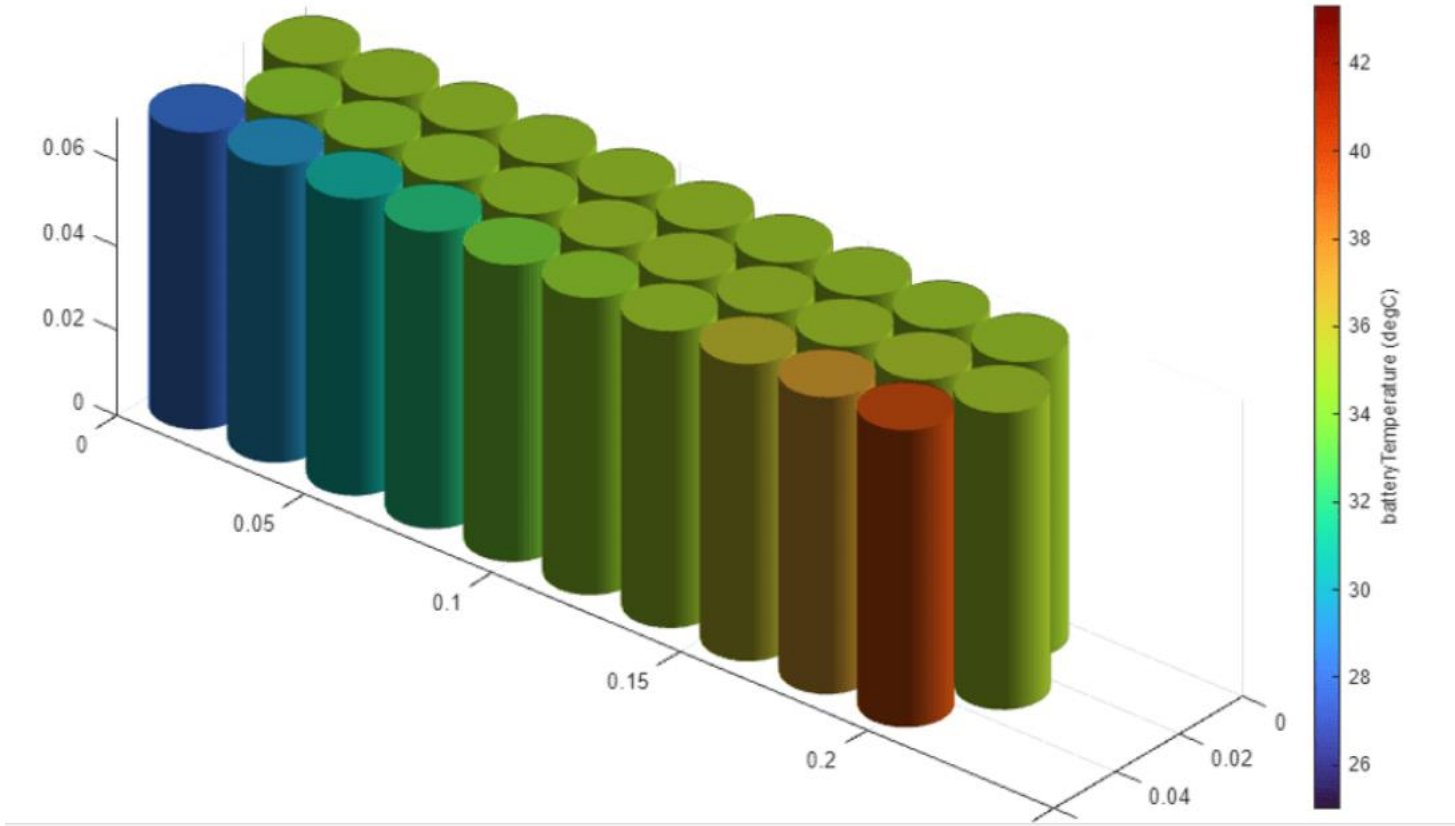
Lumped



» More to Model Resolution

电池模型添加热边界条件





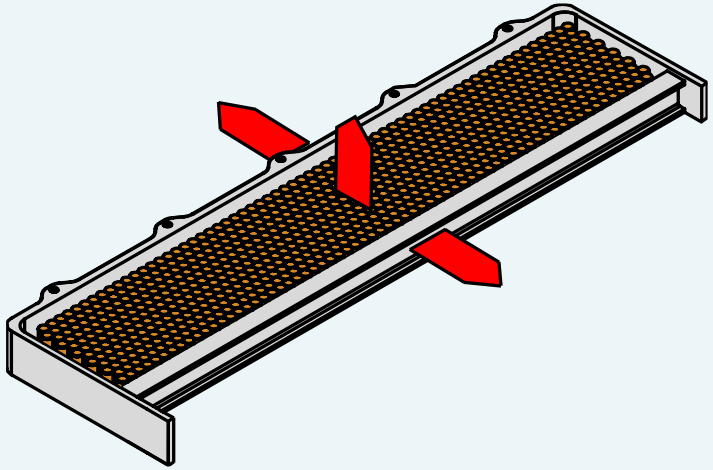
[Add Vectorized and Scalar Thermal Boundary Conditions to Battery Models - MATLAB & Simulink (mathworks.com)]

