



KULI eco
ENERGY MANAGEMENT OPTIMIZATION

Thermal Management Simulation for
EVs and HEVs

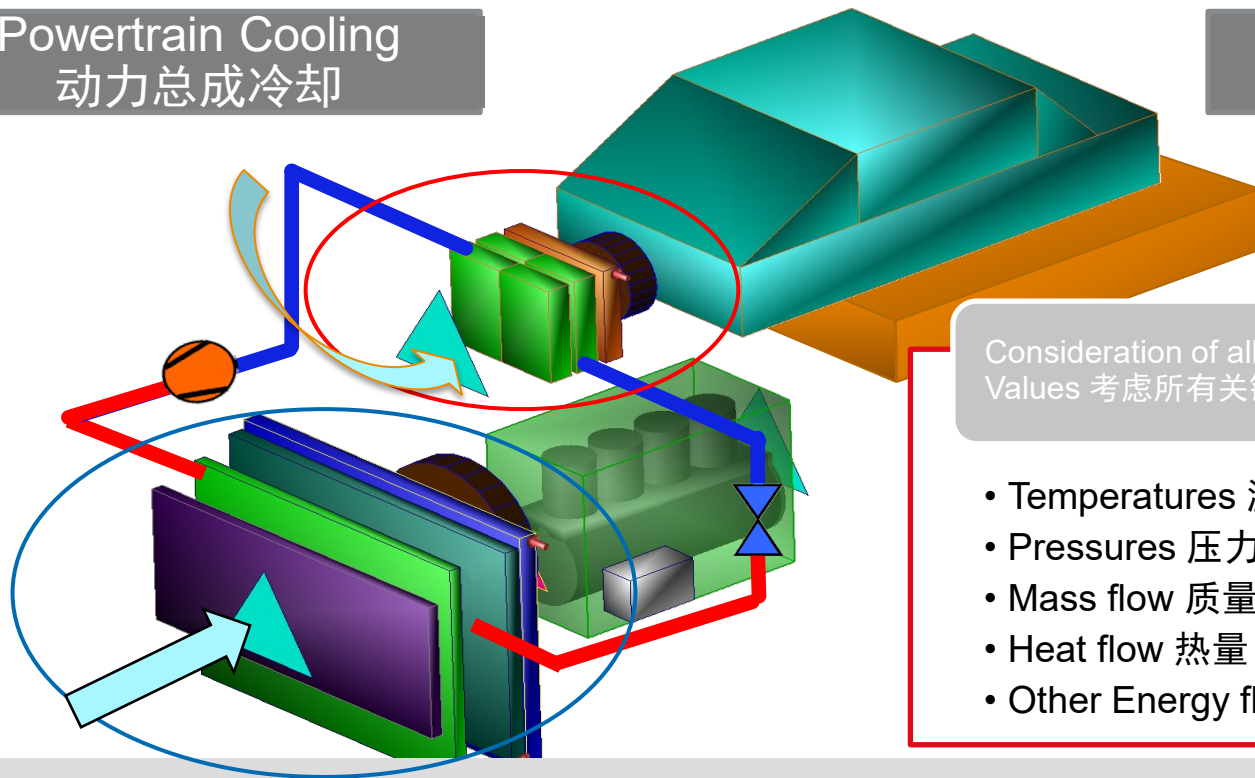
电动车及混合动力热管理仿真

What is KULI?

什么是KULI?

Powertrain Cooling
动力总成冷却

Air Conditioning
空调系统



Consideration of all Thermodynamic Key Values 考虑所有关键热力学参数

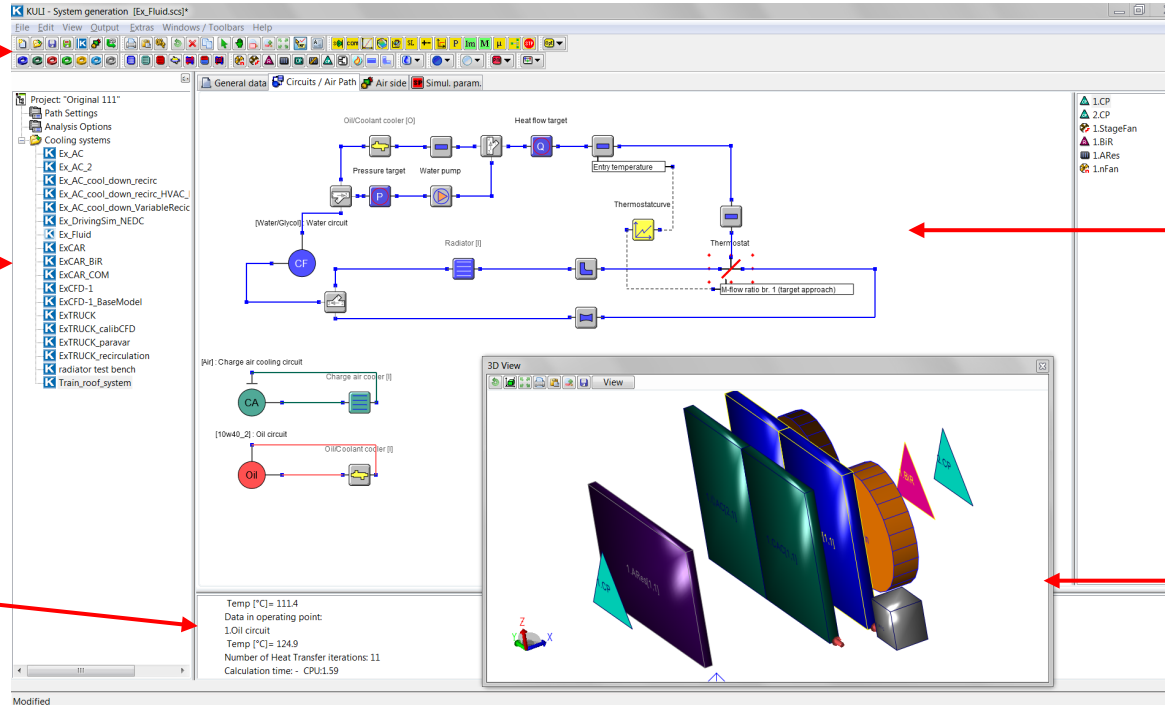
- Temperatures 温度
- Pressures 压力
- Mass flow 质量流量
- Heat flow 热量
- Other Energy flows 其它能量流

Windows Desktop Software for the 1D-Simulation of the Vehicle Thermal Energy Management
用于车辆能量管理的Windows一维仿真桌面级软件

Component
& Function
Toolbars
零部件&功能
栏

Project
Organization
项目管理

Analysis
Progress Info
分析过程信息

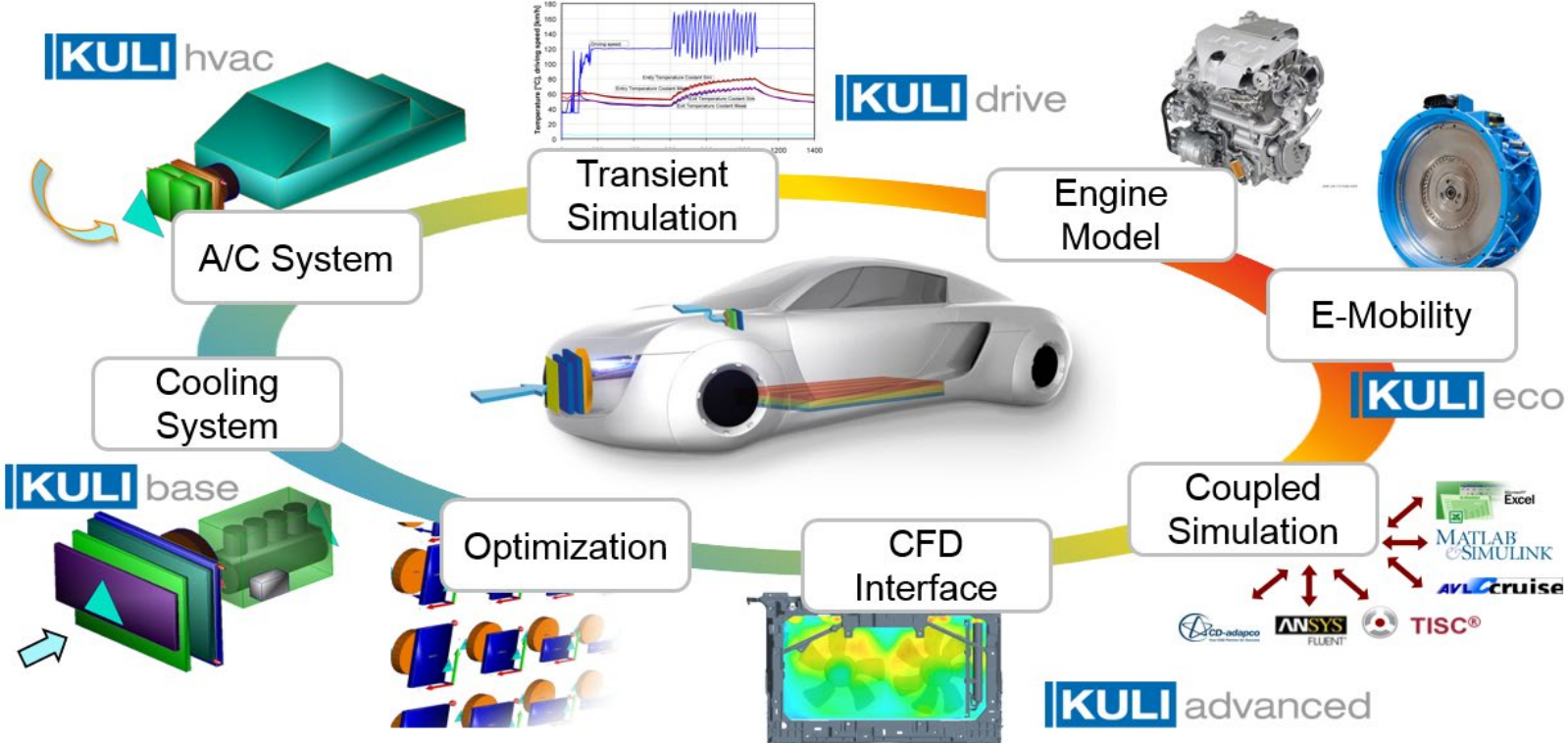


2D Fluid
Network View
二维管网图

3D Air
Network View
三维空气管网

1-dimensional Fluid Network Analysis – Quasi 1-dimensional Air Flow Network Analysis
一维流体管网分析 – 类一维空气流动管网分析

