



MODELING OF A FORMULA STUDENT ELECTRIC VEHICLE'S COOLING SYSTEM

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**ART TU CLUJ-
NAPOCA**

**FORMULA
STUDENT TEAM**



SUMMARY

1. The team
2. Powertrain configuration
3. Radiator design
4. Liquid cooling model
5. Water pump analysis
6. Battery model
7. Overall vehicle thermal model
8. Control algorithms
9. Future developments

1. THE TEAM

ART TU Cluj-Napoca Formula Student

History

- Founded in **2019** by **20** students
- First FS team from the country in the EV category
- Developed **3** race cars and participated in **4** official competitions since **2022**

Objectives

- Pass all technical inspections
- Score points in dynamic events
- Multiple test sessions to validate our design



Challenges

High Voltage system

Safety circuits

Modeling of a formula student electric vehicle's cooling system

1. THE TEAM

History of Kuli



First steps in Kuli in 2020 – Master thesis

- Radiator design
- Water pump choice
- Control algorithm of the active components
- Energy efficiency optimization

Advantages

- Reduces physical testing
- Iterative approach
- Helps to achieve the team's goals

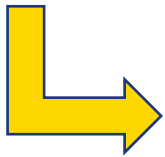


2. POWERTRAIN CONFIGURATION

Specifications and challenges

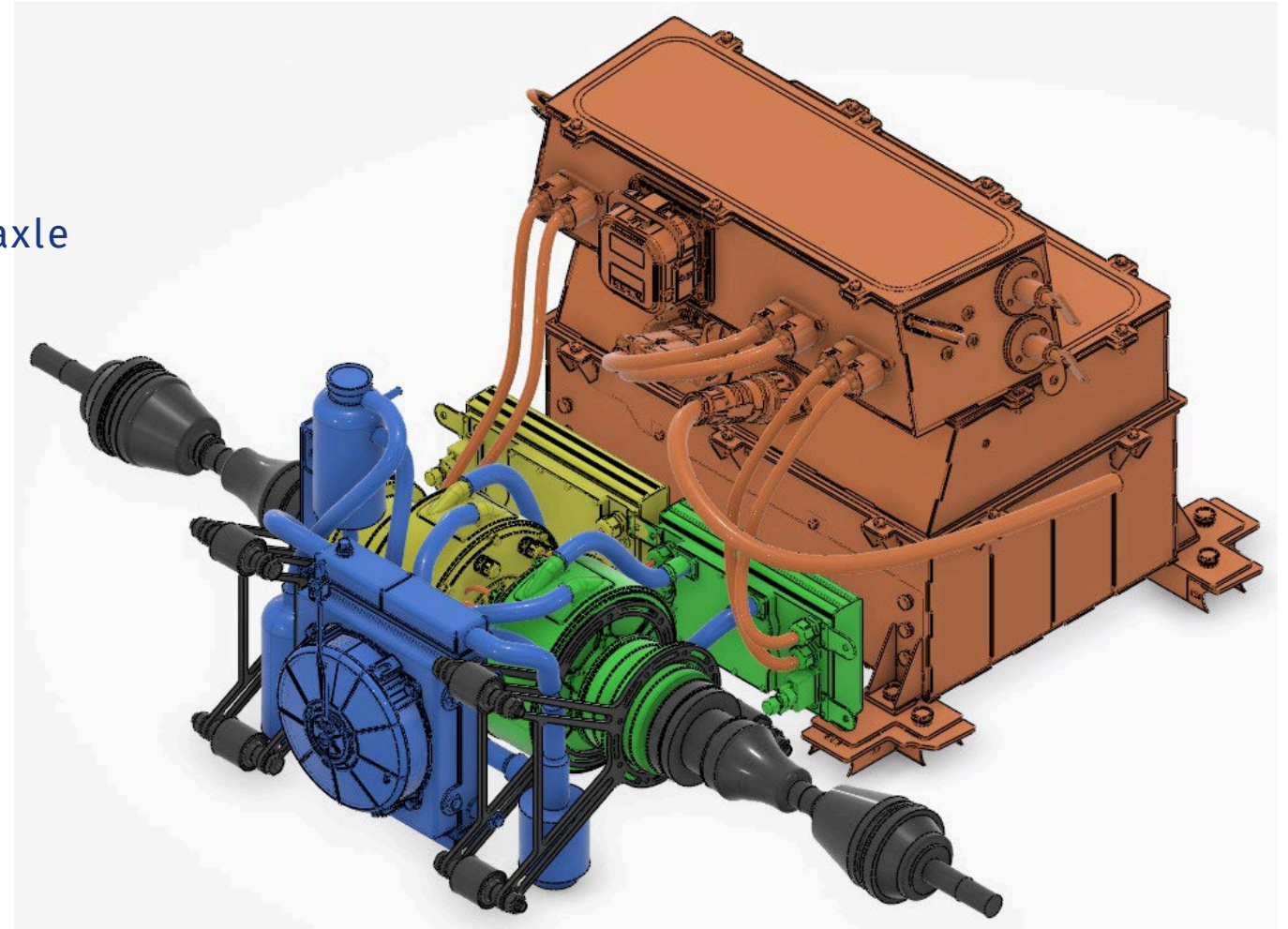
Specifications

- 5.2 kWh battery pack
- 2 independent BLDC motors on the rear axle
- 60 kW maximum power output
- 2 parallel cooling circuits