电池包热行为建模

单体间热传导、热交换和热辐射建模

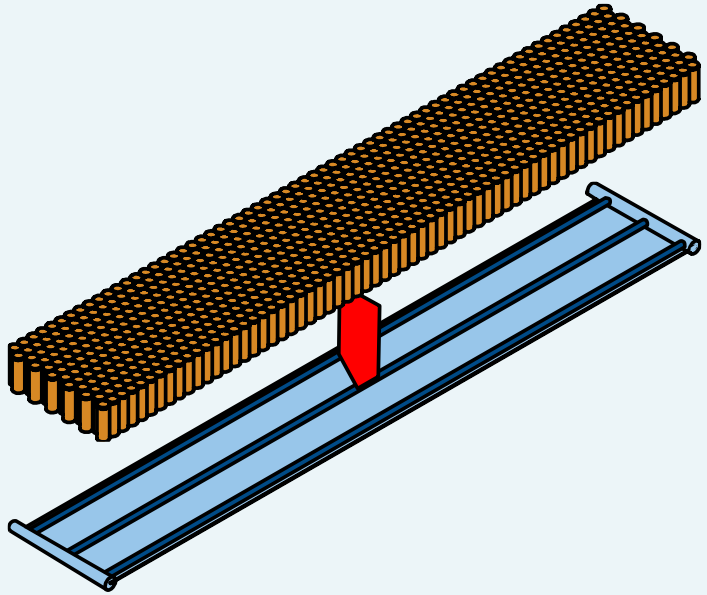
与环境

应用

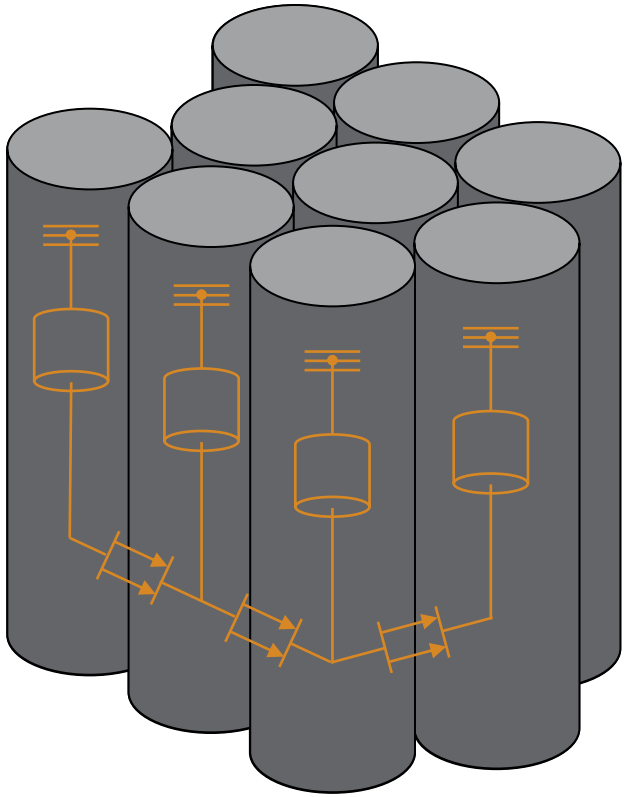


与冷却板

应用

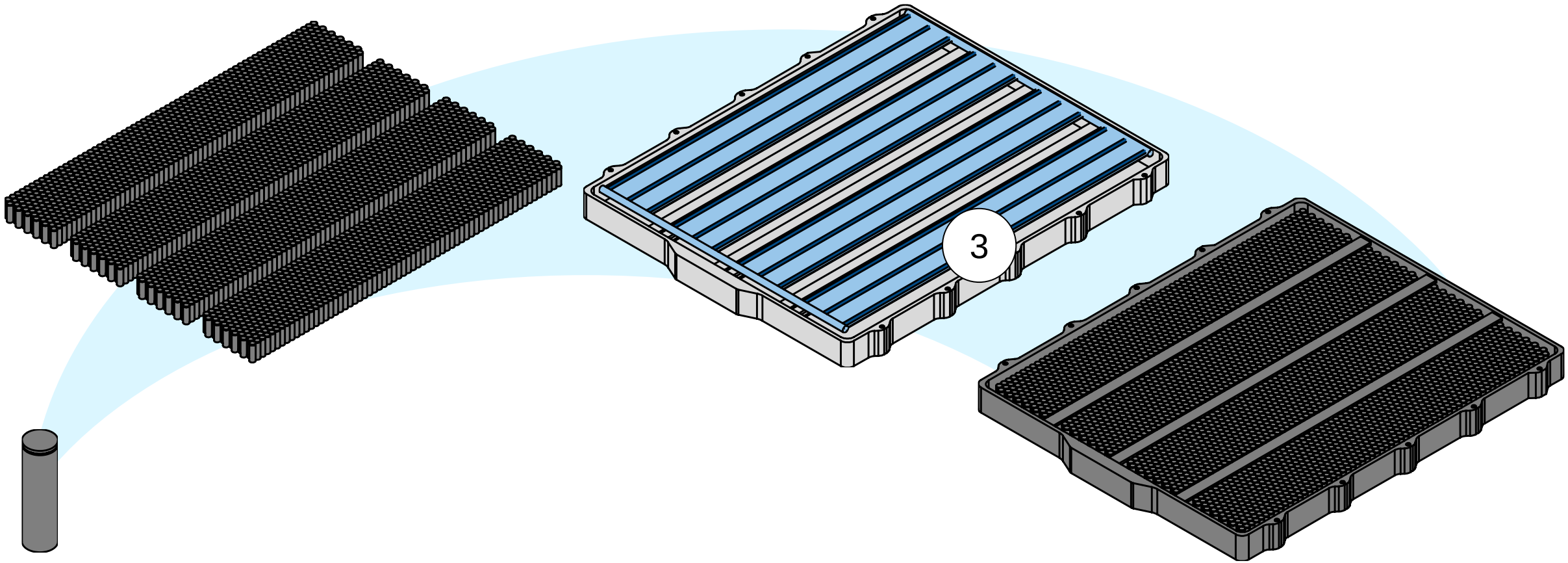


单体间

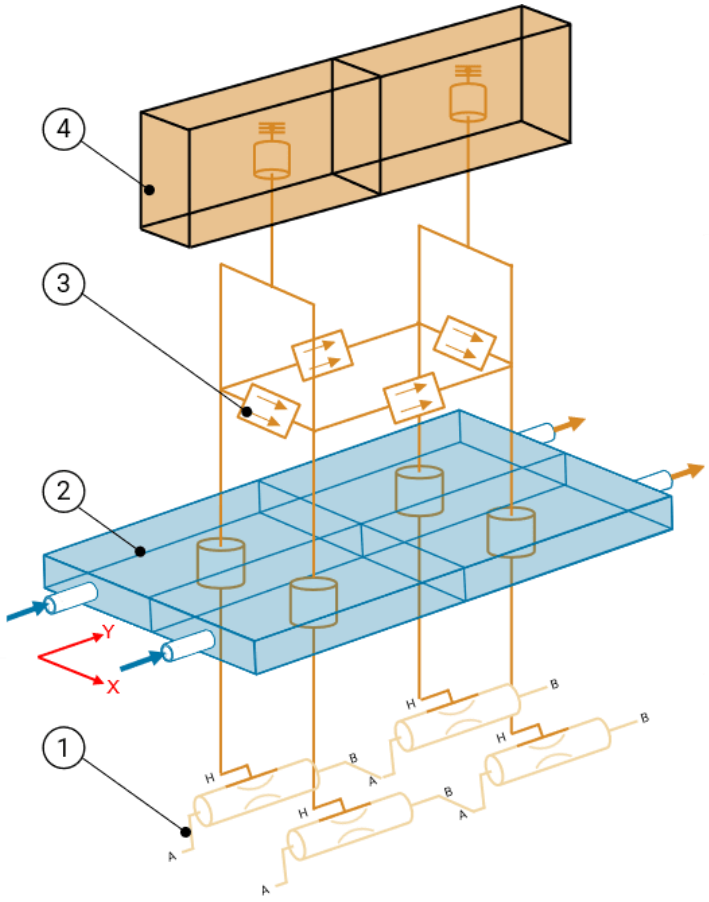


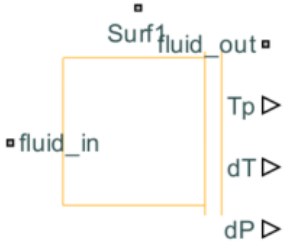
从单体到电池包: 快充工况下行为仿真

冷却系统匹配与部件选型

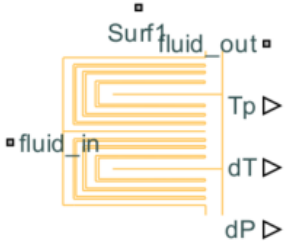


冷却板建模

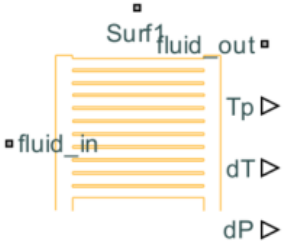




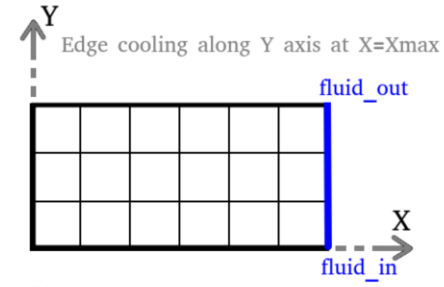
Edge Cooling

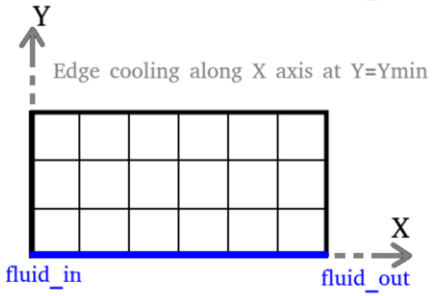