Energy Management Software 能量管理软件



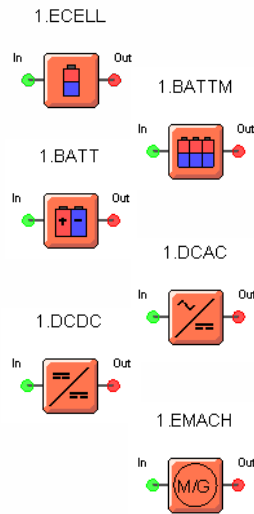
Capabilities of KULI eco

KULI eco模块功能

- **Battery Cell**
- **Battery Module**
- **Battery Pack**

- **DC/AC**
- **DC/DC**

- **Electric Motor / Generator**



El. Energy Storage

El. Energy Conversion

Electric Propulsion



Simulation of the **complete electric drivetrain...**

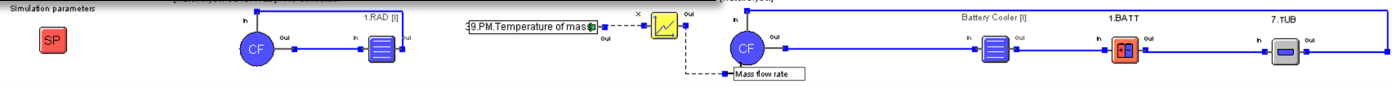
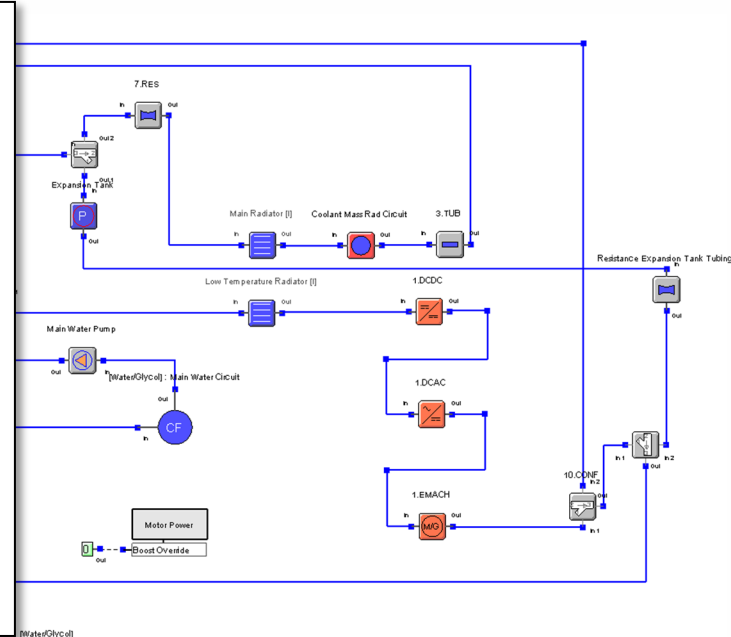
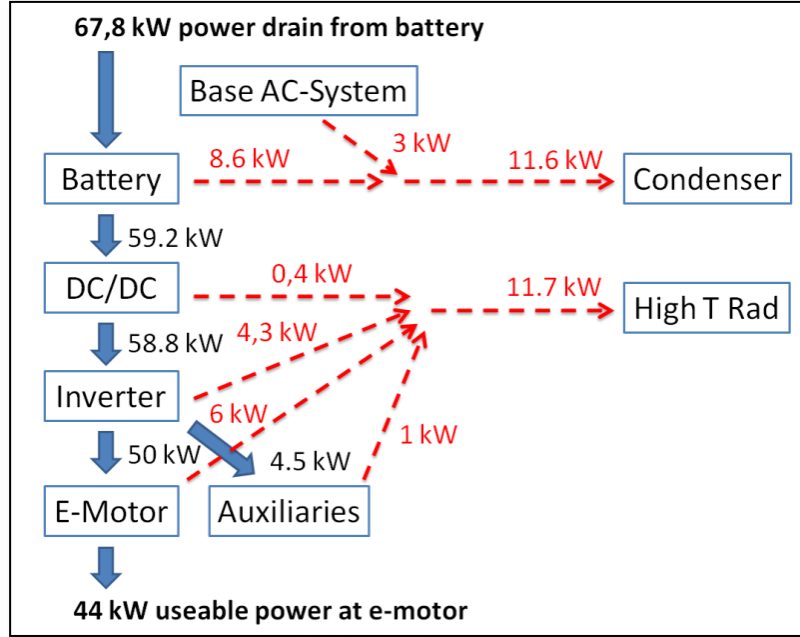
计算完整的动力总成
Thermal management
and **electric power consumption...**
热管理及能耗计算...

... for both
EVs and **HEVs**



Typical Applications 典型案例

Application Example – Energy Flow Analysis 能量流分析

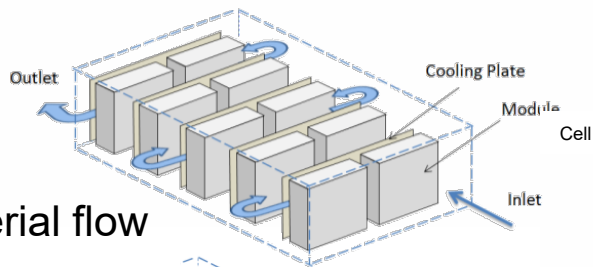


Quickly assess where the energy is going!
快速查阅能量的走向

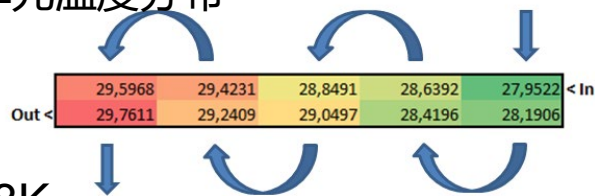
Application Example – Battery Cooling Concepts 电池冷却设计



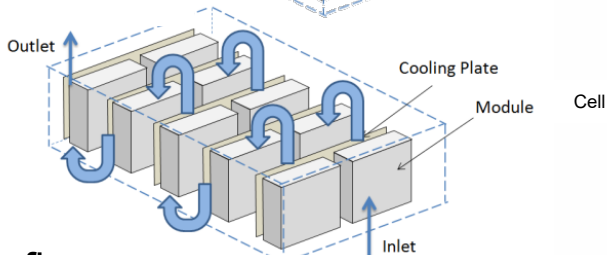
Steady state cell temperature distribution:
稳态电池单元温度分布



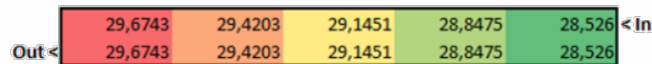
10 cell serial flow



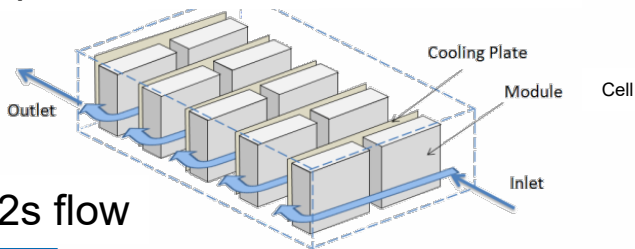
$$\Delta T = 1.8K$$



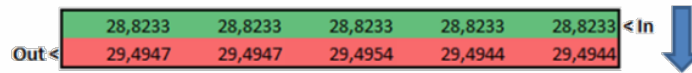
5s / 2p flow cells parallel flow



$$\Delta T = 1.15K$$



5p / 2s flow



$$\Delta T = 0.67K$$

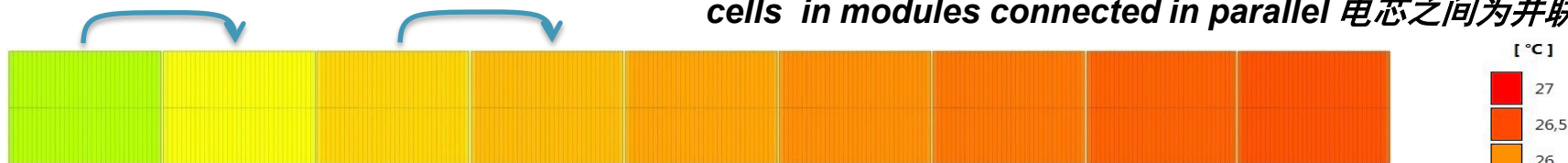
(also lowest dp!)

Application Example – Transient Temperature Distribution in a Complete Battery Pack 在一个复杂电池包中的瞬态温度分布

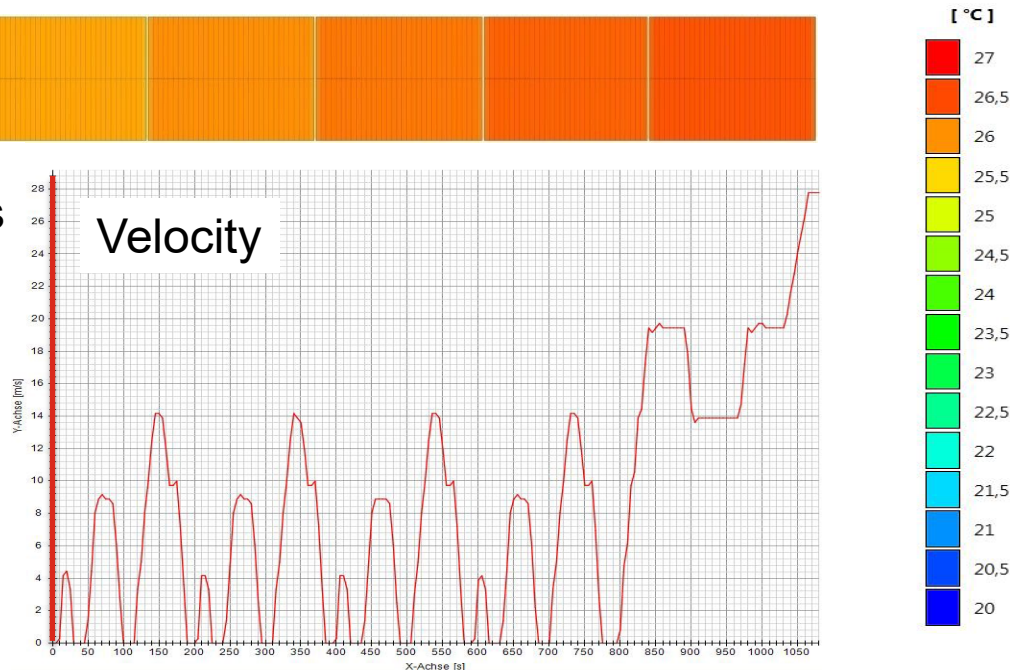
Transient simulation of a battery pack with $33 \times 9 = 297$ cells

电池包瞬态仿真 $33 \times 9 = 297$ 个电芯

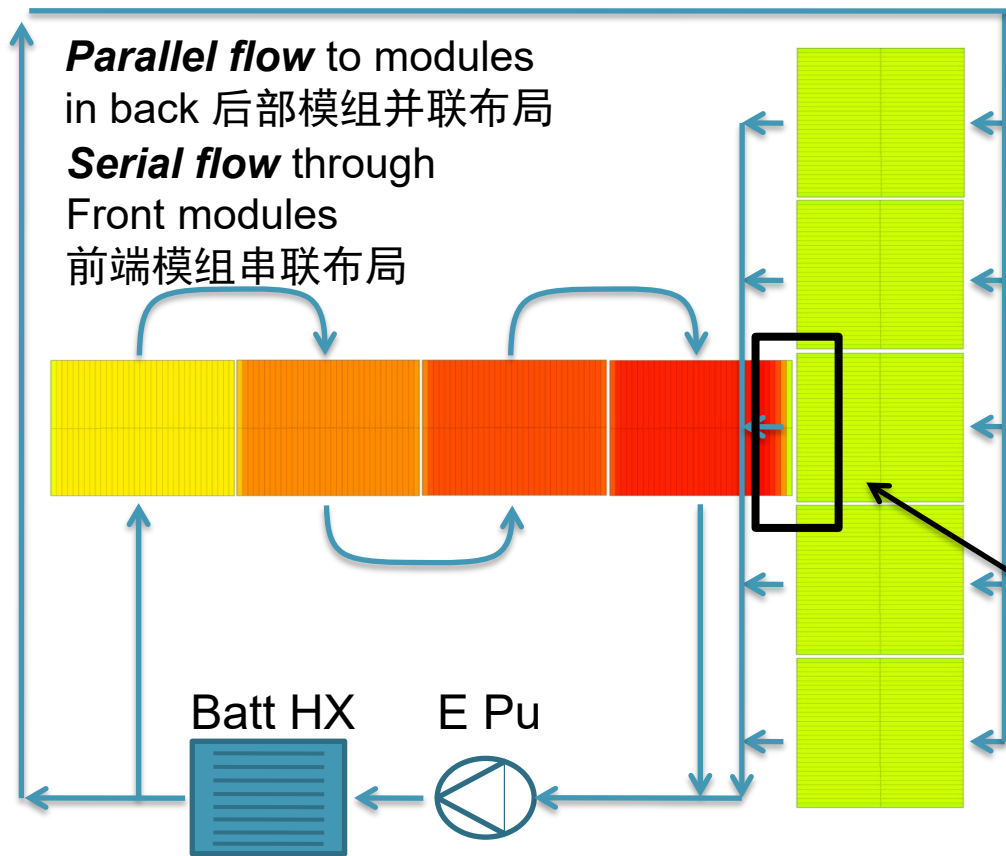
Cooling plates between cells 冷板在电芯之间: **modules connected in series** 模组之间为串联, **cells in modules connected in parallel** 电芯之间为并联



