2024 MathWorks
中国汽车年会

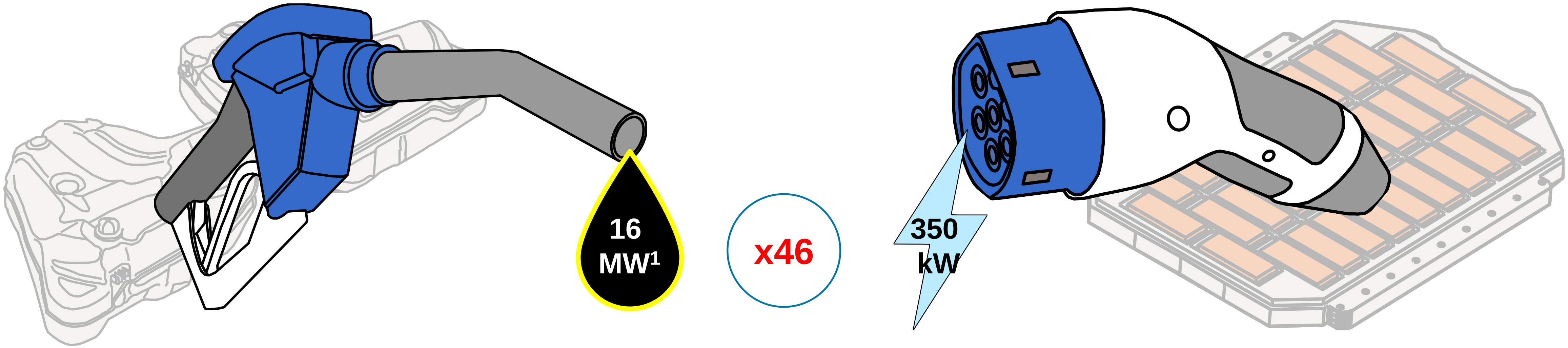
快速充电探索: 从电芯到电池组的仿真 Simscape Battery 新功能

杨兴, MathWorks

MathWorks

为什么提及电池快充

和燃油车对比

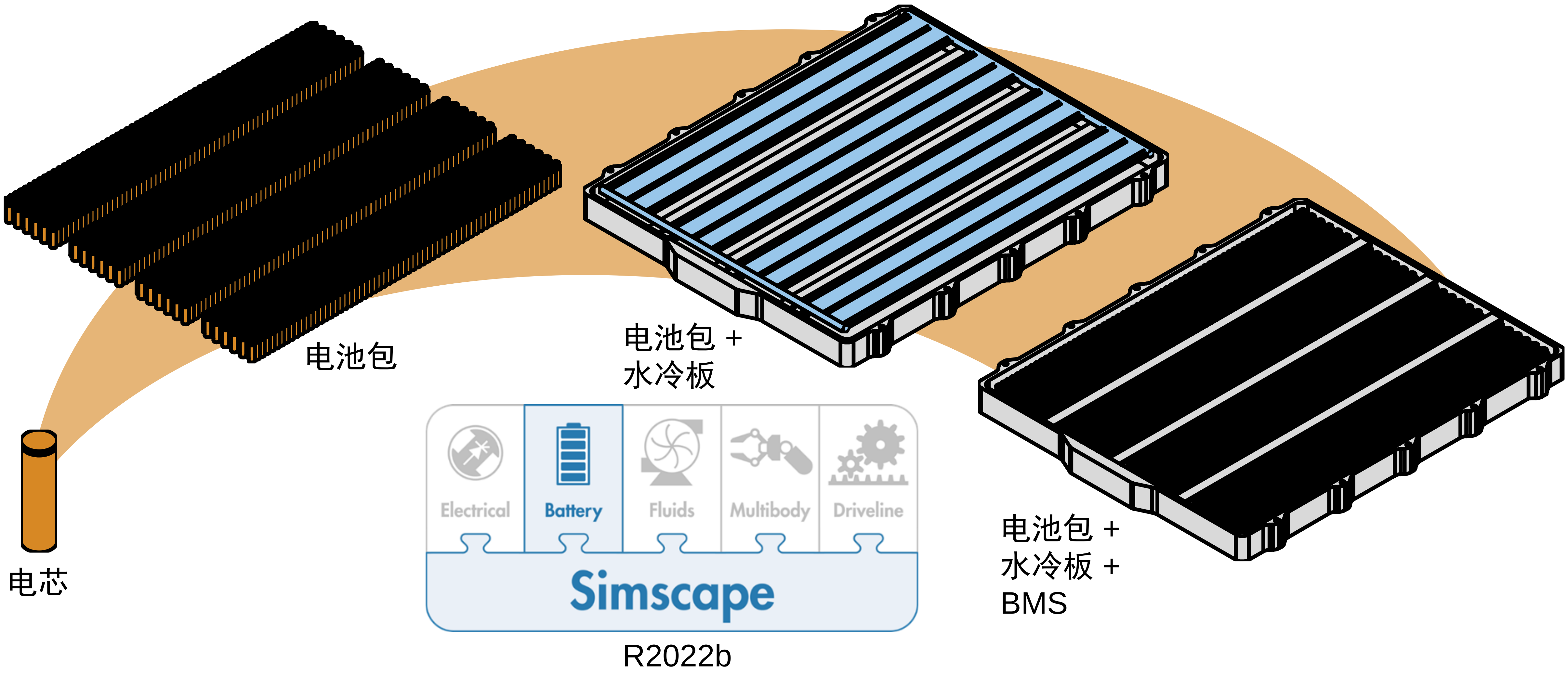


- 电池快充任务经常需要对电芯特性行为有更深入的研究
- 不合适的电池快充策略会加速电芯老化
- 需要有恰当的**温度和电流控制**
- 这个复杂领域的探讨，离不开**仿真模型**

[1]M. Sterner, I. Stadler, “Energiespeicher: Bedarf, Technologien, Integration“, 2014

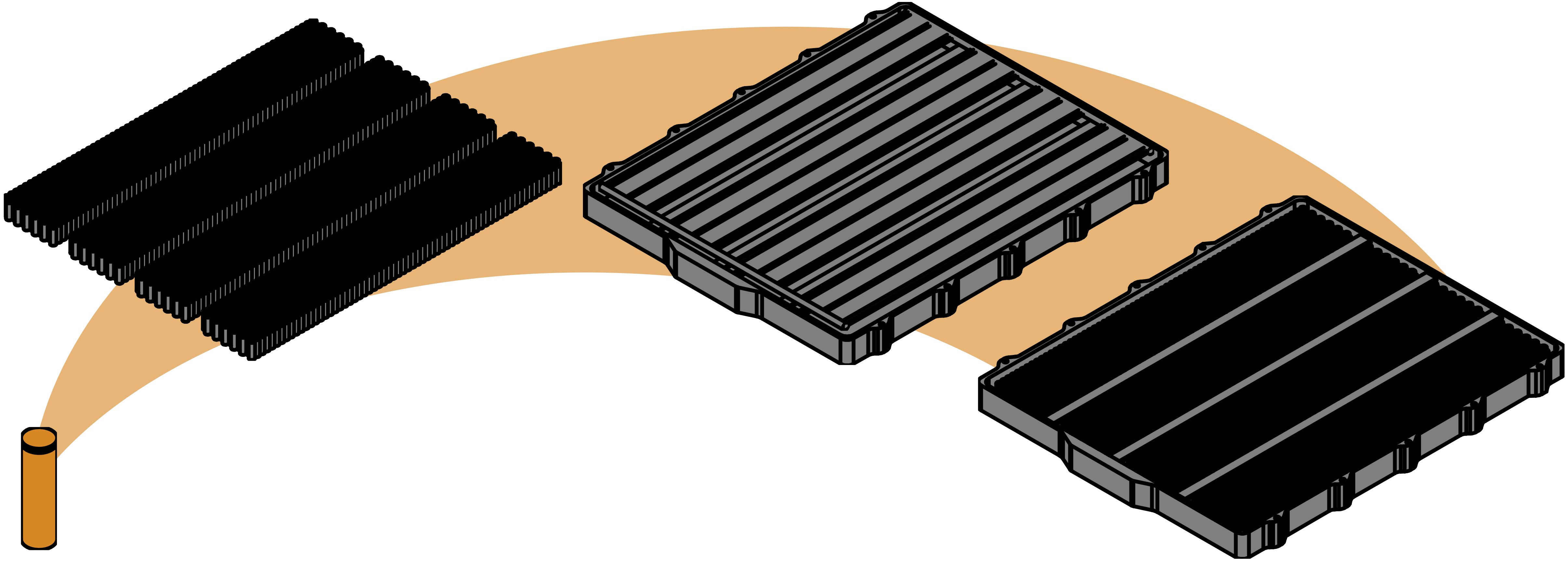
今日大纲

Simscape Battery 新功能



电芯模型

特性与新功能



现有的电芯模型

根据需要选择合适的模型

Battery Equivalent Circuit Block

模拟对象	Battery	Battery (Table-Based)	Battery Equivalent Circuit
Can be used to build packs (Battery Builder or API)	No	Yes	Yes
Electrical parameters (R_0, R_1, C_1…)	Constants	SOC/T dependent	SOC/T dependent
Maximum Number of RC blocks	5	5	3
Hysteresis Model	No	No	Yes
Reversible heat Model	No	No	Yes
Fade and Calendar Aging	No	Yes	Yes
Possibility to Inject Faults	No	No	Yes

新电化学电芯模型

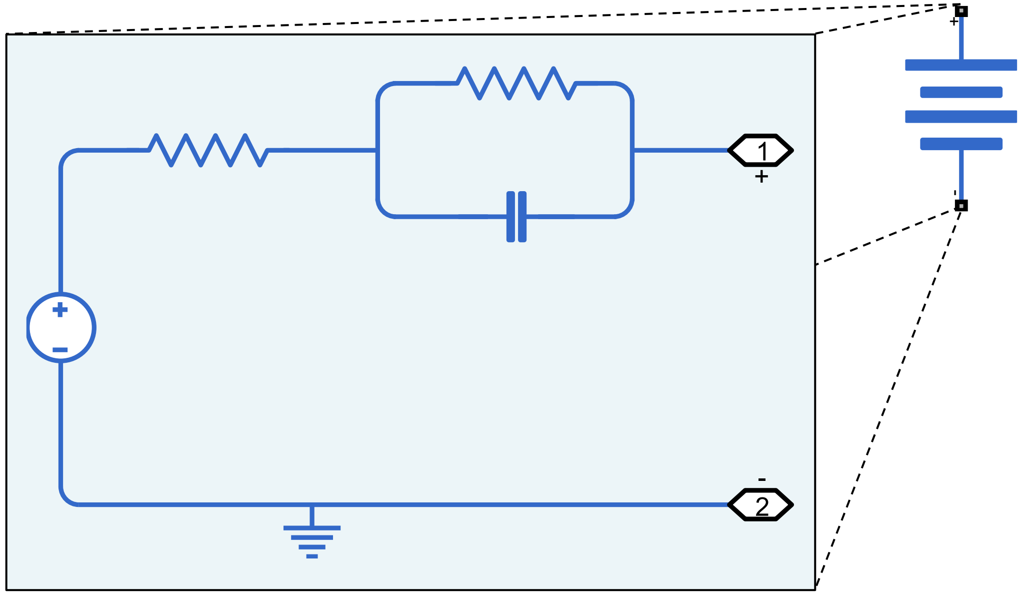
根据需要选择合适的模型

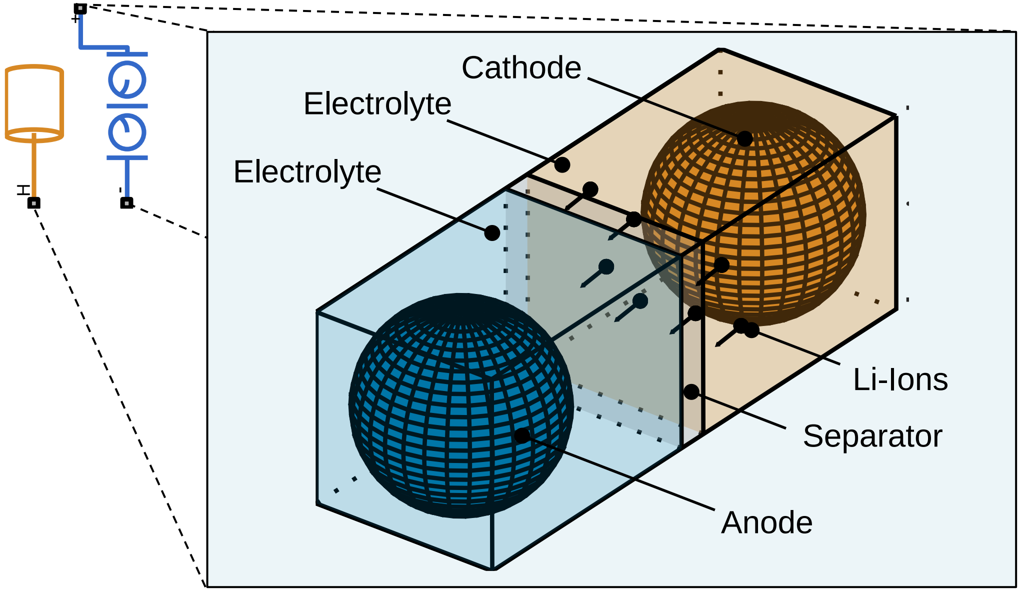
经验模型

- Equivalent Circuit Model (ECM)
- 实现简单且容易理解
- 表达的特性有限

电化学模型 R2024a

- Single Particle Model (SPM)
- 精度提高以及合适的复杂度
- 需要详细的参数





单粒子模型 Single Particle Model

基本假设

Anode Particle

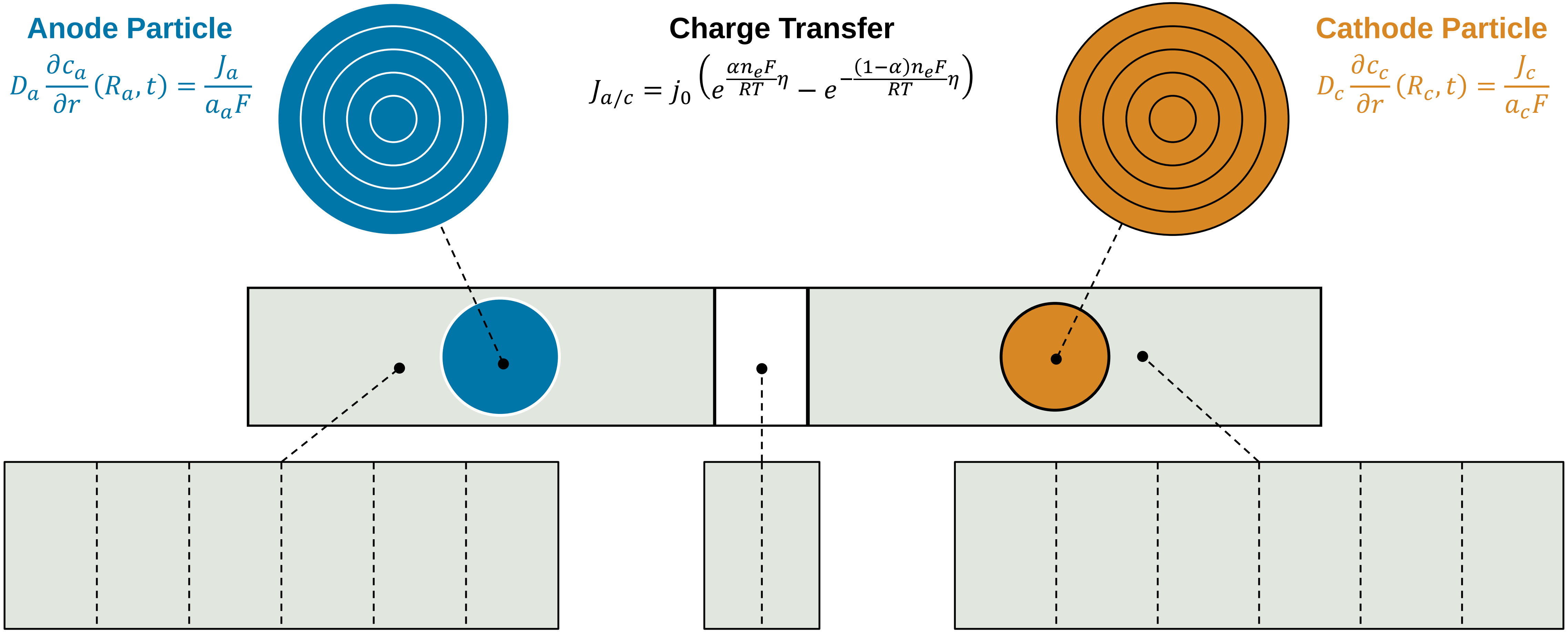
$$D_a \frac{\partial c_a}{\partial r}(R_a, t) = \frac{J_a}{a_a F}$$

Charge Transfer

$$J_{a/c} = j_0 \left(e^{\frac{\alpha n_e F}{RT}\eta} - e^{-\frac{(1-\alpha) n_e F}{RT}\eta} \right)$$

Cathode Particle

$$D_c \frac{\partial c_c}{\partial r}(R_c, t) = \frac{J_c}{a_c F}$$



Electrolyte Anode Side

$$\varepsilon_a \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left(D_e \frac{\partial c_e}{\partial x}(x,t) - \frac{J_a(1 - t_0^+)}{F} \right)$$

Separator

$$\frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left(D_e \frac{\partial c_e}{\partial x}(x,t) \right)$$

Electrolyte Cathode Side

$$\varepsilon_c \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left(D_e \frac{\partial c_e}{\partial x}(x,t) + \frac{J_c(1 - t_0^+)}{F} \right)$$

单粒子模型 Single Particle Model

模块参数化

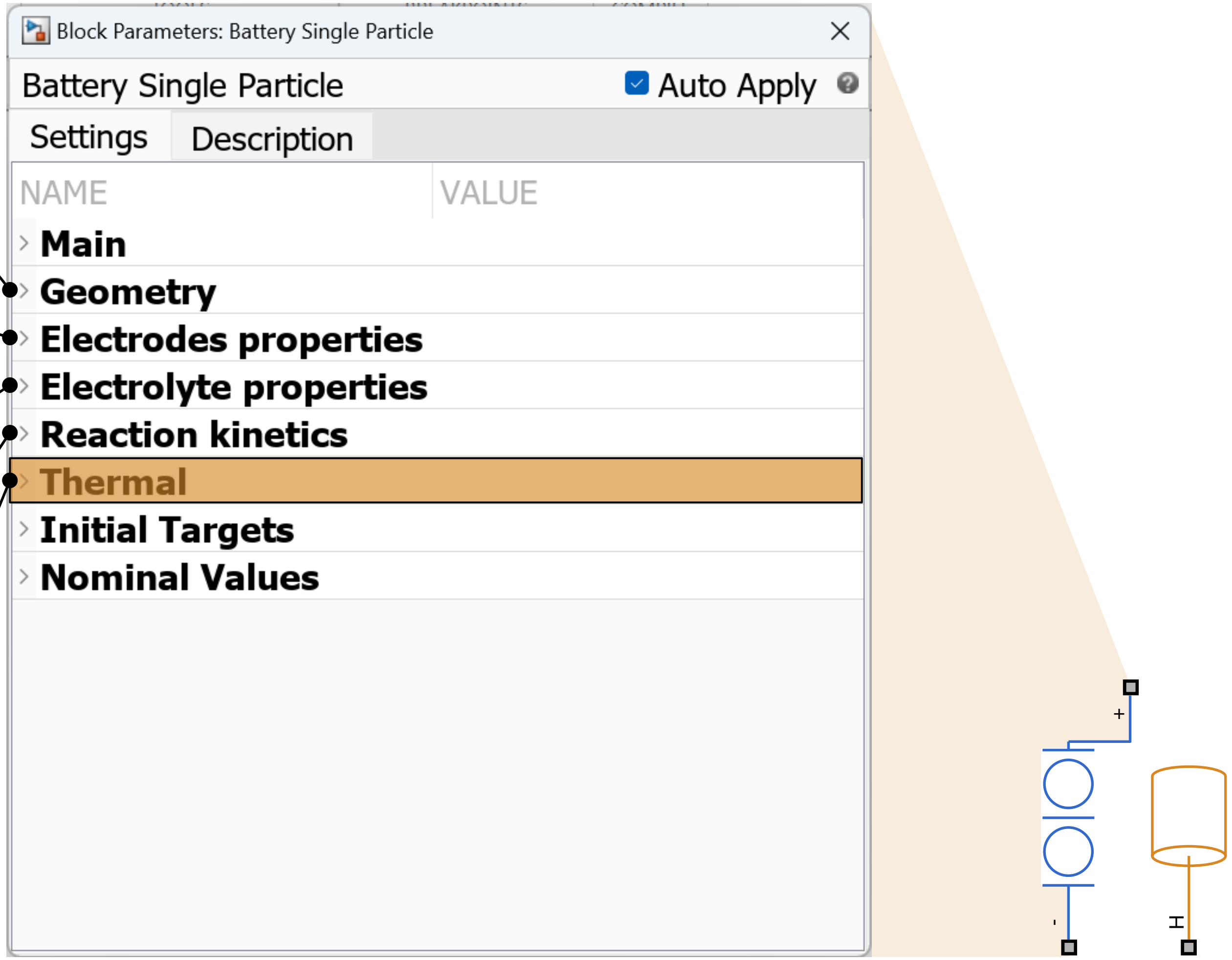
电极/隔膜/电解质区域的
几何尺寸以及离散化设置

电极材料属性，比如扩散率、电导率、
活性材料体积分数等等

电解质属性，比如体积分数、电导、
扩散率，迁移数等等

电极电荷转移常数

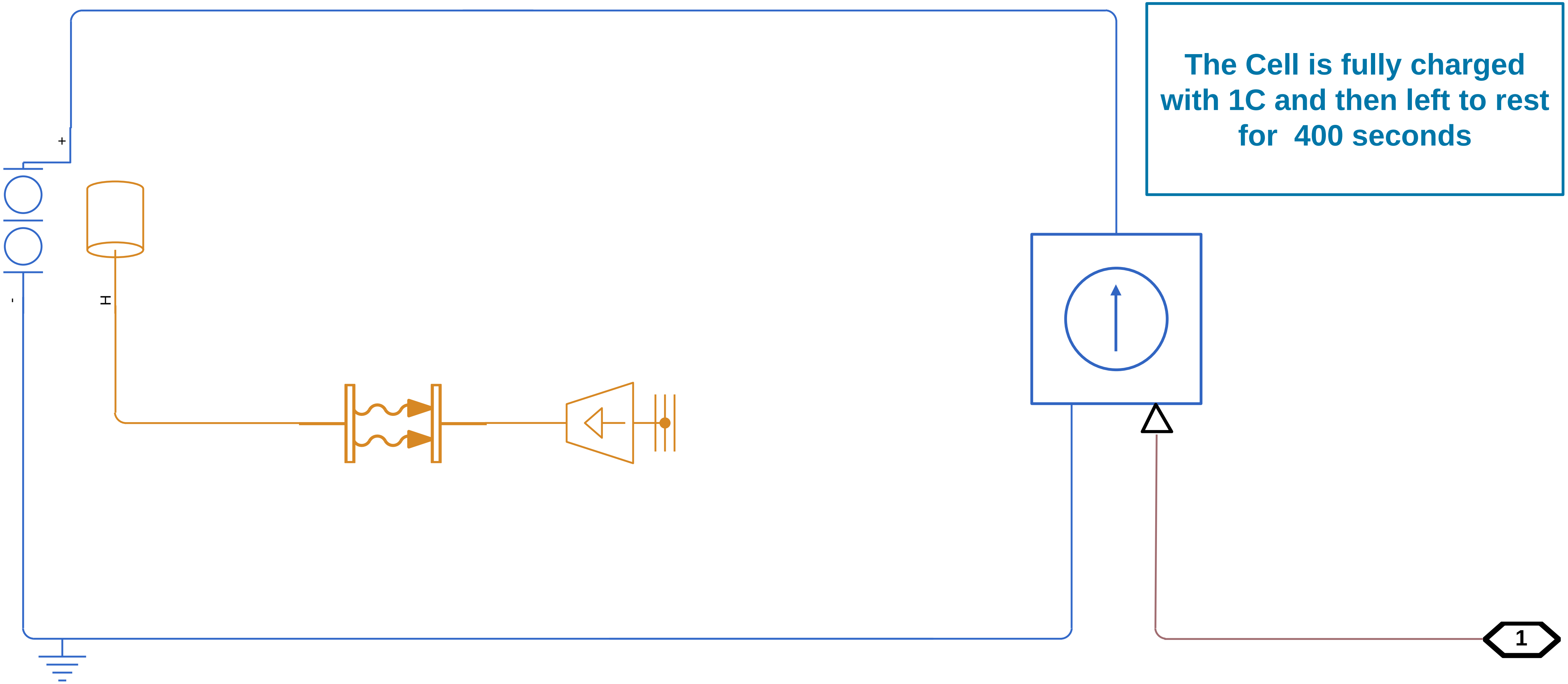
热质以及材料活化能



» [Battery Single Particle]

单个充电周期

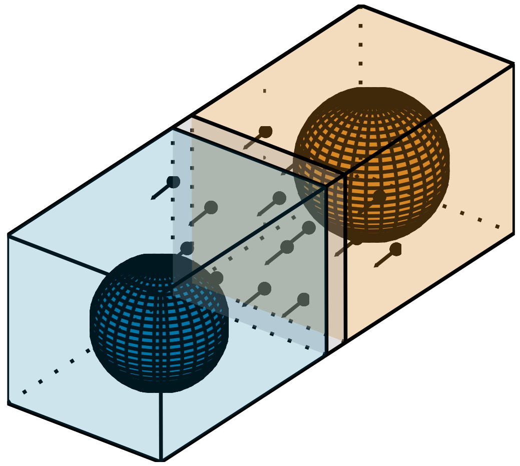
SPM 模型



The Cell is fully charged with 1C and then left to rest for 400 seconds

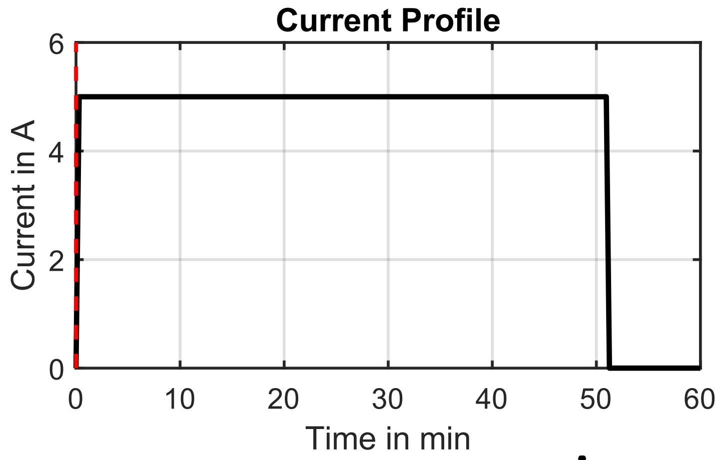
Simscape Battery 的电化学模型

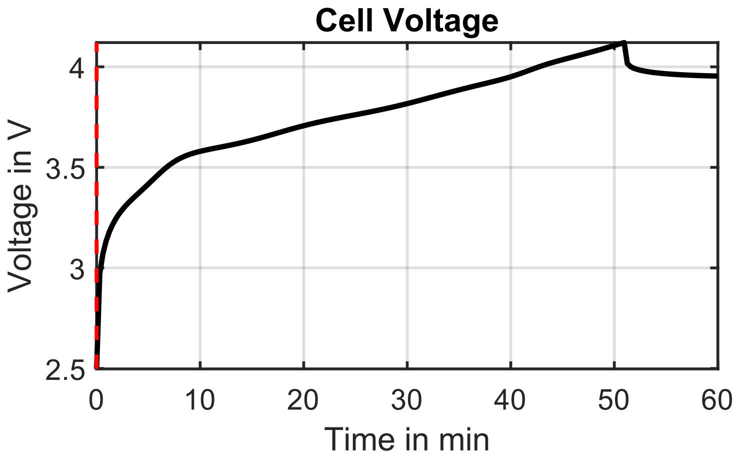
充电过程 (from 0% to 80% SOC)

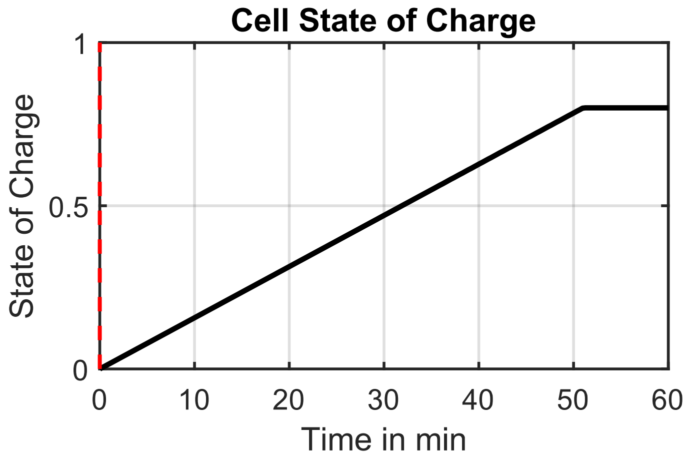


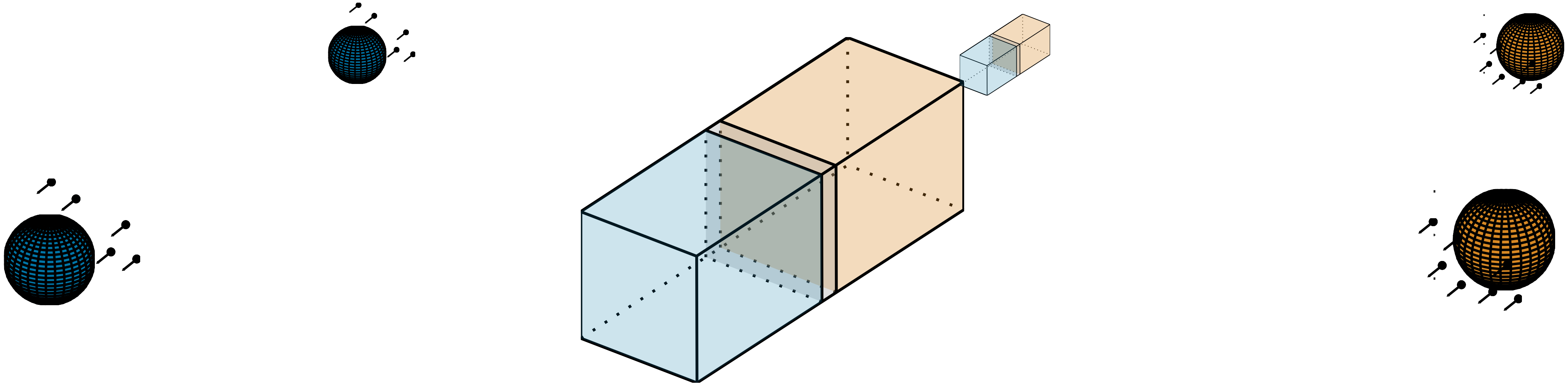
Simscape Battery 的电化学模型

充电过程 (from 0% to 80% SOC)



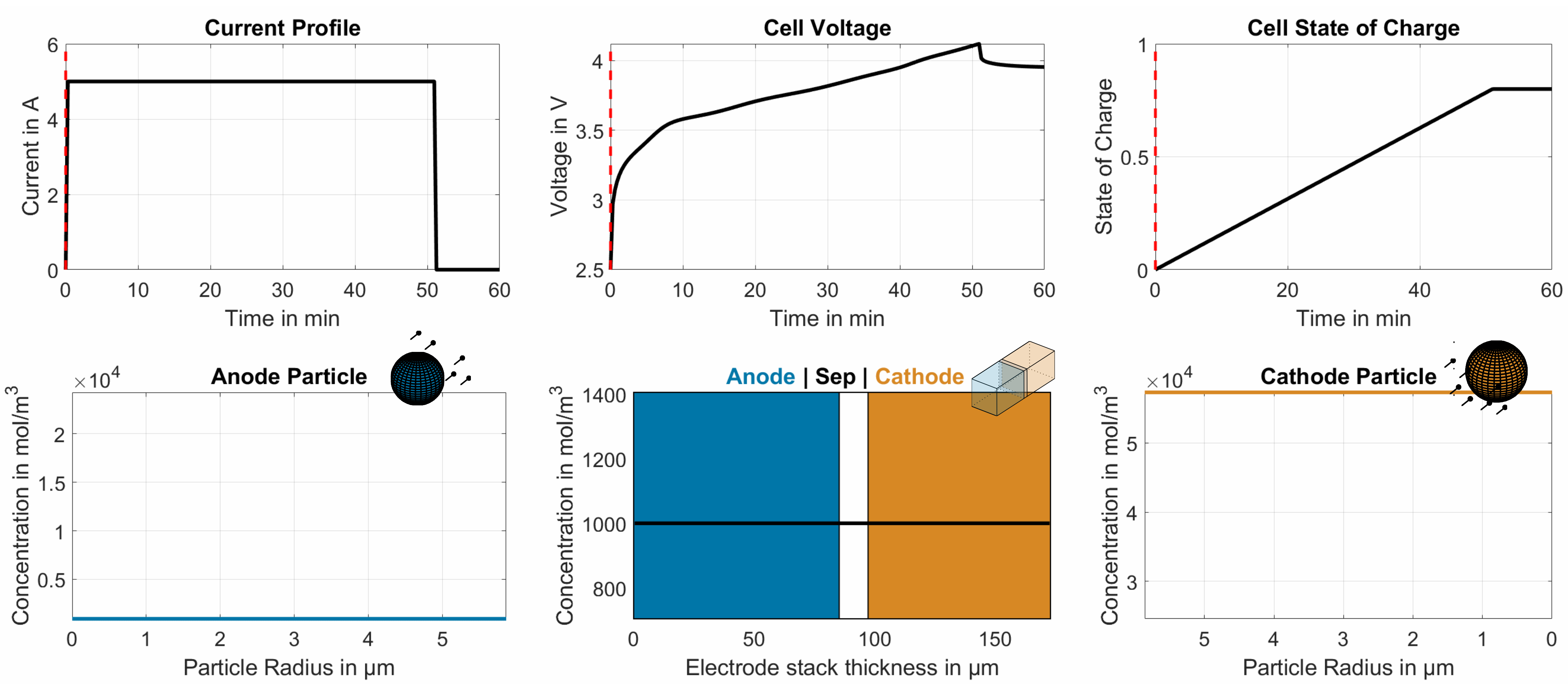






Simscape Battery 的电化学模型

充电过程 (from 0% to 80% SOC)



SPM 模型开源

基于现有的模型基础框架轻松修改

```
component batterySingleParticle
    % Battery Single Particle
    % This block models the battery using the single-particle approach
    % The block considers the open-circuit potential and the overpoten
    % The block determines the mass transport overpotential for the el
    % by modeling the concentration of the active material within a re
    % Similarly, the block obtains the mass transport overpotential fo
    % by modeling the concentration of the active material in the elec
    % across the cell's cross section.
    % To account for the overpotential from the reaction kinetics, the
    % Thermally, a lumped thermal mass represents the battery and ohmi

    % Copyright 2023 The MathWorks, Inc.


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

    parameters
        % Main
        ExtrapolationMethod = simscape.enum.extrapolation.nearest;

        % Geometry
        ThicknessAnode = {3.4E-5,"m"};
        ElectrolyteLayerCountAnode = 10;
        ThicknessSeparator = {2.5E-5,"m"};
        ElectrolyteLayerCountSeparator = 5;
```

Block Parameters: Battery Single Particle

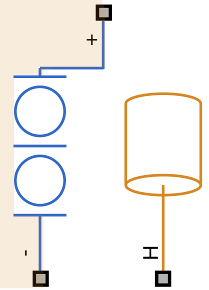
Battery Single Particle ☑ Auto Apply

Settings | Description

Battery Single Particle

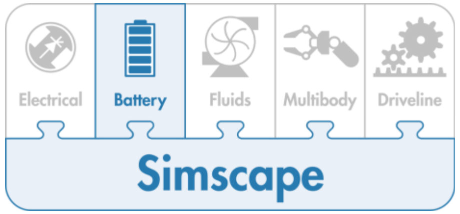
This block models the battery using the single-particle approach. The block considers the open-circuit potential and the overpotentials from the mass transport and reaction kinetics. The block determines the mass transport overpotential for the electrode by modeling the concentration of the active material within a representative spherical particle. Similarly, the block obtains the mass transport overpotential for the electrolyte by modeling the concentration of the active material in the electrolyte across the cell's cross section. To account for the overpotential from the reaction kinetics, the block analytically solves the Butler-Volmer equation. Thermally, a lumped thermal mass represents the battery and ohmic losses are taken into account.