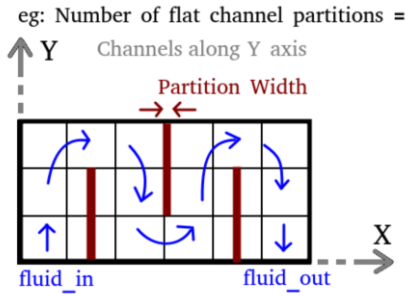
U-shaped Channels

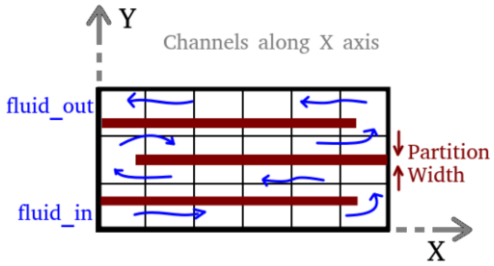


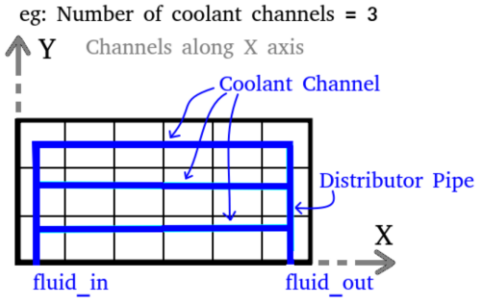
Parallel Channels

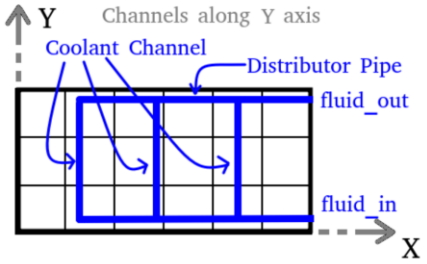












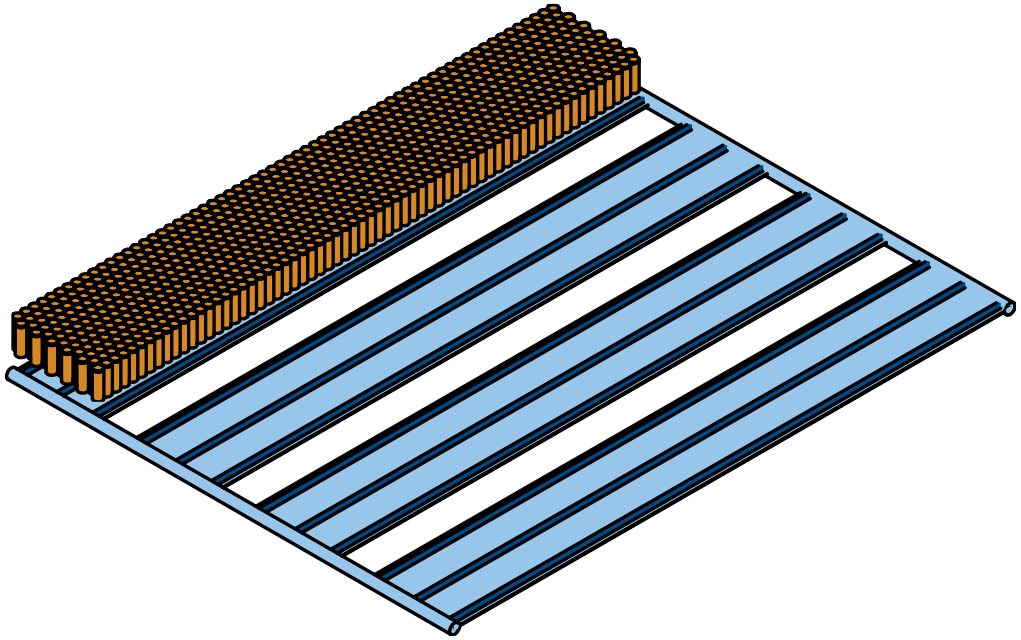
冷却系统匹配和部件选型

选择冷却板拓扑结构

- 冷却板模块模拟电池、液冷系统以及环境之间的传热
- 不同的冷却板拓扑结构
  - 边冷，并行流道，U形流道
  - 单边板、双边板
- 适配模型精度

应用

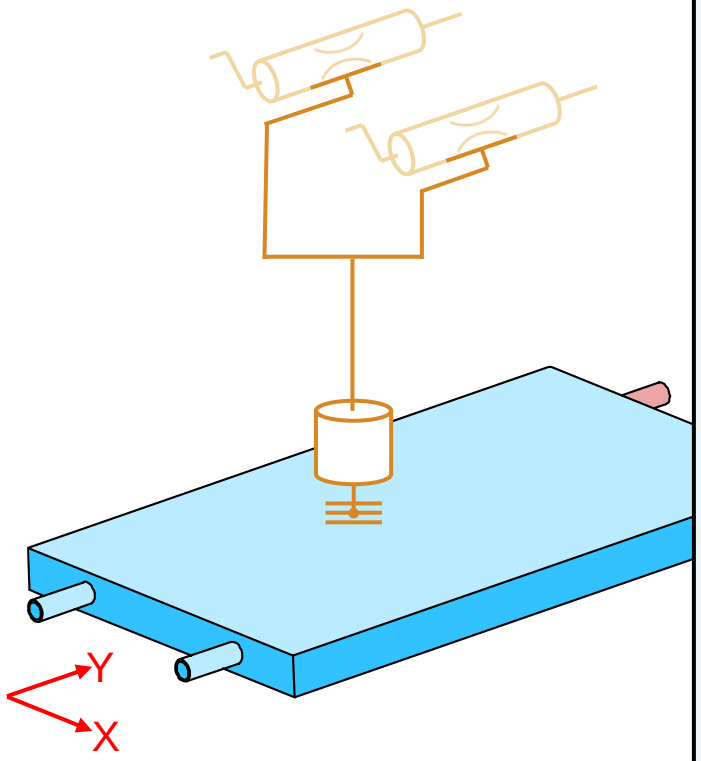
- 并行流道冷却板
- 每个模组3通道 (共12条流道)
- 液流方向沿模组长度方向