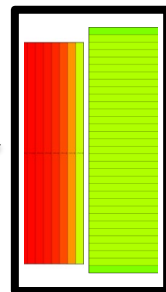
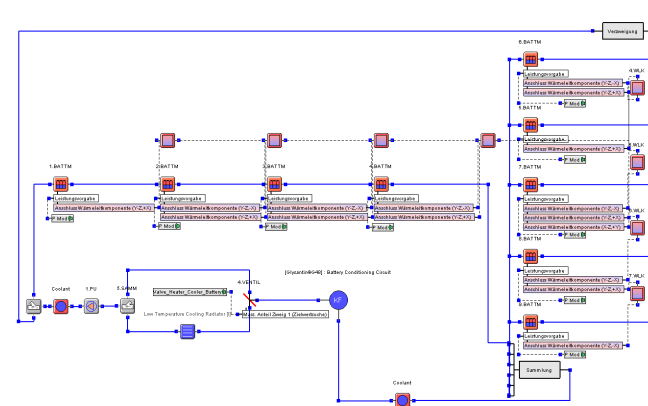
- **Each cell** is modeled **separately** 每个电芯独立建模
- **Convection** dominates over **heat conduction** 热对流主导了热传导
- **High battery loads** lead to **inhomogeneous cell temperature distribution** 高电池负荷导致电芯温度的不均匀分布



Application Example – Transient Model of a Battery with Asymmetric Layout 不对称布置电池瞬态建模



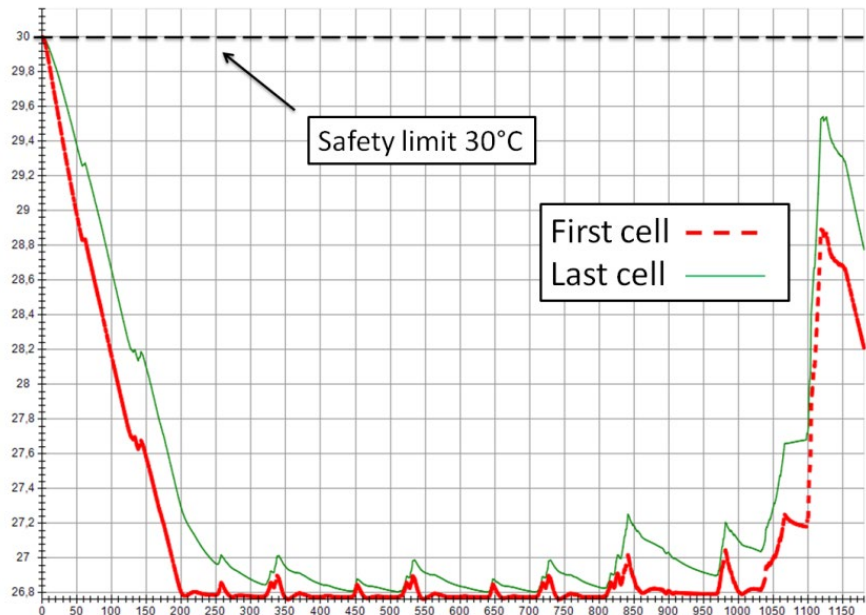
KULI battery model 电池模型 (using KULI battery modules)



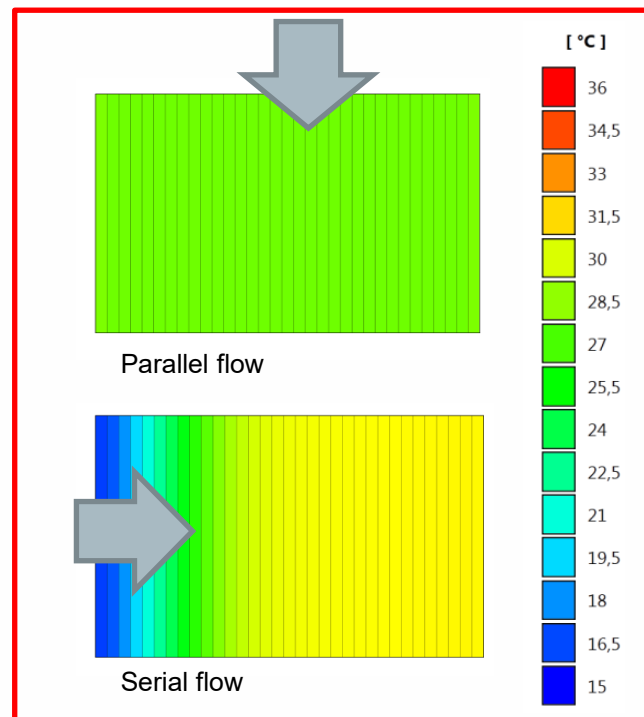
Thermal coupling between front and back by heat conduction
前后模组之间的耦合热传导

Application Example – Battery Temperature Distribution Analysis 电池温度分布分析

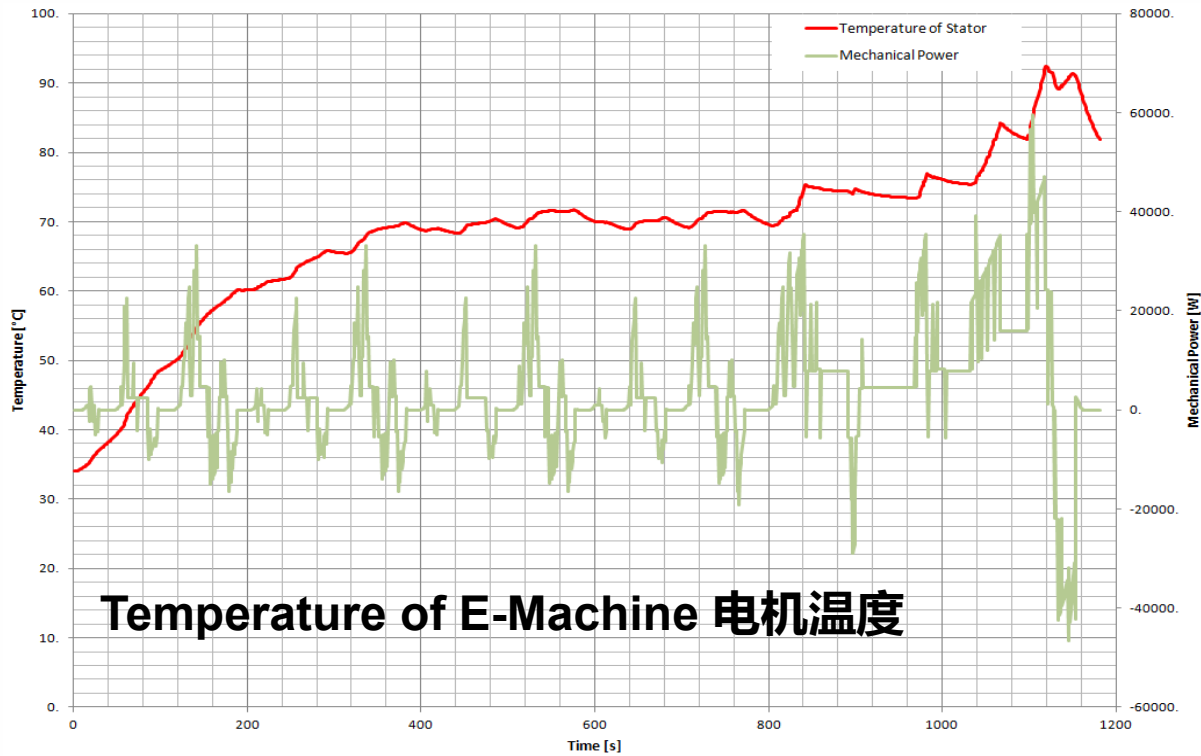
Transient maximal temperature span in module (for NEDC):
NEDC中的瞬态最高温度



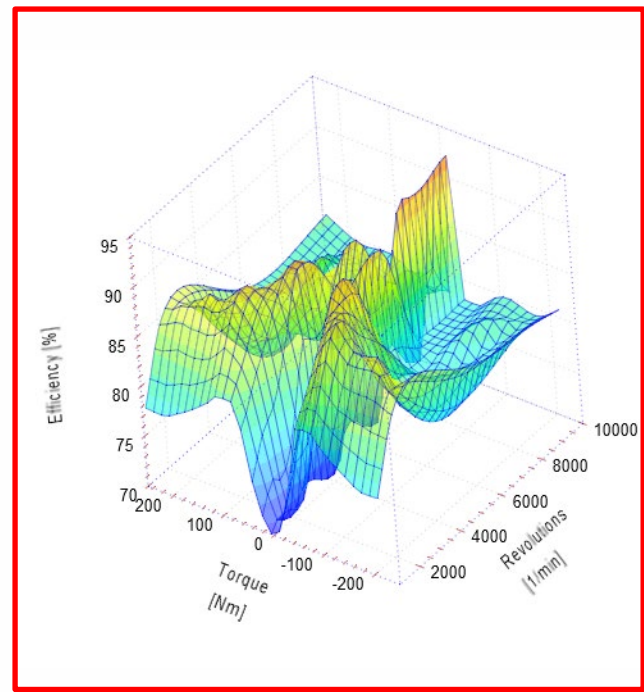
Temperature distribution in the battery module 电池模块温度分布 @ t = 1180 sec



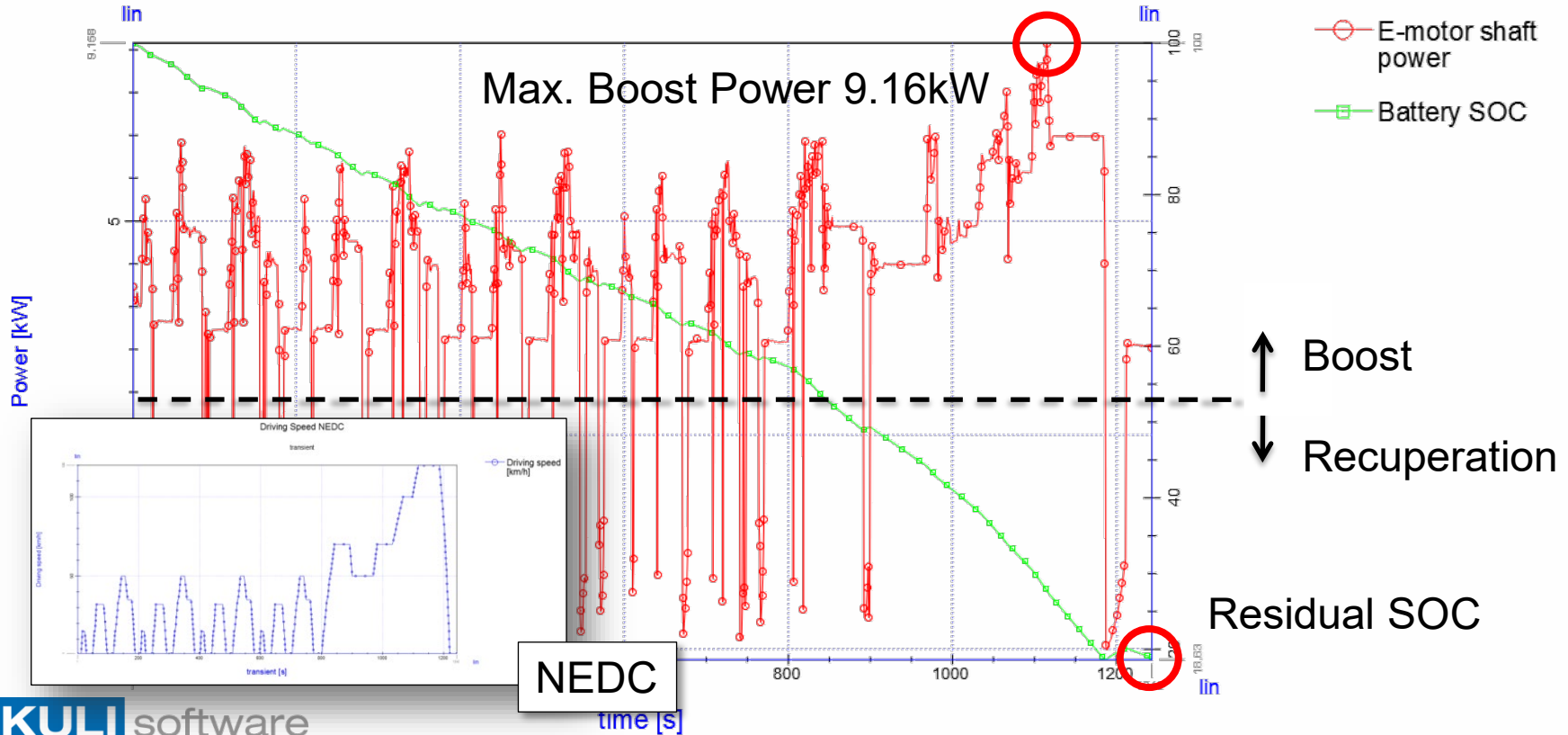
Application Example – Investigate E-Component Temperatures During Drive Cycles 行驶循环中的电子部件温度