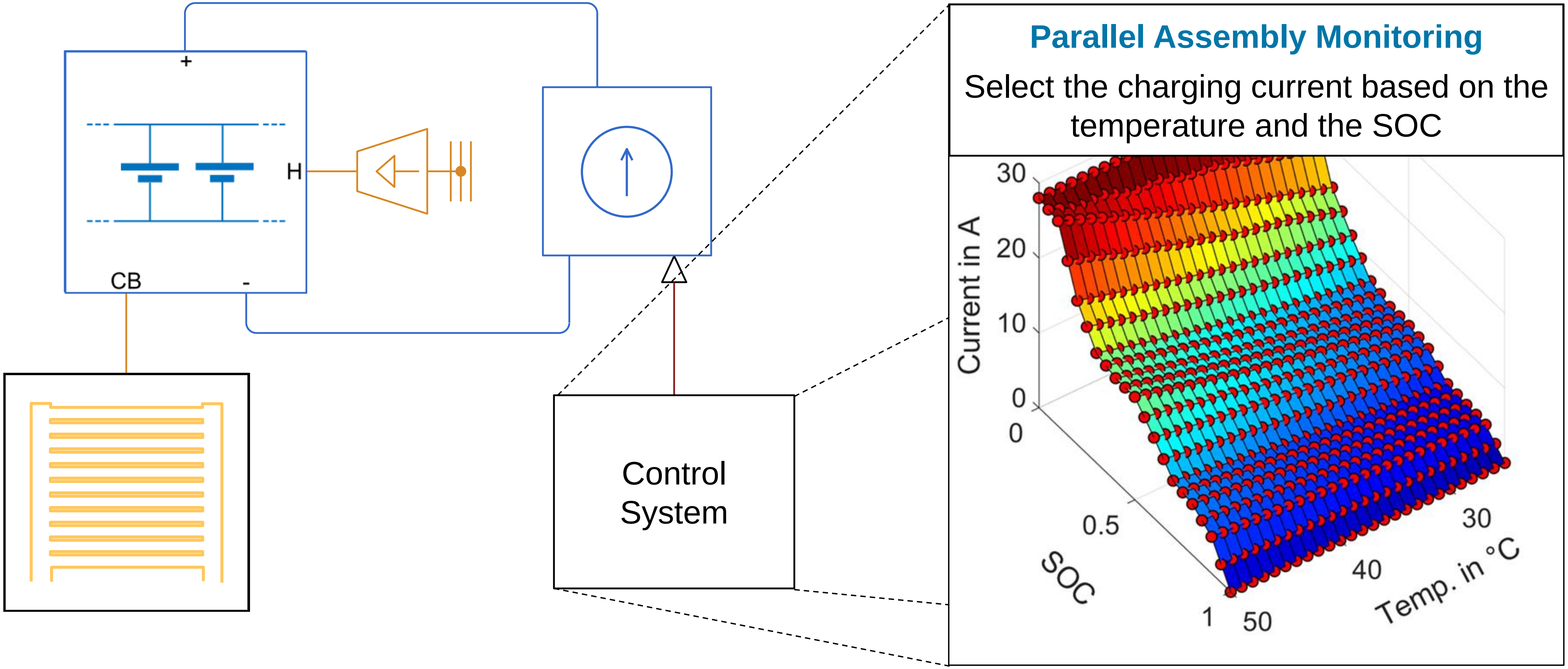
Source code



从电芯到并联组

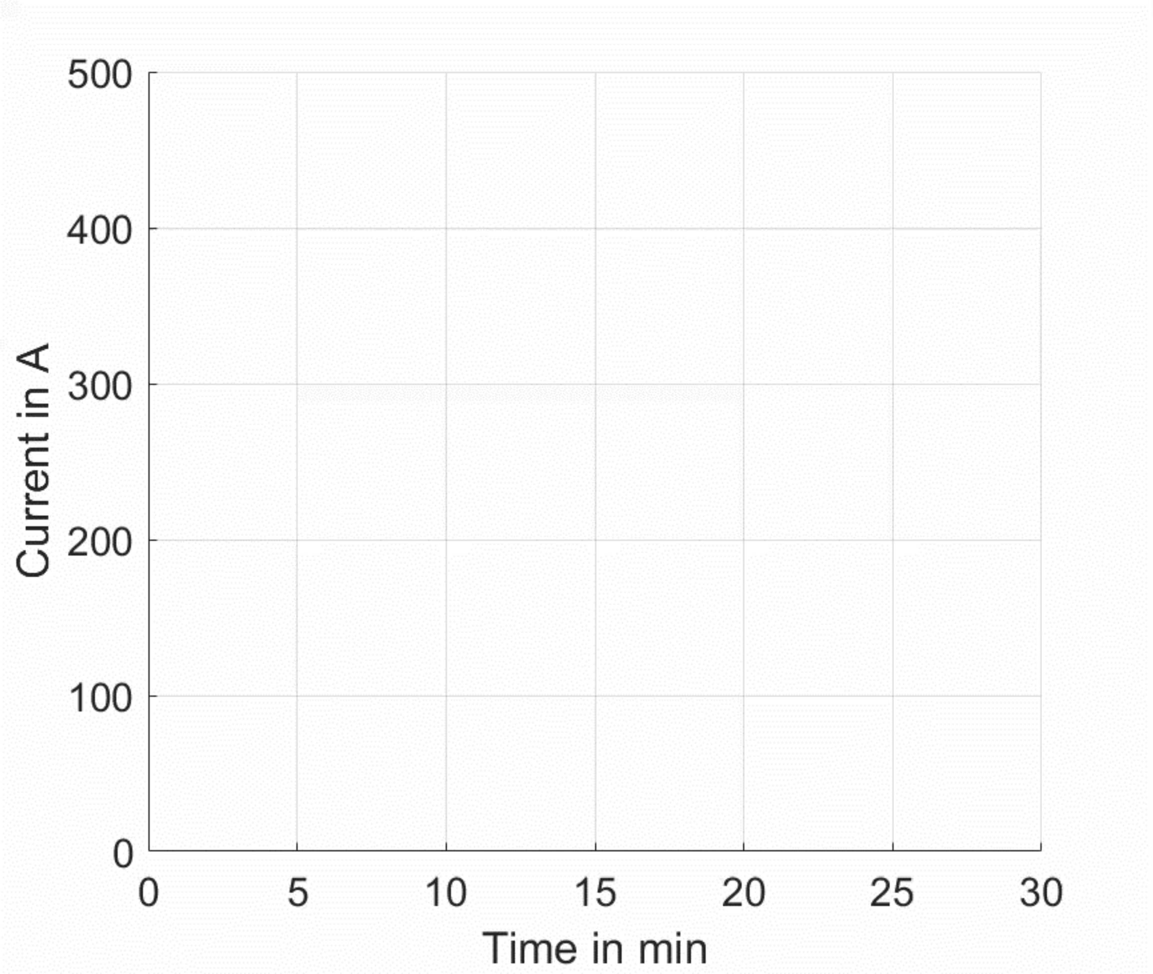
并联组快充

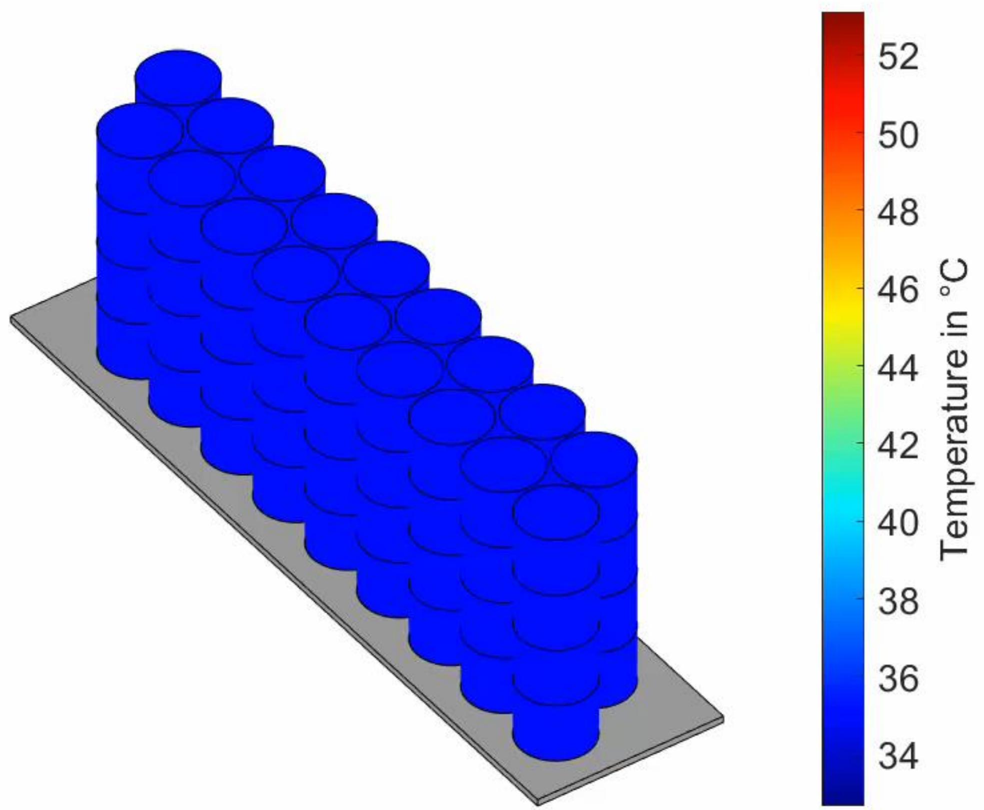




从电芯到并联组

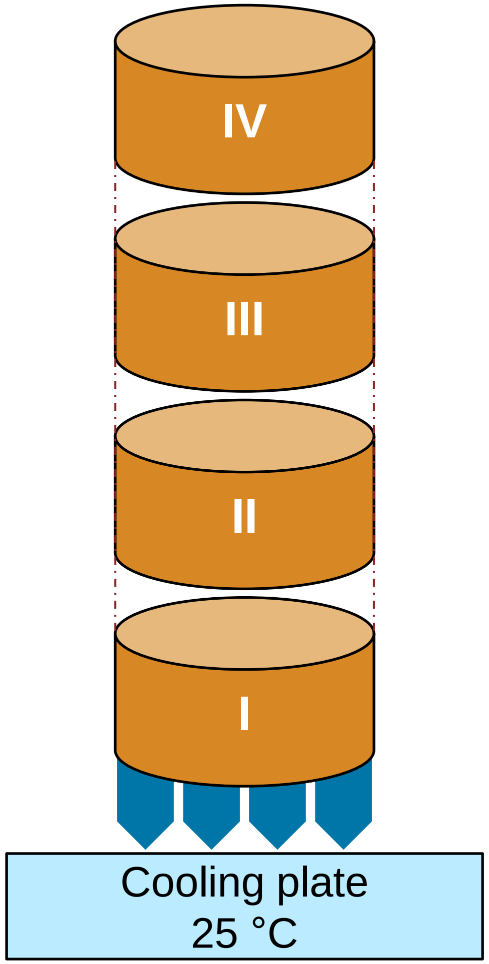
并联组快充

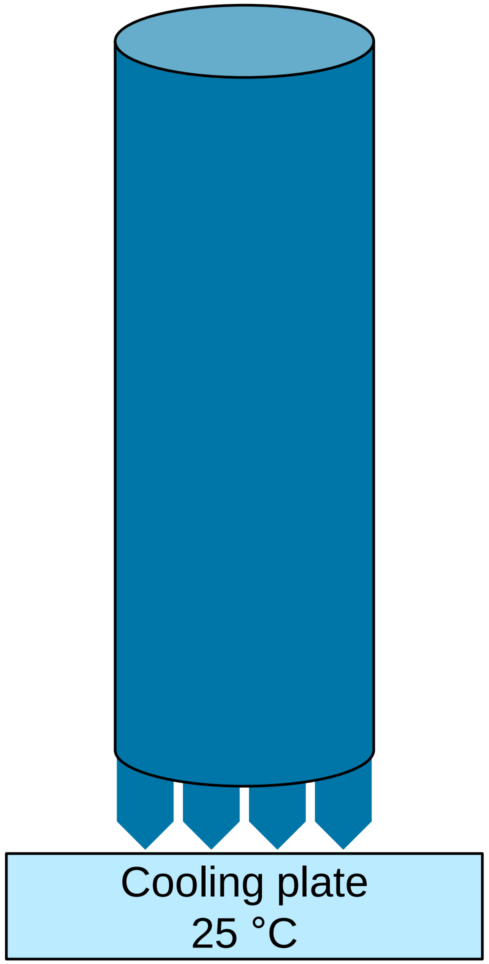




热模型空间离散化

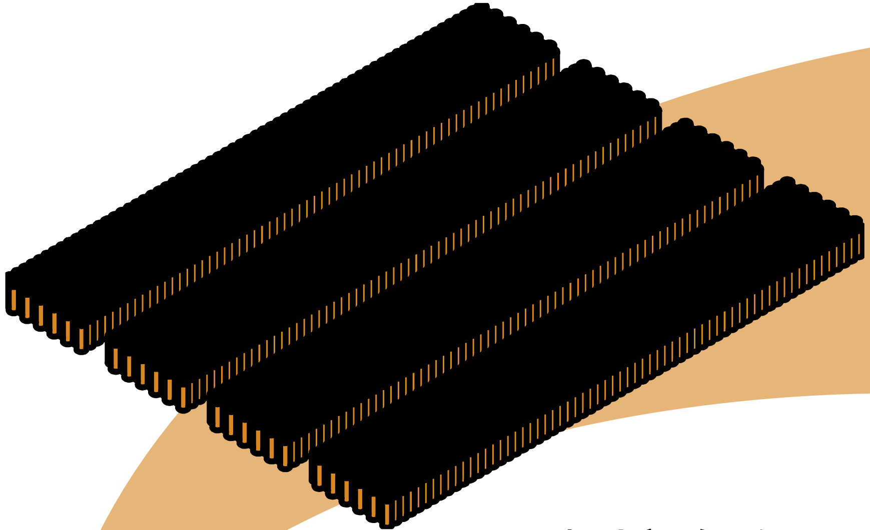
能获得的电芯充放电温度数据对比

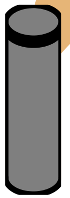


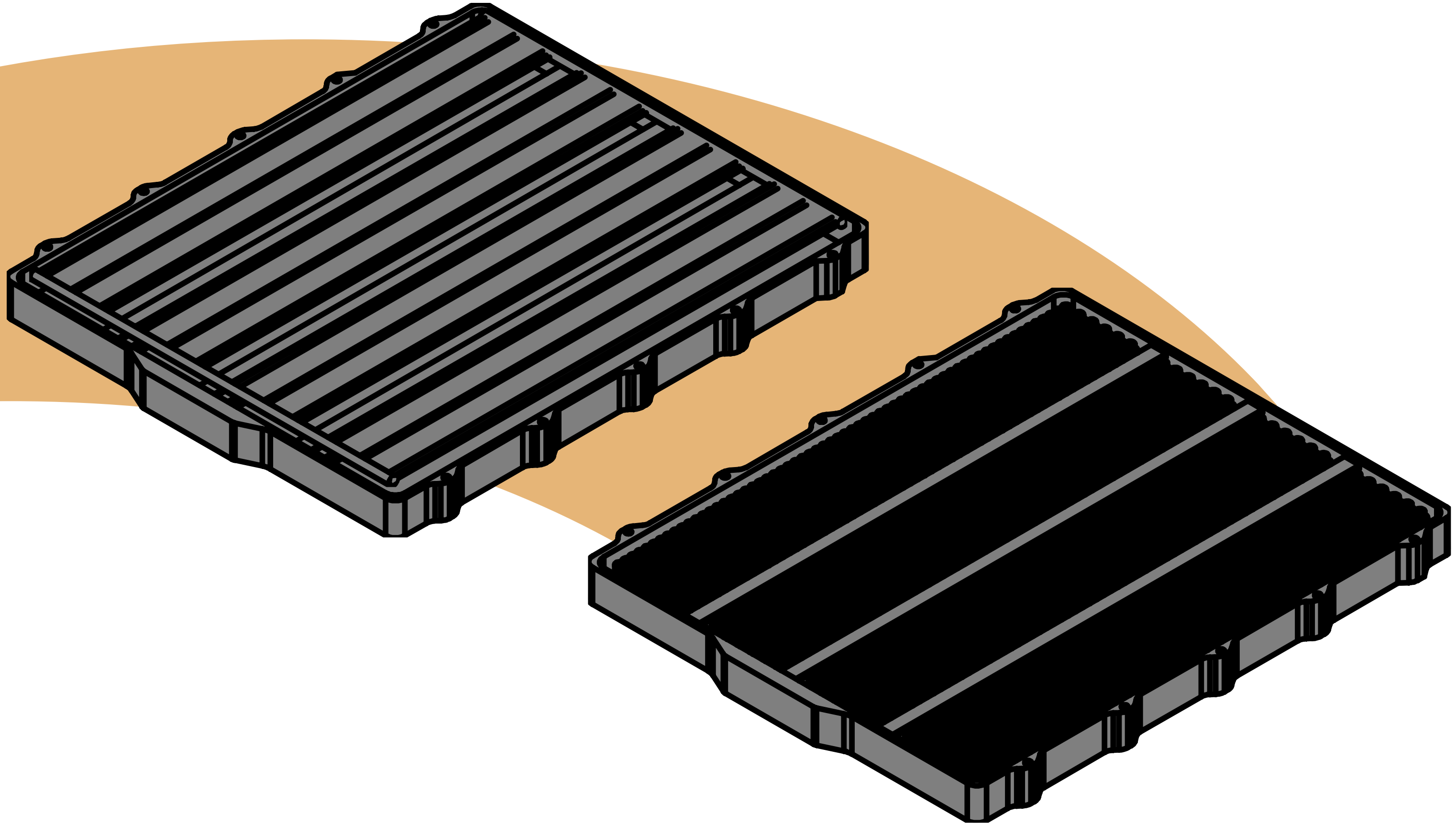


模组以及电池包建模

特性与新功能

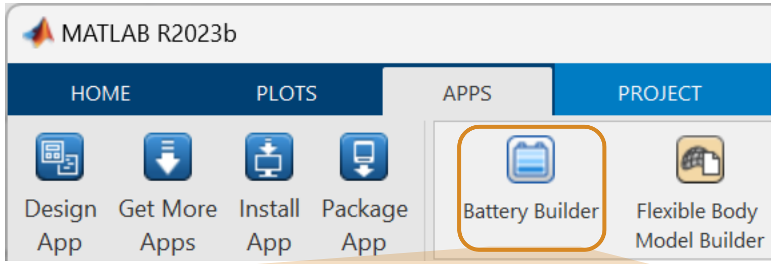






- 组装过程自动化
- 复杂度切换
- 电芯与外界传热
- 电芯间传热
- 电芯不一致模拟
- 电芯均衡控制
- 整体结果可视化

基于 MATLAB 脚本的构造函数简单易用…
以及 Battery Builder App




```matlab
% Import the battery builder
import simscape.battery.builder.*

% Create the cell
cell = Cell(Geometry = CylindricalGeometry);

% Create the parallel assembly
pAsmb = ParallelAssembly(Cell=cell,...
                         NumParallelCells=48,...
                         Topology="Hexagonal",...
                         Rows =4);

% Create the module
mAsmby = Module(ParallelAssembly=pAssembly,...
                NumSeriesAssemblies=4,...
                StackingAxis="Y");

% Create battery chart
BatteryChart(Battery = mAssembly)
```

R2023b

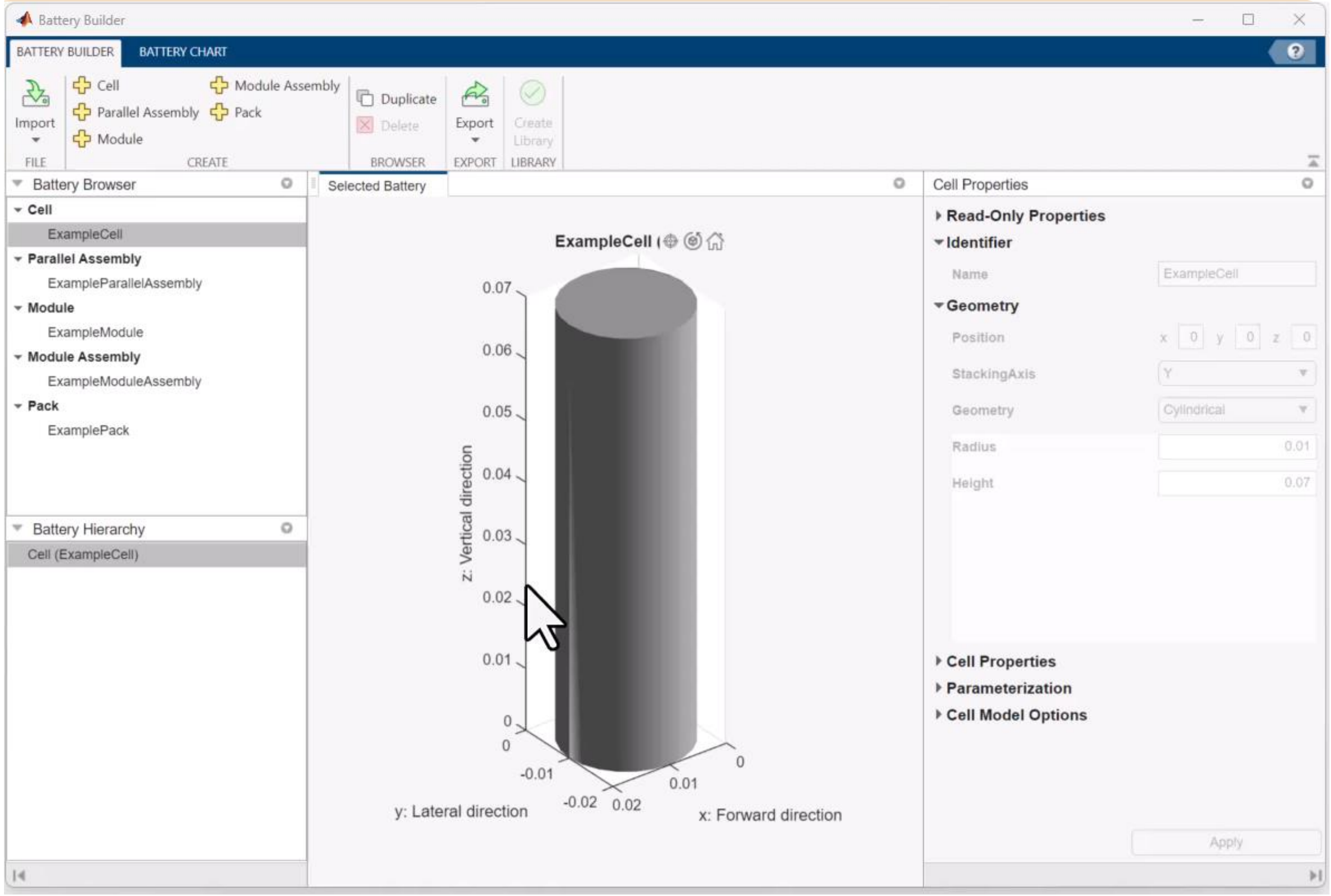
```matlab
% Create the cell
cell = batteryCell(batteryCylindricalGeometry);

% Create parallel assembly
pAsmb = batteryParallelAssembly(cell,48,...
                               Topology="Hexagonal",..
                               Rows=4);

% Create the module
mAsmb = batteryModule(pAssembly,4,StackingAxis="Y");

% Plot the Battery Chart
batteryChart(mAssembly)
```

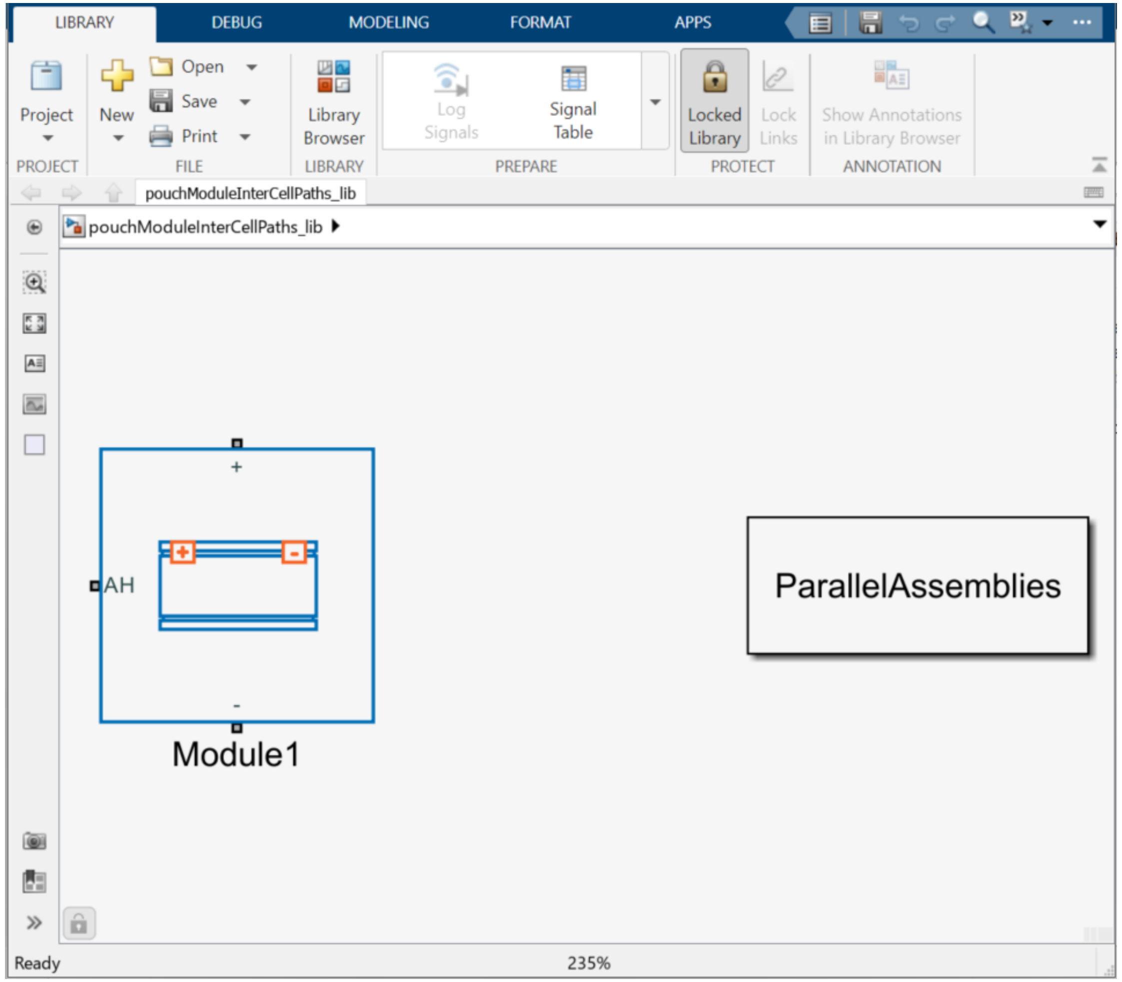
R2024a
进一步简化使用

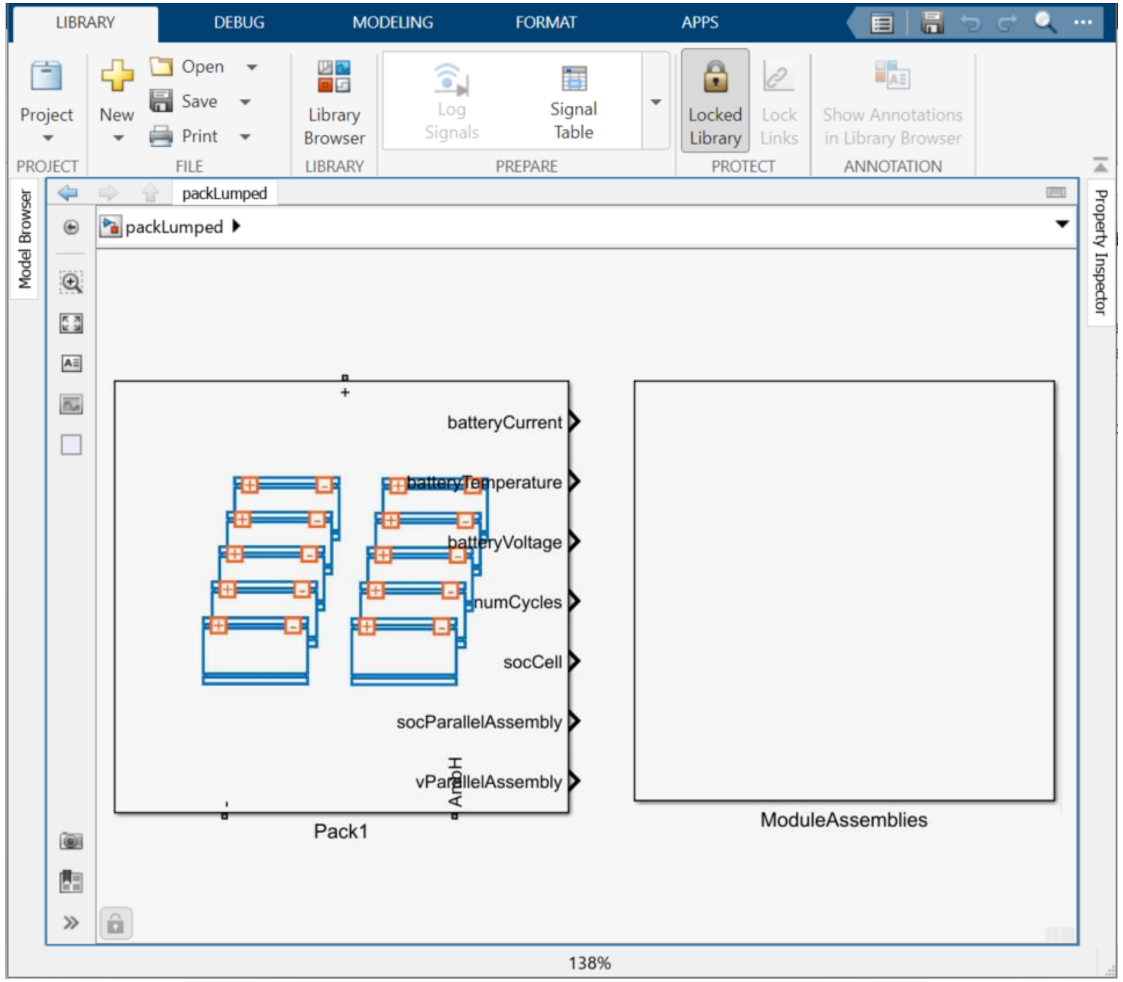


» [Battery Builder]