平衡仿真速度和精度

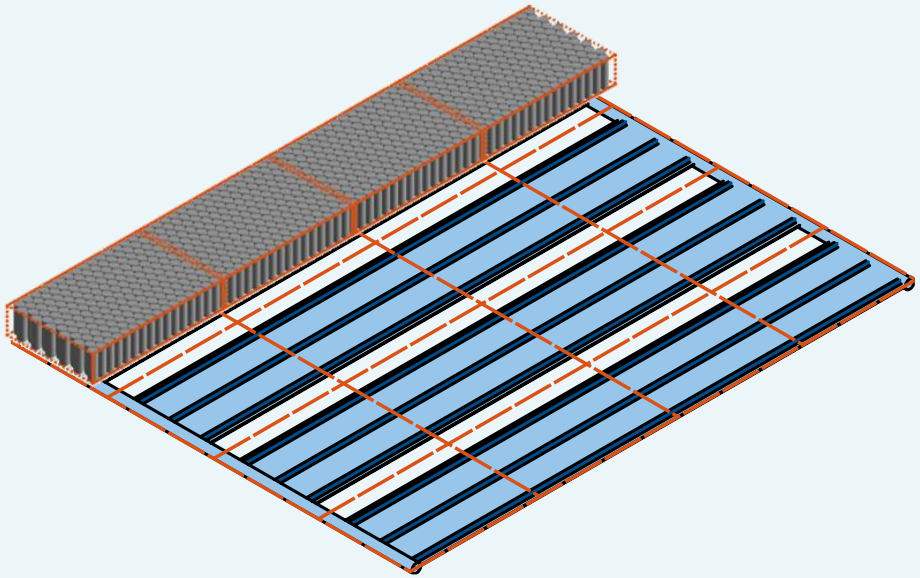
选择合适的冷却板模型精度

集总模型

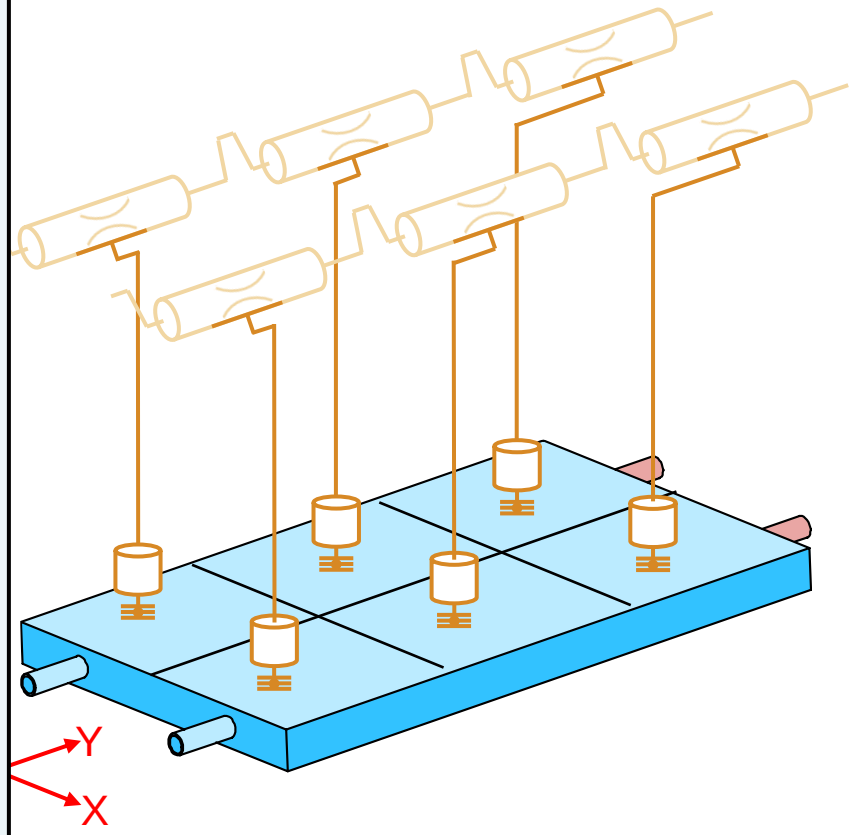


应用

冷却板被离散成分为4X4布局

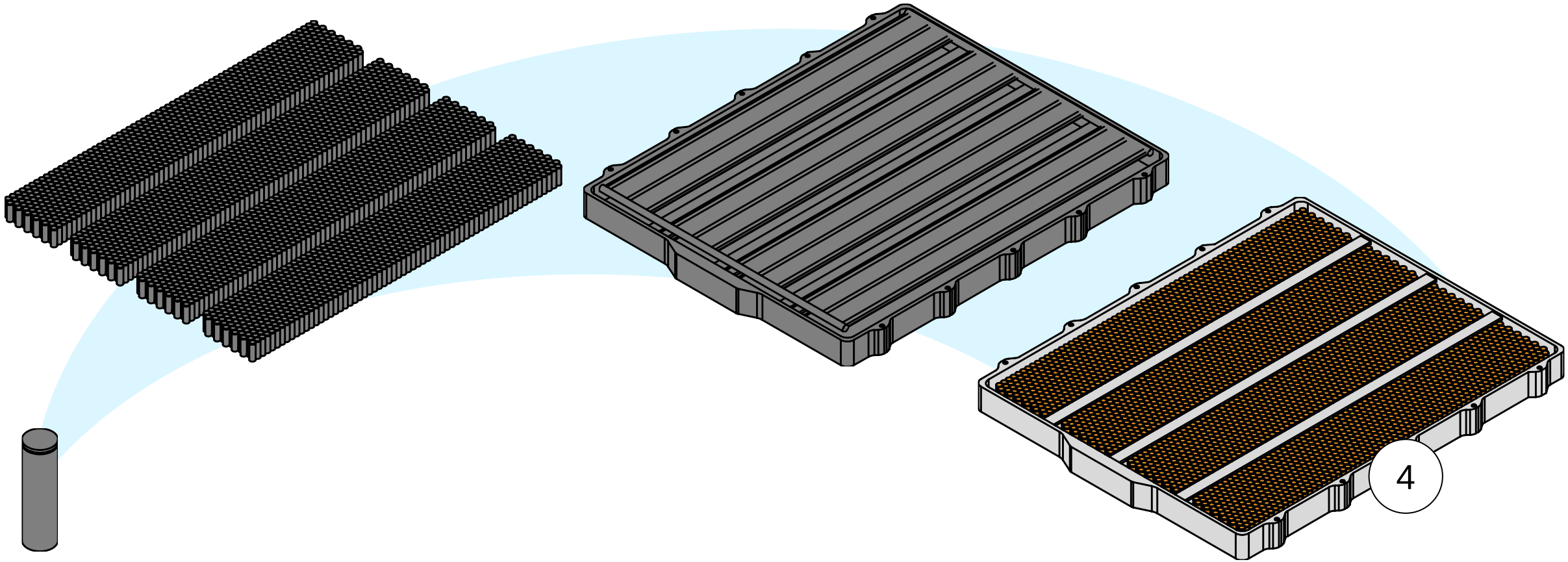


沿X,Y向切分



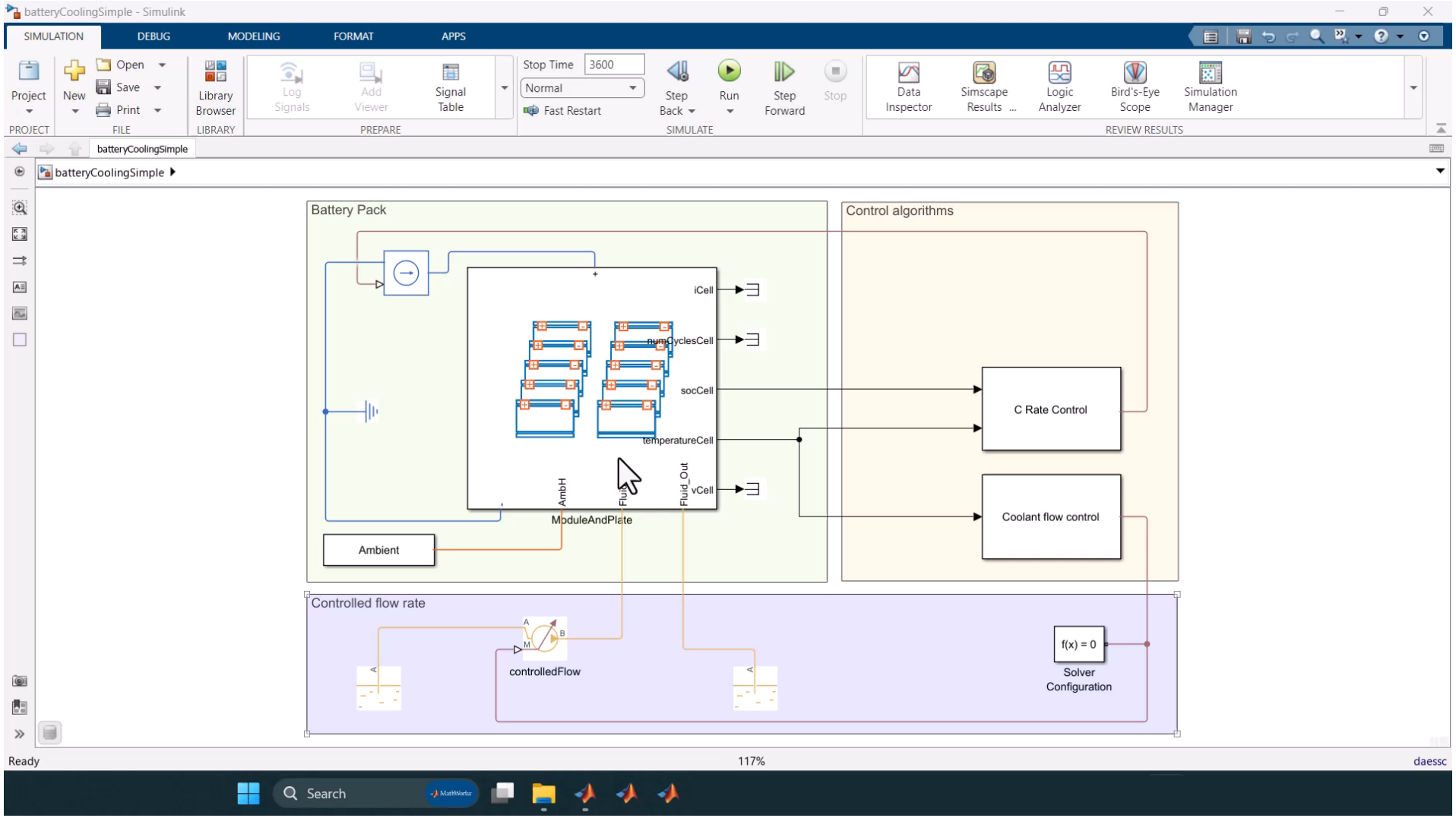
从单体到电池包: 快充工况下行为仿真

仿真快充工况下系统行为



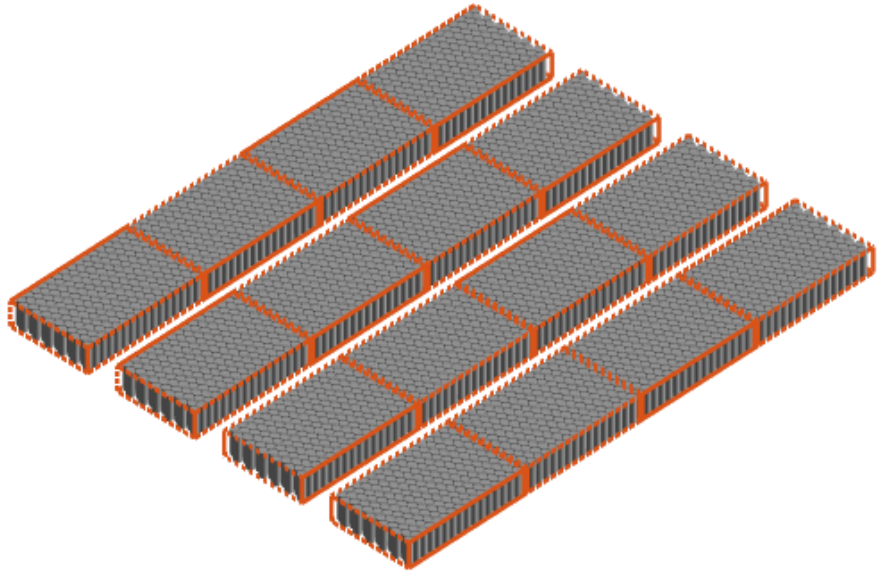
快充工况行为仿真

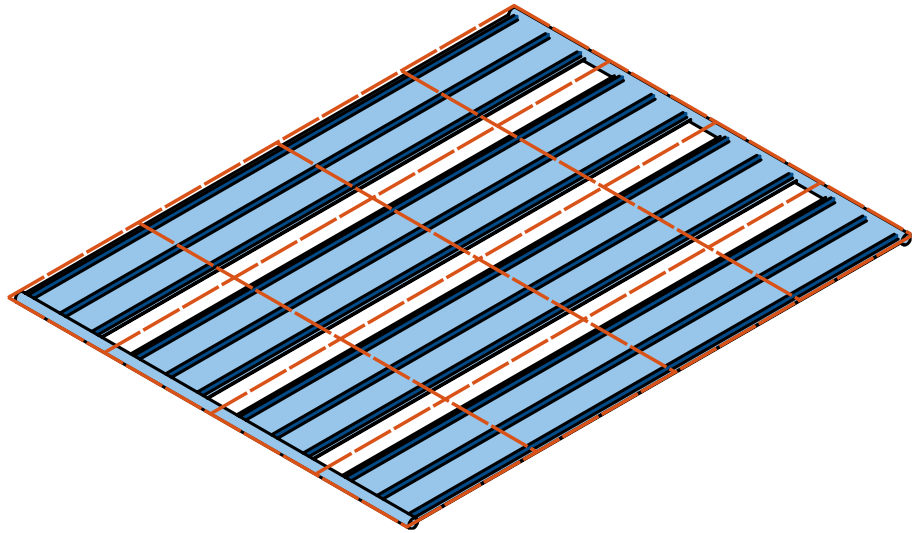
理解模型应用



快充工况行为仿真

结果





电动车热管理

Electric Vehicle Thermal Management

1. Configure scenario (see code):
   (i) drive cycle, (ii) cool down, (iii) cold weather
2. Plot power consumption in the system (see code)
3. Open Model Workspace to explore parameters (see definition script)
4. Explore simulation results using Simscape Results Explorer
5. Learn more about this example