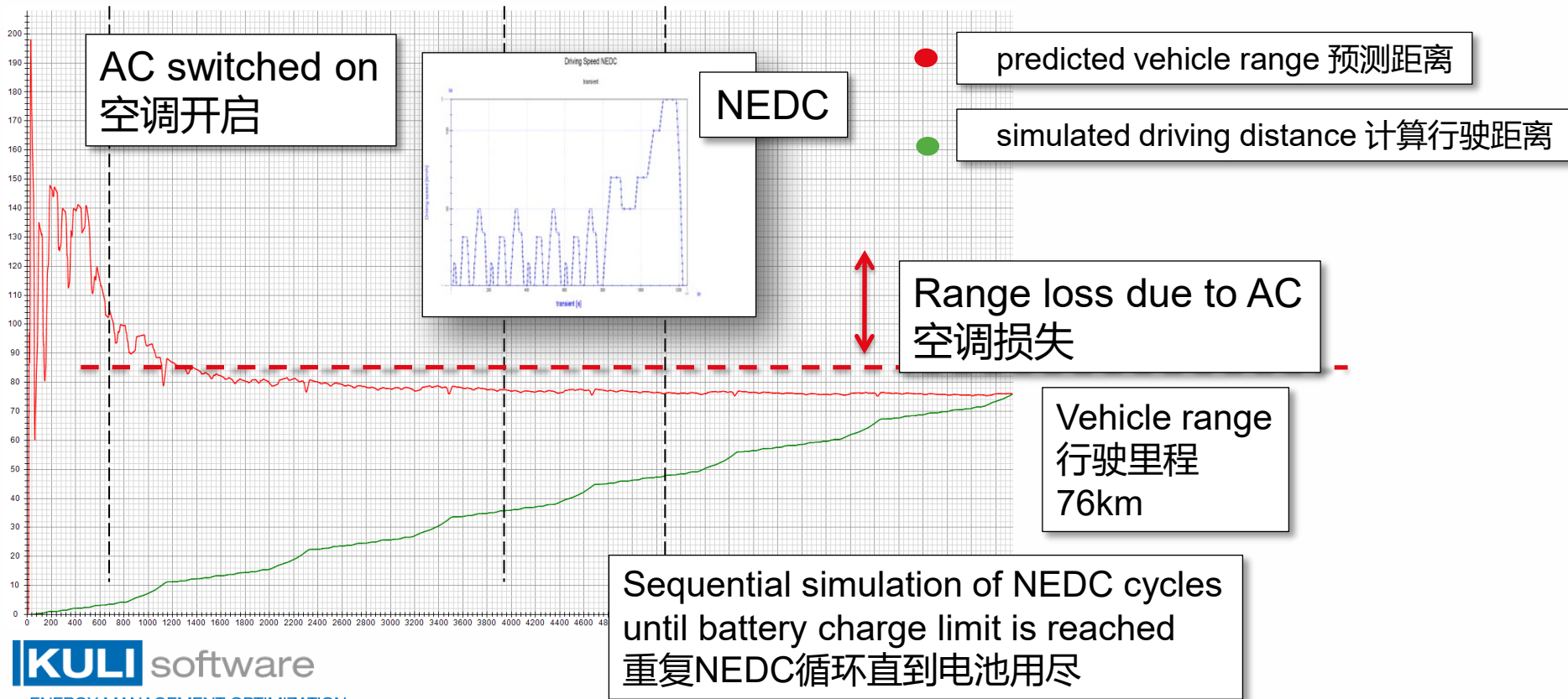
Temperature of E-Machine 电机温度



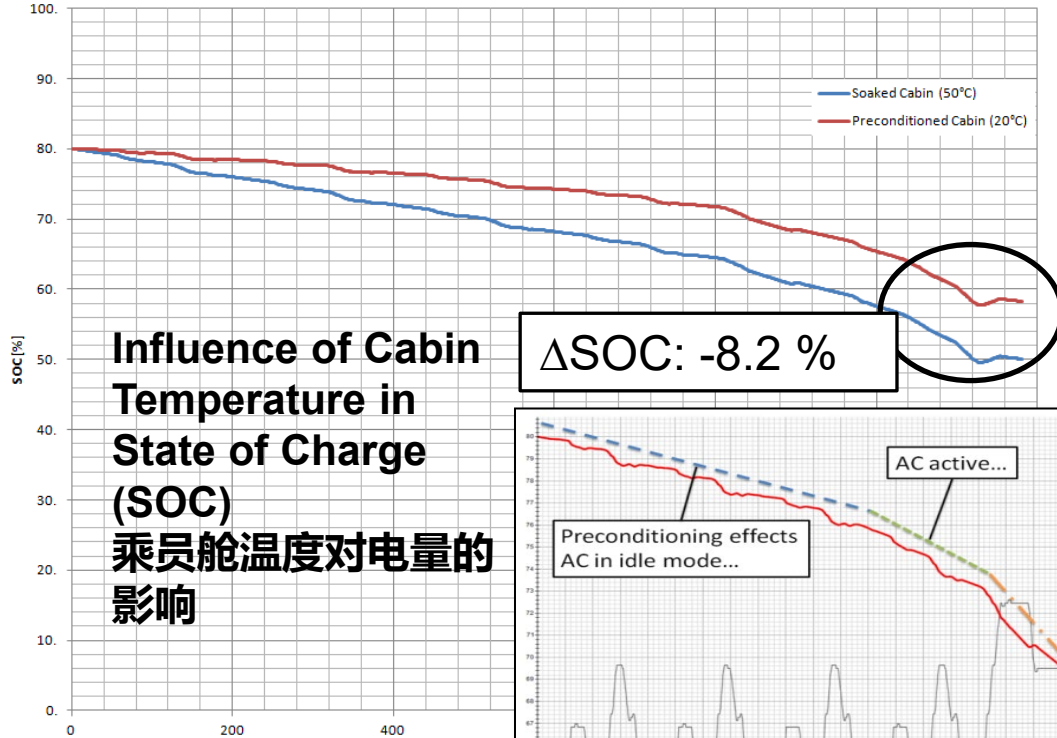
Application Example – Simulate Boost Power and Recuperation for Hybrid Vehicles 混合动力能量回收仿真



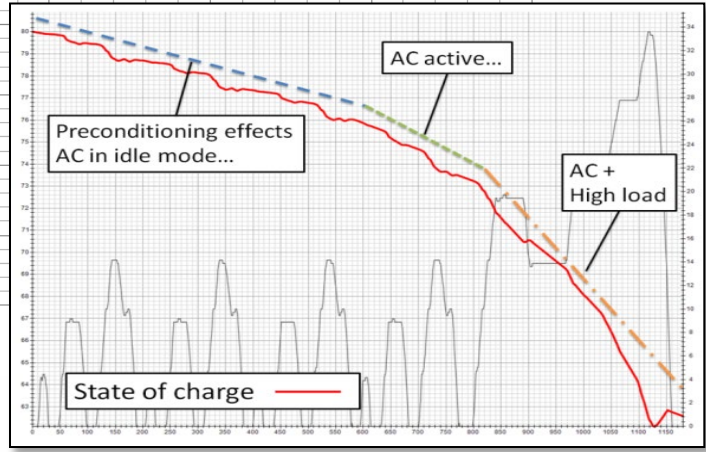
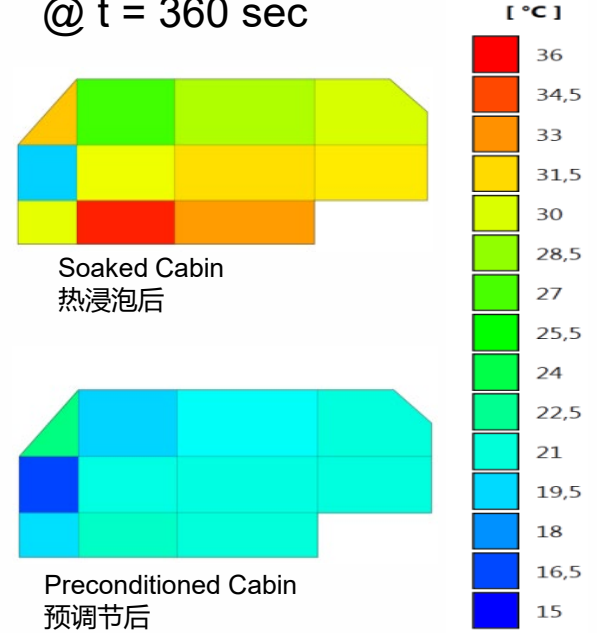
Application Example - Range Prediction of an Electric Vehicle 预测电动车行驶里程



Application Example – Influence of HVAC System on Electric Driving Range 空调系统对行驶里程的影响



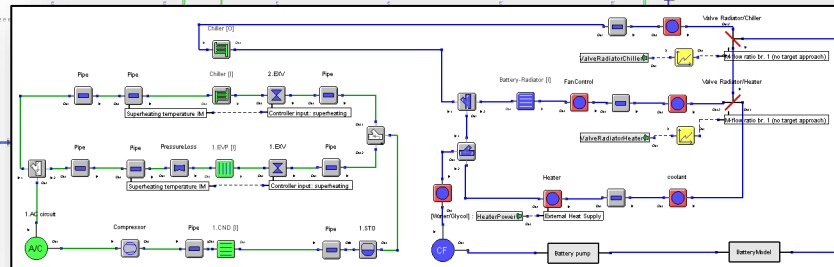
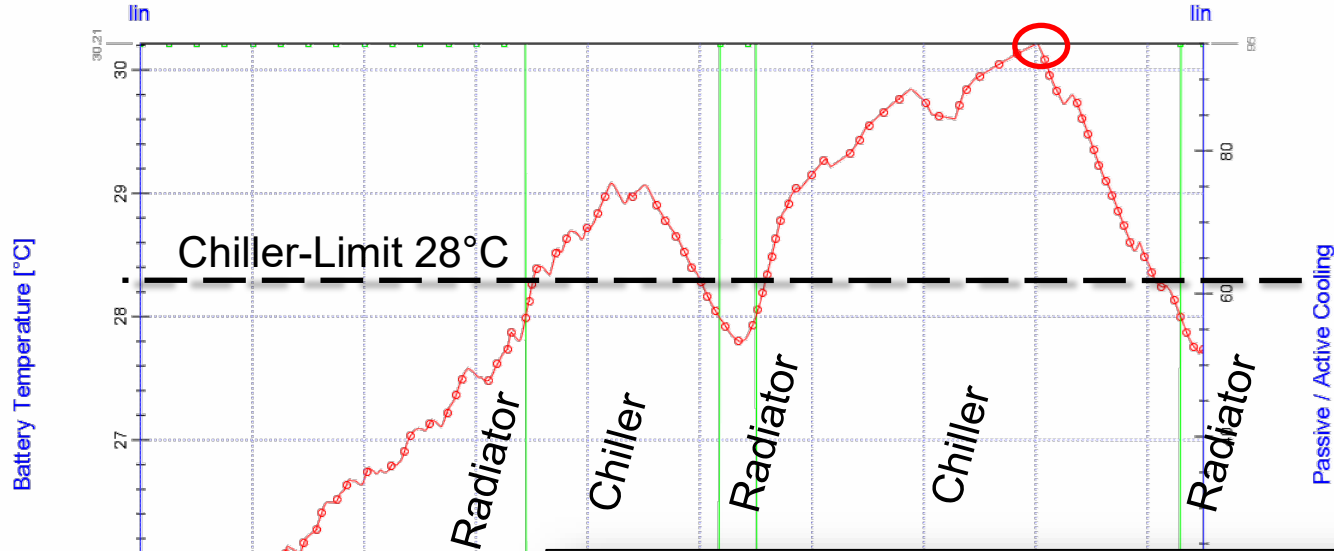
Temperature distribution @ t = 360 sec