自动生成各层级电池模块库

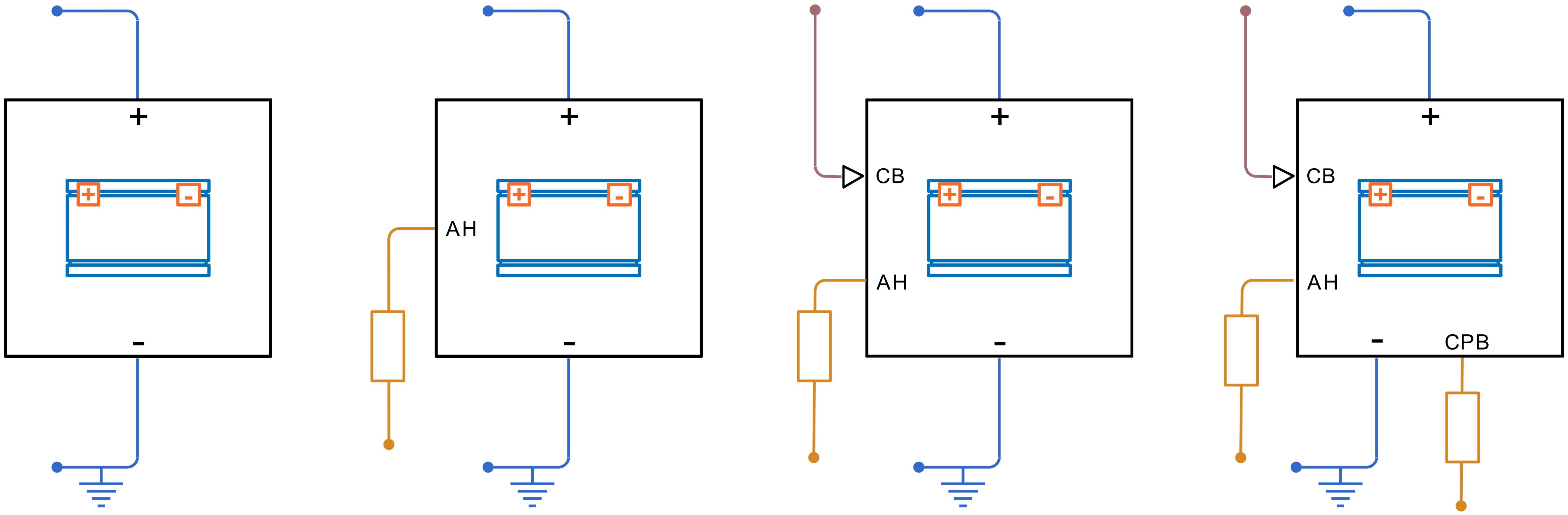
Library 示意图





关于模组

电池包通常会包含若干个模组



Electric Connection

Thermal Path Ambient

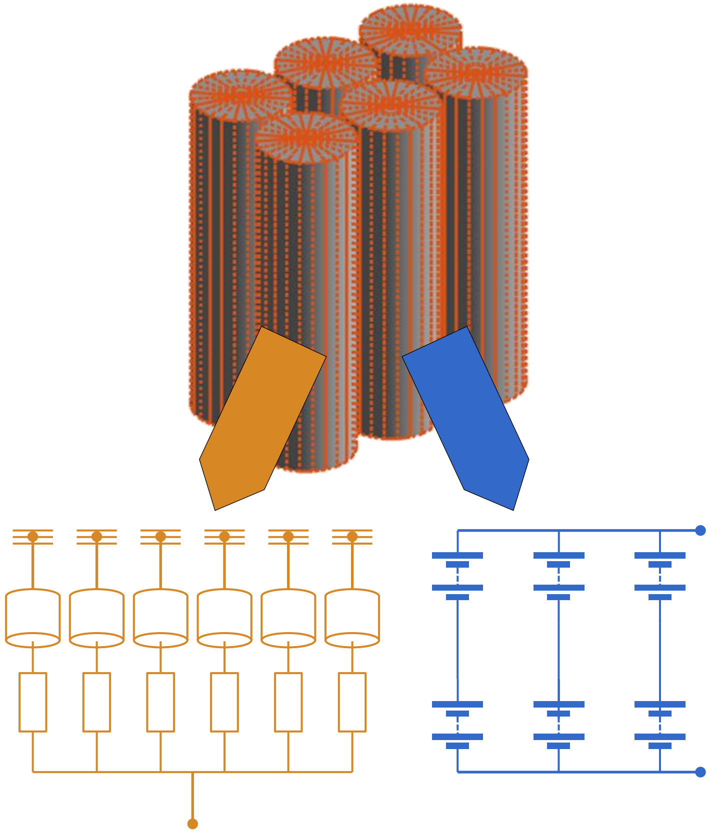
Balancing Signal

Thermal Path Plate

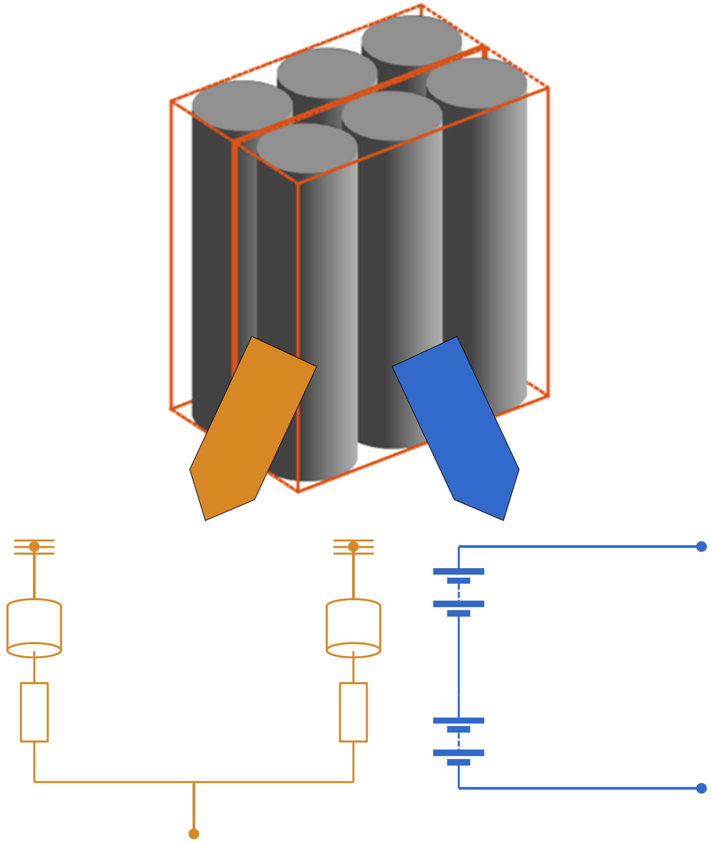
仿真速度和精度的平衡

随时切换合适的模型细节等级参数

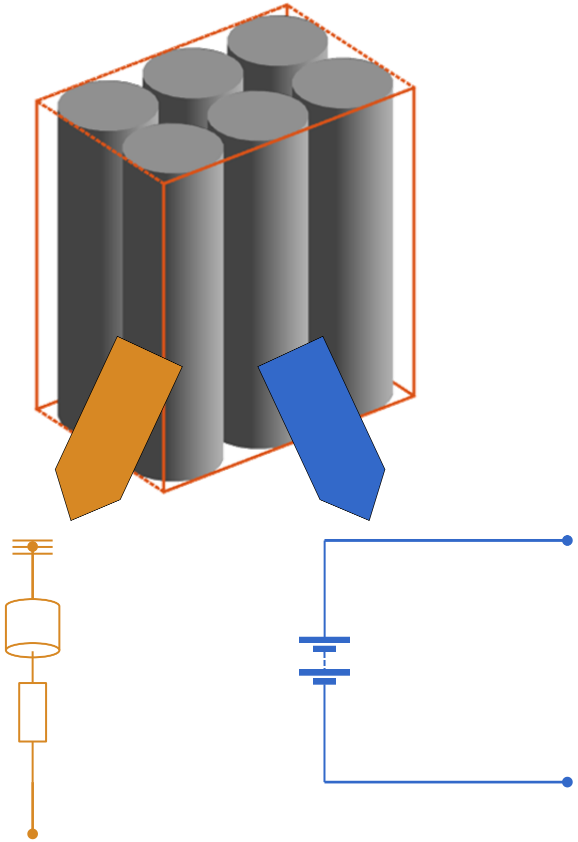
Detailed



Grouped



Lumped

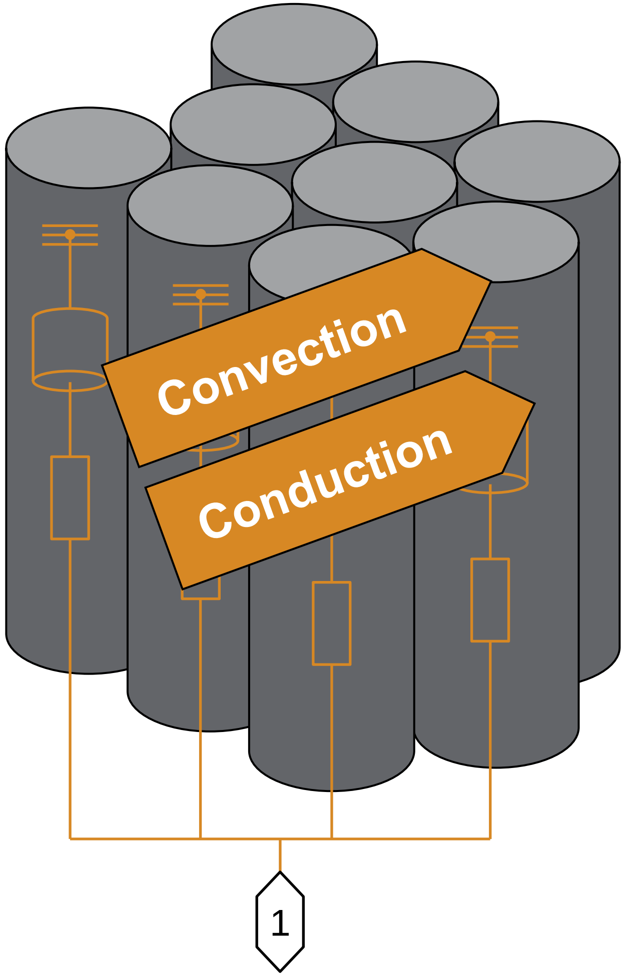


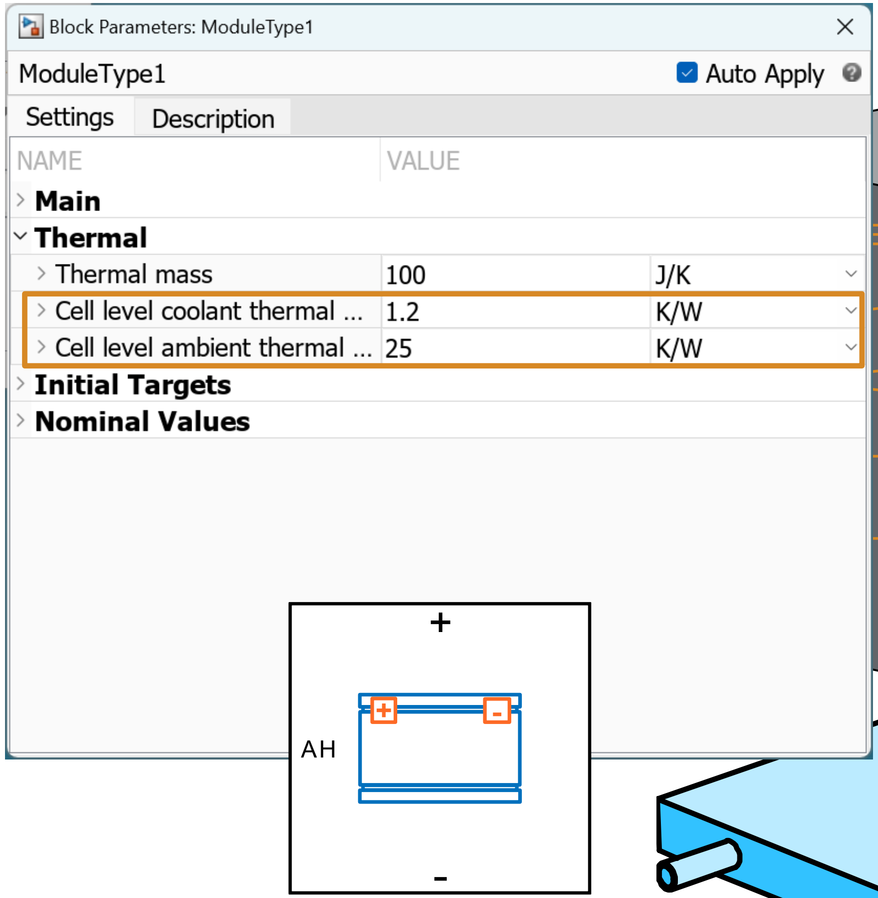
» More to Model Resolution

模组对外热模型

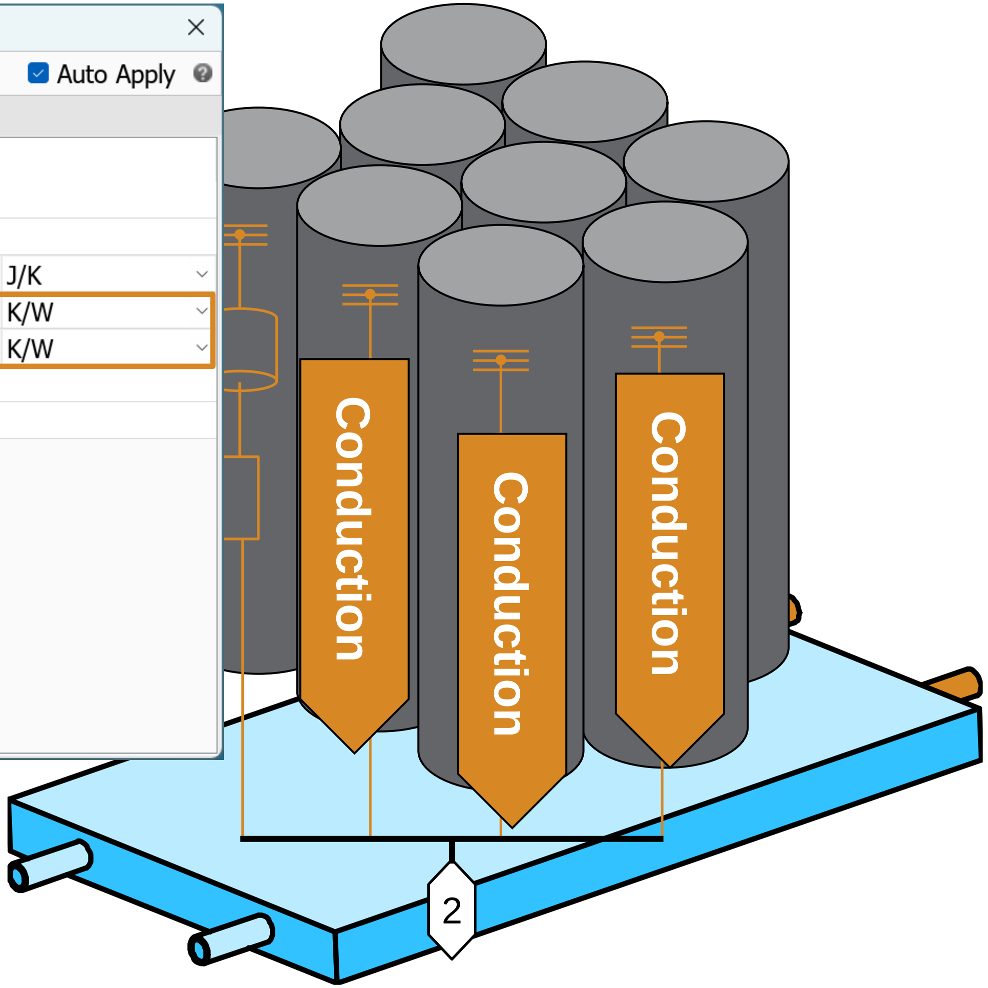
模组和外界环境(空气/冷却水板)之间的热传导、热对流

Thermal path to ambient





Thermal path to cooling plate

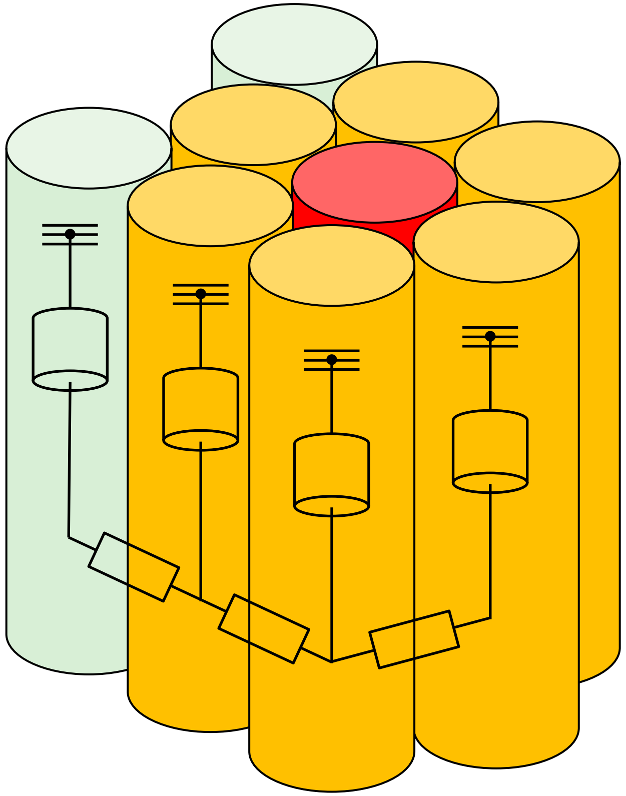


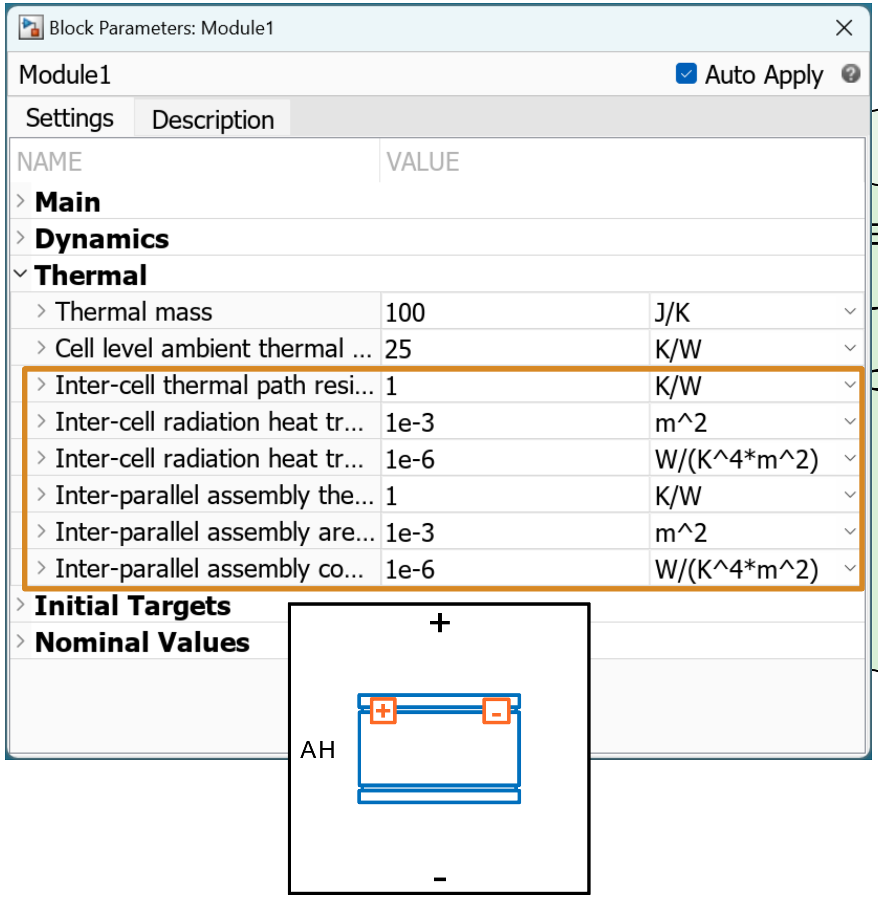
模组内部热模型

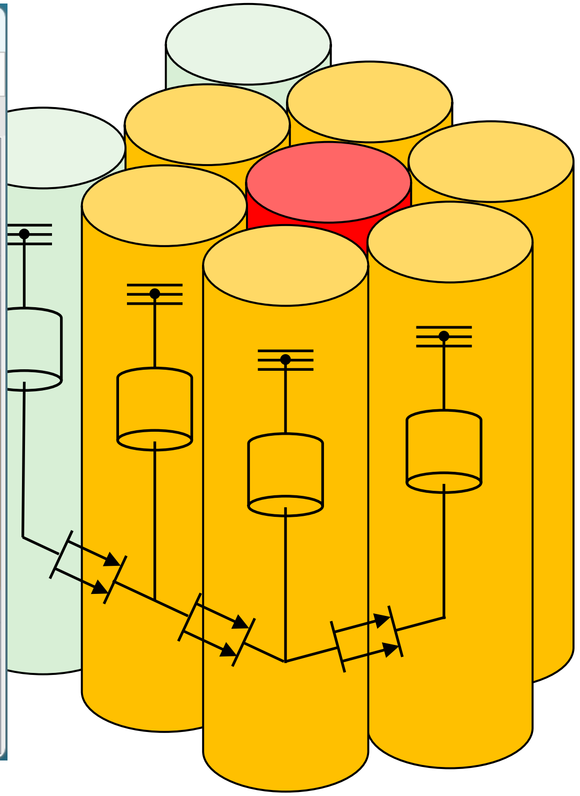
模组电芯之间的热传导、热对流、热辐射

Inter cell path

Inter cell radiative path







» [Module with Inter-Cell Heat Exchange]

模组电芯参数分布设置

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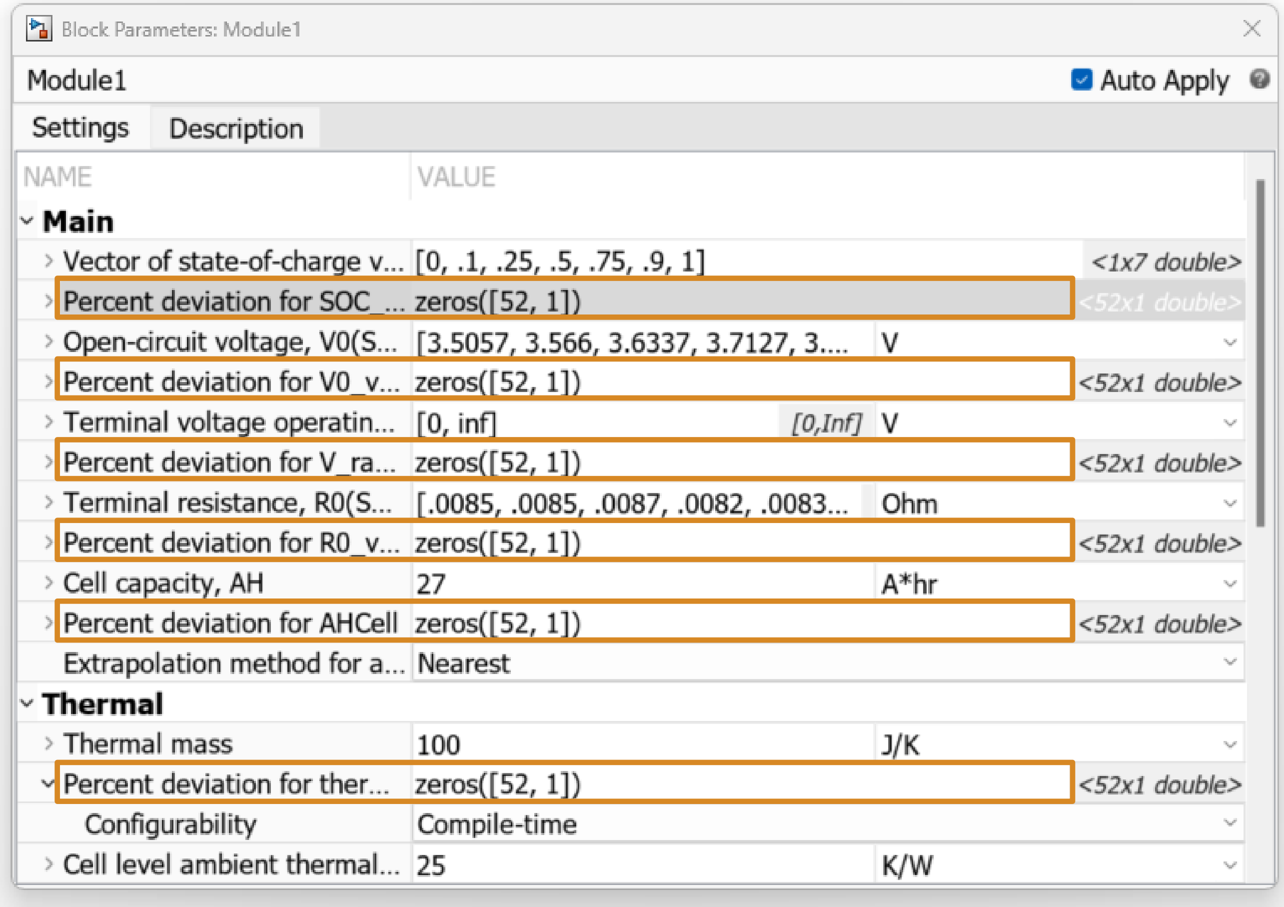
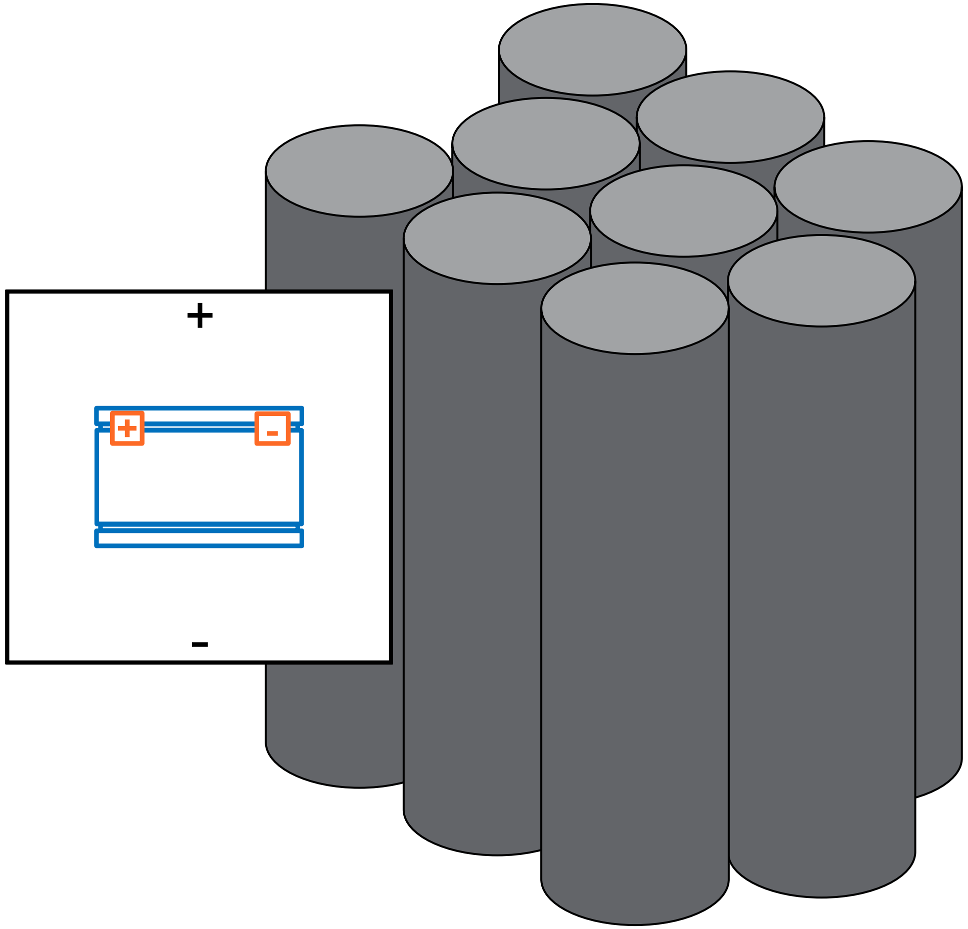
电芯参数差异性



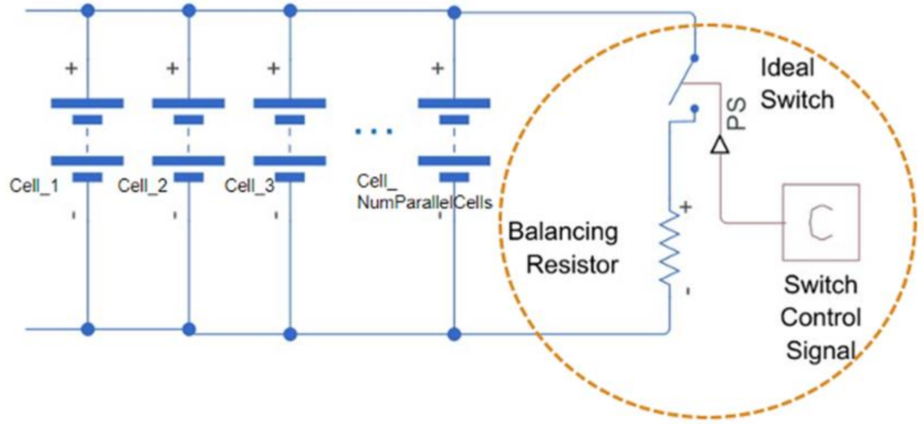


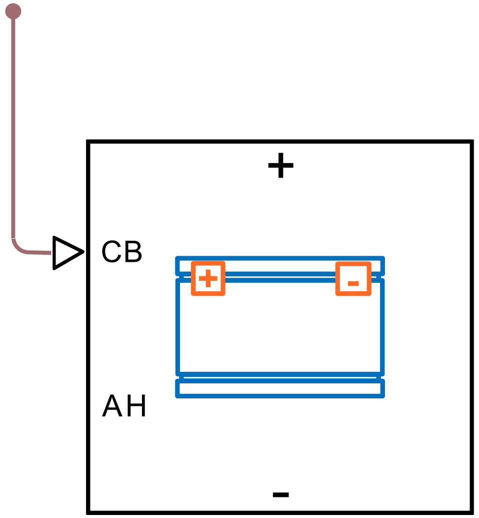
» [Apply Parameter Variation to Cells in Module]

新的均衡控制端口

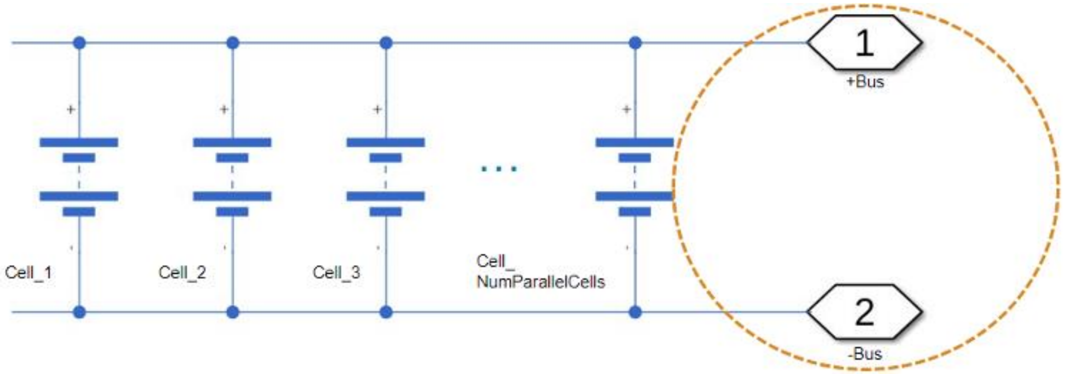
自定义均衡控制策略

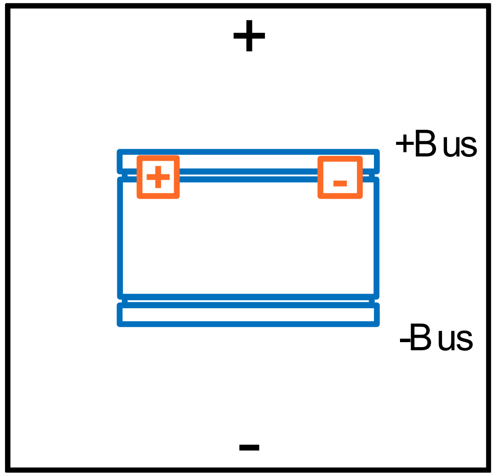
the only available strategy is “Passive“





Starting from 24a "External"