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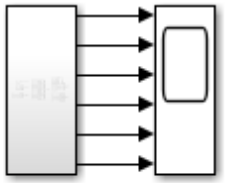
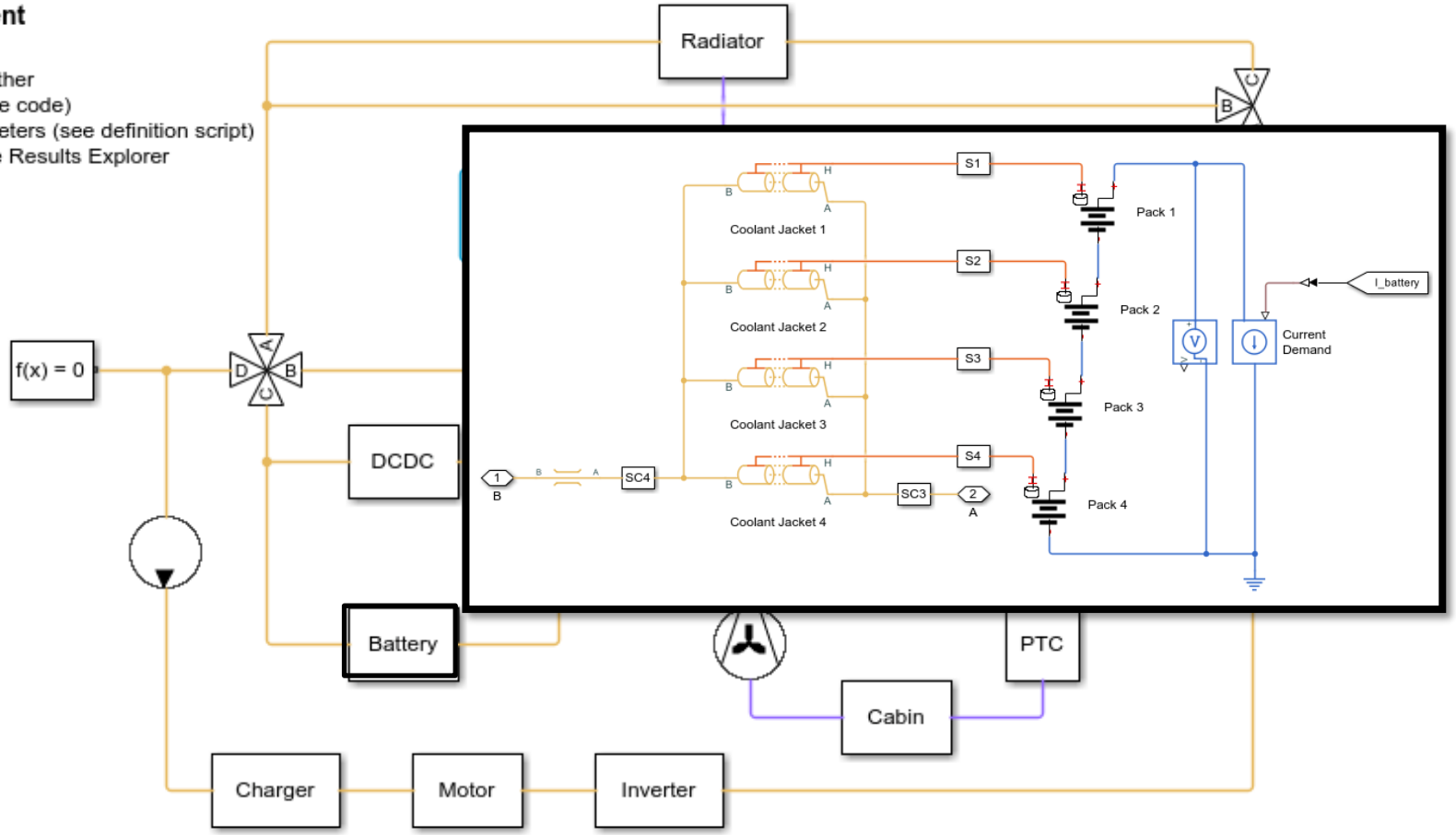
Scenario
drive cycle