Application Example – Simulate AC-Coupled Battery Cooling Systems 空调及电池冷却耦合仿真



Maximal Battery Temp. 30.21 °C



Application Example – Controller Development with the KULI Simulink Toolbox 采用KULI Simulink工具箱进行控制器开发



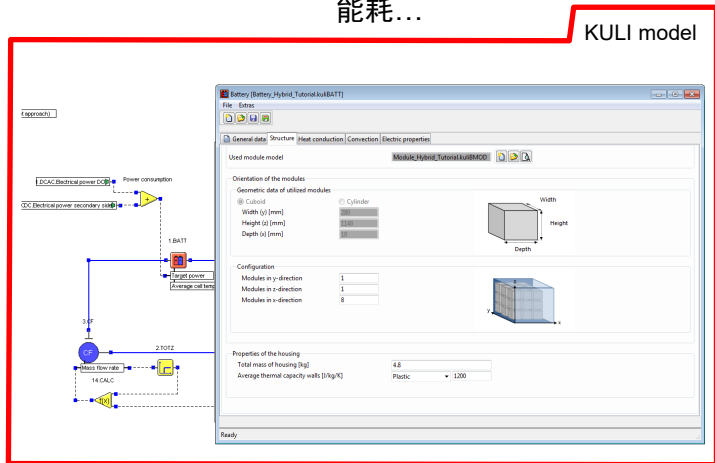
KULI provides the *thermal simulation model*:

KULI提供热仿真模型:

- Battery thermal model 电池热模型
- Cooling circuits (Coolant, A/C) 制冷循环
- Cabin model 乘员舱模型

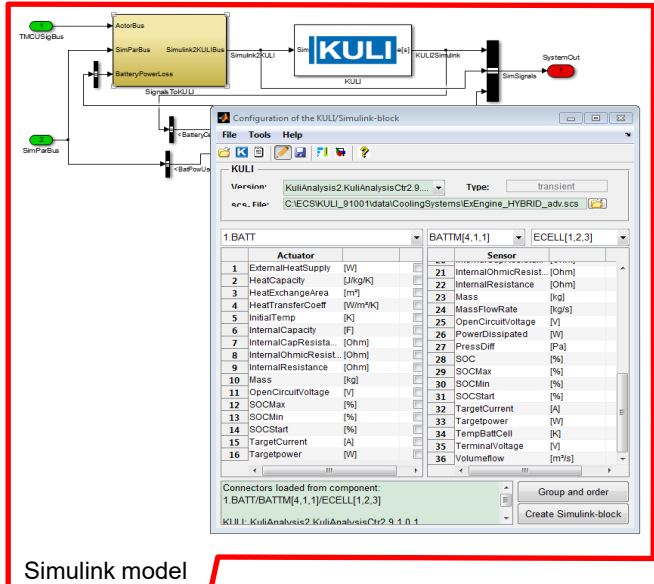
- Temperature Levels 温度
- Volume flows 流量
- Energy consumption 能耗...

Results



Data Exchange 数据交换 via 通过

KULI
Simulink
Toolbox



Simulink model

- Pump / fan rpm 泵 / 风扇转速
- Chiller ON / OFF
- Valve position 阀口位置

Results

Simulink provides an ideal environment for developing *controlling strategies*.
Simulink提供了一个理想的控制逻辑开发环境

Application Example – Using a Matlab/Simulink Cell Model in KULI 采用Matlab/Simulink电芯模型

- Use your **existing Matlab/Simulink Cell-, Module- or Battery Models** in KULI!
您可以在KULI中使用您现有的Matlab/Simulink 单元、模组或电池模型
- Example: An **existing detailed cell model** (considering the **internal structure of the battery cell**) can be linked into the KULI environment: 案例：一个现存的电芯模型（考虑了电芯的内部结构）可以直接连接至KULI仿真环境

– **No effort for re-building already existing models**

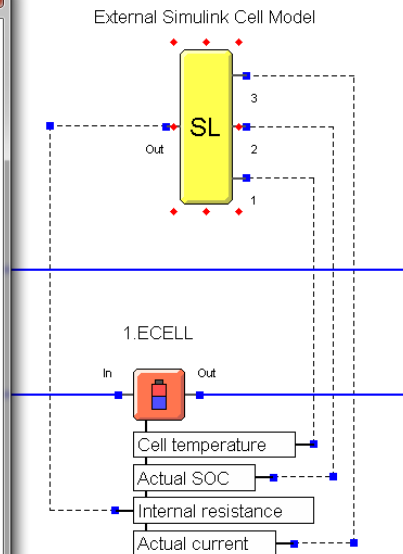
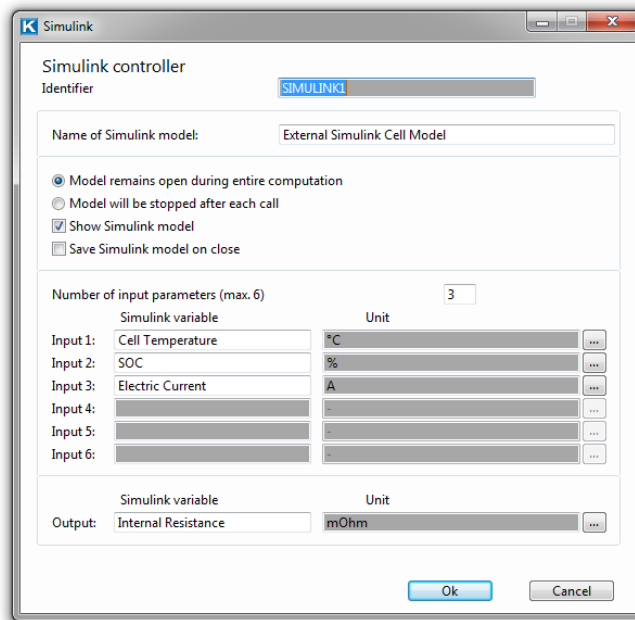
不必重新建模

– The **cooling system** is simulated using **KULI**

使用KULI仿真冷却系统

- Coolant **warm-up** 冷却液温升
- **Pressure drops** 压力损失
- **Mass flows** 质量流量

It is also **possible** to model the **complete battery in Matlab** (KULI handles the cooling sys.)
同样可以通过Matlab建模整个电池（采用KULI处理冷却系统）



Components and Features

零部件及特性

Battery - Different levels of detail 不同细节建模

	Lumped Mass	Module Level	Cell Level
Modelling effort	😊	😐	😞
Simulation of avg. cell temperature	😊	😊	😊
Simulation of temperature spread	😞	😐	😊
CPU time	😊	😊	😐
Cooling system design	😐	😐	😊
Controller development	😞	😐	😊

Annotations:

- A red box highlights the 'Modelling effort' row in the 'Lumped Mass' column.
- A red box highlights the 'Simulation of temperature spread' row in the 'Cell Level' column.
- A red arrow points from the 'Modelling effort' cell to the 'Simulation of temperature spread' cell.
- A text box containing "... with the effort of *that!*" is positioned near the arrow.
- A text box containing "We do *this...*" is positioned near the 'Simulation of temperature spread' cell.

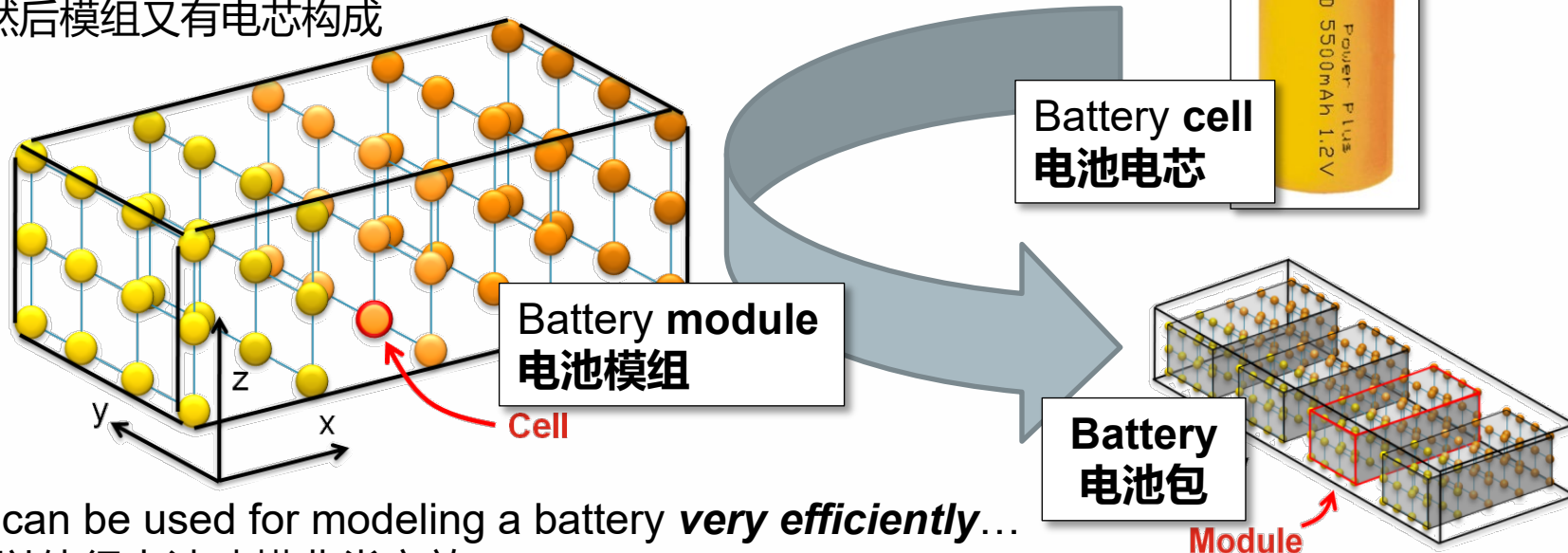
Battery - Typical Internal Structure 典型电池内部结构

Internally most traction batteries are *subdivided into modules*...

多数电池内部可以细分为模组

... and modules *consist of individual cells*.

... 然后模组又有电芯构成



This can be used for modeling a battery *very efficiently*...