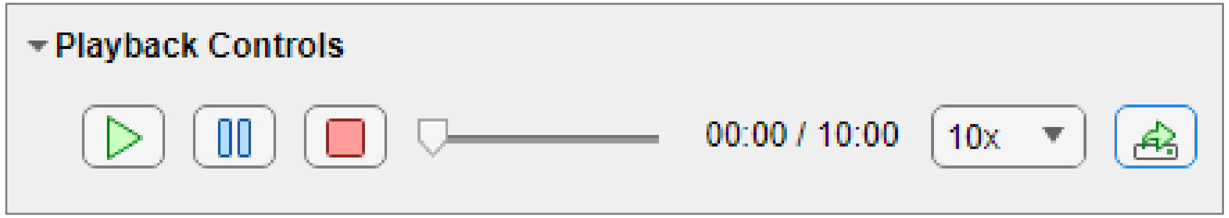


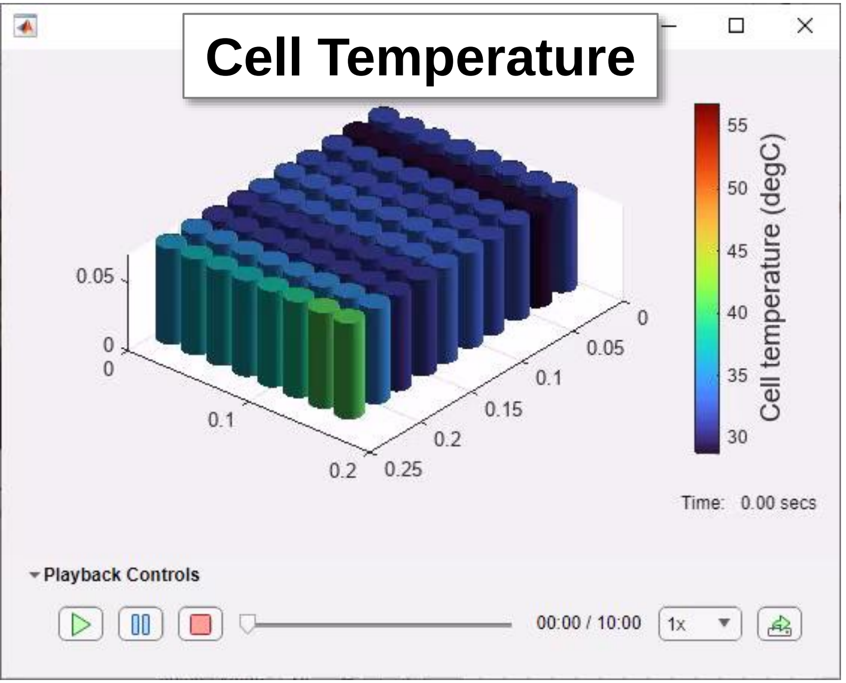
custom balancing strategy

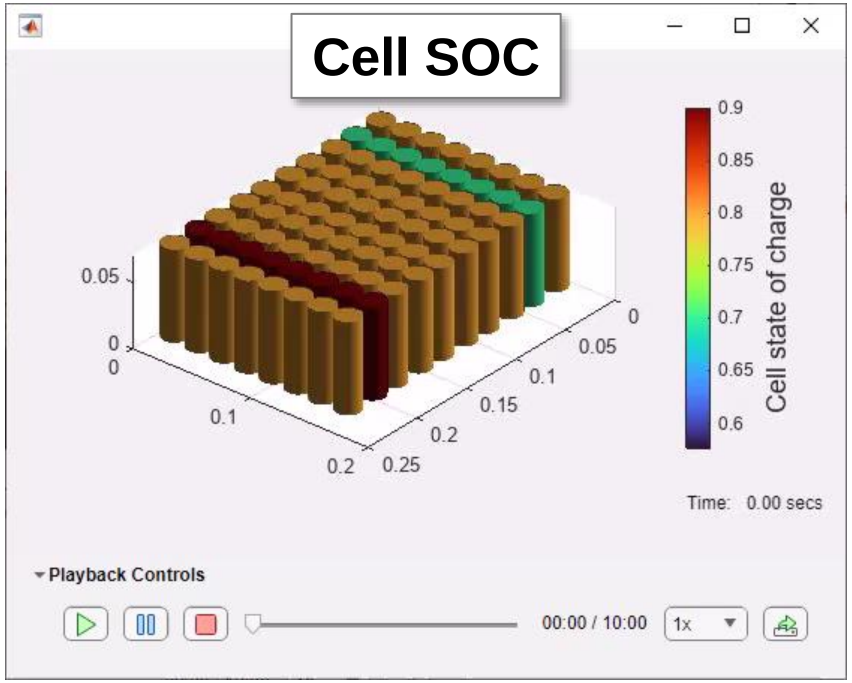
Simscape Battery 结果显示

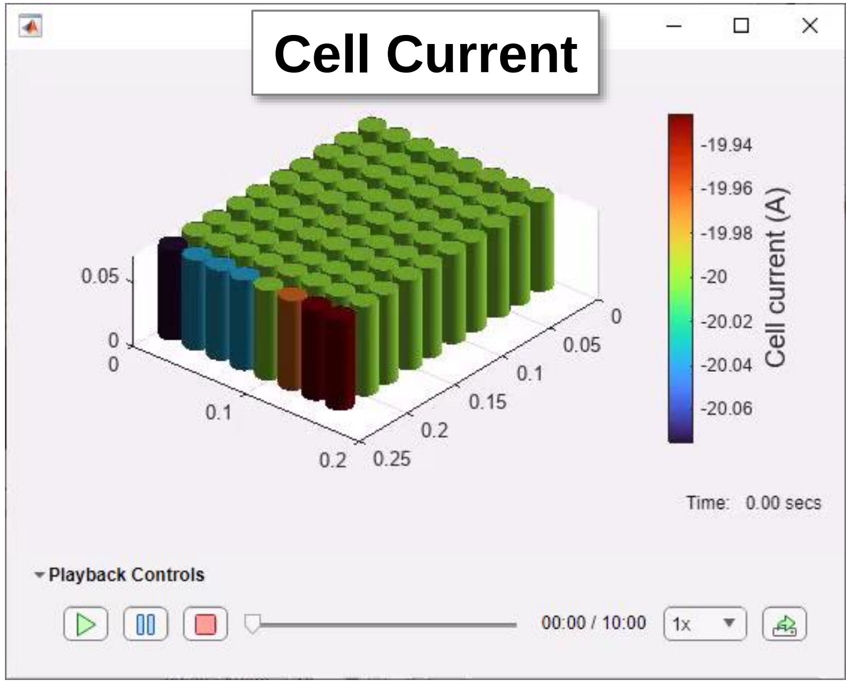
R2023b

- Animate battery pack visualization with simulation results
  - Display quantities such as current, temperature, and SOC for each cell within the battery pack
- Use playback controls to control animation and save to a video file



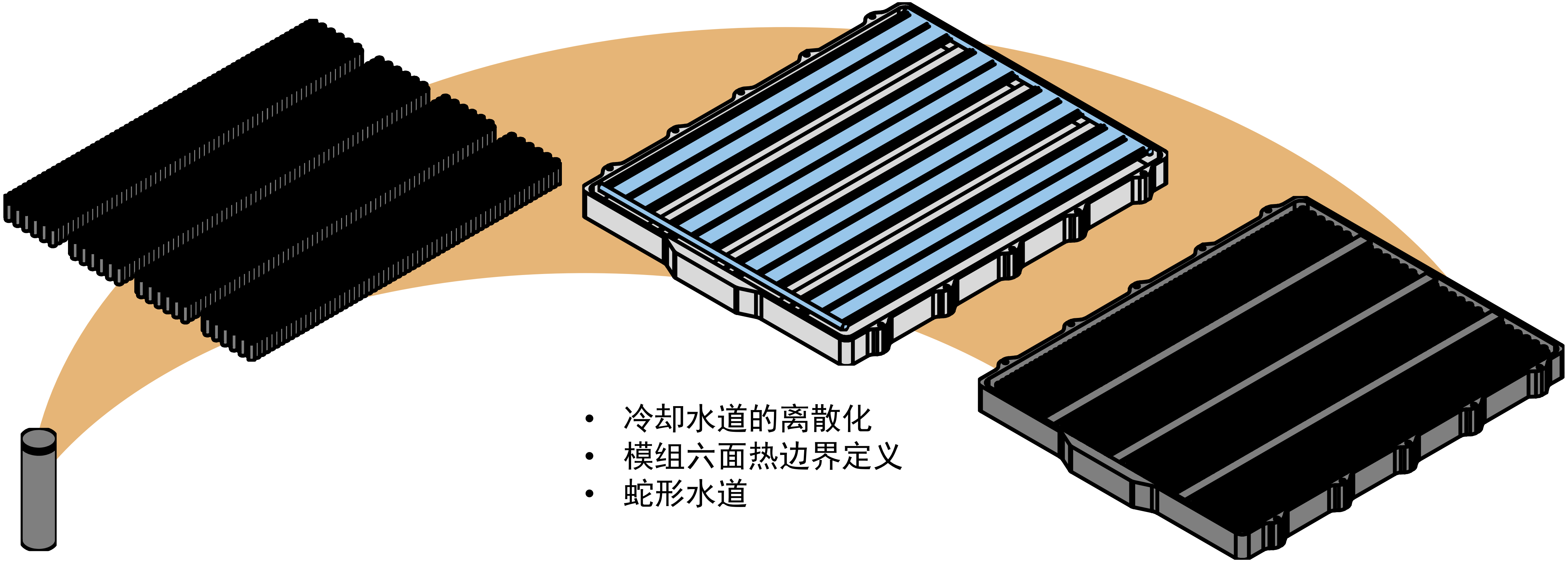






冷却板模型

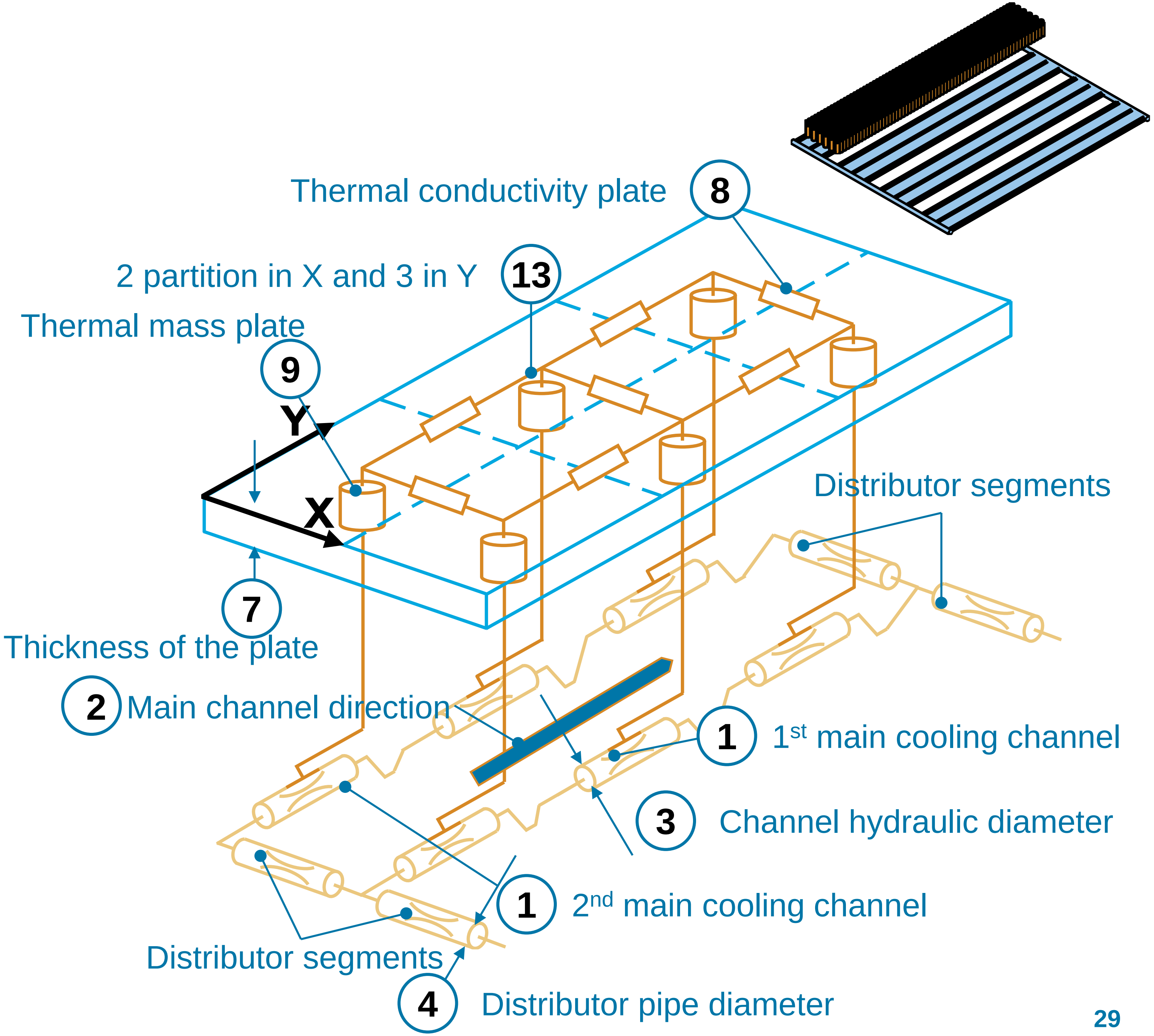
特性与新功能



- 冷却水道的离散化
- 模组六面热边界定义
- 蛇形水道

冷却水道的离散化解析模型

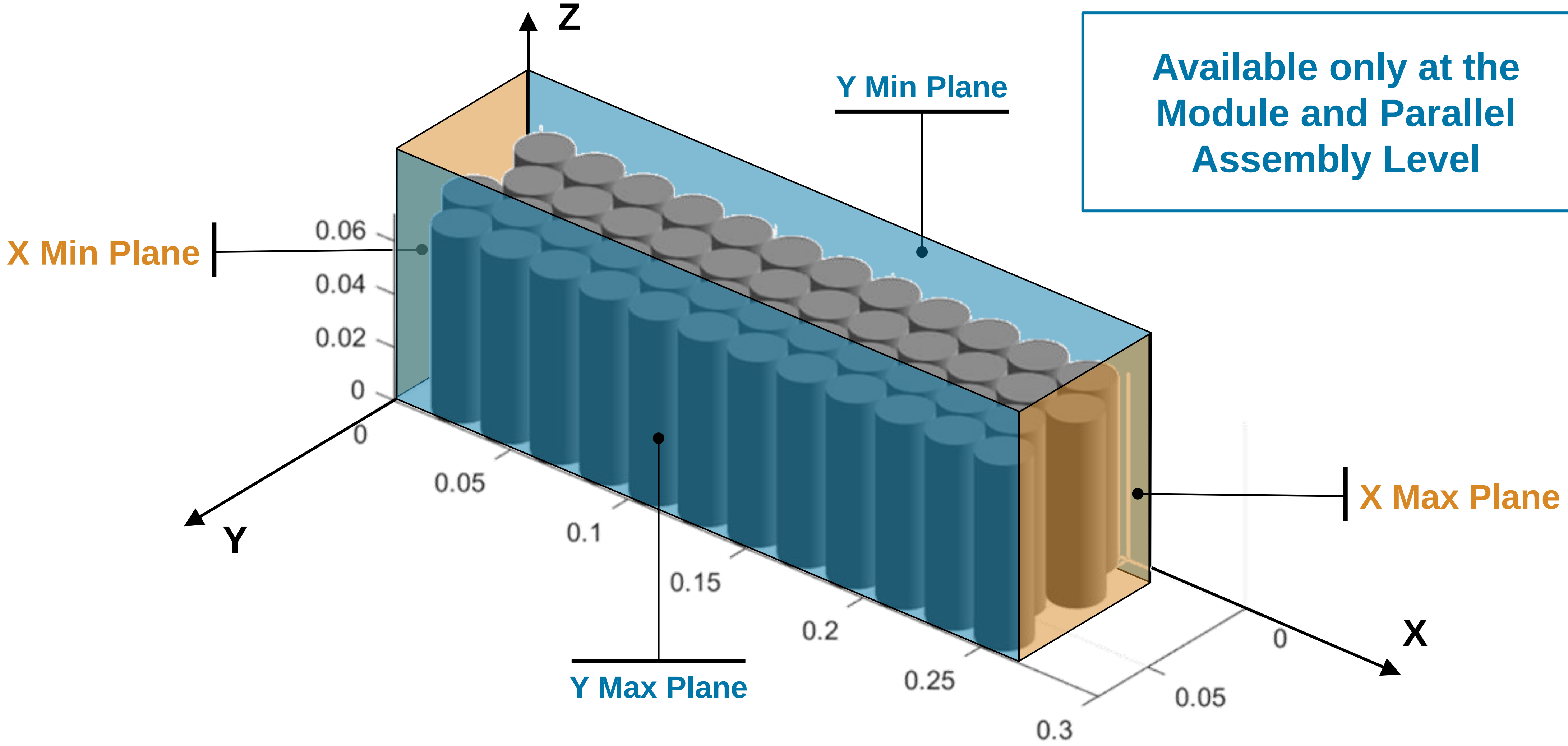
- The 1st elementary block (modeling the cooling channels) is the Pipe (TL) block
- The 2nd elementary block (modeling the plate material) is the thermal mass
- The number of pipes/thermal masses depends on the plate discretization



暴露更多热端口

自定义冷却环境

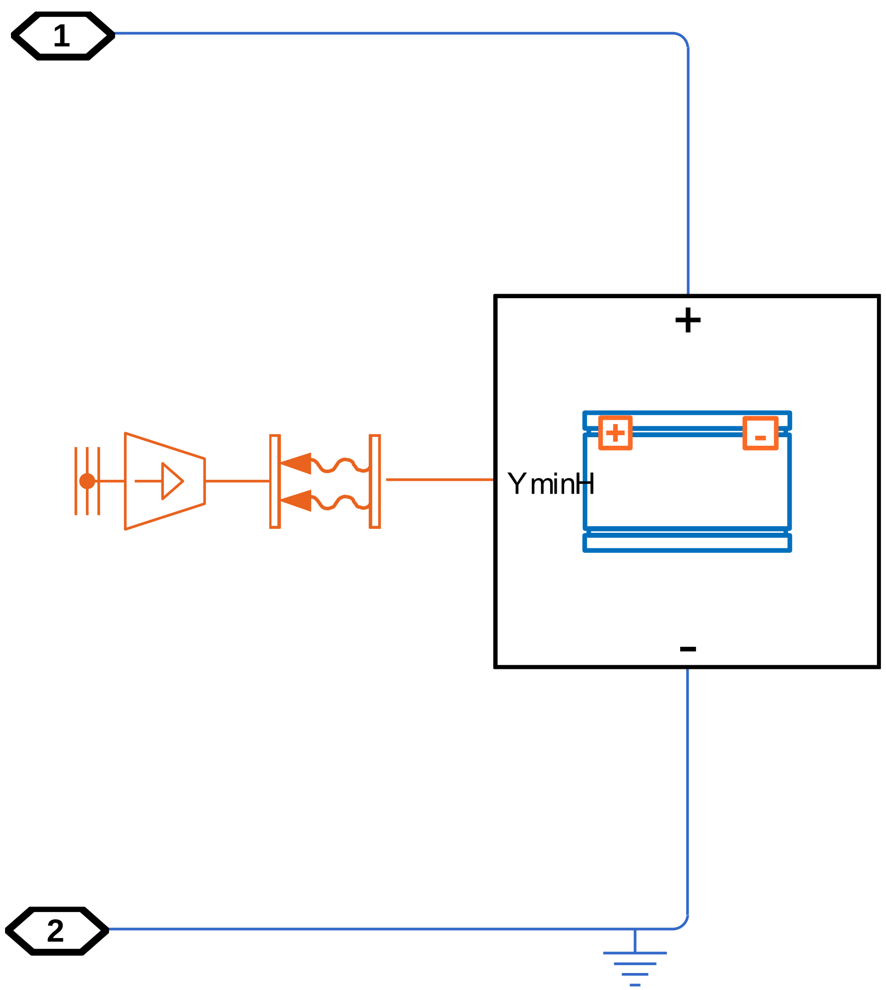
R2024a

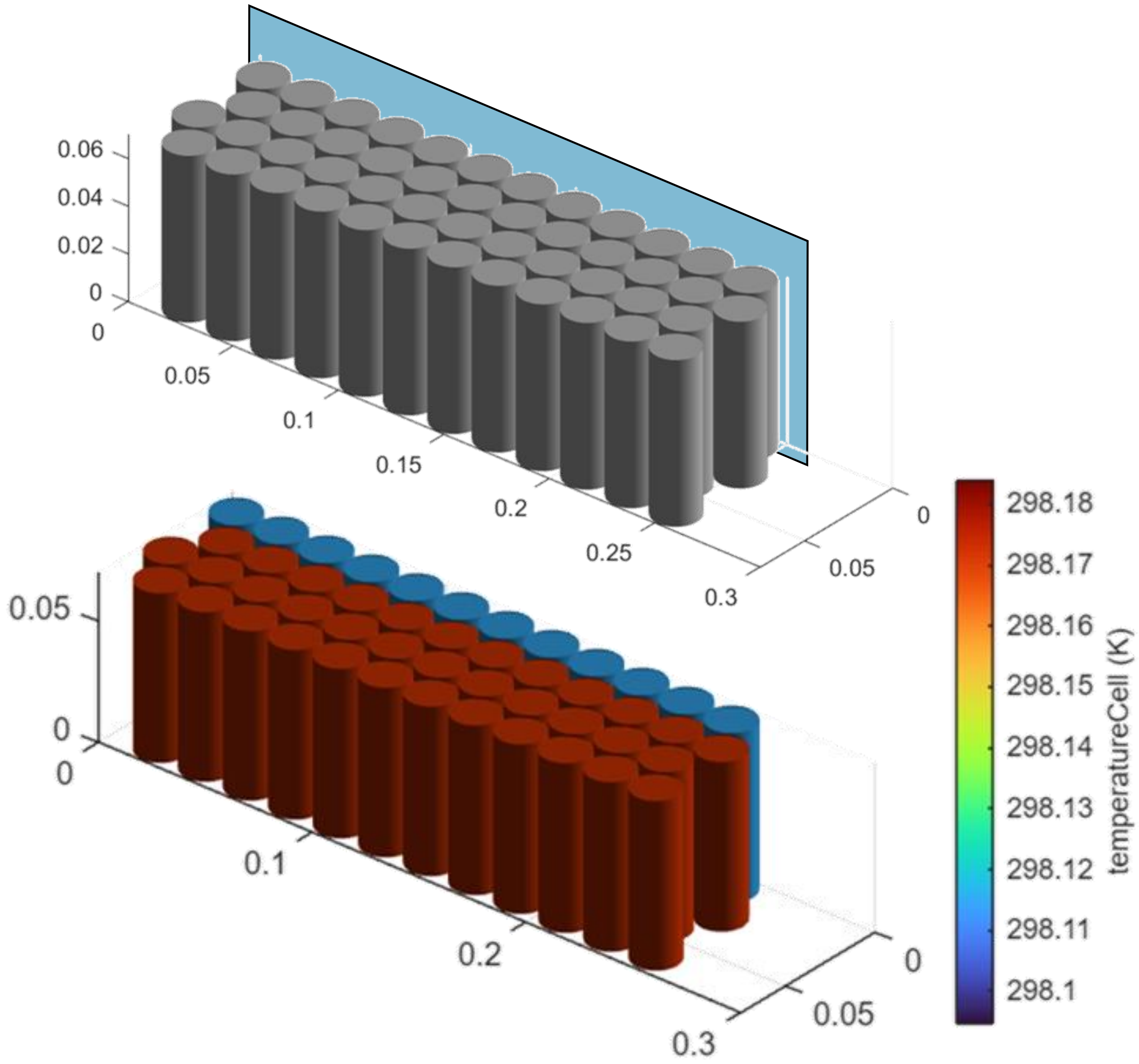


Available only at the Module and Parallel Assembly Level

暴露更多热端口

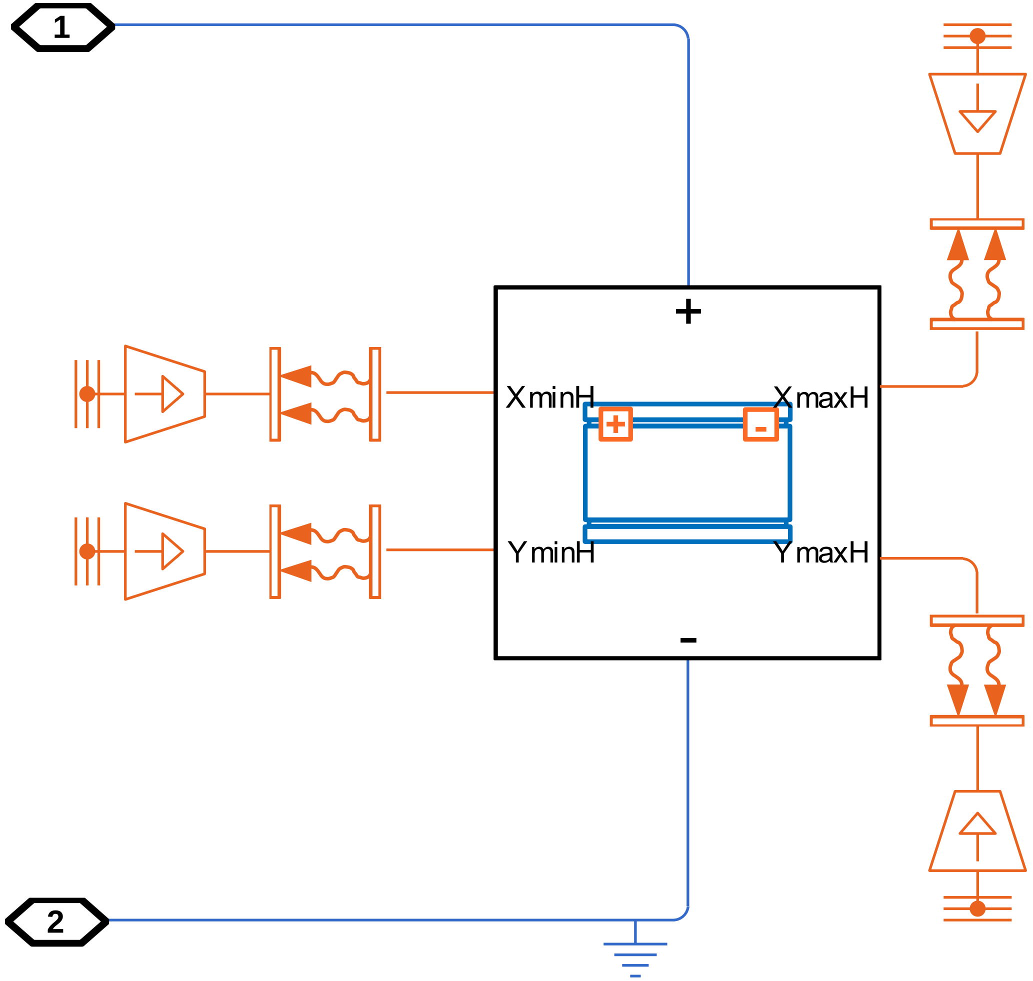
比如 Ymin 側面熱對流

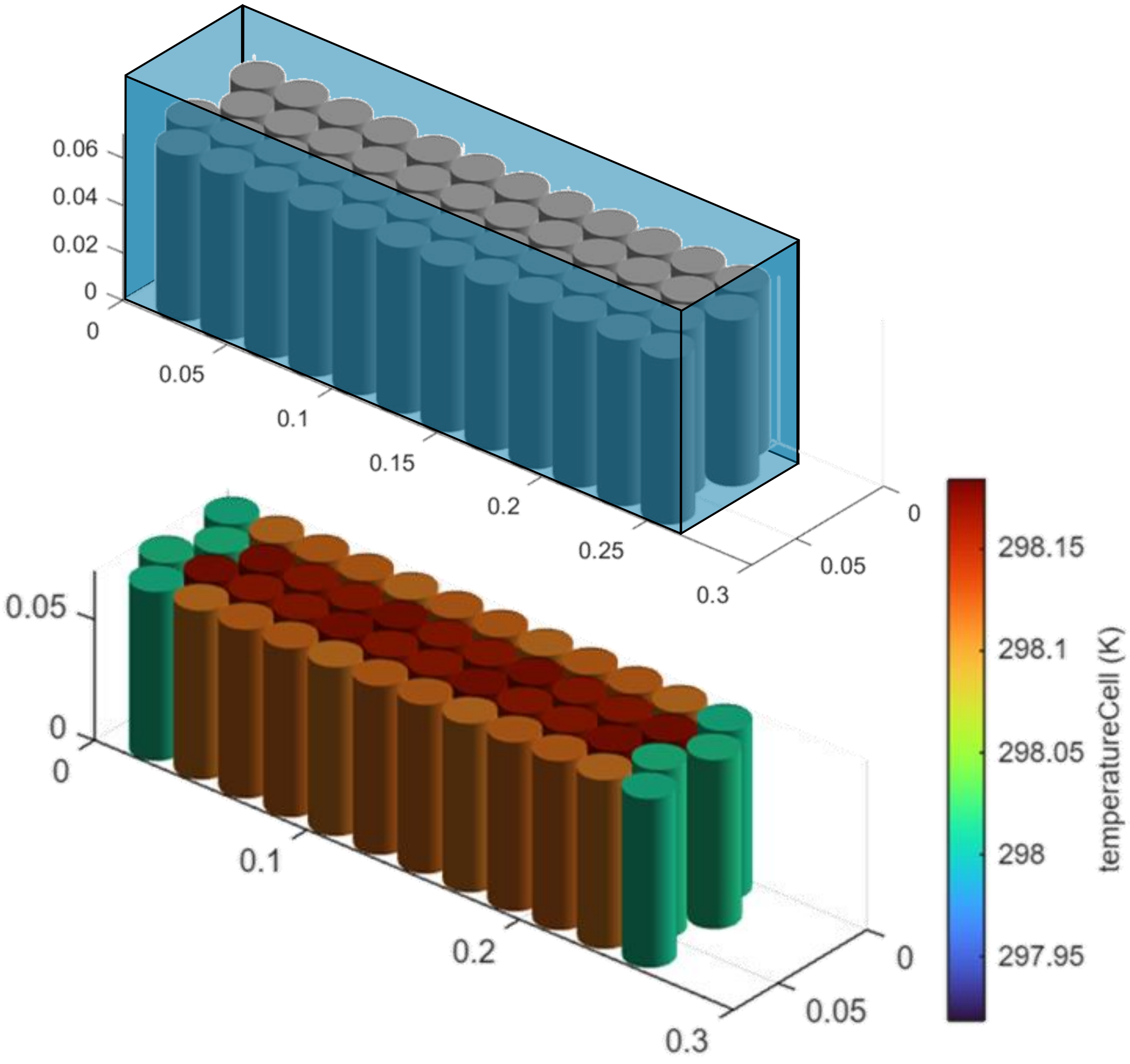




暴露更多热端口

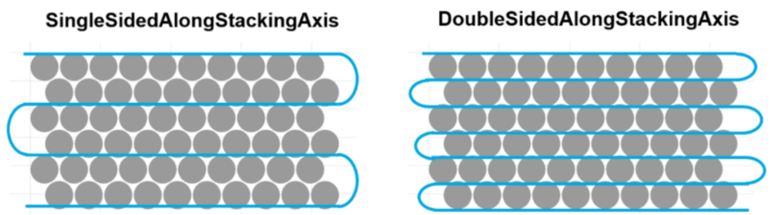
所有側面熱對流





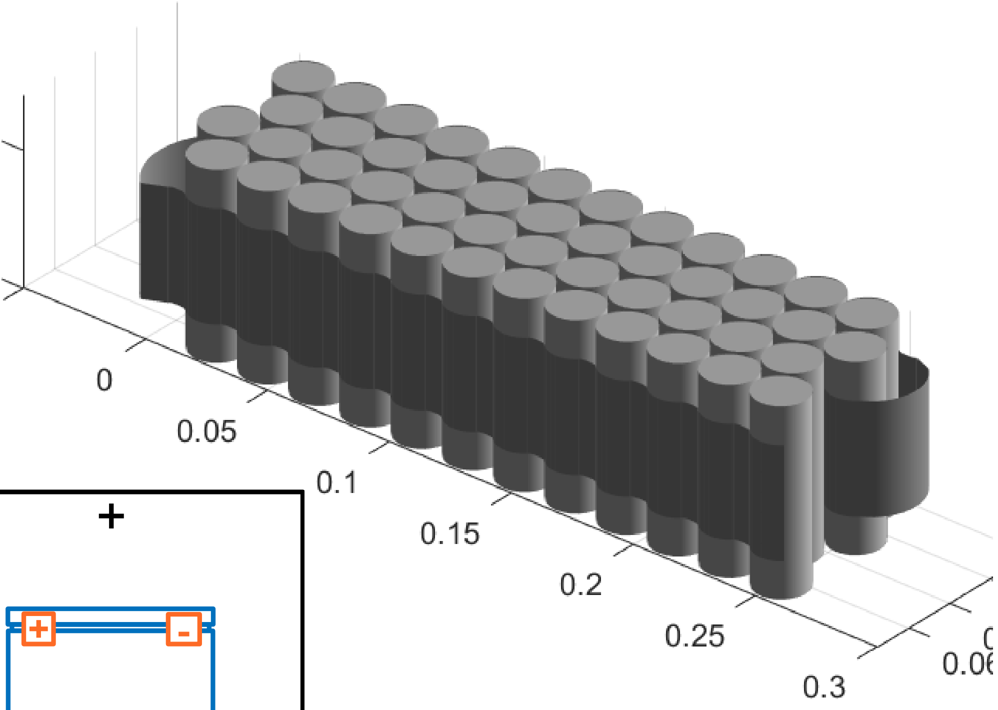
新蛇形板模型 New Serpentine Plate

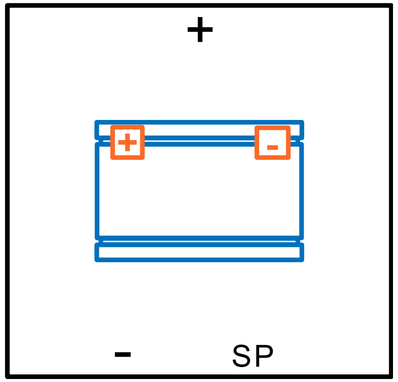
针对圆柱电芯



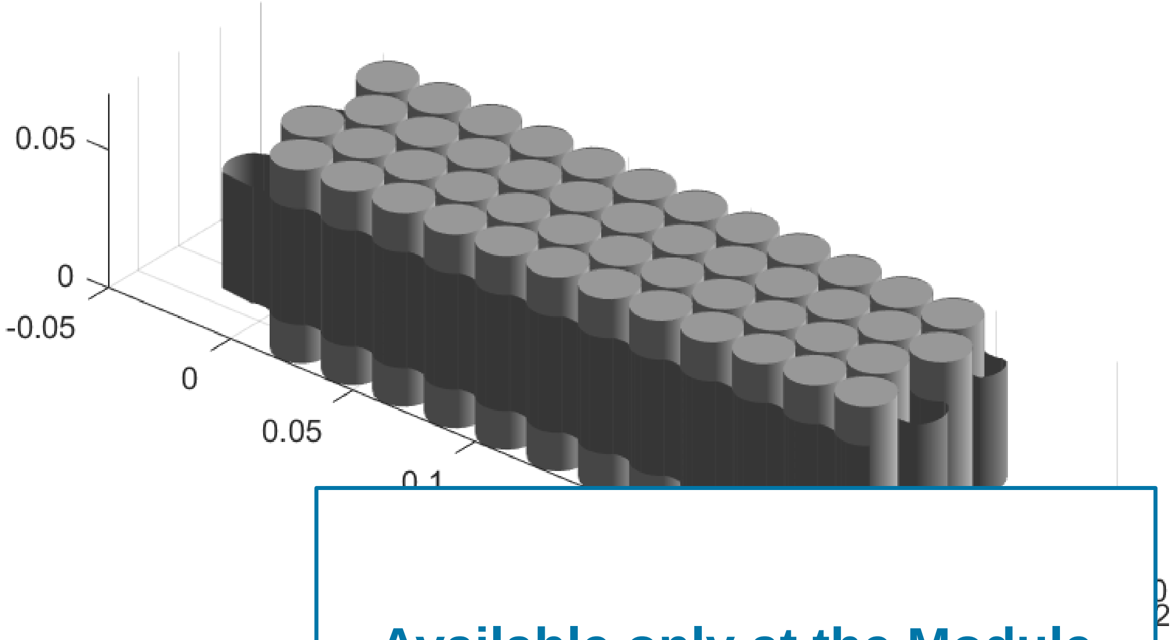
R2024a

Single Sided





Double Sided

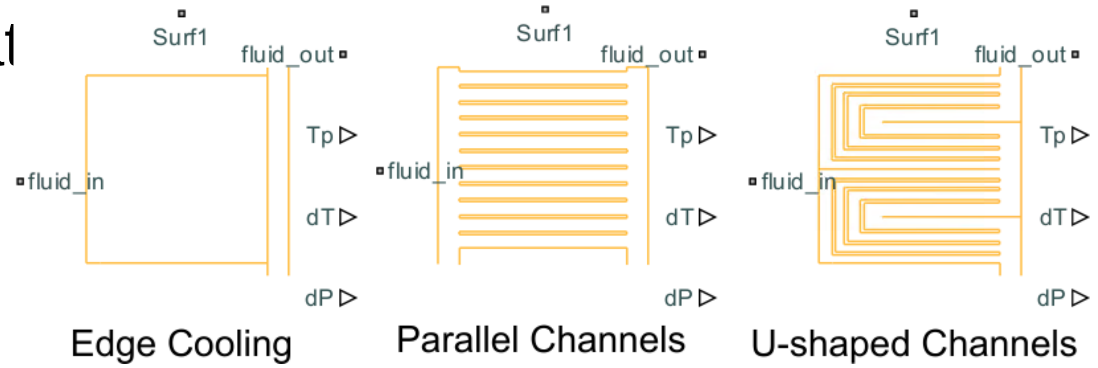


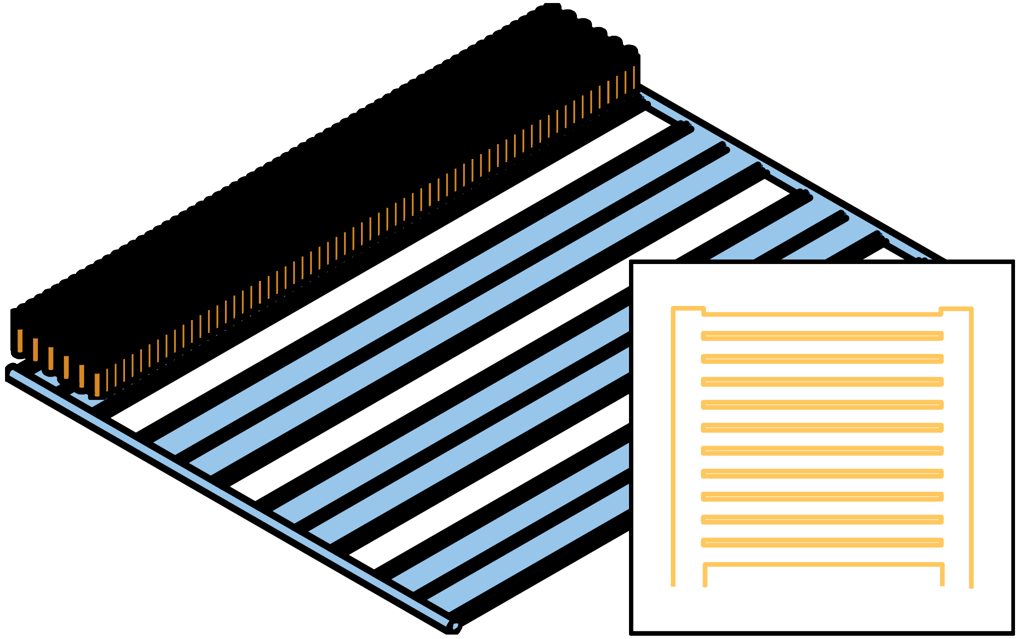
Available only at the Module and Parallel Assembly Level