Controls

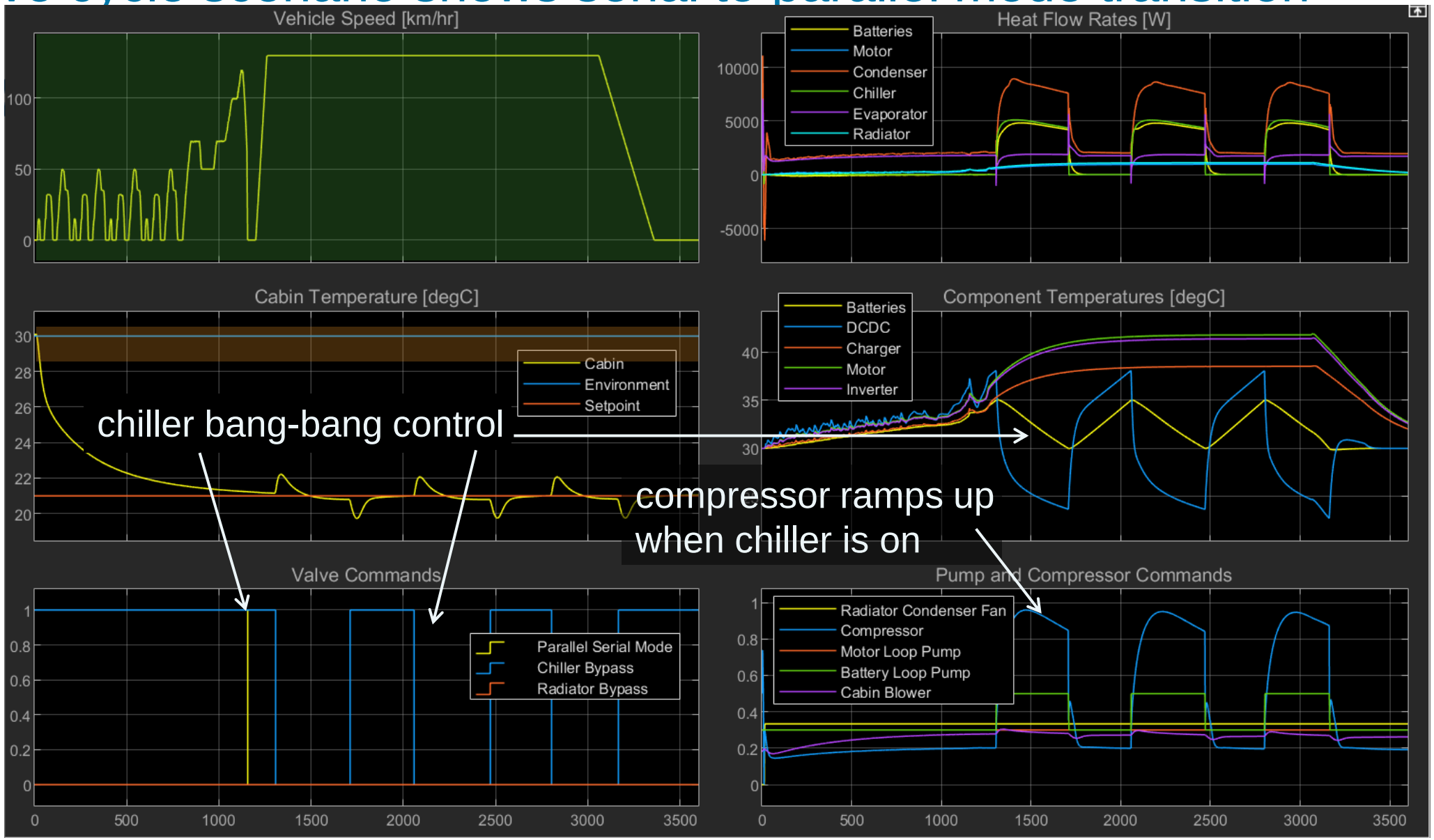


Measurements

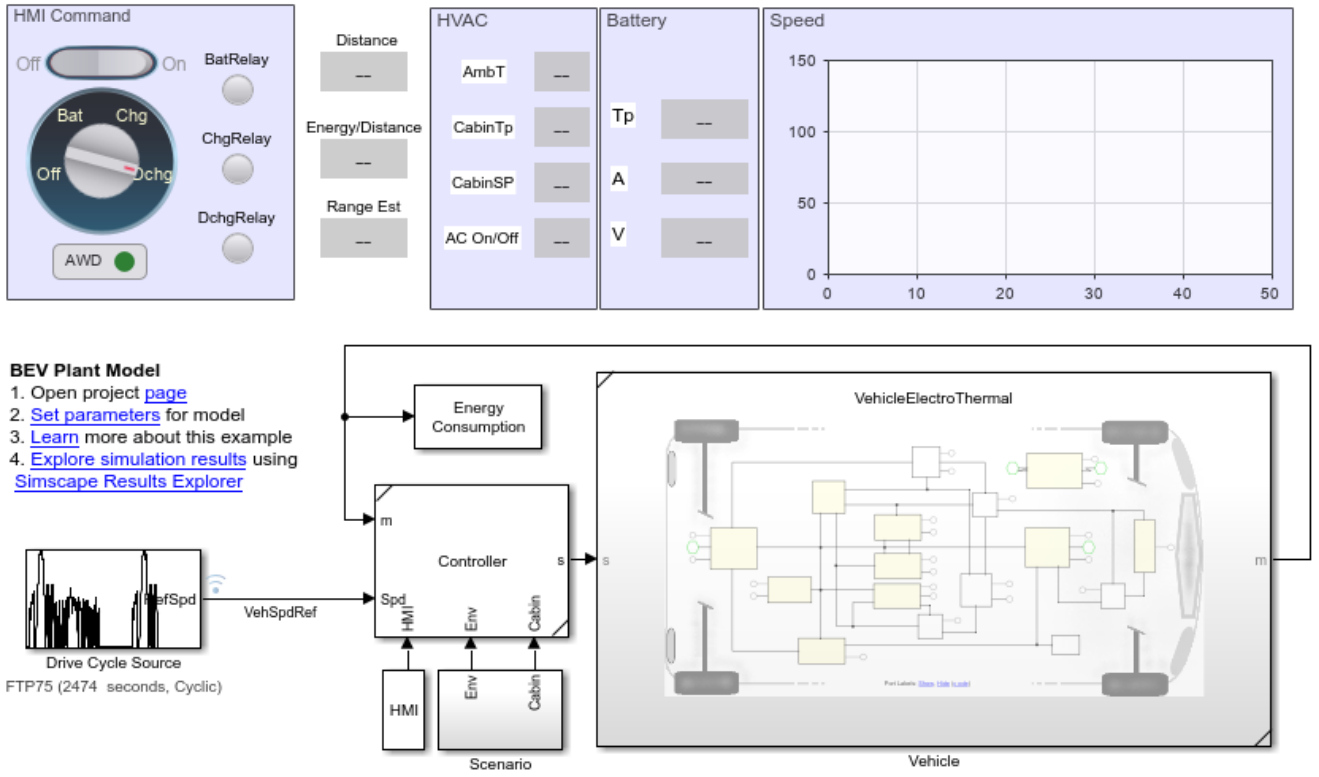


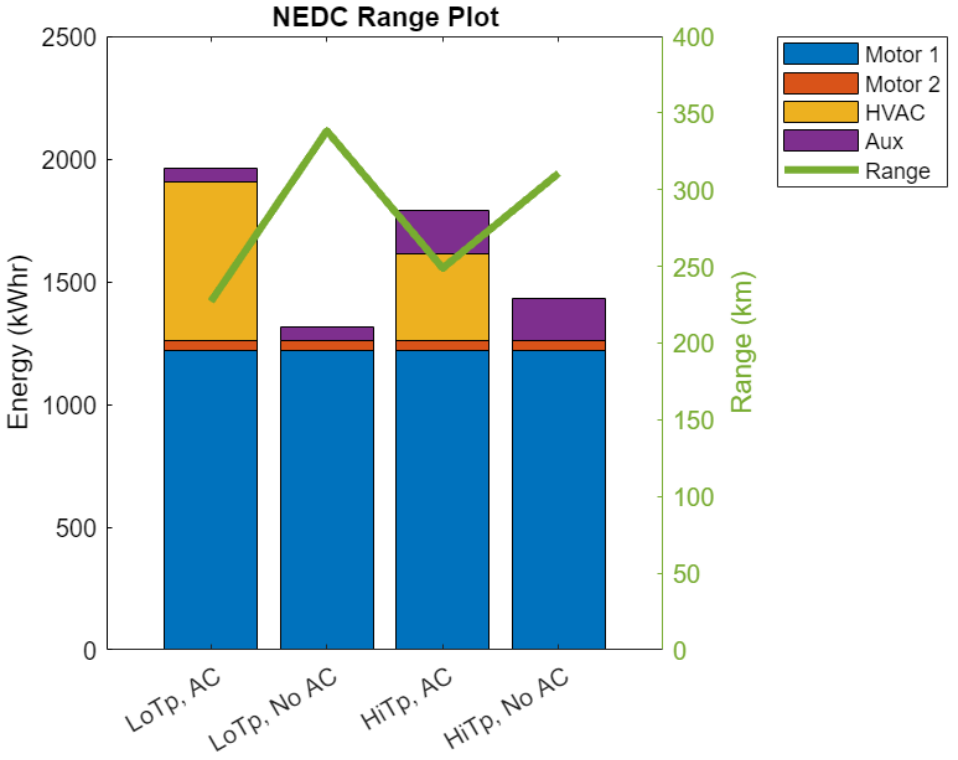
» EV Thermal Management System

Drive cycle scenario shows serial to parallel mode transition



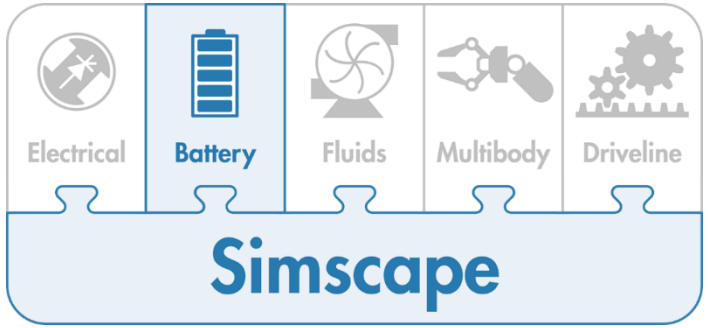
不同操作工况和环境条件下，续航里程估计





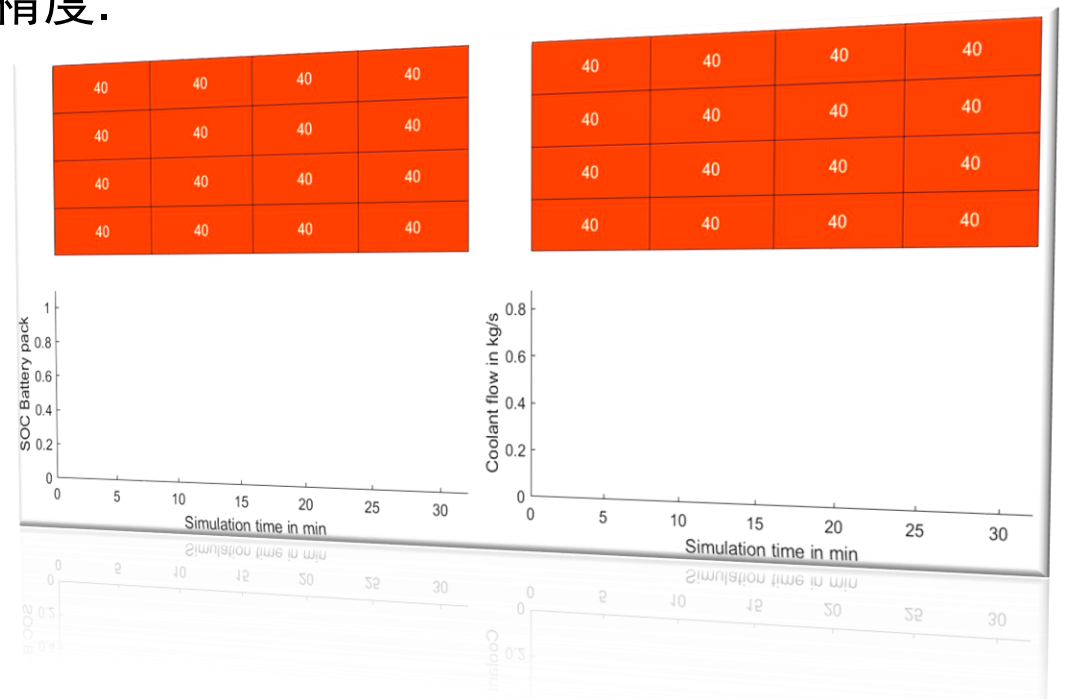
» EV Range Estimation at different environment and operating conditions