这可以使得电池建模非常高效

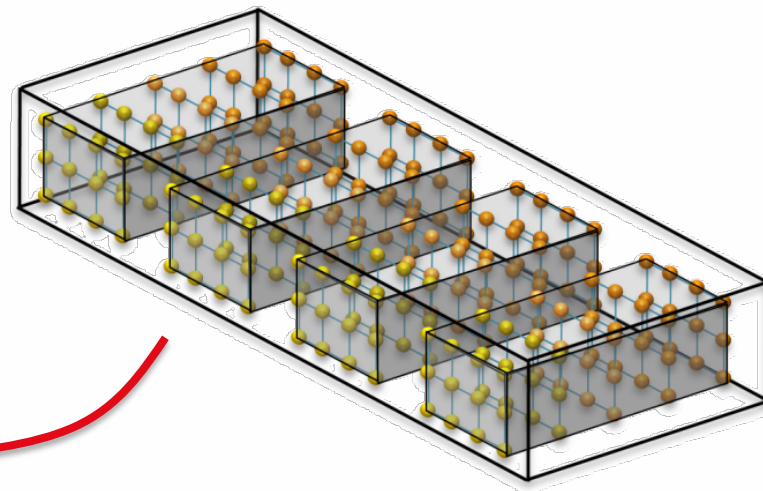
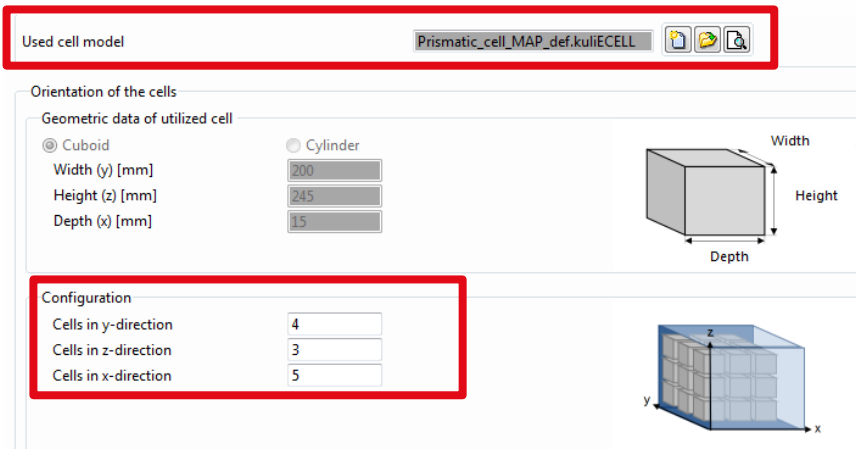
Battery - Setting Up Complex Structures 建立复杂结构

KULI makes *intensive use of symmetry*

to facilitate the setup process of even very complex structures.

即便在非常复杂的结构中，KULI也能大量使用对称性便捷地建模

Although modeling is *easy*, simulation results for all *individual cells* are available!
虽然建模便捷，但依旧能够得到每个电芯的仿真结果



Example:

Definition of a module set up from 4x3x5 identical cells.
定义一个4x3x5相同电芯的模组
Battery is similarly set up from 1x4x1 of these modules.
电池采用1x4x1个模组构成

Battery - KULI Modeling Options 电池建模选项

All of these variants will lead to a **detailed model** that allows evaluation of **individual cell temperatures!**

所有情况下都可以评估每个单元的温度

Are the cells arranged regularly in the modules?

Yes

Are the modules arranged regularly in the pack?

Yes

Use the **KULI Battery Pack!**

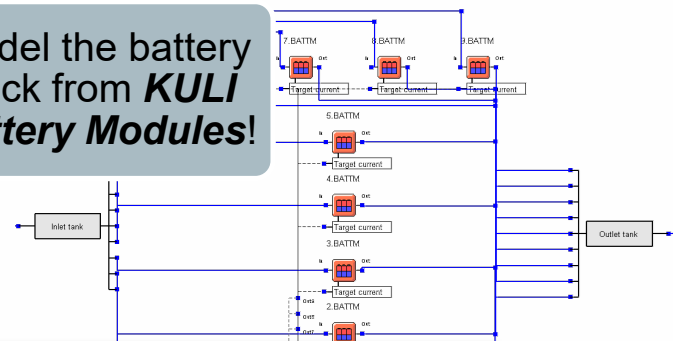
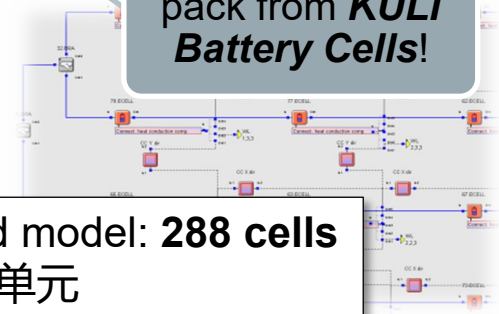
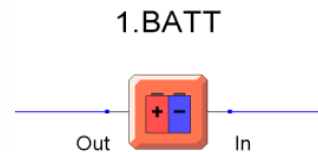
No

Model the battery pack from **KULI Battery Cells!**

Model the battery pack from **KULI Battery Modules!**

e.g. manual cell based model: **288 cells**
例如：手动建模288个单元

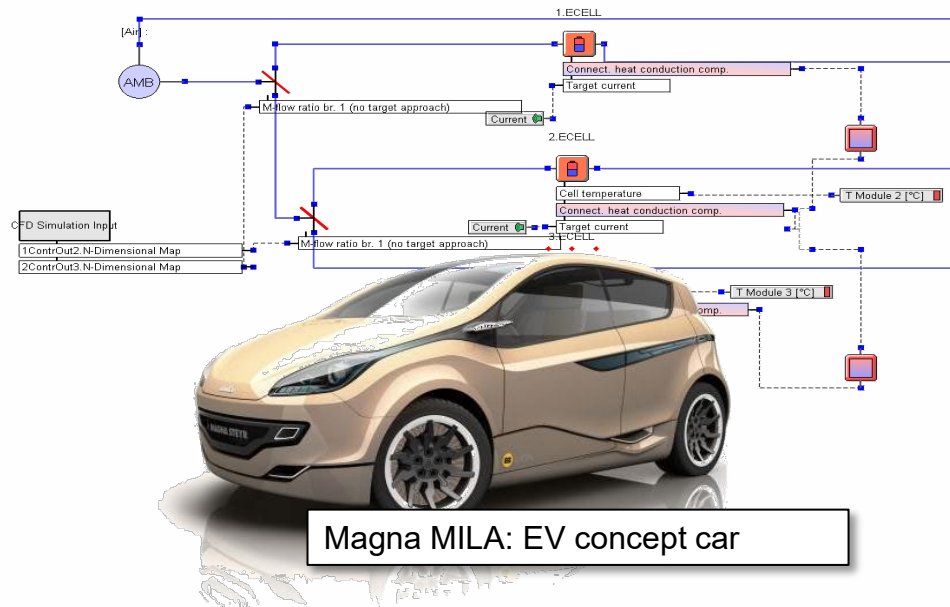
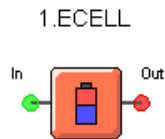
Battery model: **1 integrated component** (cells and modules modeled automatically)
电池模型：单独集成的零部件（电芯和模组自动建立）



Module based model: **9 modules** (cells modeled automatically)
基于模组模型：9个模组（单元自动建立）

Features of Battery Cell 电池单元特性:

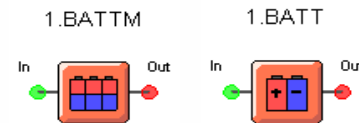
- **Heat transfer to 换热**
 - Fluid 流体
 - Ambient 环境
 - Refrigerant 制冷剂
 - Any supported component by conduction 热传导
- **Applicable as 应用于**
 - Pouch & Prismatic cell 袋状&菱形电芯
 - Cylindrical cell 圆柱形电芯
- **Electric Circuit 电圈**
 - **Resistance Model 电阻模型**
 - » Constant 常量
 - » Temperature dependant 基于温度
 - » SOC dependant 基于SOC
 - » Temperature & SOC dependant 同时基于温度&SOC
 - » R- or RC-model R或RC模型
 - **External Model (Simulink, ..) 外部模型 (Simulink...)**



Features of Battery Module / Pack:

电池模组 / 电池包特点:

- Can be assembled from cells / modules with a few clicks
通过鼠标点击便可完成来自单元/模组的集成
- Inherits geometrical data from cells / modules
继承电芯/模组的几何
- Several Cooling options:
多种冷却选项
 - Fluid Cooled 液冷 (flow through module)
 - Air Cooled 风冷 (flow around module)
 - Heat Conduction 热传导
- Can inherit electrical data from battery cells / modules
可以继承电池芯体/模组的电子数据
- Supports heat conduction to other modules / components
支持热传导至其他模组/零部件



Used cell model: Prismatic_cell_MAP_def.kuliCELL

Orientation of the cells

Geometric data of utilized cell

Cuboid Cylinder

Width (y) [mm]: 200

Height (z) [mm]: 245

Depth (x) [mm]: 15

Configuration

Cells in y-direction: 4

Cells in z-direction: 3

Cells in x-direction: 5

Battery Example - Air Cooled (Honda Insight)

电池案例 - 空冷式 (本田Insight)

General data | Structure | Heat conduction | Convection | Electric properties

Flow through
 Flow around the battery
 Flow through the battery
 Both
 No convection

Flow through

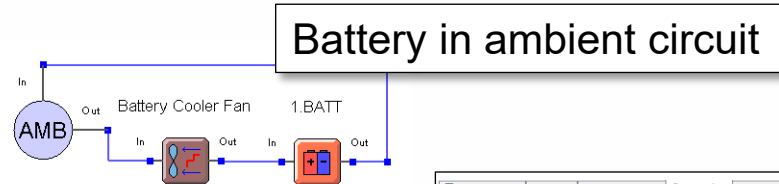
Convection type of utilized module
 Flow around the module
 Flow through the module

Configuration
 Flow direction: in +y-direction
 Cross section [cm²]: 80
 Volume of coolant [l]: 2

Fitting factor
 Factor: Heat transfer to module: 1

Pressure loss
 Pressure loss model

Battery



General data | Structure | Heat conduction | Convection | Electric properties

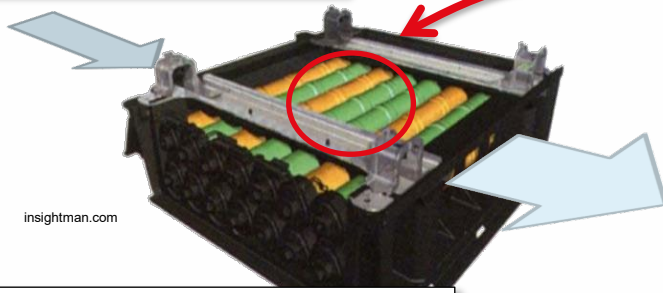
Flow through
 Flow around the module
 Flow through the module
 No convection

Flow around

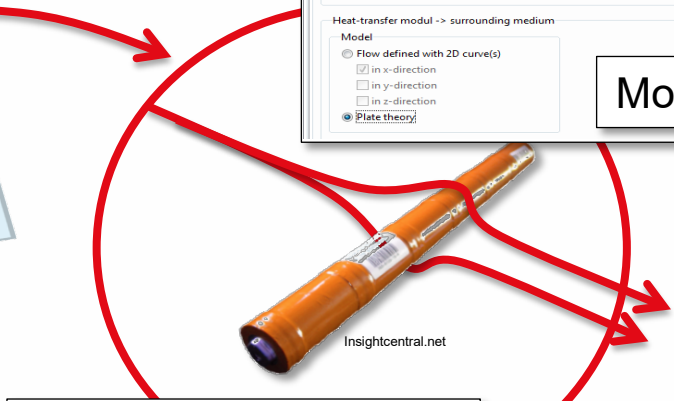
Fitting factor
 Heat transfer to cell: 1

Heat-transfer modul -> surrounding medium
 Model
 Flow defined with 2D curve(s)
 in x-direction
 in y-direction
 in z-direction
 Plate theory