评估冷却系统拓扑结构

选型

- The cooling plate blocks model the heat transfer between battery, liquid cooling system, and environment
- Different cooling plate topologies
  - Edge, parallel channel, U-shaped channel
  - Single- and double-sided plates



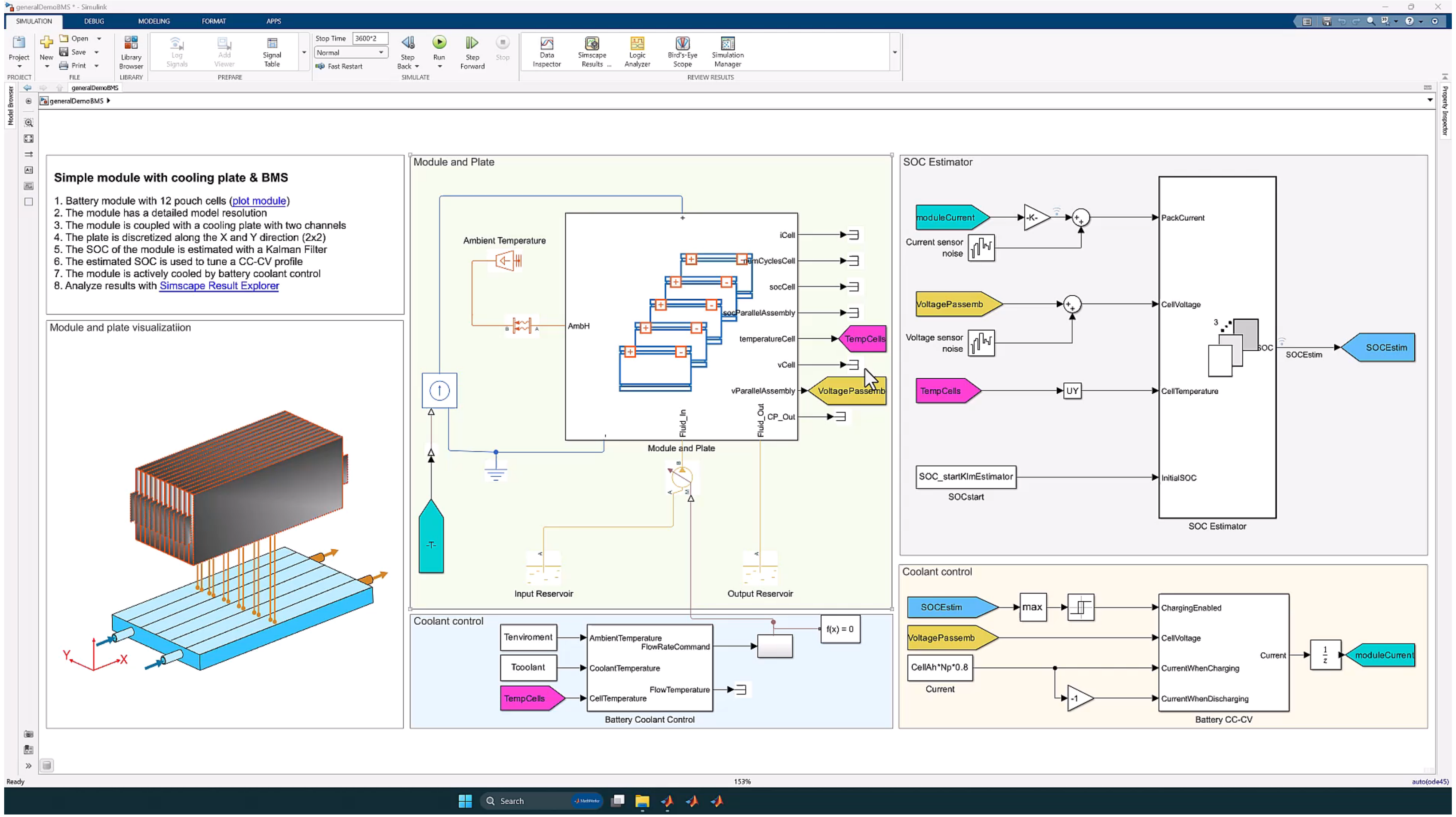


Challenge

It is almost impossible to define a plate blocks which account for all possible configurations

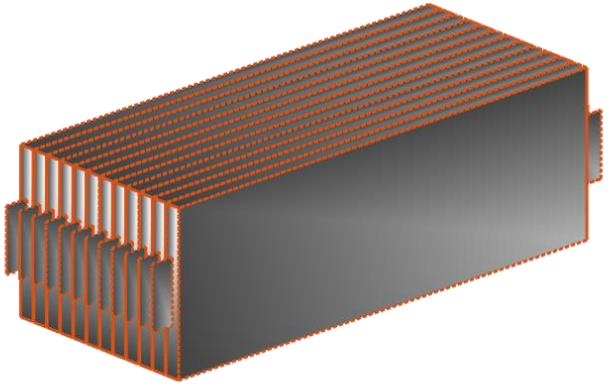
电池包/冷却板/BMS模块

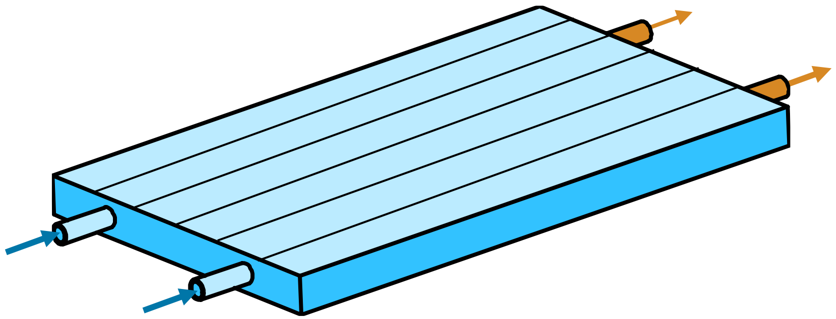
案例模型



电池包/冷却板/BMS模块

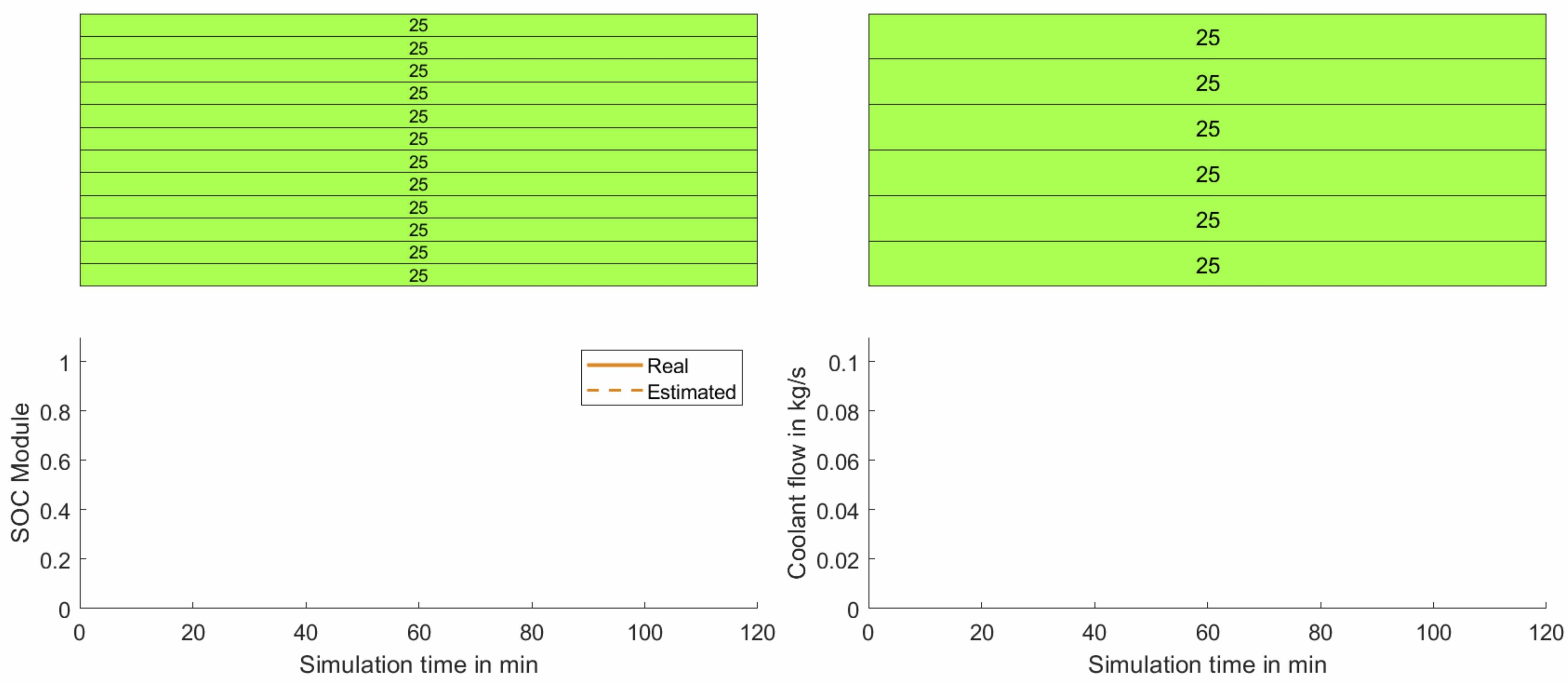
仿真结果





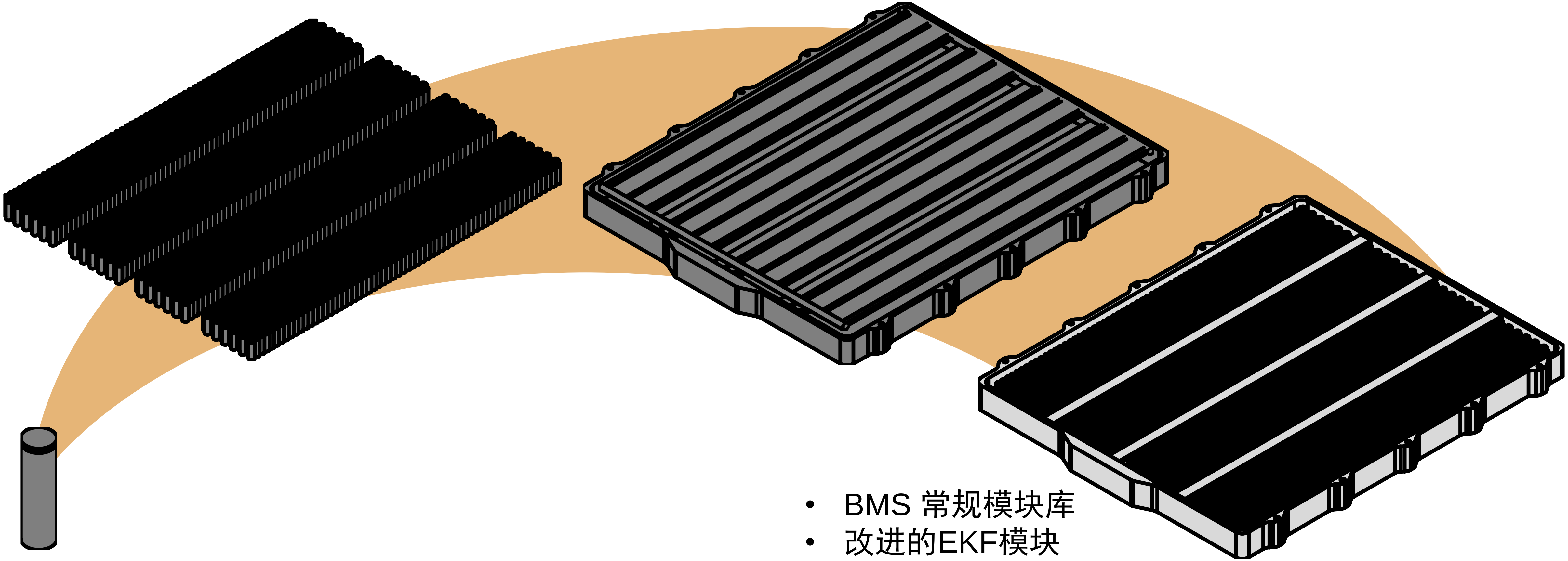
电池包/冷却板/BMS模块

仿真结果



BMS 算法模块库

特性与新功能



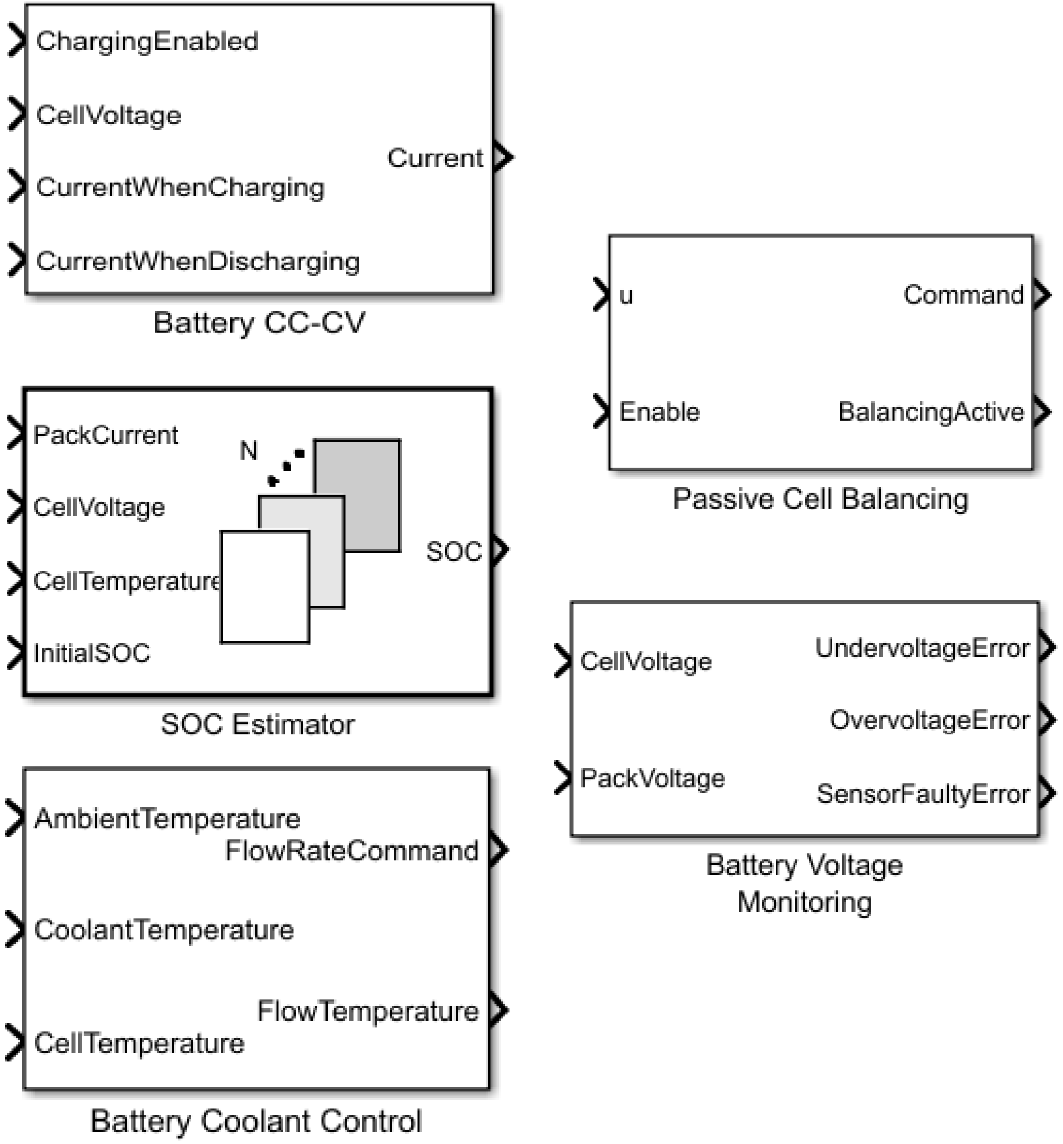
- BMS 常规模块库
- 改进的EKF模块
- 电池失效模型

BMS 模块库

概览

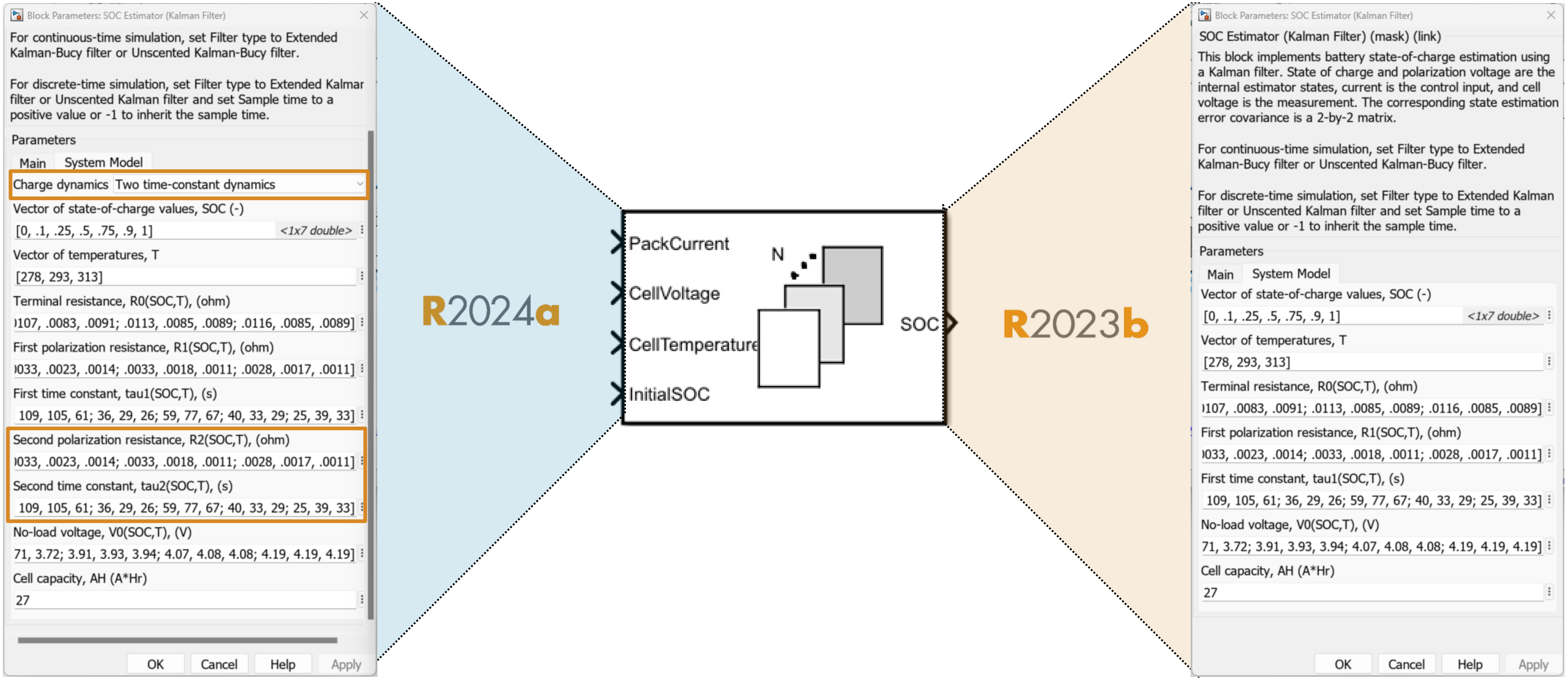
- Charge and discharge
  - CC-CV, current limits
- Passive cell balancing
- **Estimators**
  - **SOC, SOH, SOE**
- Protection
  - Current, voltage, temperature monitor
  - Fault qualification
- Thermal management
  - Coolant and heater control

» [Overview BMS blocks]



改进的等效电路电池模型

针对各 SOC 和 SOE estimator 模块

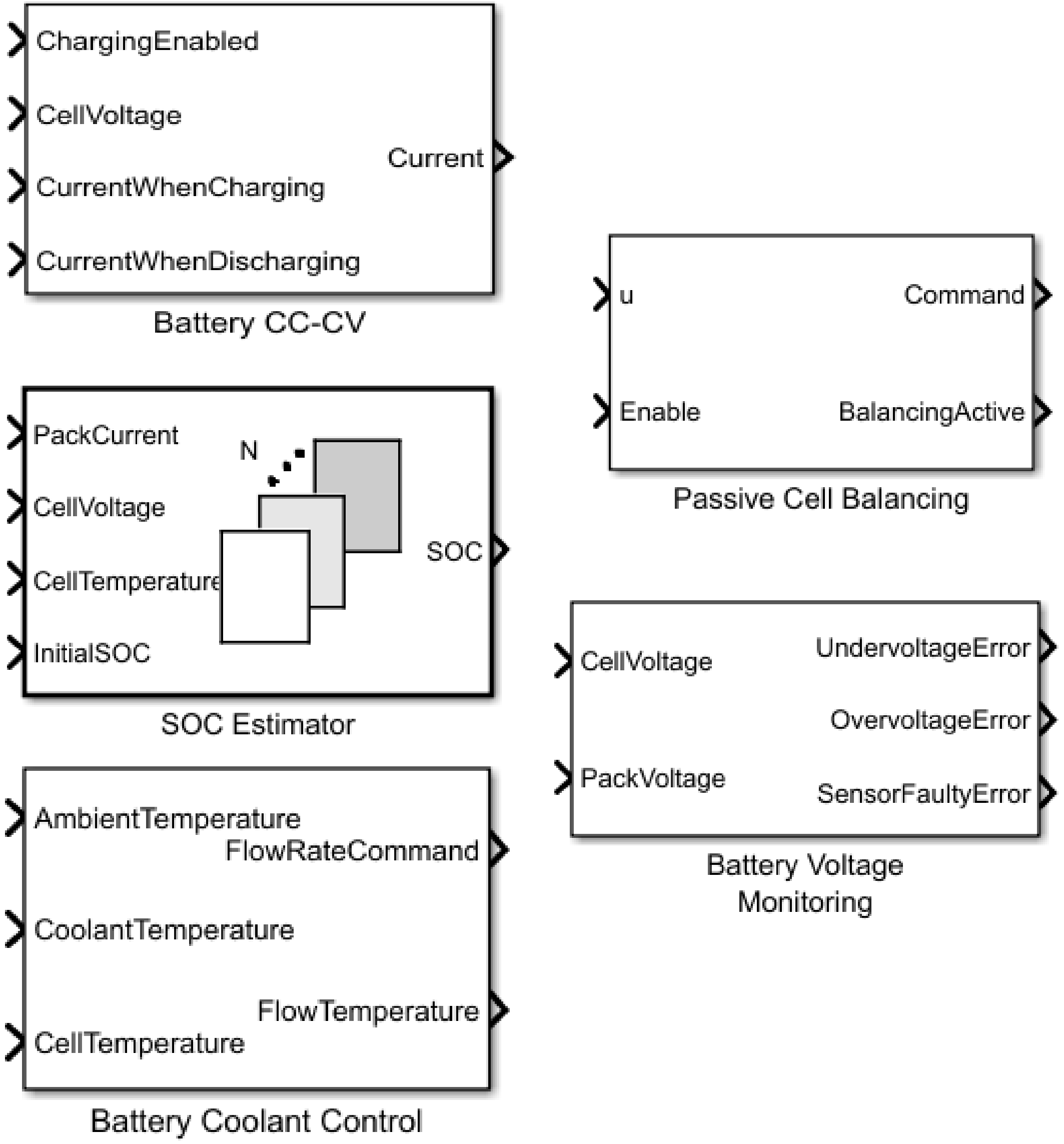


» [Charge and Discharge Battery Module with State of Charge Estimator]

BMS 模块库

概览

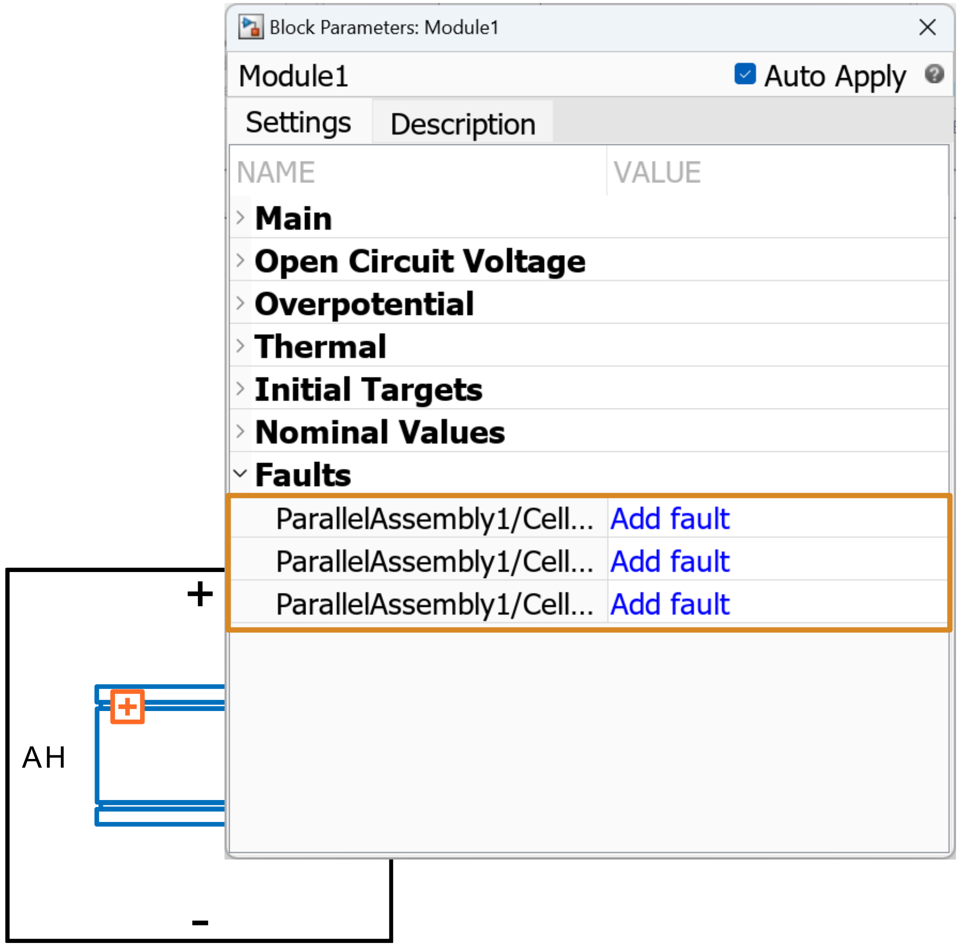
- Charge and discharge
  - CC-CV, current limits
- Passive cell balancing
- Estimators
  - SOC, SOH, SOE
- **Protection**
  - **Current, voltage, temperature monitor**
  - **Fault qualification**
- Thermal management
  - Coolant and heater control



» [Overview BMS blocks]

失效仿真 Faults

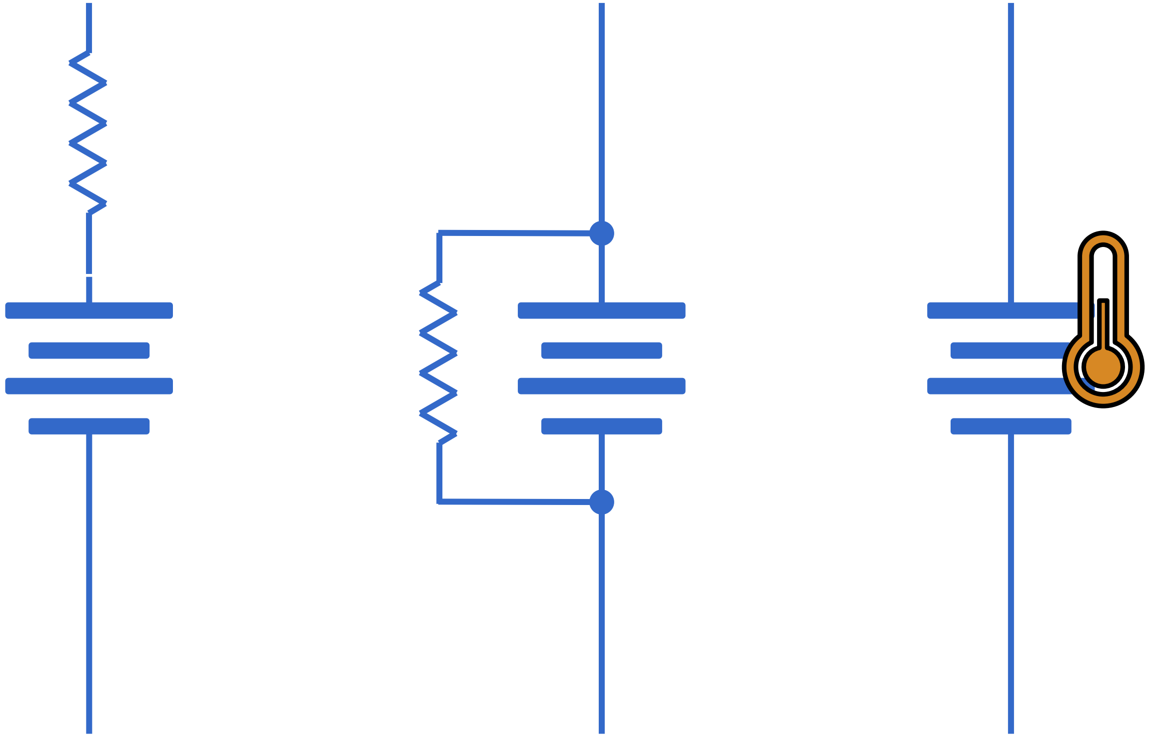
R2023b



Additional Resistance Fault

Internal Short Fault

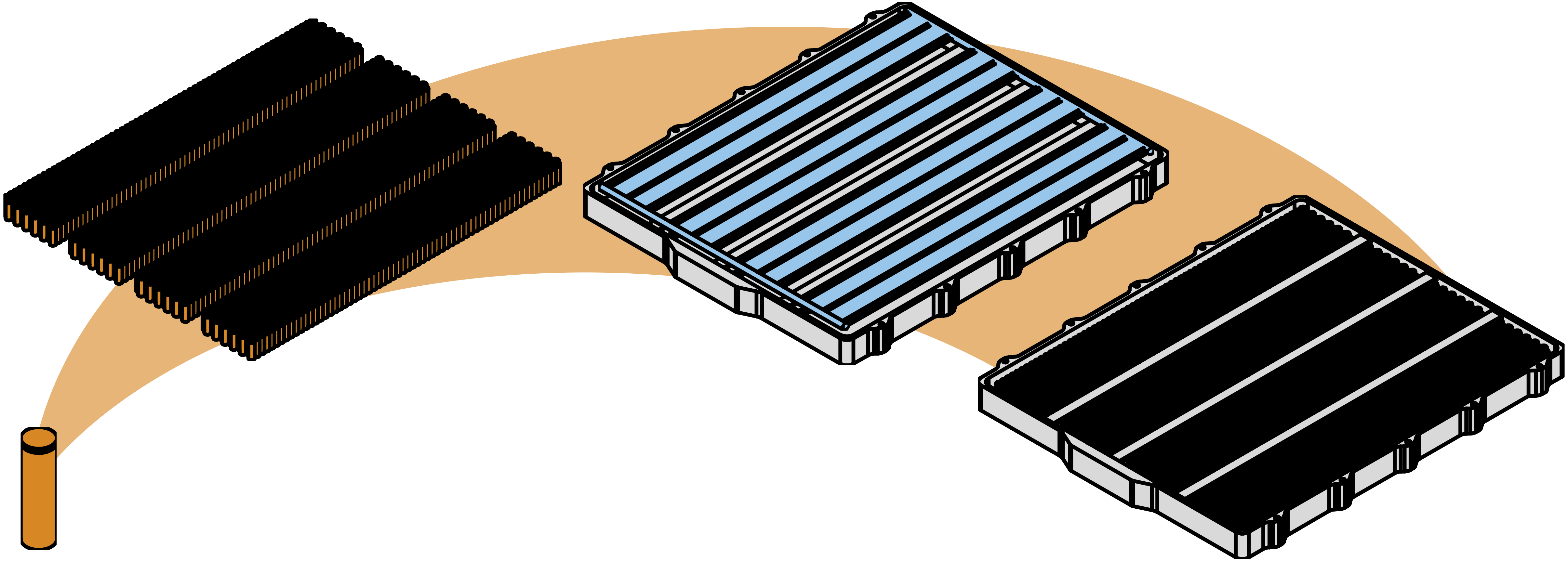
Exothermic Reaction



» [Inject Faults in Battery Models]