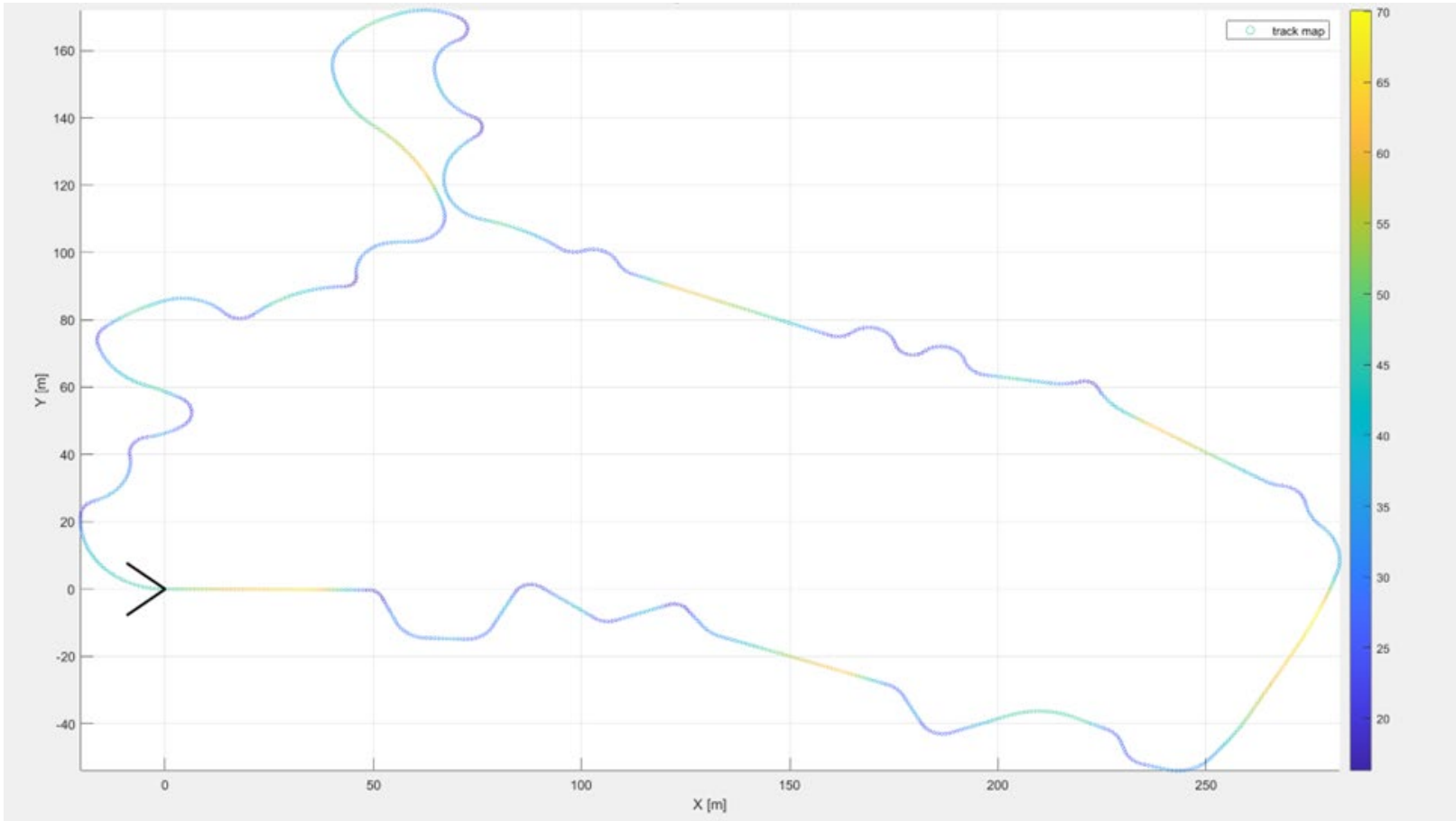
Potential thermal imbalance

- ☐ Packaging
- ☐ Positioning of components
- ☐ Routing design



3. RADIATOR DESIGN

Lap time simulation



Motor torque

Motor speed

Battery current

Battery State-of-Charge

Lap time

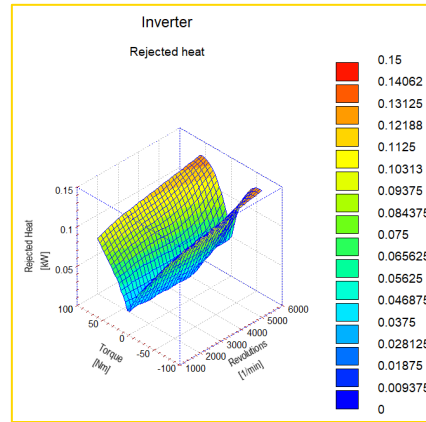
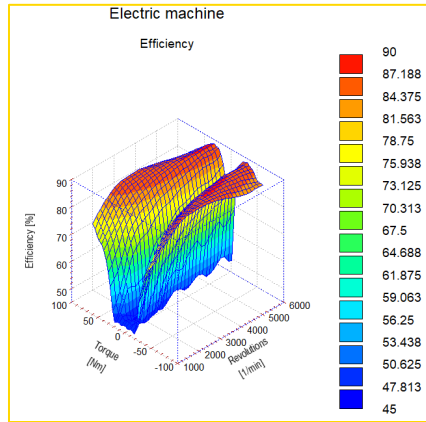