Module

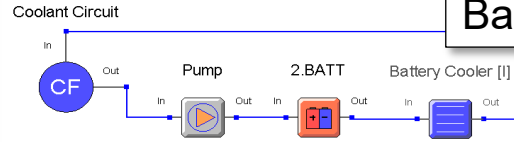
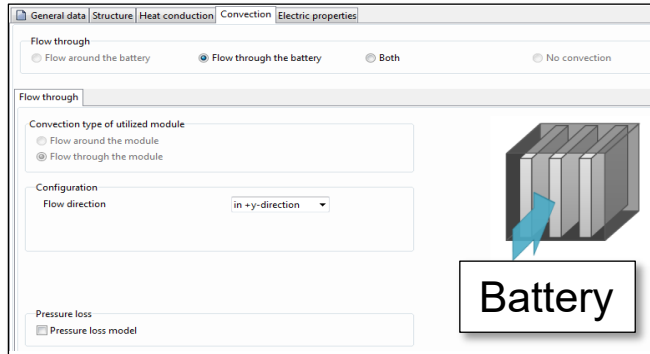


Air flow through battery

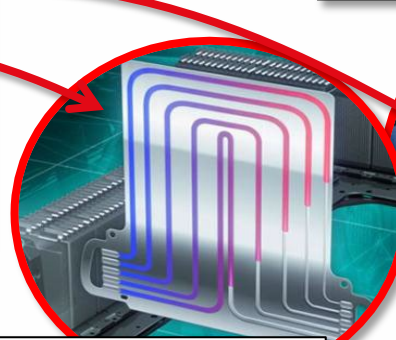
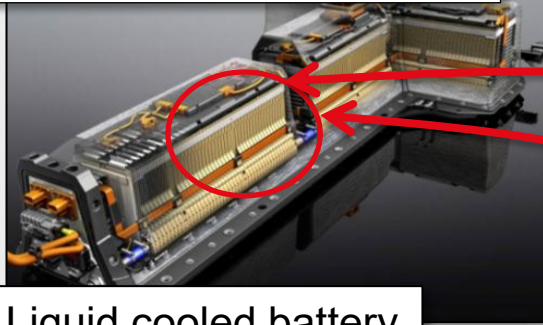
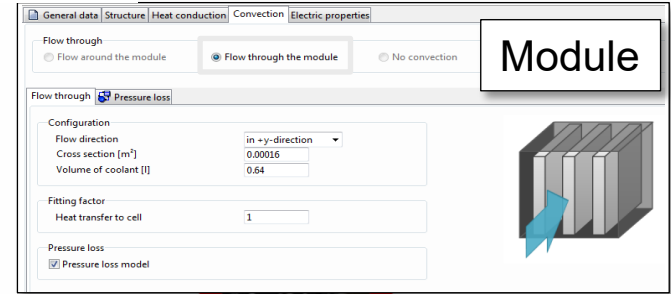


Air flow around module

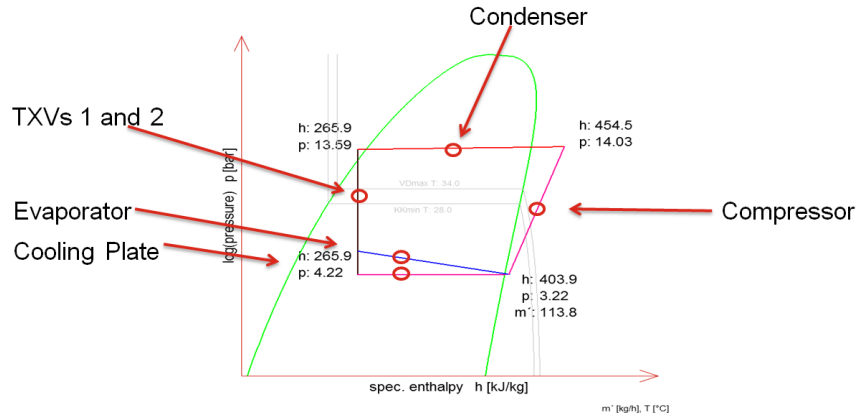
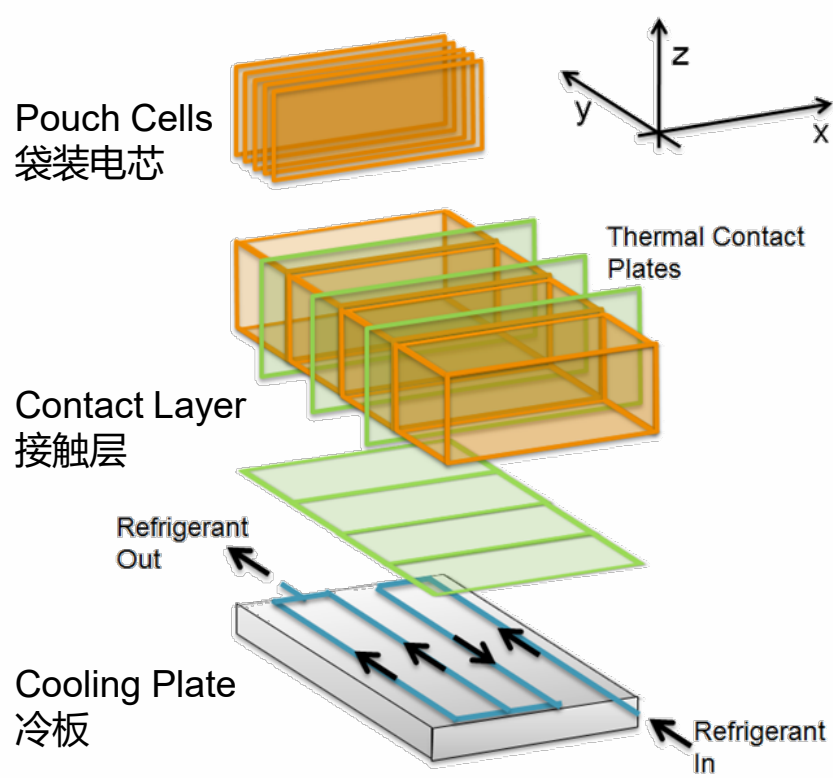
Battery Example - Fluid Cooled (Opel Ampera) 液冷电池



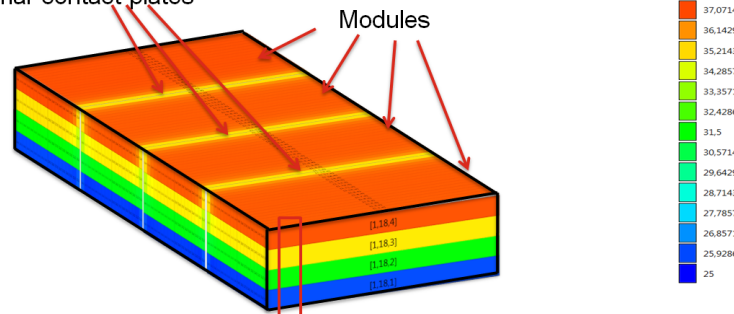
Battery in coolant circuit



Example: Refrigerant Cooled Battery 直冷式电池



Effect of thermal contact plates



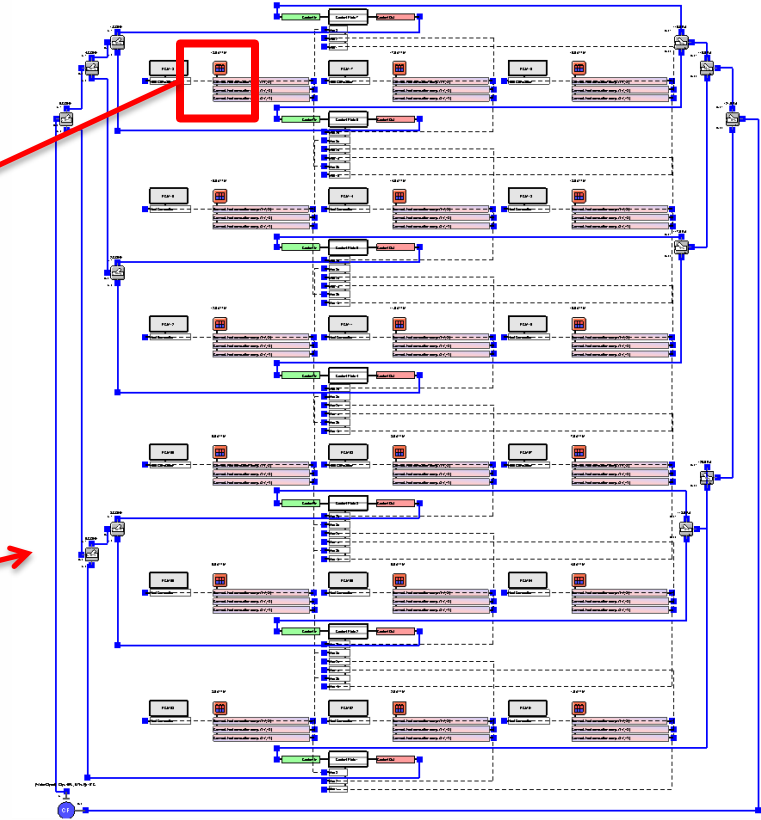
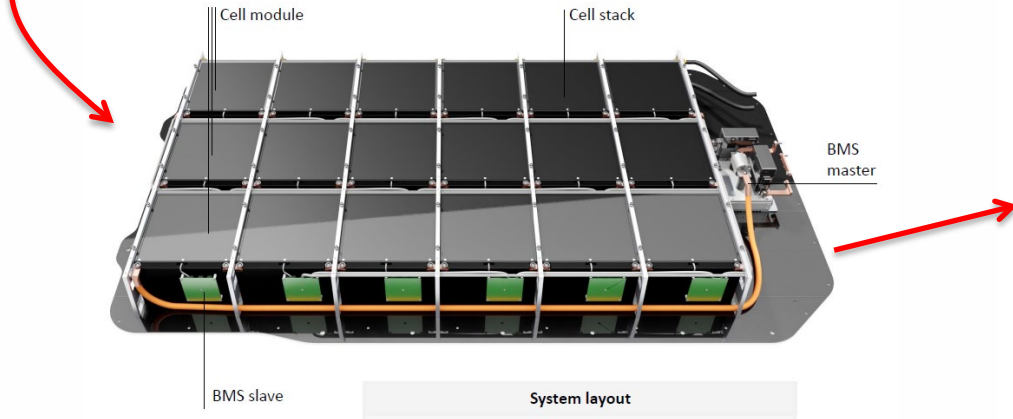
Cooling plate on bottom of modules leads to temperature spread in z-direction

Average Cell T: 32.1°C
Total Dissipated Power: 1080W

Example: Fluid Cooled Battery (TUM Create Taxi) 液冷式电池



18 Cell Stacks
à 12 cells



KULI eco - Electric Machine



Features of Electric Machine

电动机特点

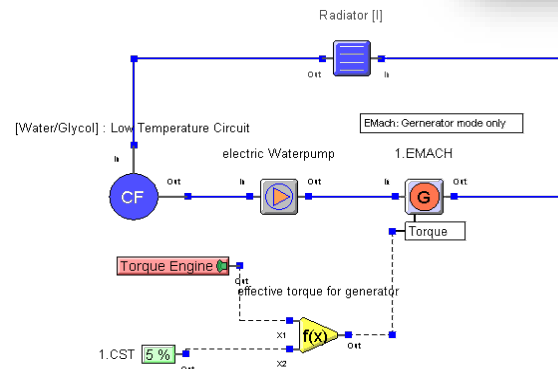
- **OP defined by torque and RPM**
工况由扭矩和转速定义
 - Motor- and generator-mode
电动机模式及发电模式
- **Waste heat 余热**
 - Efficiency map (Torque, rpm)
效率图 (扭矩, 转速)
- **Electrical power requirement**
需求电功率
- **Temperature Levels of**
温度组成
 - Stator 定子
 - Rotor 转子
 - Coolant 冷却液
- **Heat transfer to 热交换**
 - Fluid 流体
 - Ambient 环境
 - Other components (conduction)
其他零部件 (热传导)