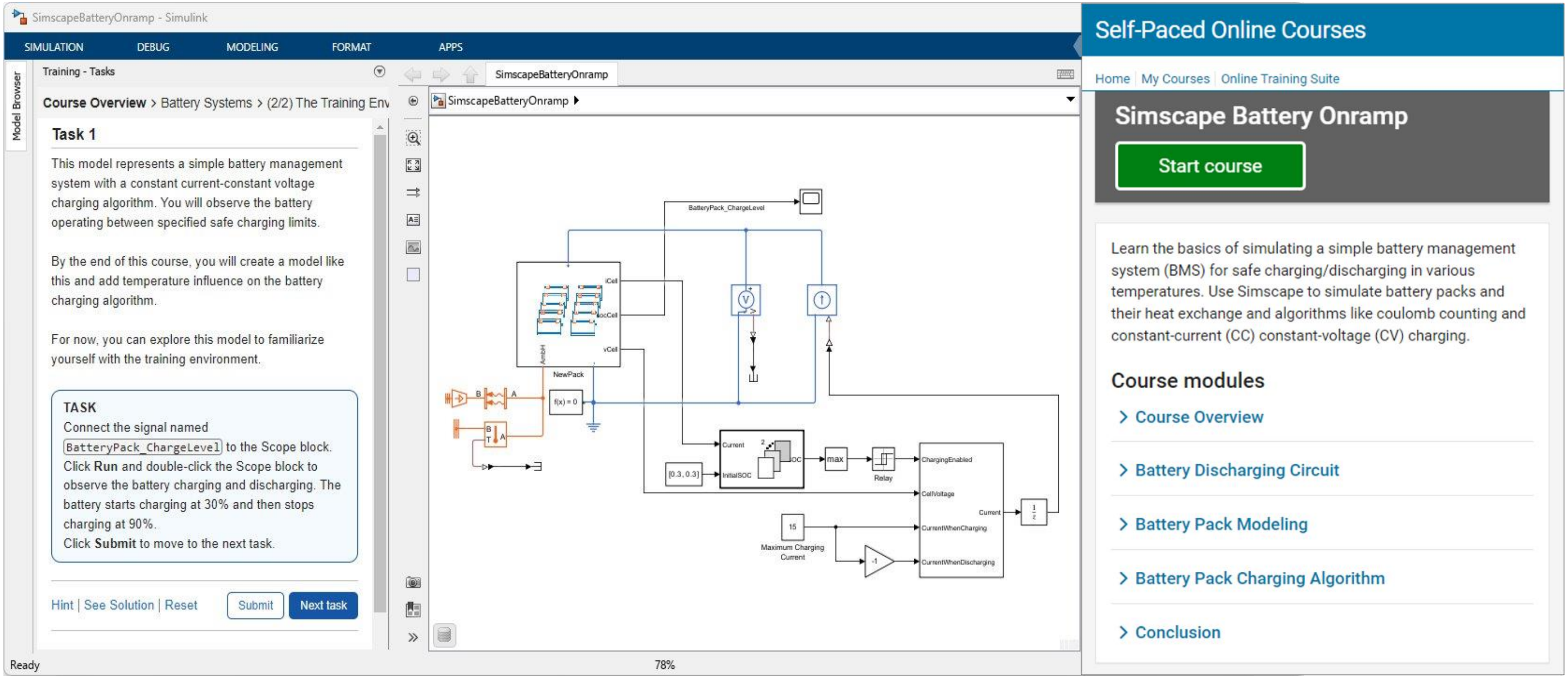
一些资料

Onramp and Training



入门教程以及培训:

Simscape Battery Onramp Now Available

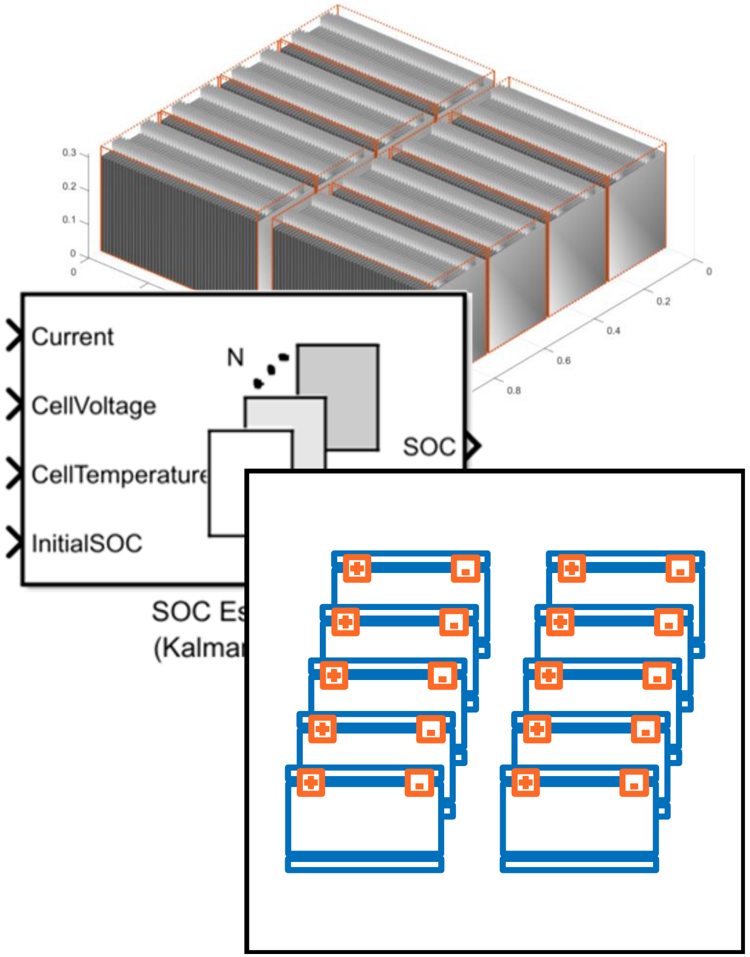


» [Simscape Battery Onramp]

入门教程以及培训:
New Instructor-Led Training

After this two-day training you will be able to:

- Model a cell unit including thermal and fading characteristics
- Perform cell characterization
- Construct battery packs and attach cooling plates
- Estimate State-Of-Charge and State-Of-Health
- Design the key functionalities of a battery management system including supervisory control, cell balancing, and fault diagnosis



» Battery Modeling and Algorithm Development with Simulink

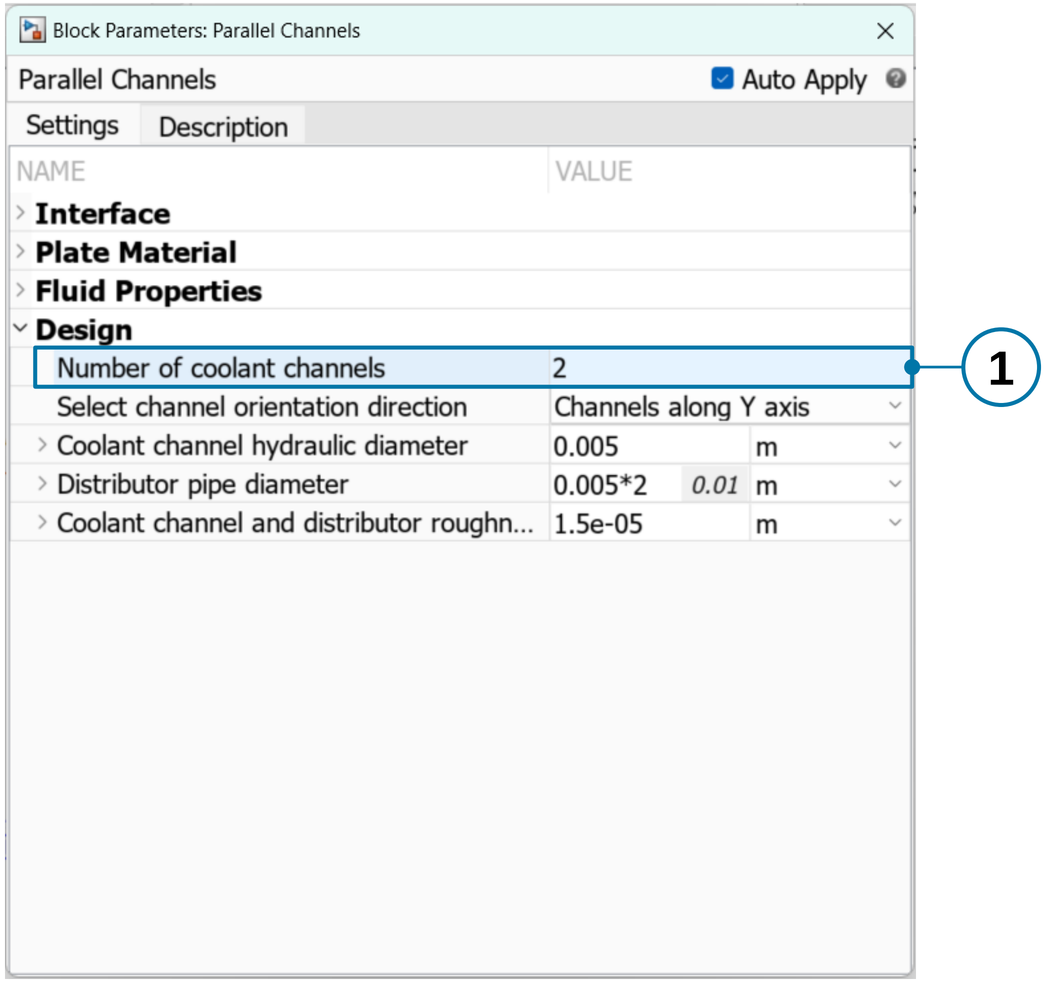
2024 MathWorks
中国汽车年会

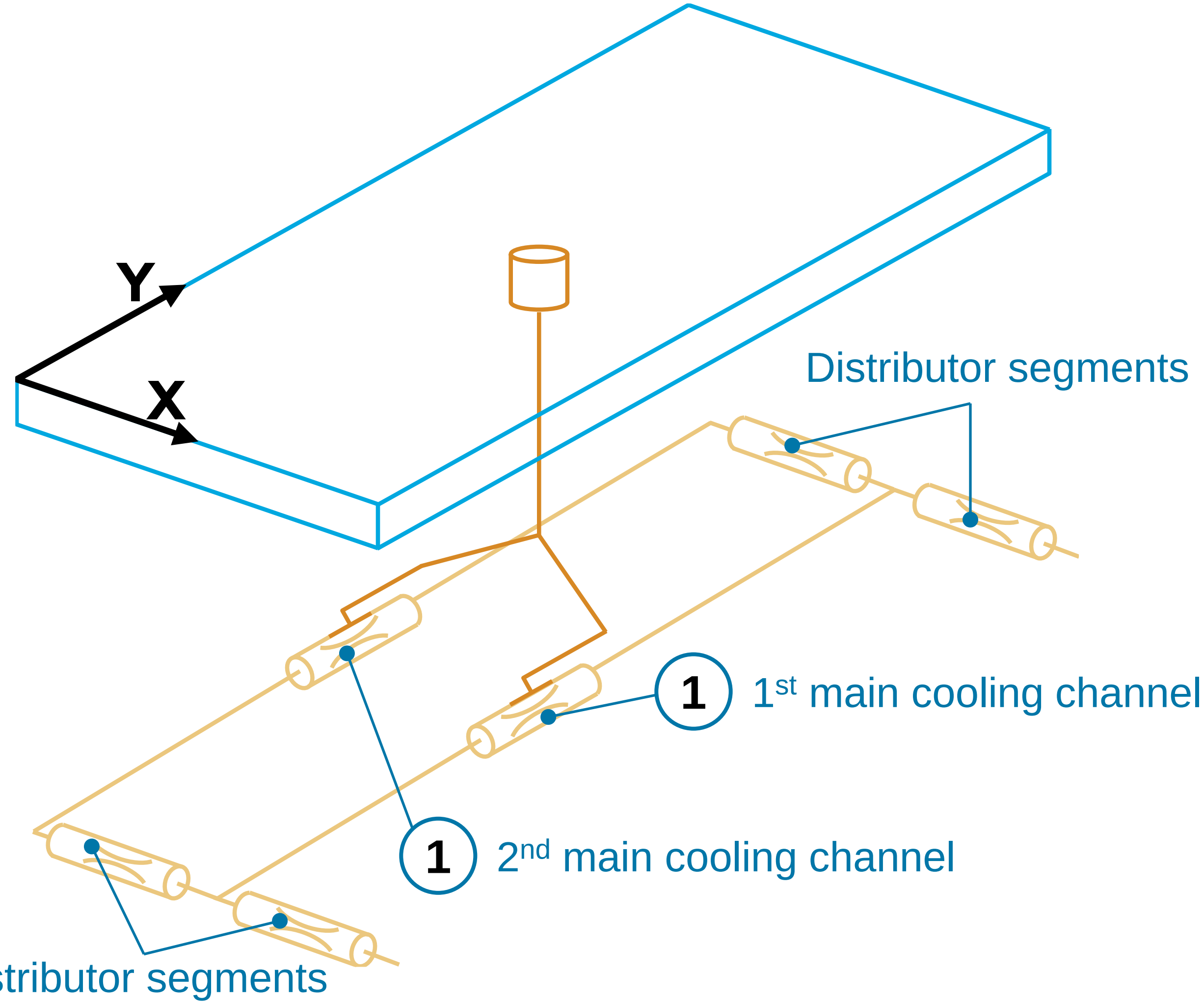
谢谢！

MathWorks

冷却水道的离散化解析模型

Parallel Channels Plate | Design | Number of Channels





冷却水道模型的离散化解析

Parallel Channels Plate | Design | Channel Orientation (in Y)

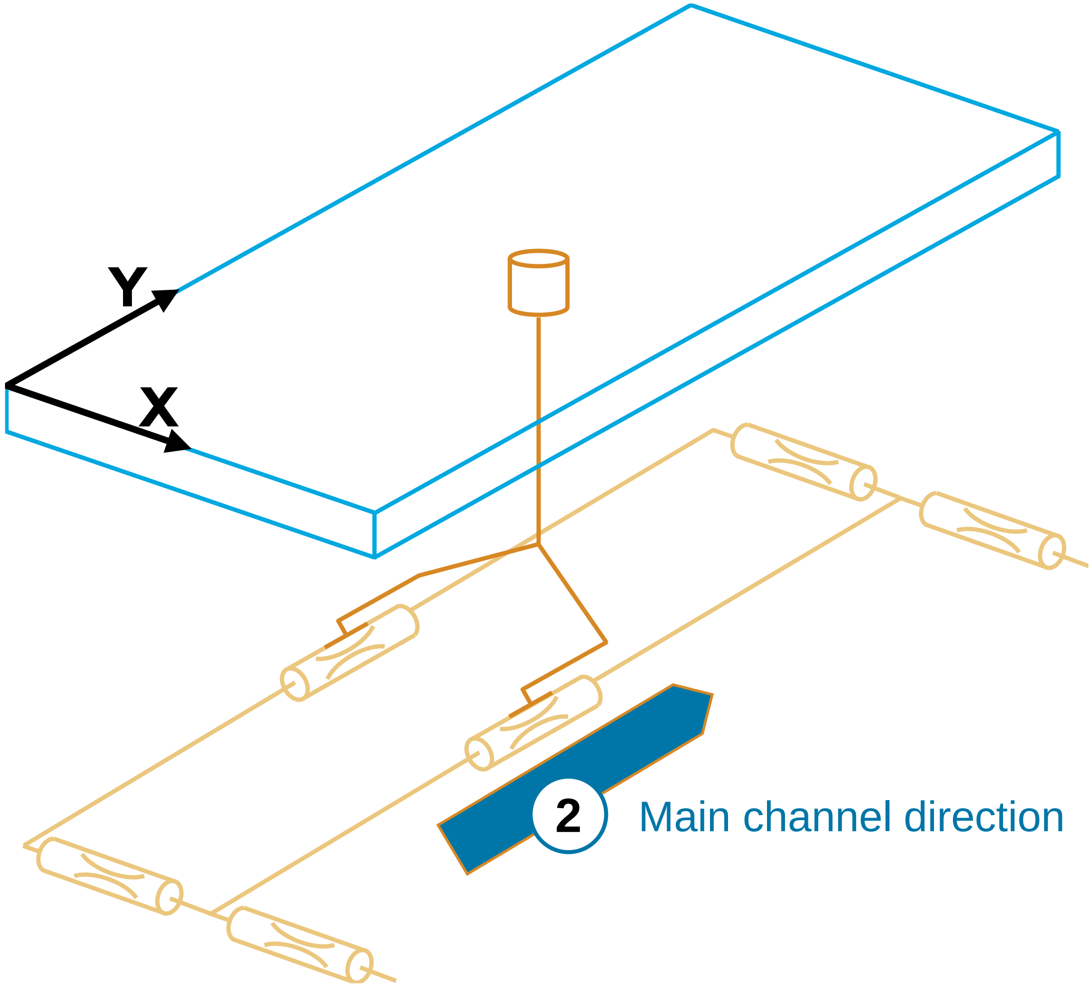
Block Parameters: Parallel Channels

Parallel Channels — Auto Apply

Settings | Description

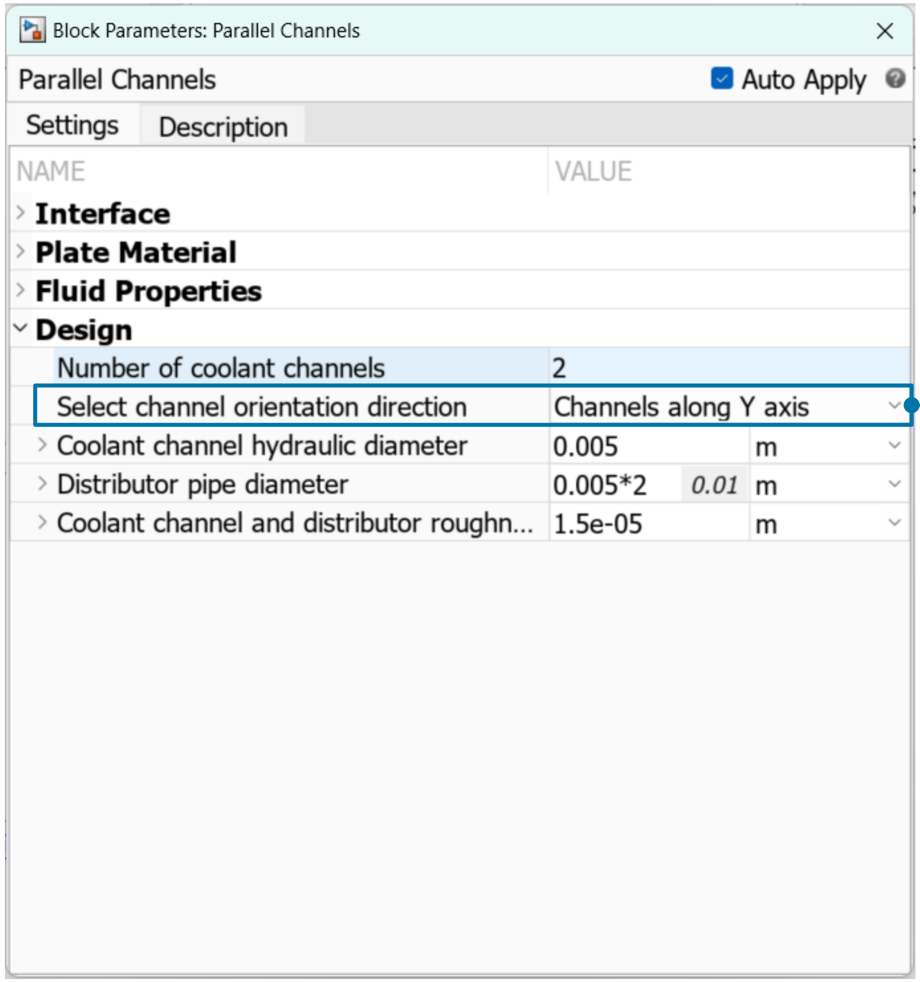
NAME	VALUE	
Interface		
Plate Material		
Fluid Properties		
Design		
Number of coolant channels	2	
Select channel orientation direction	Channels along Y axis	
Coolant channel hydraulic diameter	0.005	m
Distributor pipe diameter	0.005*2 *0.01*	m
Coolant channel and distributor roughn...	1.5e-05	m

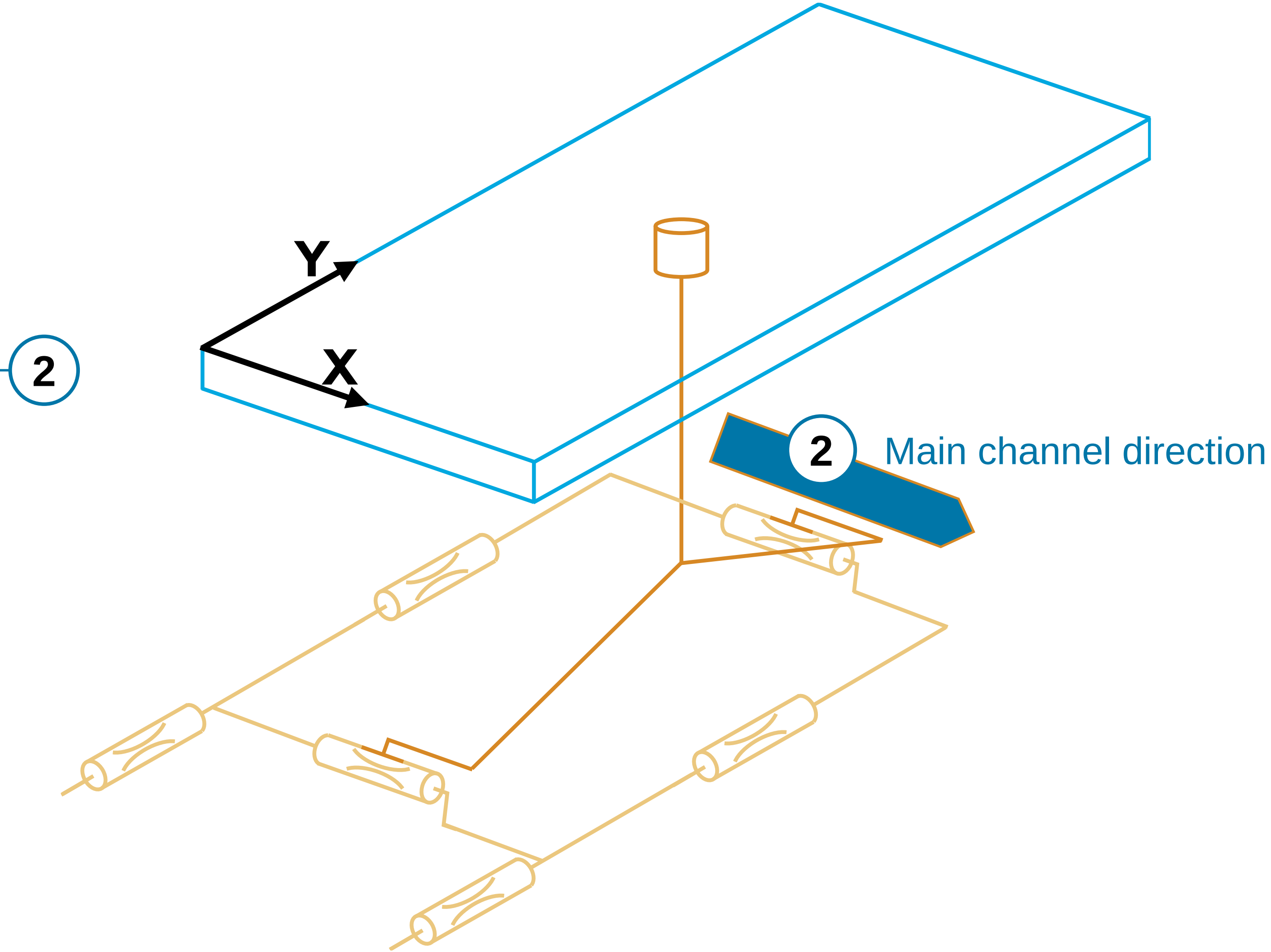
2



冷却水道模型的离散化解析

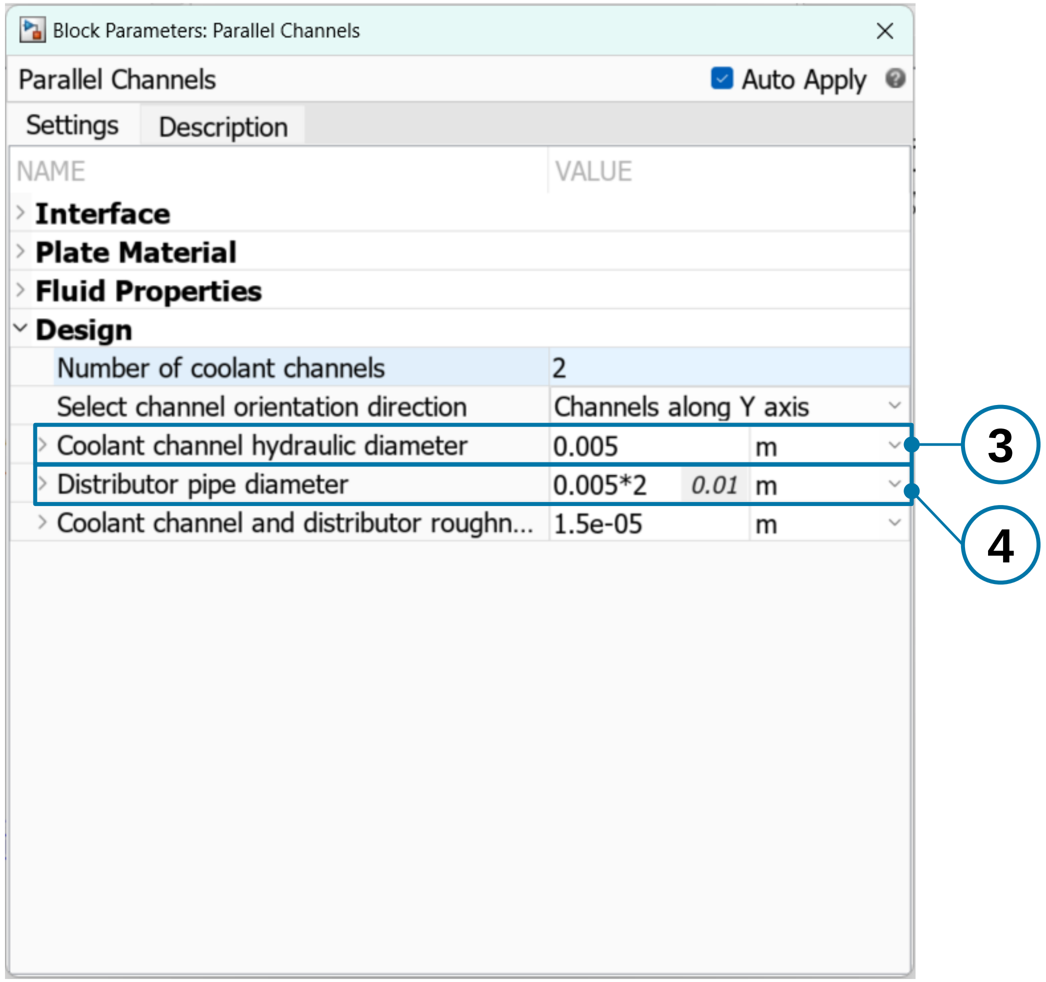
Parallel Channels Plate | Design | Channel Orientation (in X)

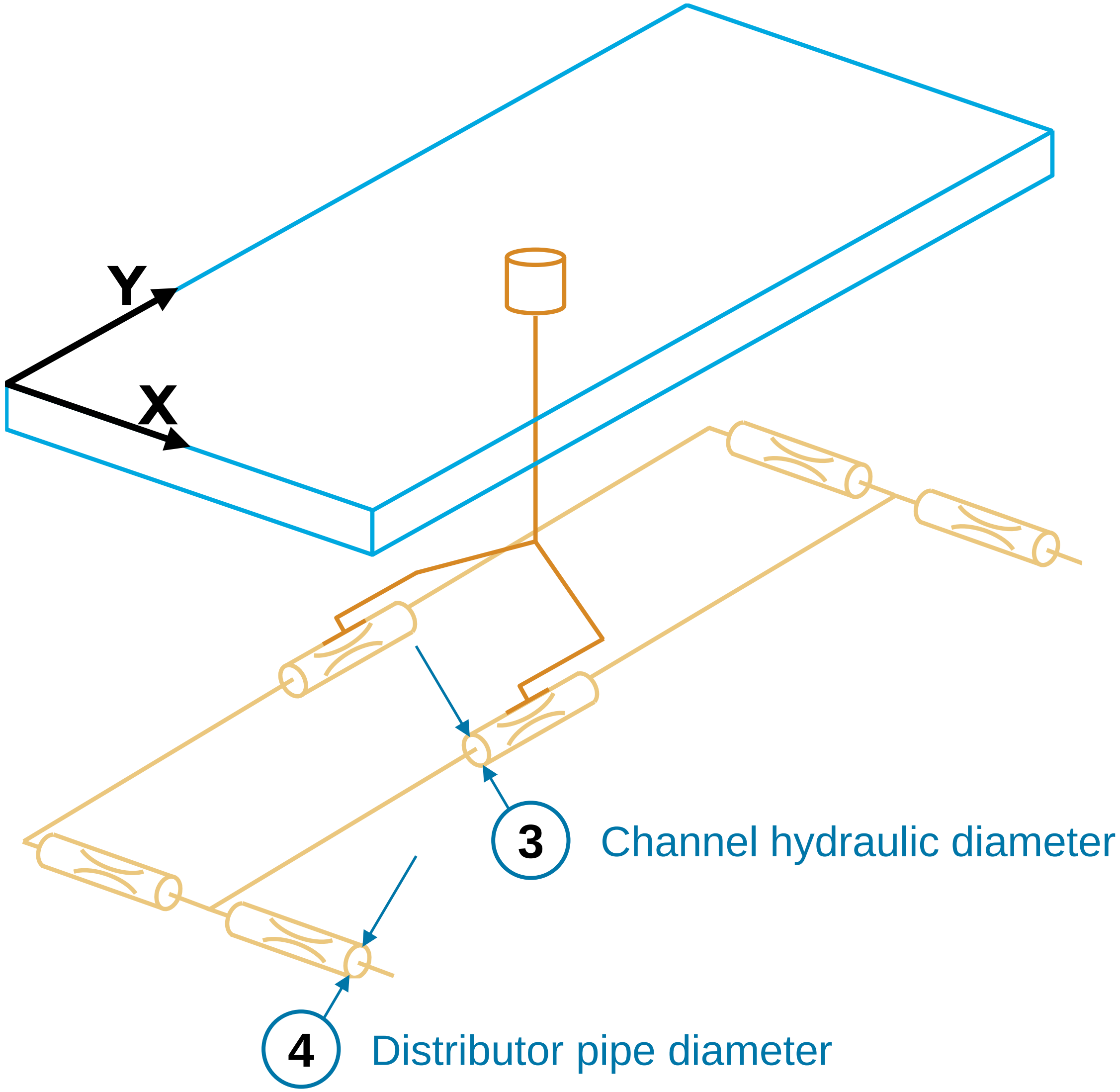




冷却水道模型的离散化解析

Parallel Channels Plate | Design | Channel & Distributor Diameters





冷却水道模型的离散化解析

Parallel Channels Plate | Design | Channel Roughness

Block Parameters: Parallel Channels

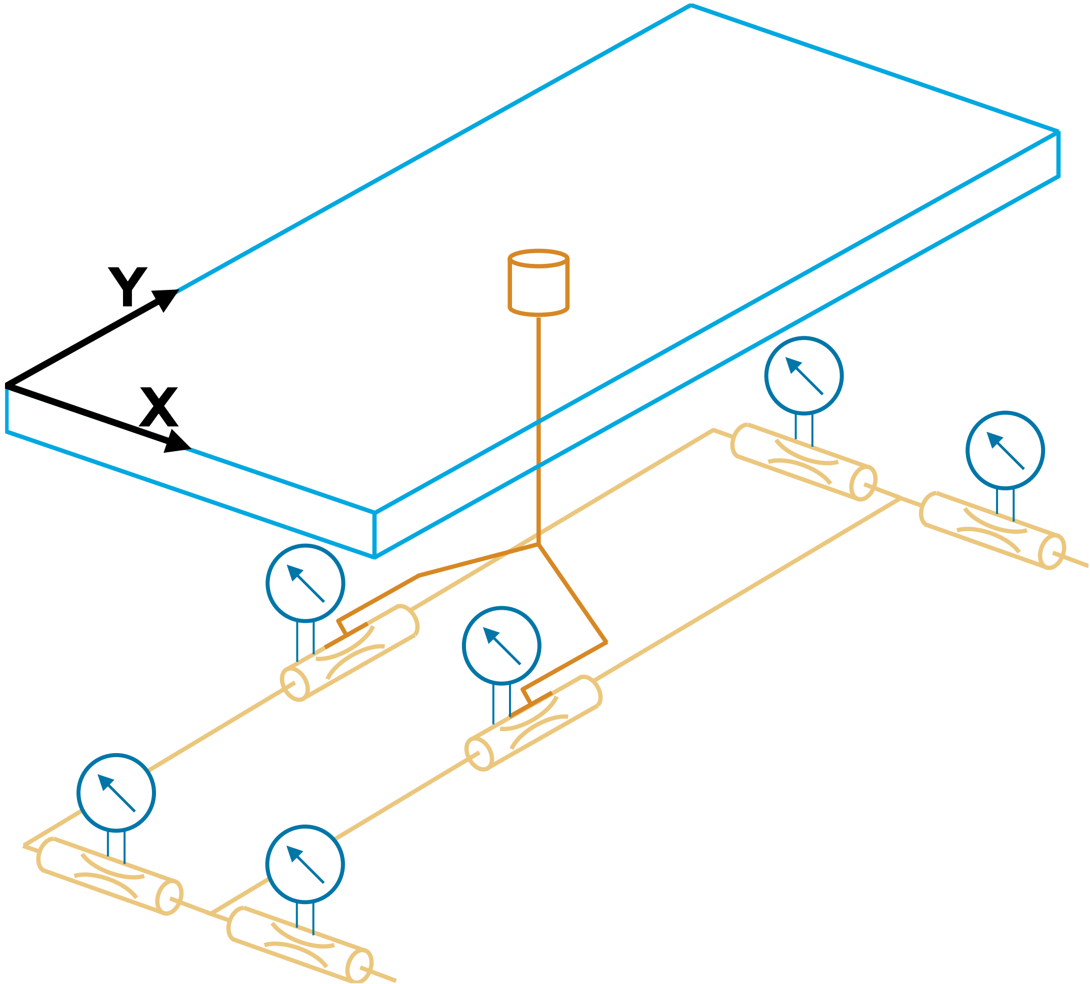
Parallel Channels — Auto Apply

Settings | Description

NAME	VALUE	
Interface		
Plate Material		
Fluid Properties		
Design		
Number of coolant channels	2	
Select channel orientation direction	Channels along Y axis	
Coolant channel hydraulic diameter	0.005	m
Distributor pipe diameter	0.005*2 0.01	m
Coolant channel and distributor roughn...	1.5e-05	m