总结



- 重点:
  - Simscape Battery 是一款强有力的仿真工具，可以帮助用户进行电池包级别的电热仿真.
  - 使用Battery Builder 可以方便地生成电池包模型
  - 支持用户方便地根据自己的需求选取适配的模型精度.

- 应用:
  1. 汽车动力电池系统电热建模仿真
  2. 耦合液冷系统
  3. 快充工况下，电池包温度仿真分析
  4. 电动汽车热管理



学习资源

- 免费培训

  MATLAB Onramp

  Simulink Onramp

  Simscape Onramp

  Simscape Battery Onramp

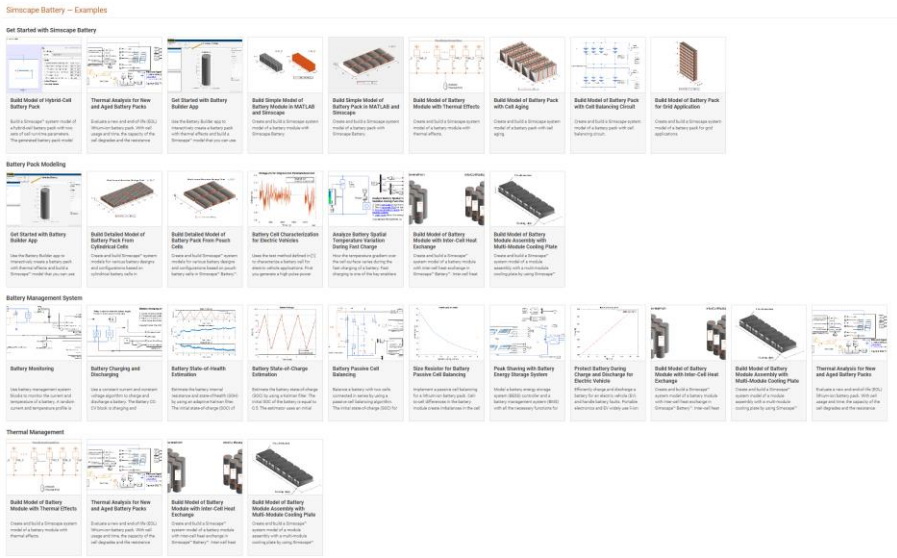
  Simscape Battery Essentials

- 付费培训

  Battery Modeling and Algorithm Development with Simulink (Instructor-led)

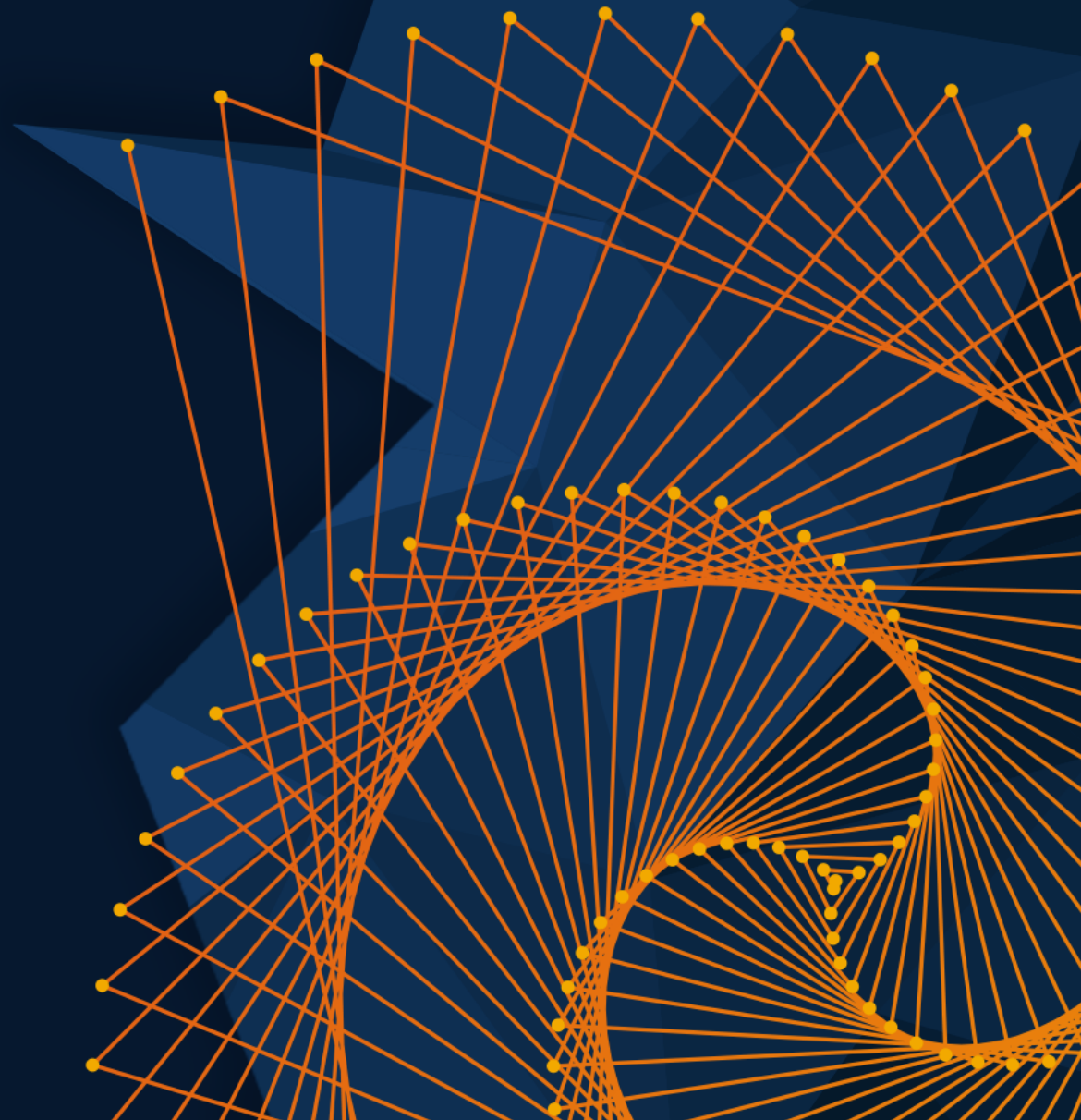
- Shipping Examples

  Simscape Battery — Examples



MATLAB EXPO

谢 谢



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