Rathberger

1.EMACH



ECS Integrated Motor/Generator



Example: simple generator model

示例：简单发电模型

Efficiency of an Electric Machine 电机效率

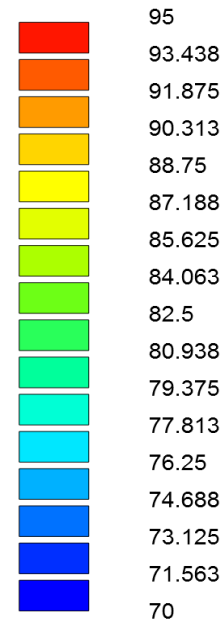
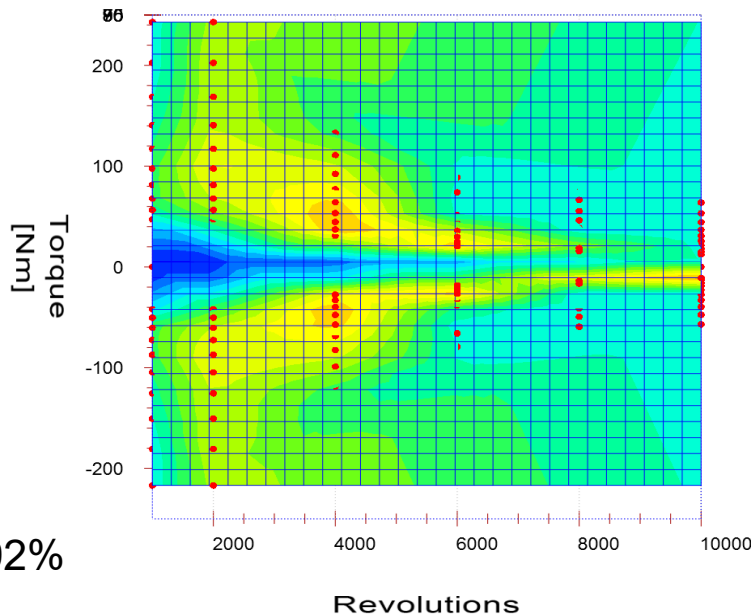


Typical E-Machine Efficiency Map:
典型电动机效率图

Electric machine
Efficiency

Positive torque:
Motor mode

Negative torque:
Generator mode
(recuperation)



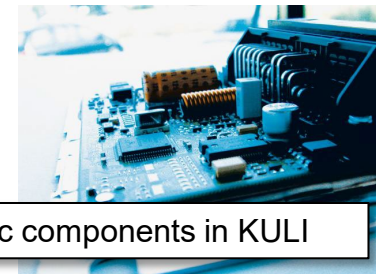
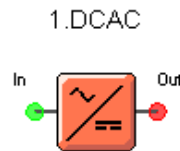
Efficiencies around 80% - 92%

效率在80% - 92%左右

(for most operating points 多数工况下)

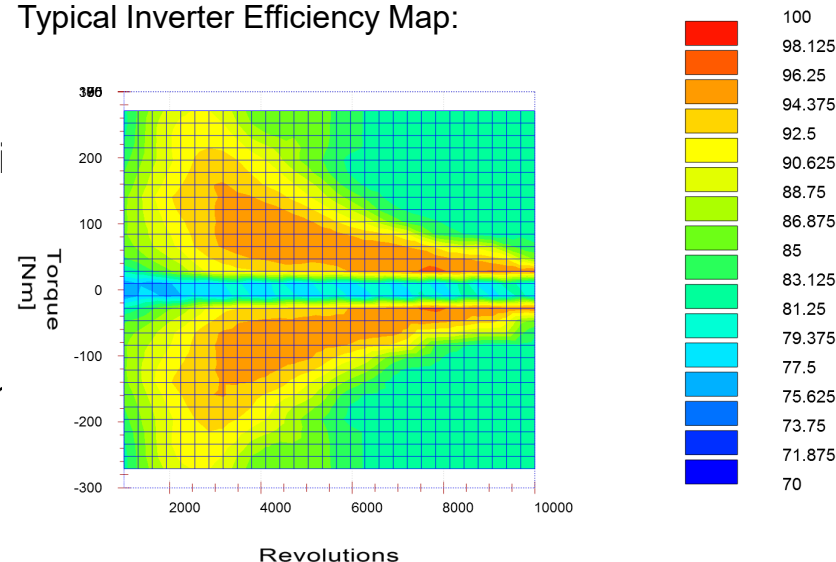
Features of Inverter (AC/DC): 逆变器特性

- **Alternating Current ↔ Direct Current**
交流直流之间的转换
- **Heat transfer to**
热传导
 - Fluid 液体
 - Ambient 环境
 - Any supported component by conducti
热传导
- **Waste heat 余热**
 - Efficiency map (Torque, rpm)
效率图 (扭矩, 转速)
 - Map of Dissipated Power (Torque, rpr
散热功率 (扭矩, 转速)



Electronic components in KULI

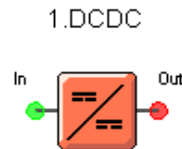
Typical Inverter Efficiency Map:



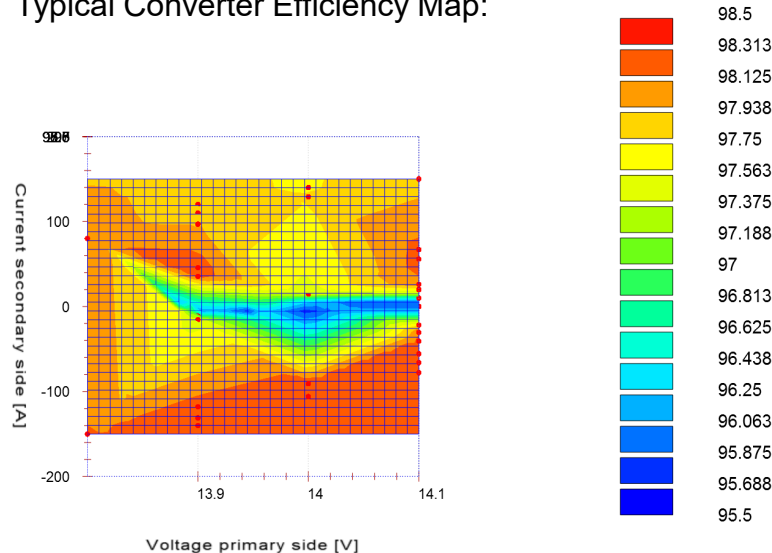
Features of Converter (DC/DC):

变流器特性

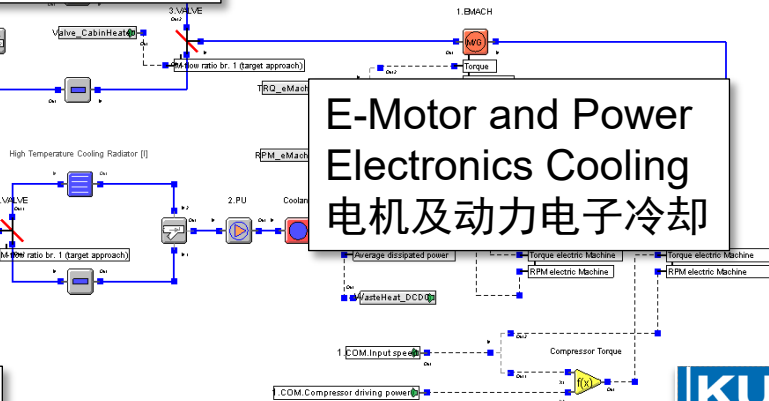
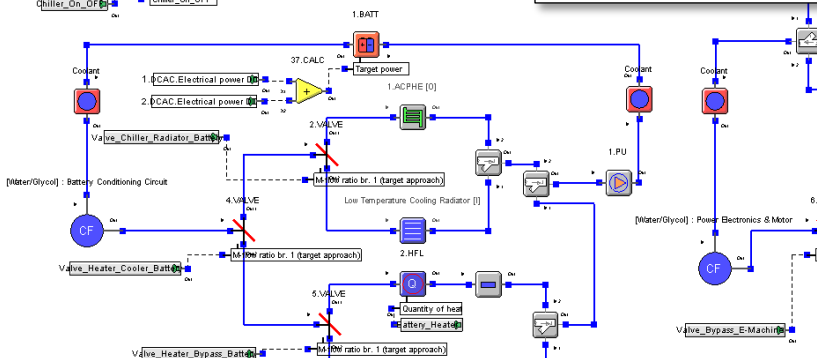
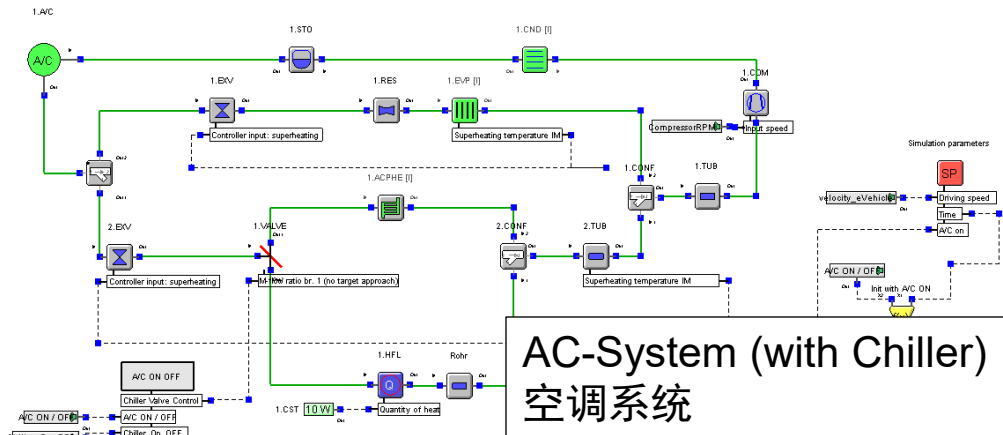
- **Direct Current ↔ Direct Current**
直流之间的转换
- **Heat transfer to**
换热至
 - Fluid 流体
 - Ambient 环境
 - Any supported component by conduction 热传导
- **Waste heat 余热**
 - Efficiency map (Power / Current, Vol
效率图 (功率/电流, 电压(LS, HS)))



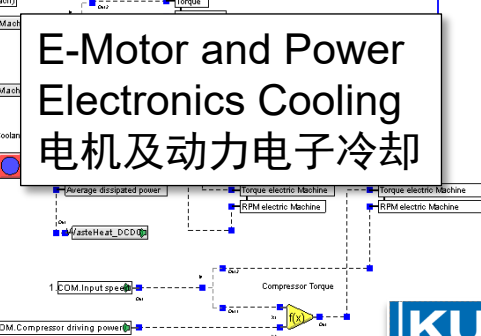
Typical Converter Efficiency Map:



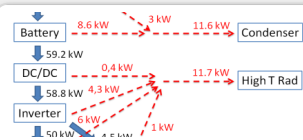
Application Example: Complete Thermal Model for an E-Car 电动车完整热模型



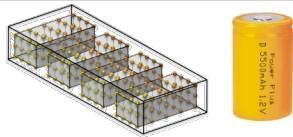
Low Temperature Battery Cooling Circuit 电池低温冷却循环



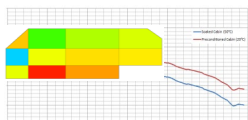
Benefits 优势



Understand the energy flows in your e-cooling system and ensure safe operation of all parts 理解您的电-冷却系统能量流并保证所有部件的安全工作



Quickly set up even very complex battery models... and evaluate them on cell-level! 快速建立非常复杂的电池模型，并分析电芯级别的表现



Compare how different operating strategies for hybrid usage and HVAC influence your range 比较混合动力及空调不同控制逻辑对行驶里程带来的影响



Integrate all your thermal management needs in one tool: engine cooling, E-cooling and AC 采用同一个工具完成您的发动机冷却、电-冷却以及空调系统集成



DRIVING **EXCELLENCE.**
INSPIRING **INNOVATION.**