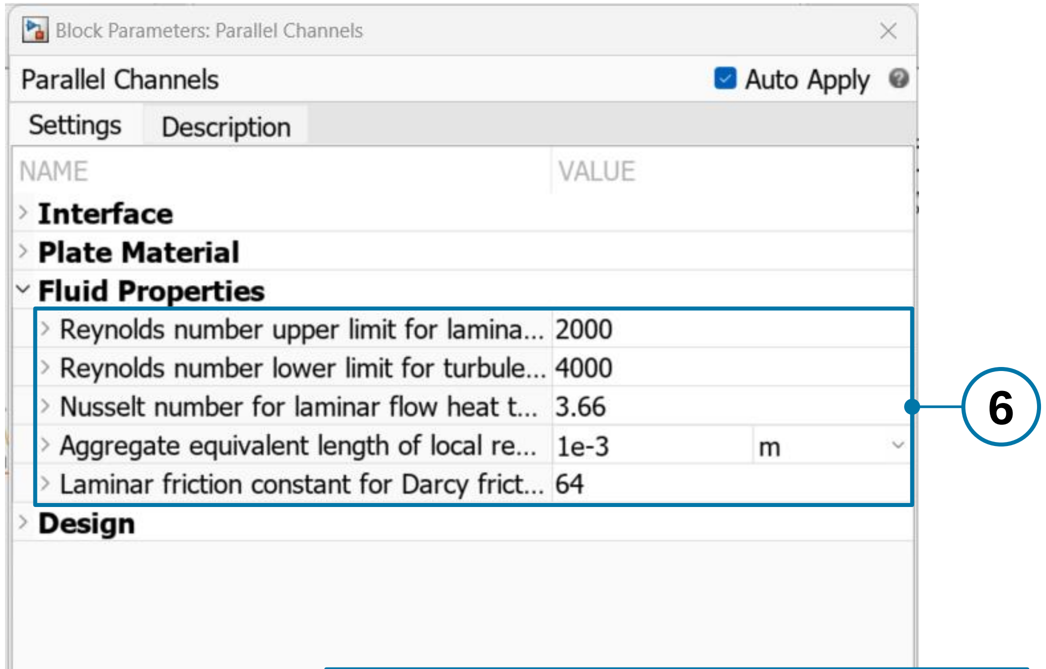
5

Roughness value is applied on all pipes (coolant channels and distributor pipes)



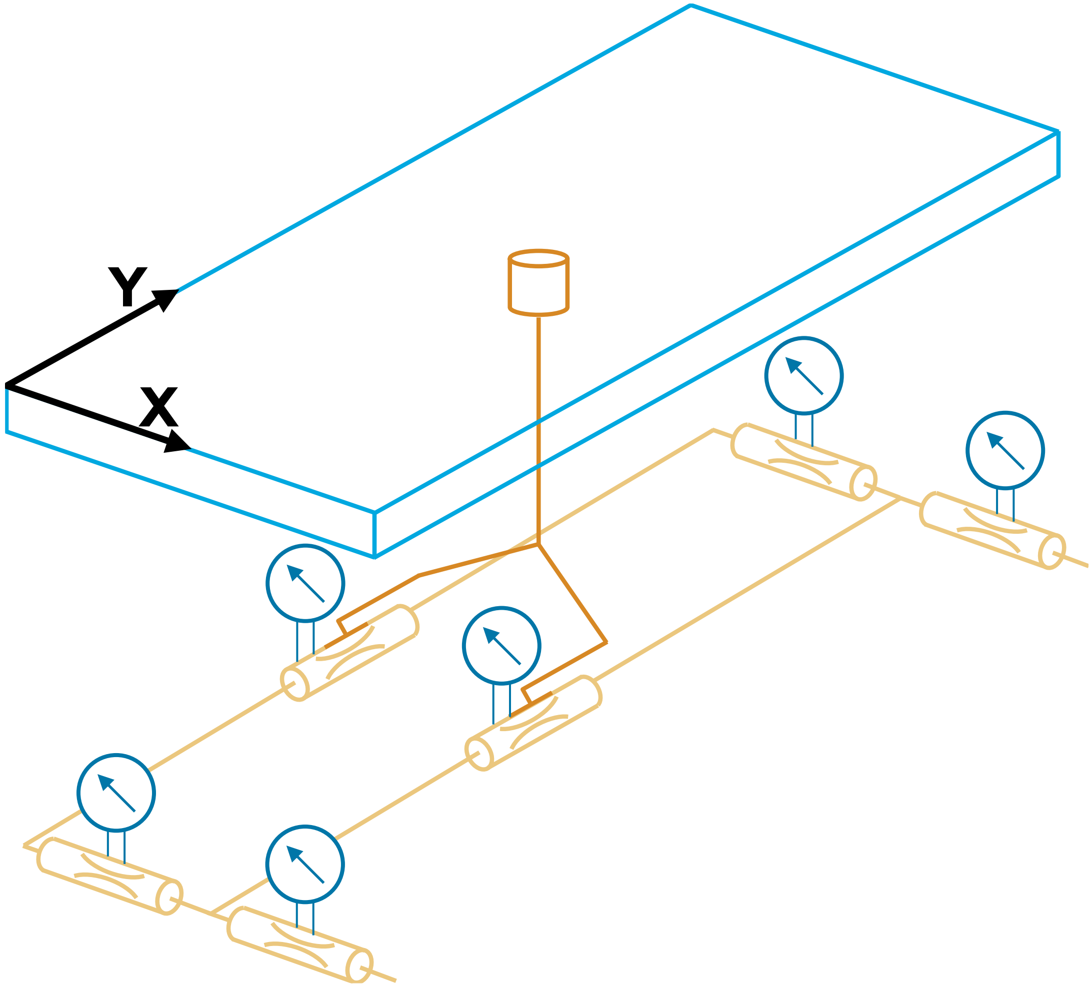
冷却水道模型的离散化解析

Parallel Channels Plate | Fluid Properties | Flow parameters



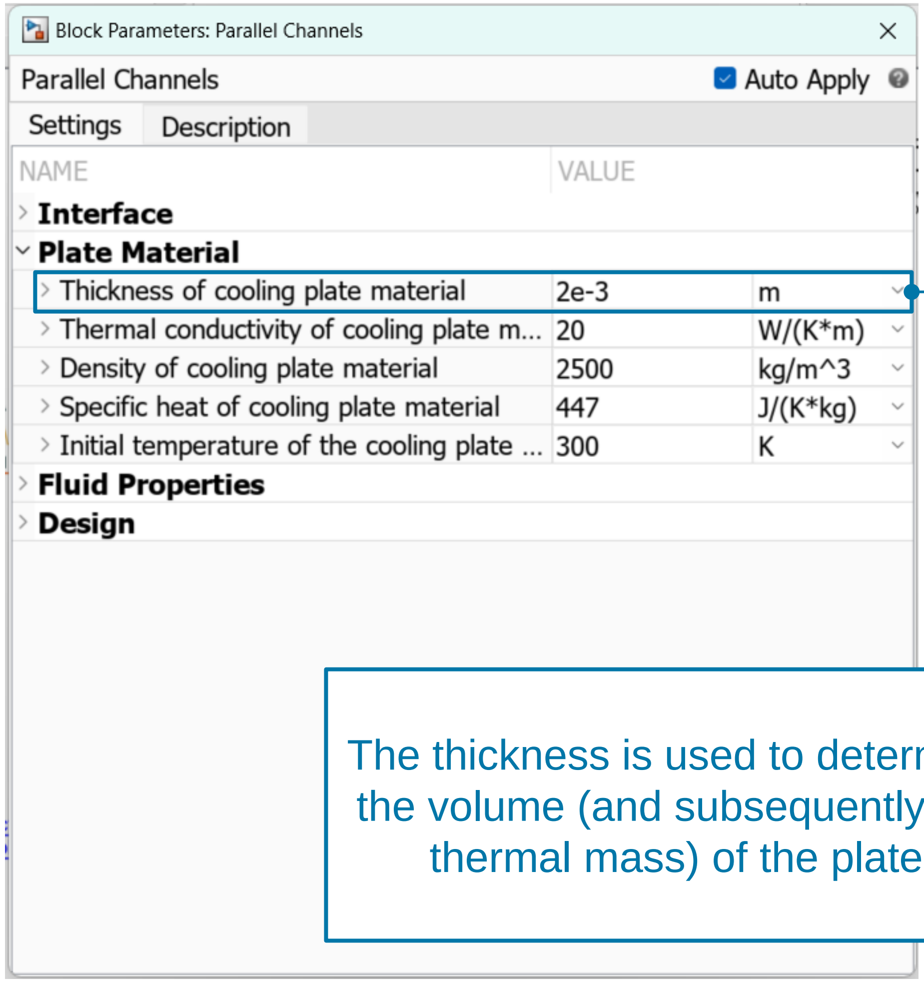
Fluid properties determine:

- Conditions for turbulent flow
- Pipe losses
- Pipe convection heat

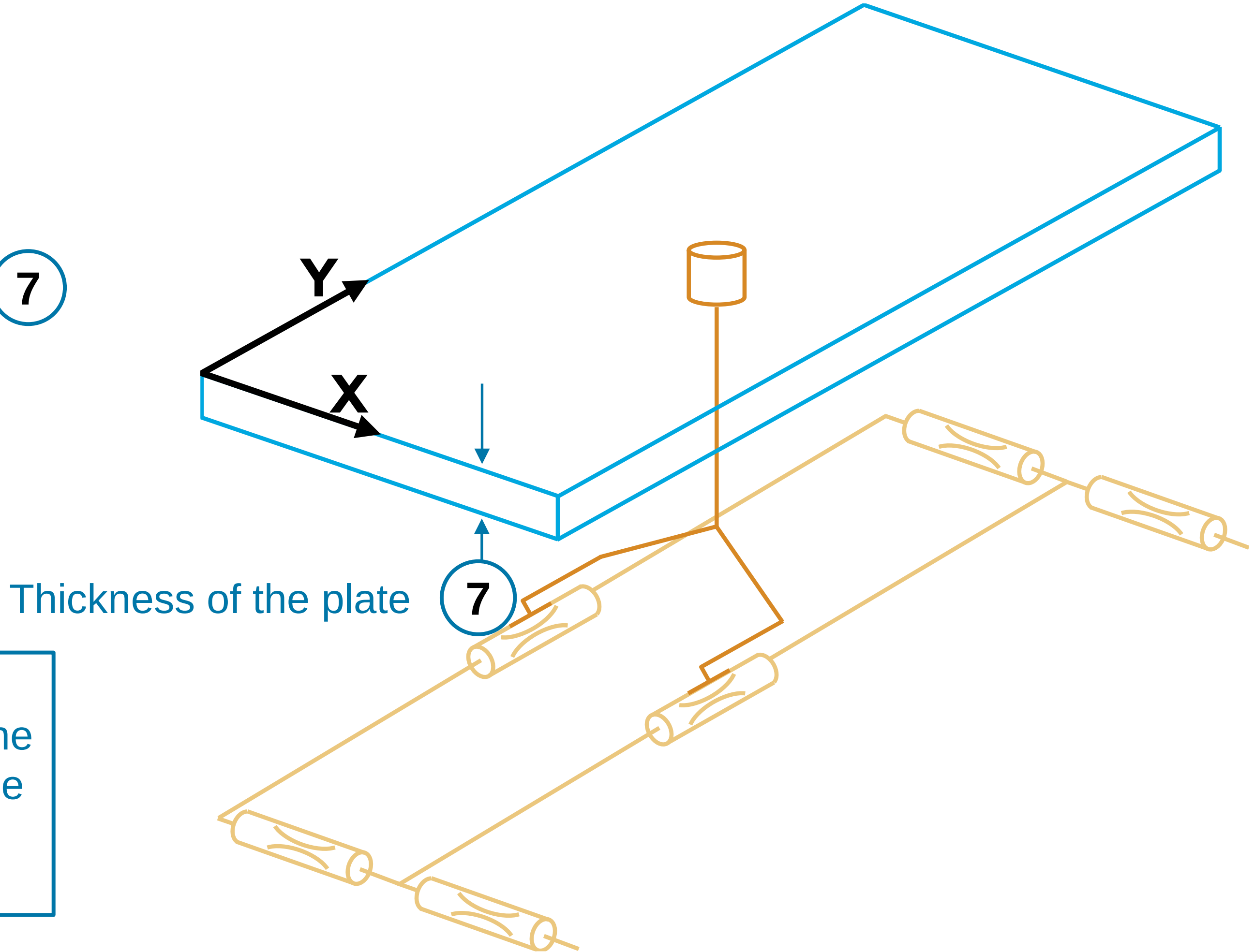


冷却水道模型的离散化解析

Parallel Channels Plate | Plate Material | Thickness

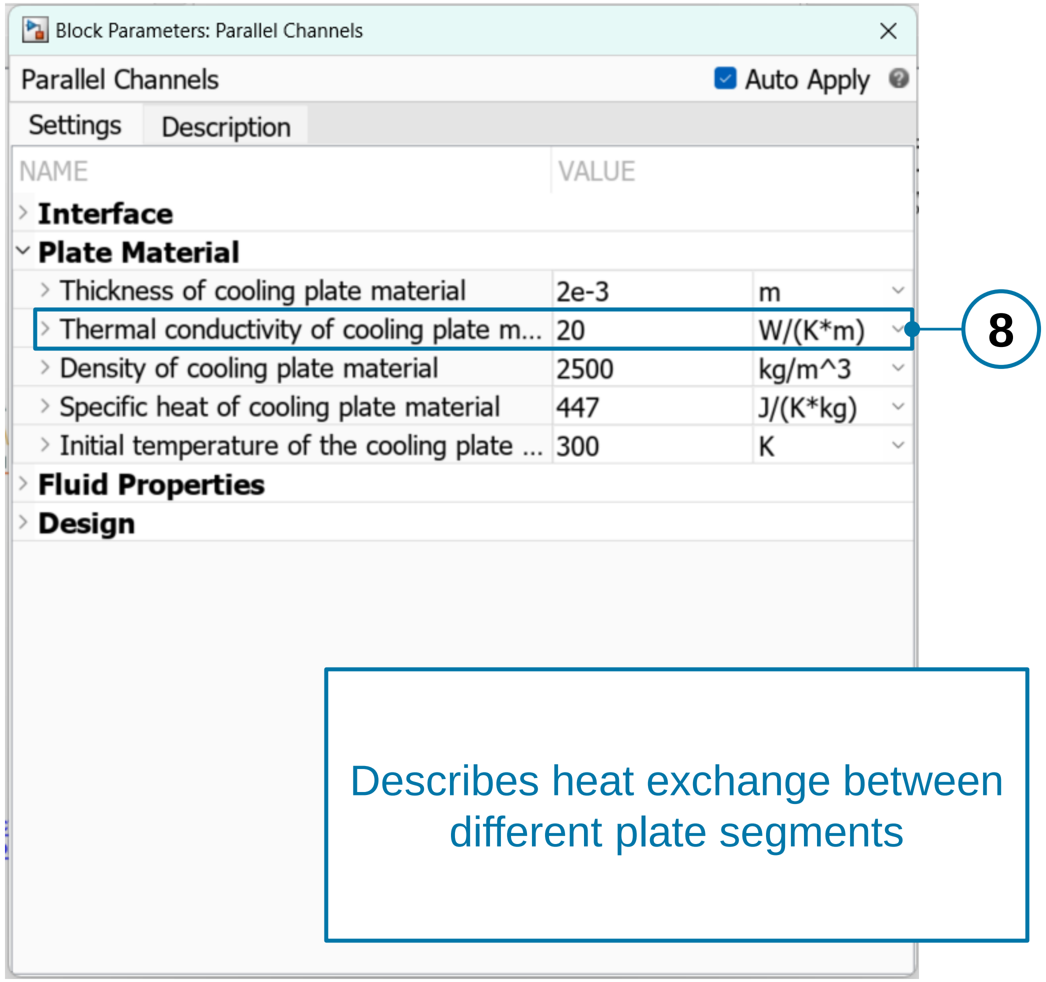


The thickness is used to determine the volume (and subsequently the thermal mass) of the plate

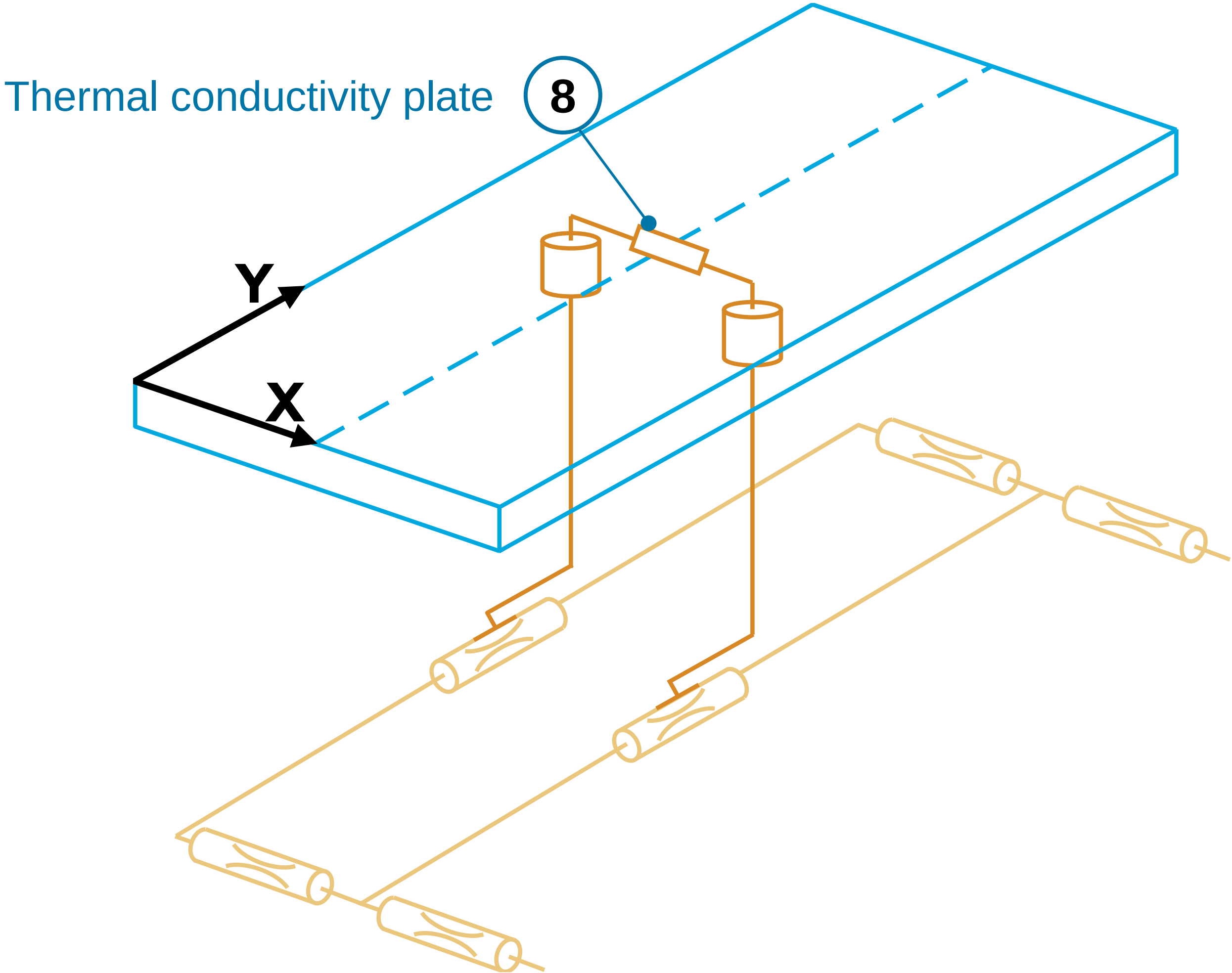


冷却水道模型的离散化解析

Parallel Channels Plate | Plate Material | Thermal Conductivity

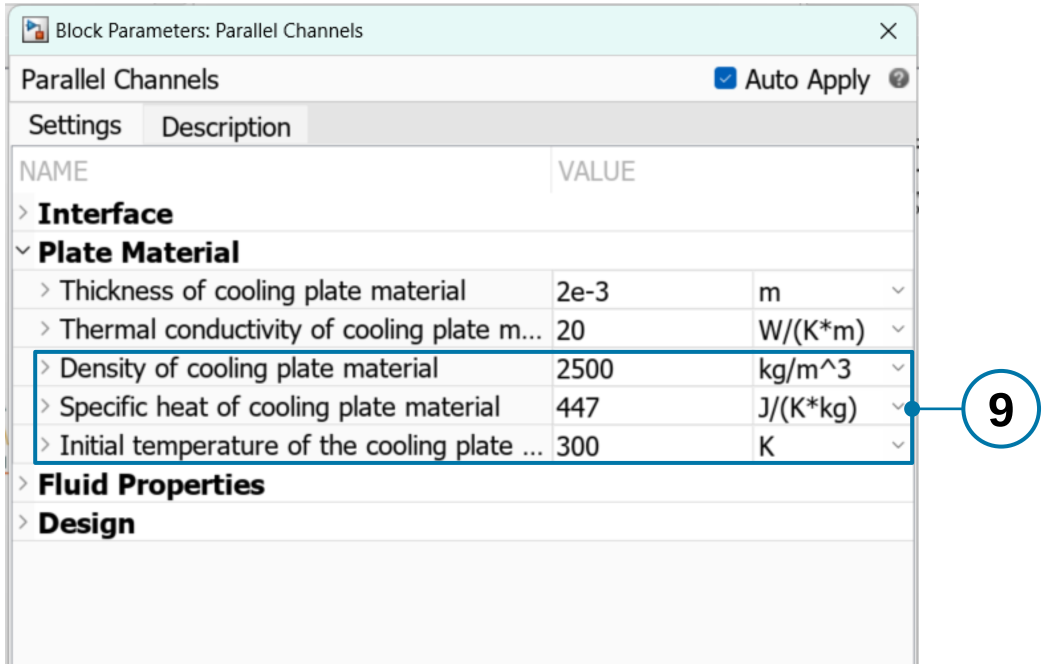


Describes heat exchange between different plate segments

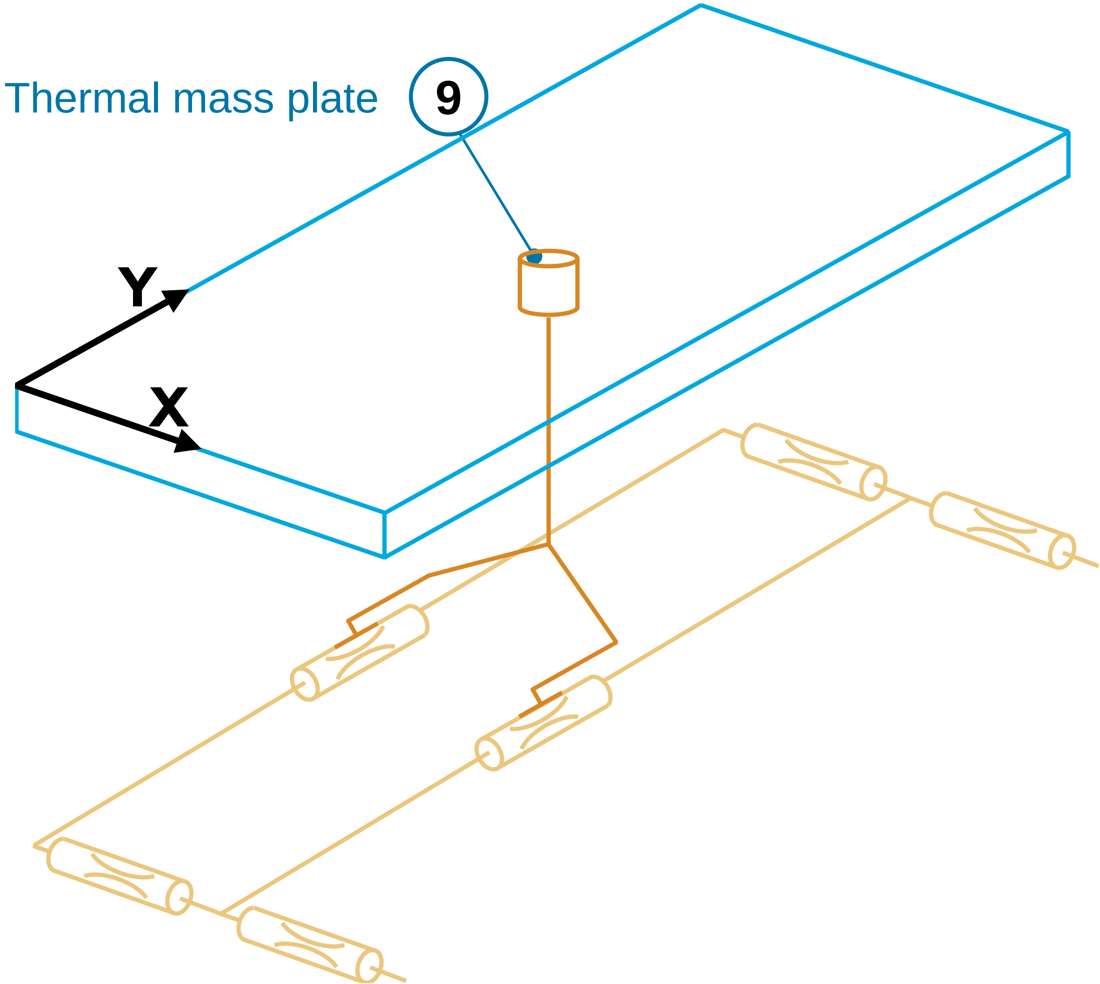


冷却水道模型的离散化解析

Parallel Channels Plate | Plate Material | Thermal parameters

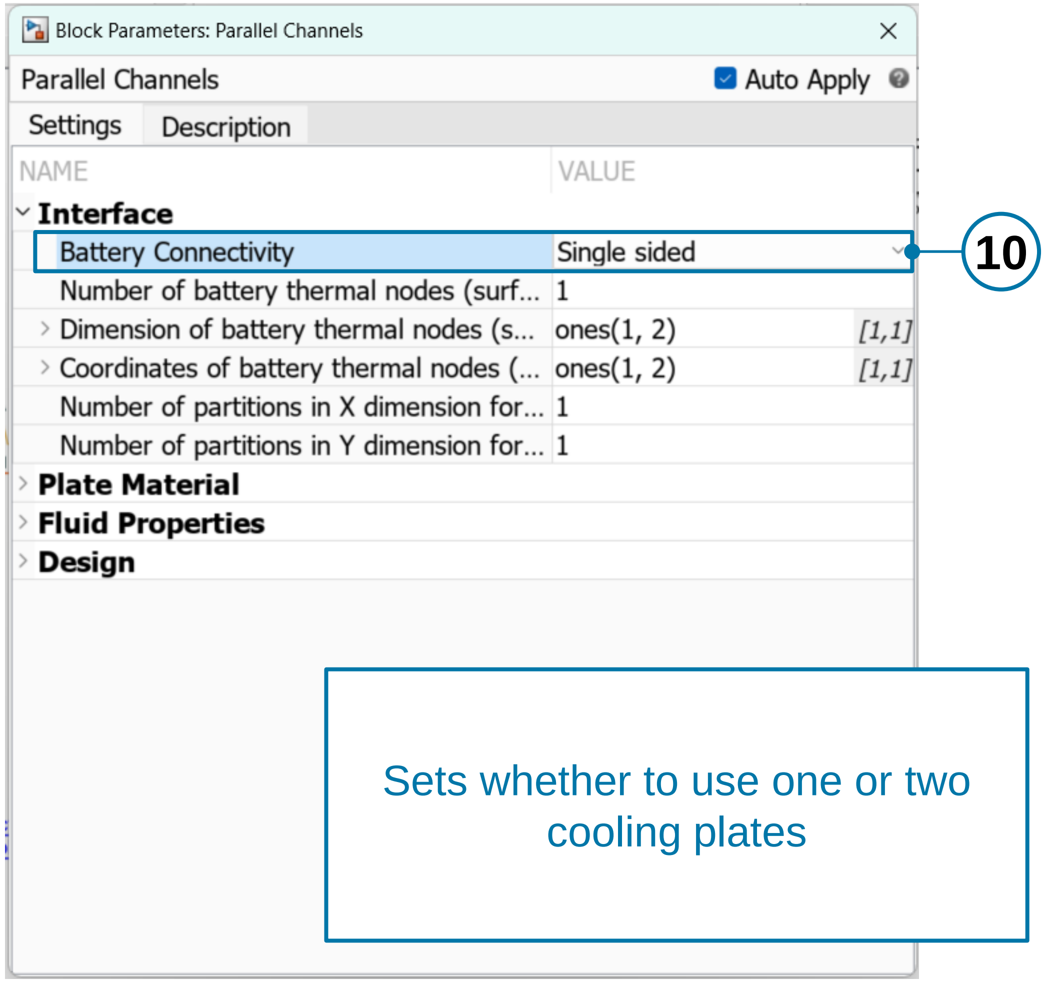


The density and specific heat are used to determine the thermal mass of the plate

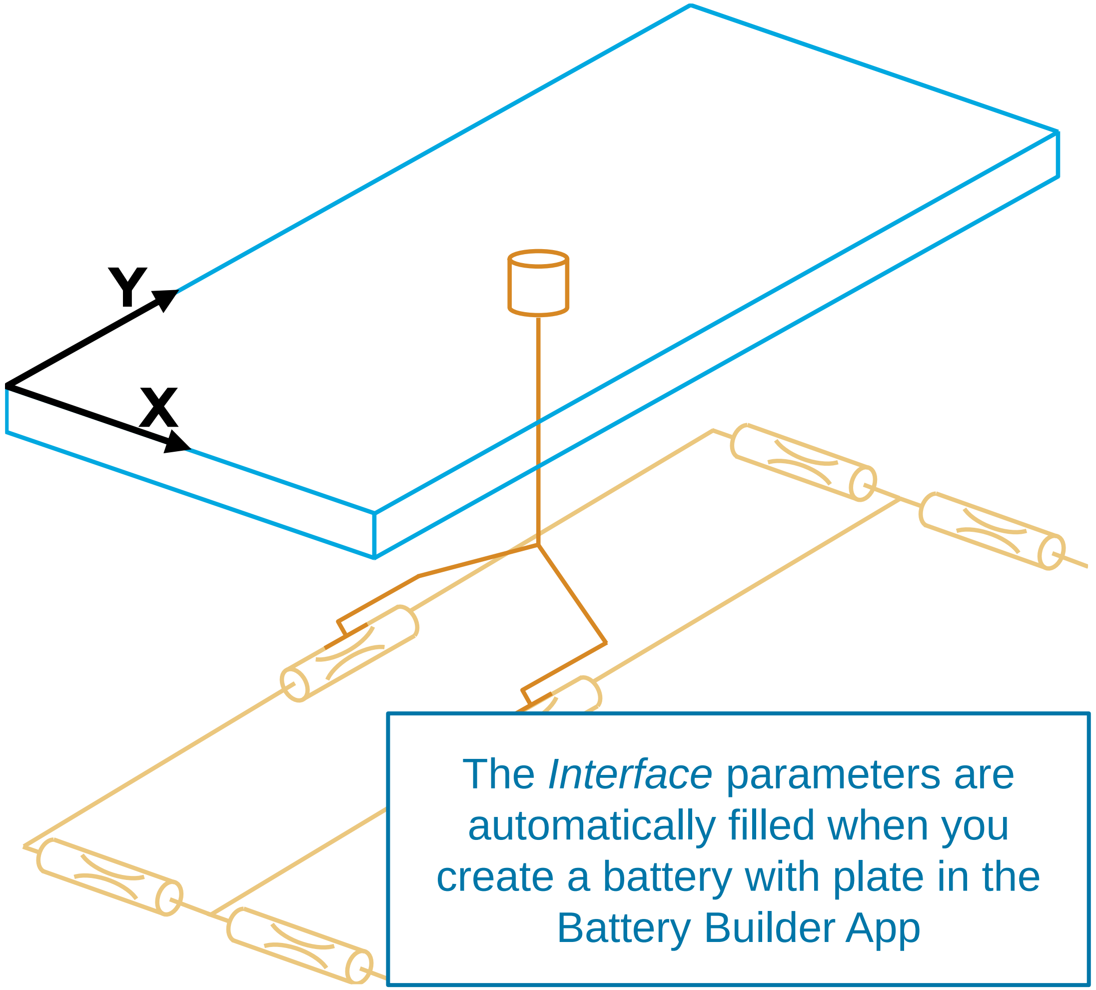


冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Battery Connectivity



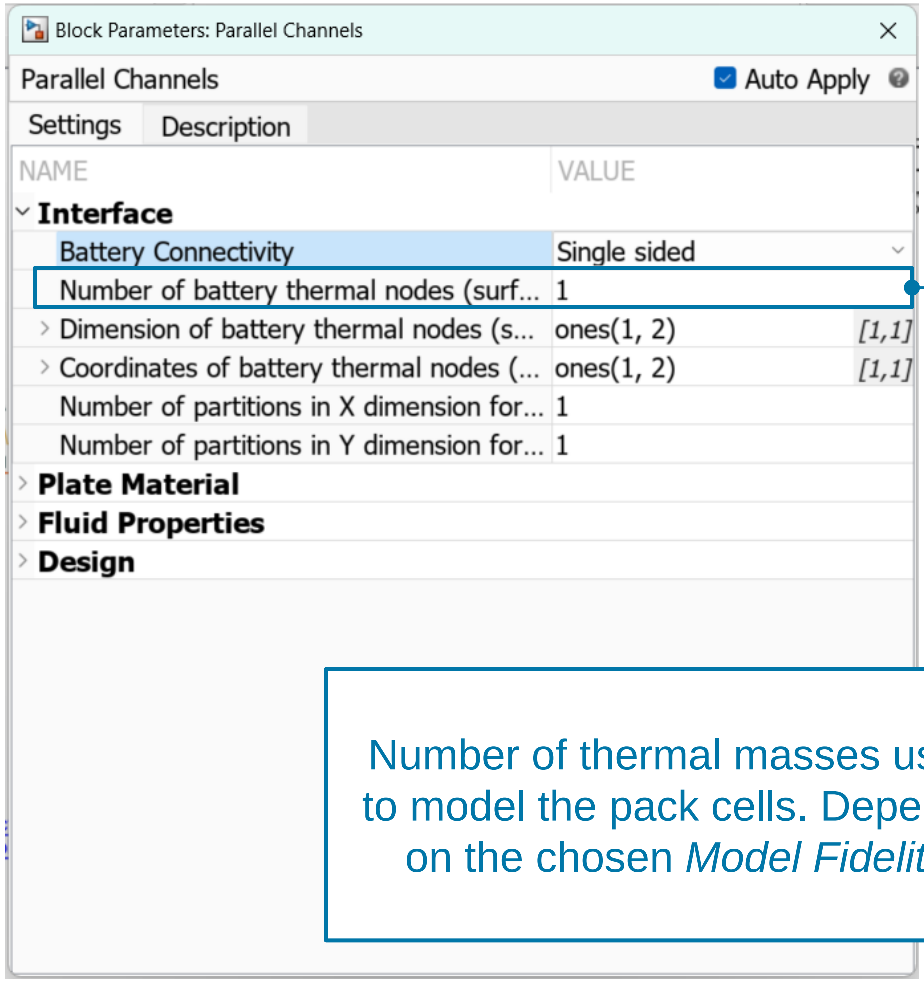
Sets whether to use one or two cooling plates



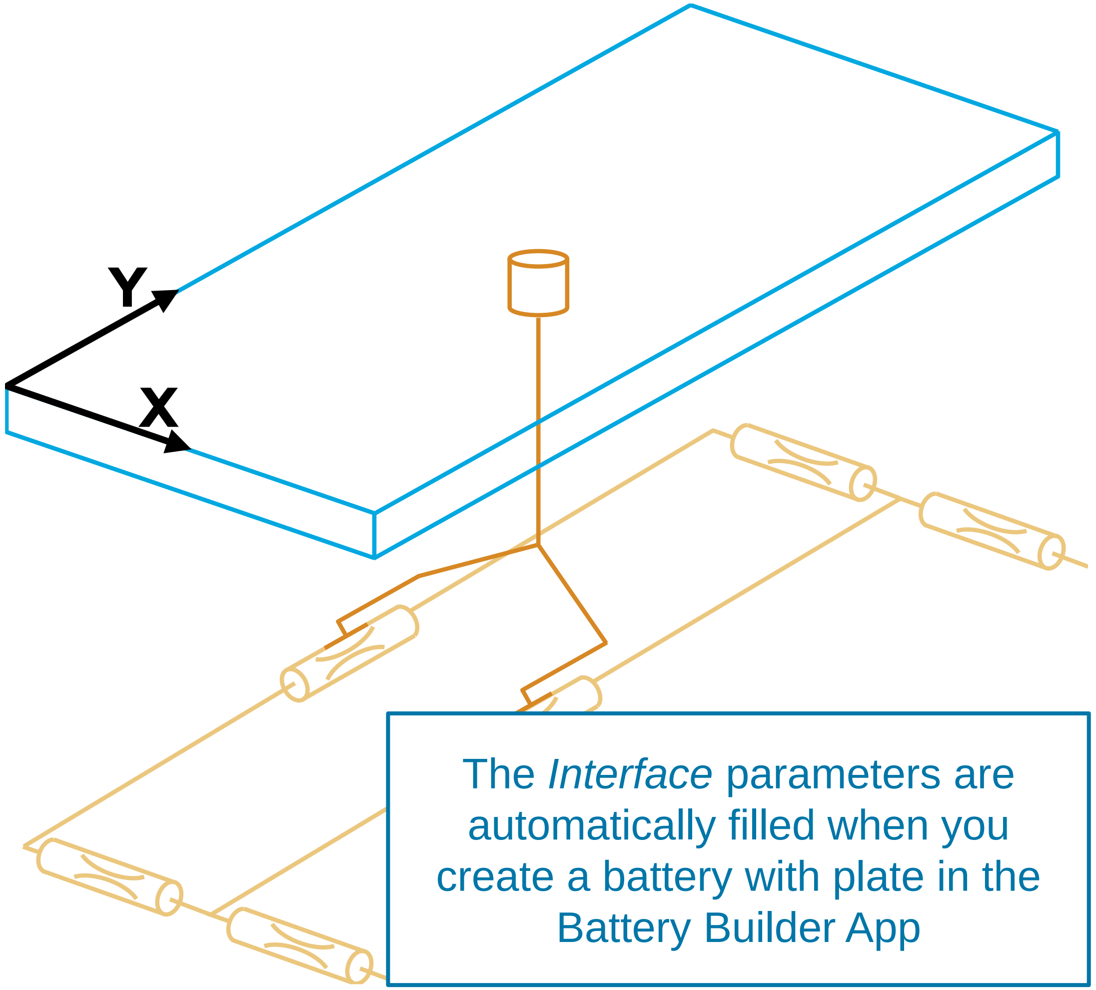
The *Interface* parameters are automatically filled when you create a battery with plate in the Battery Builder App

冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Number of Battery Nodes



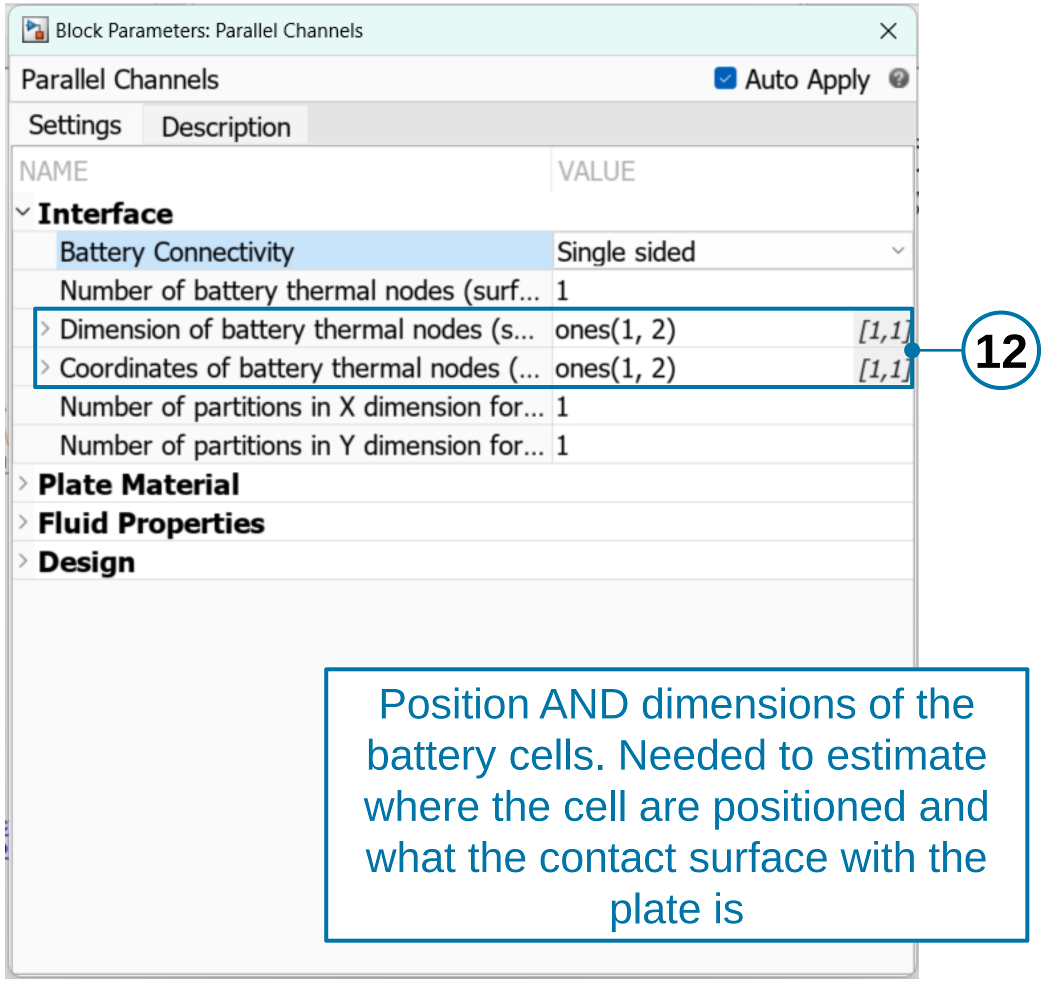
Number of thermal masses used to model the pack cells. Depends on the chosen *Model Fidelity*



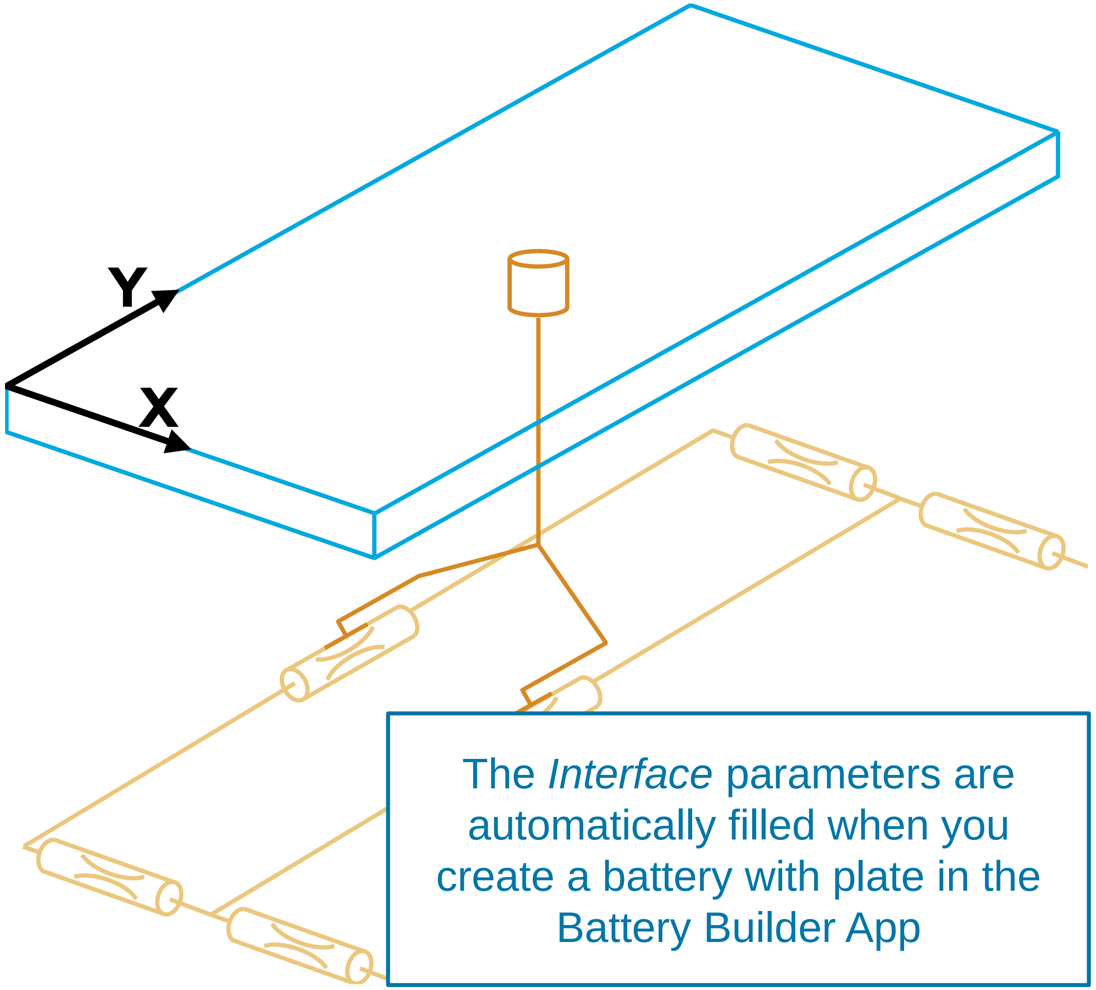
The *Interface* parameters are automatically filled when you create a battery with plate in the Battery Builder App

冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Dimension and Position of Battery Nodes



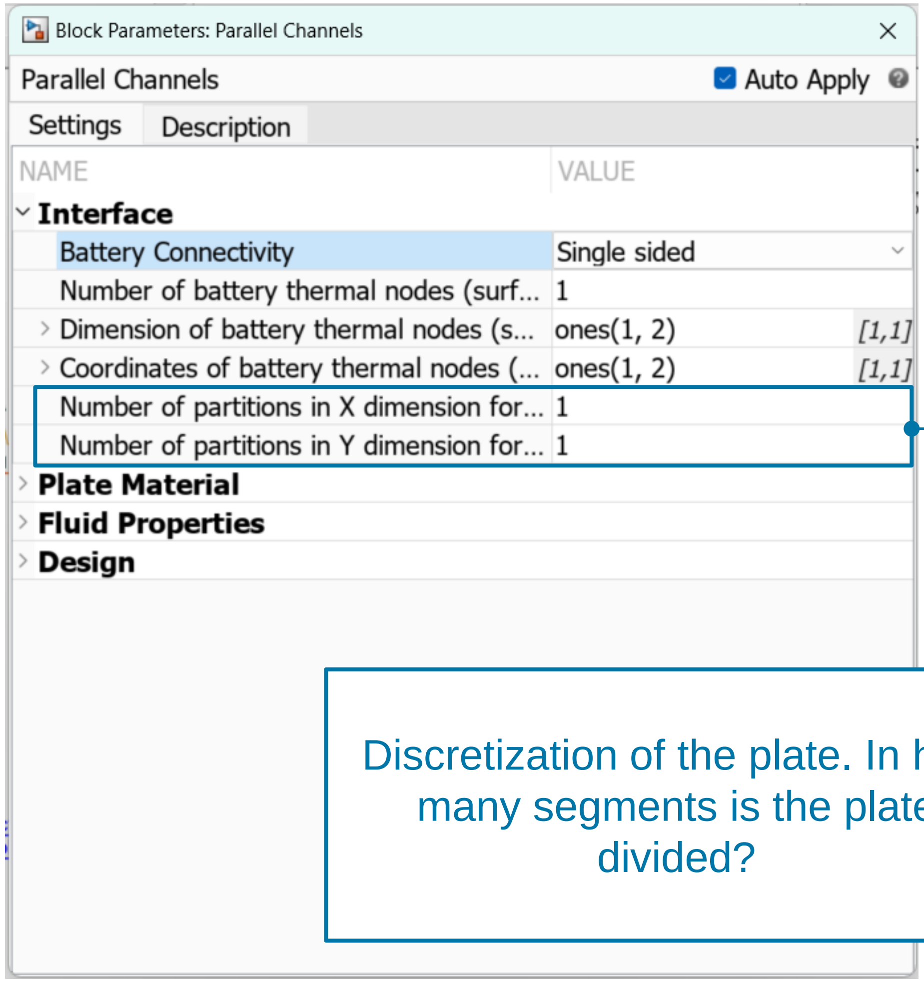
Position AND dimensions of the battery cells. Needed to estimate where the cell are positioned and what the contact surface with the plate is



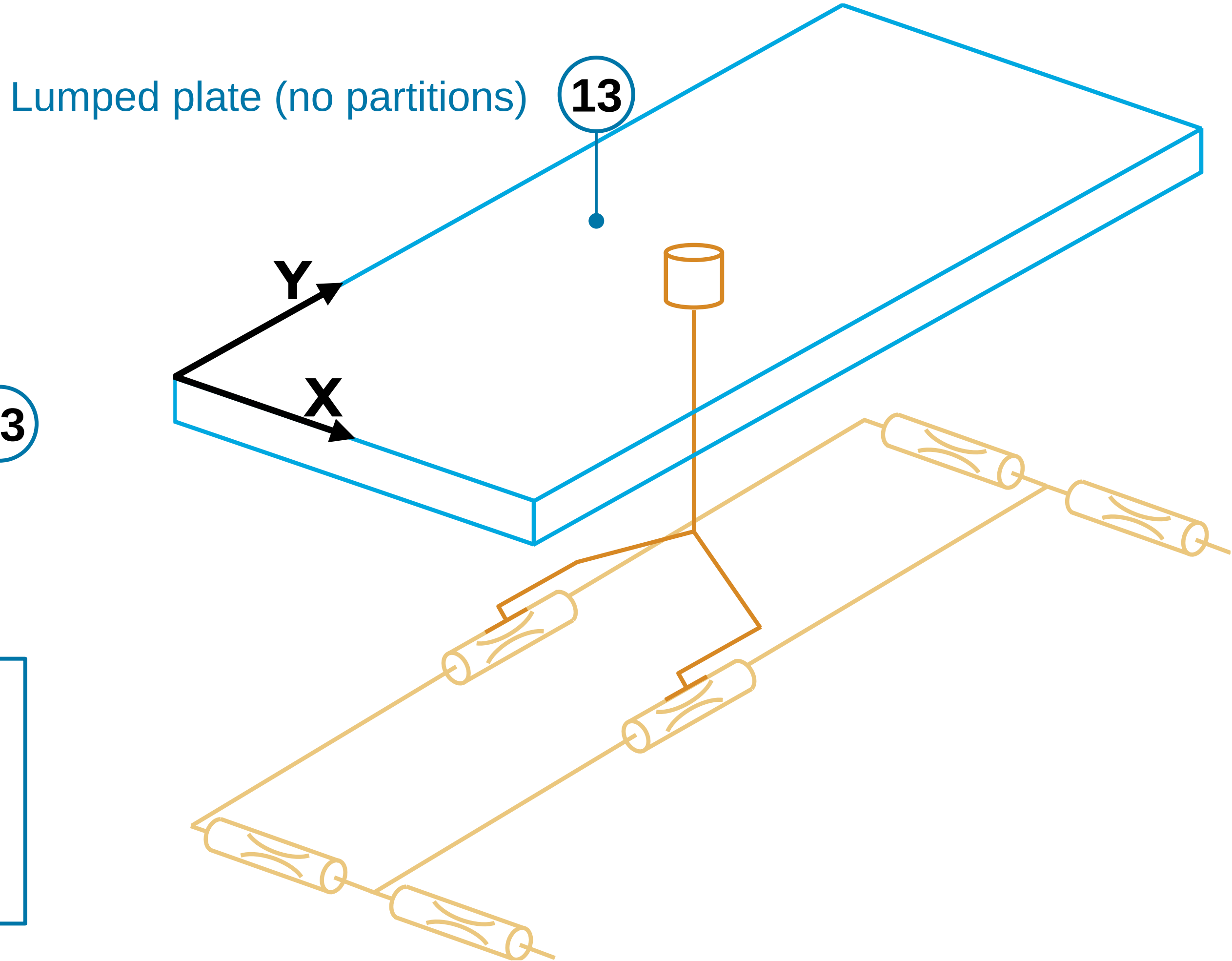
The *Interface* parameters are automatically filled when you create a battery with plate in the Battery Builder App

冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Partitions

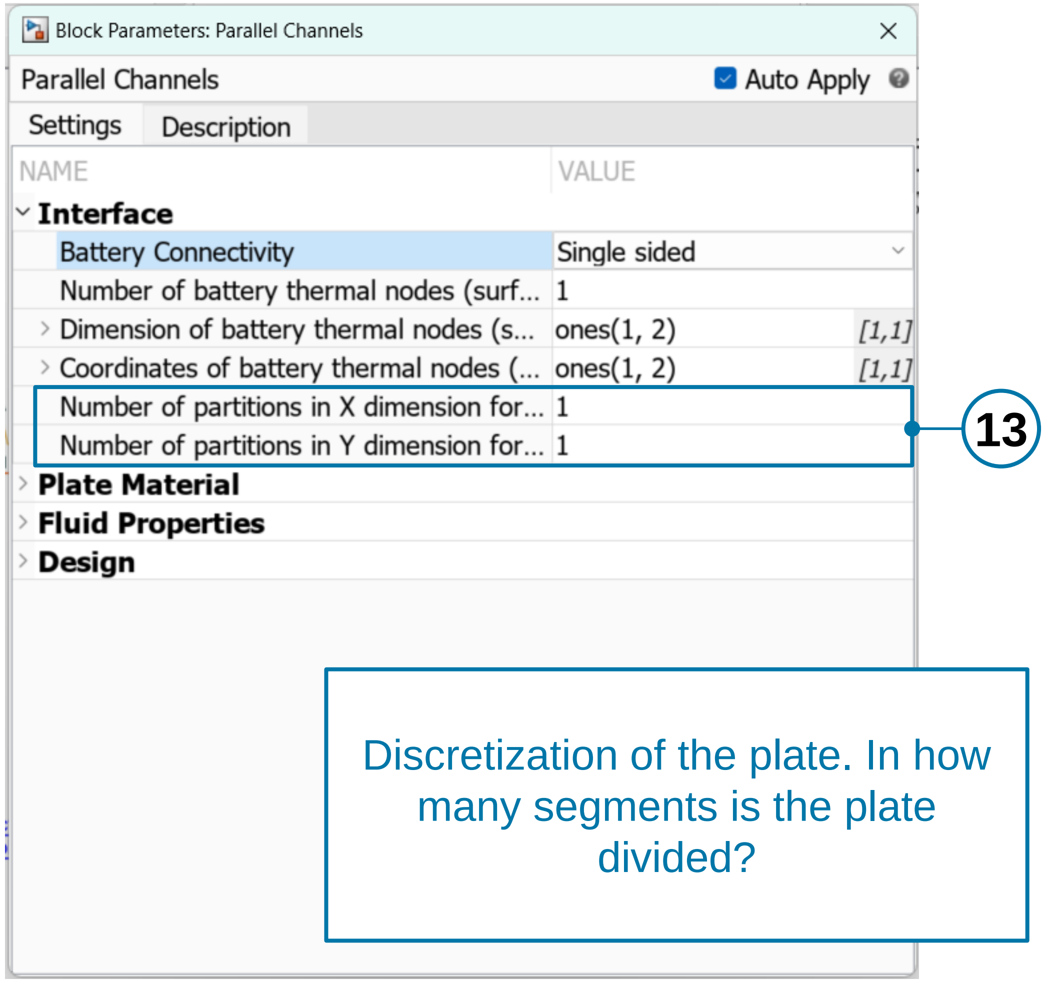


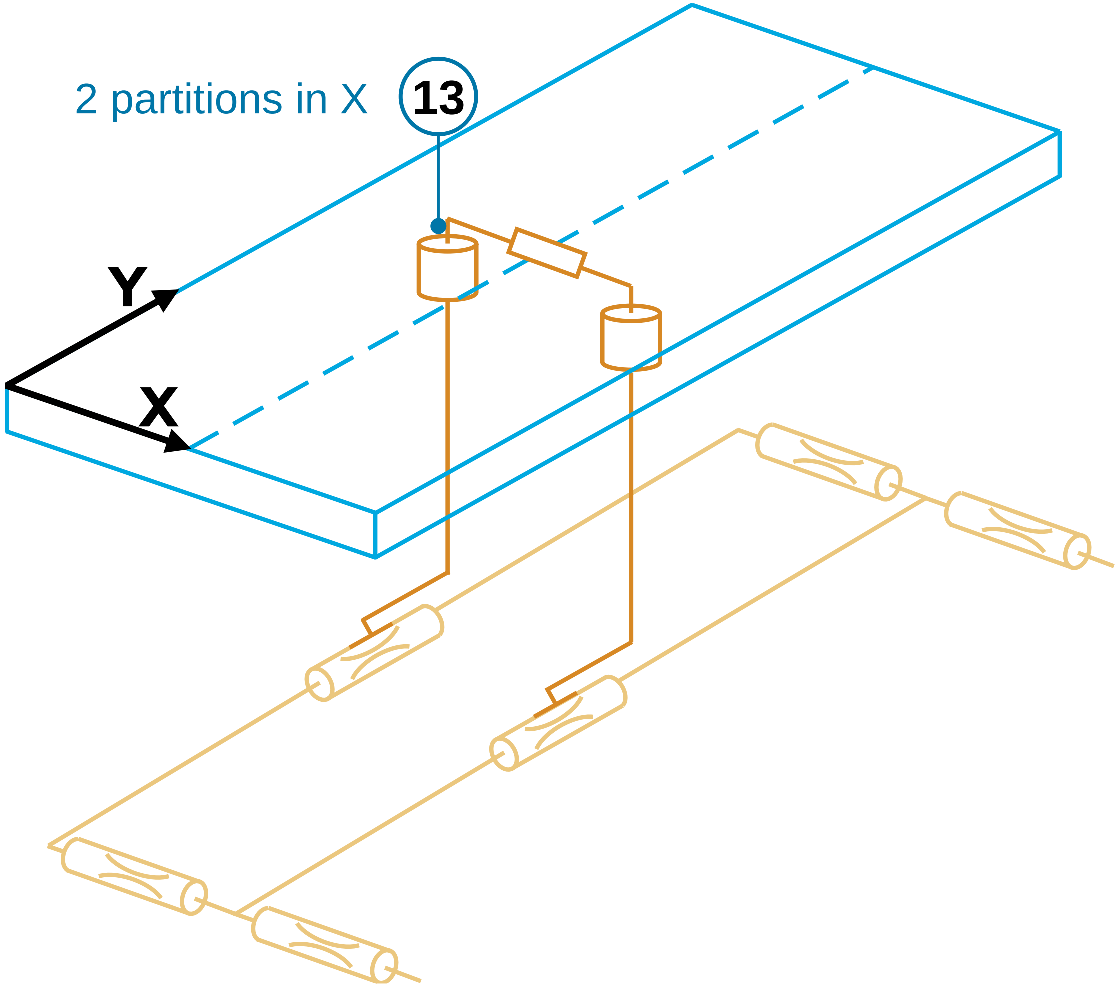
Discretization of the plate. In how many segments is the plate divided?



冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Partitions

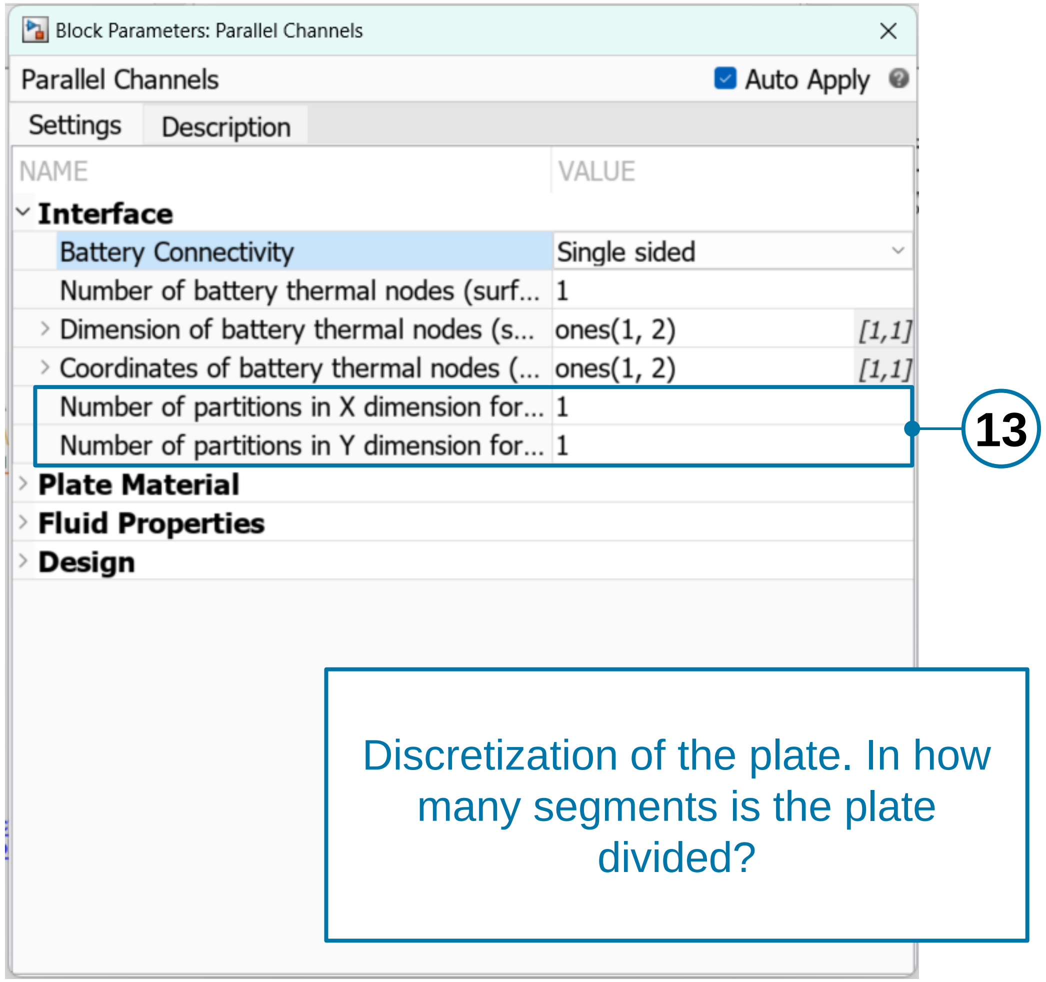




Discretization of the plate. In how many segments is the plate divided?

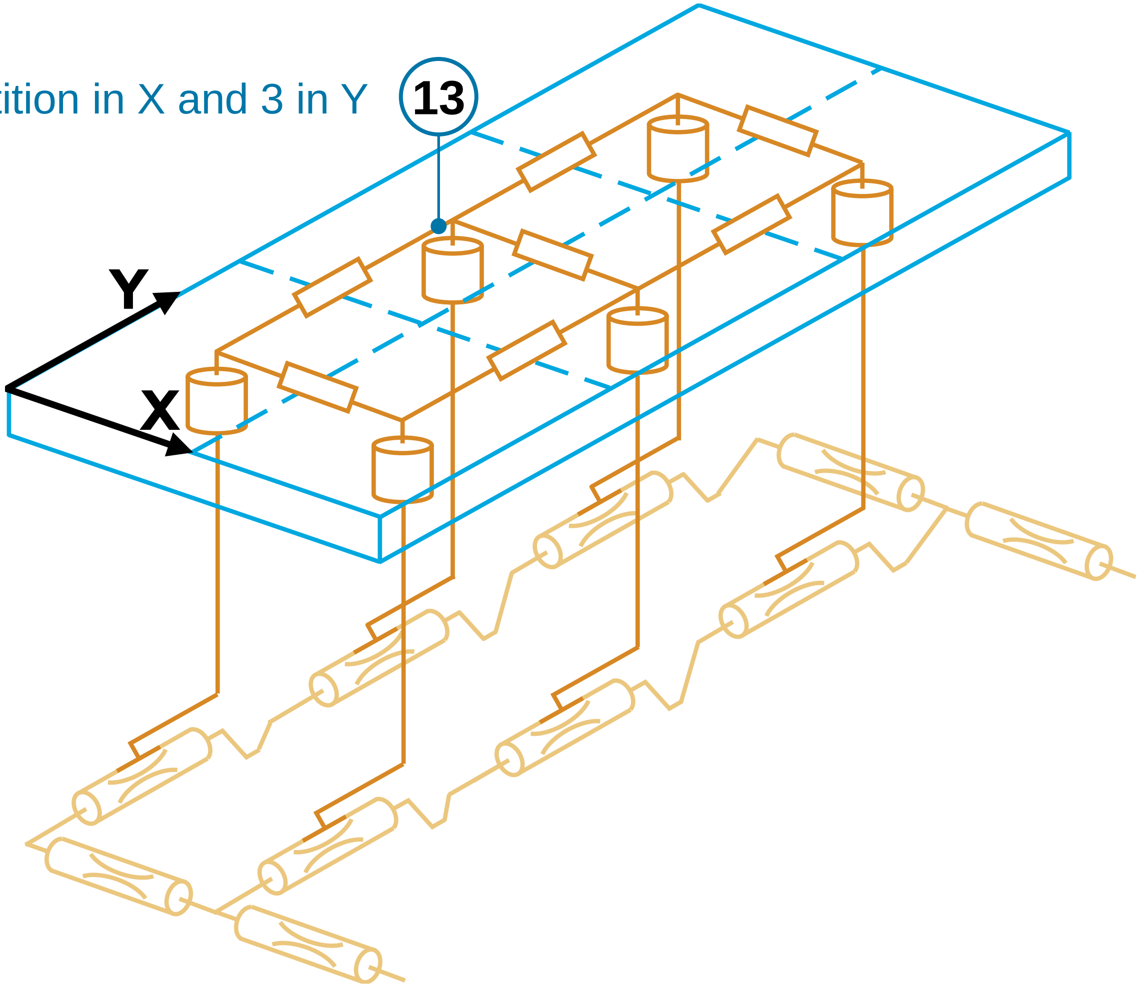
冷却水道模型的离散化解析

Parallel Channels Plate | Interface | Partitions



Discretization of the plate. In how many segments is the plate divided?

2 partition in X and 3 in Y



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