Track velocity profile

OUTPUTS

3. RADIATOR DESIGN

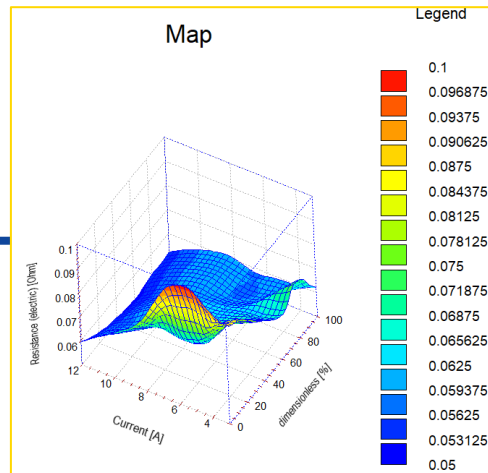
Lap time simulation

OUTPUTS



Motor and
controller
efficiency and heat
generation rate

Radiator thermal
output



Battery heat
generation rate

3. RADIATOR DESIGN

The beginnings

Worst case scenarios:

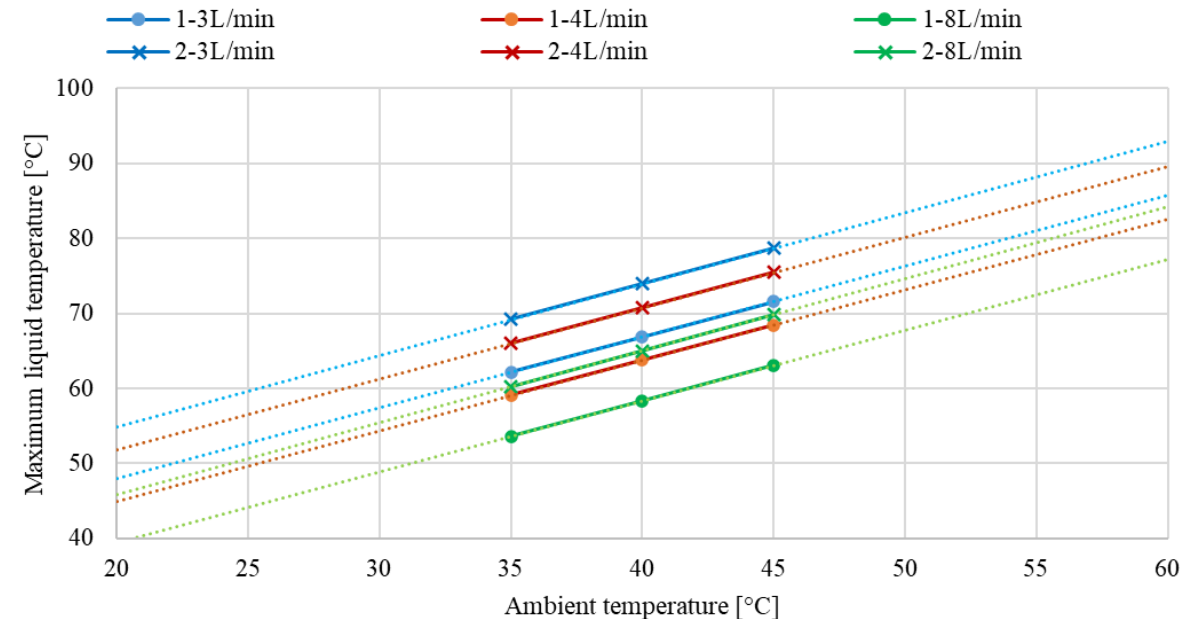
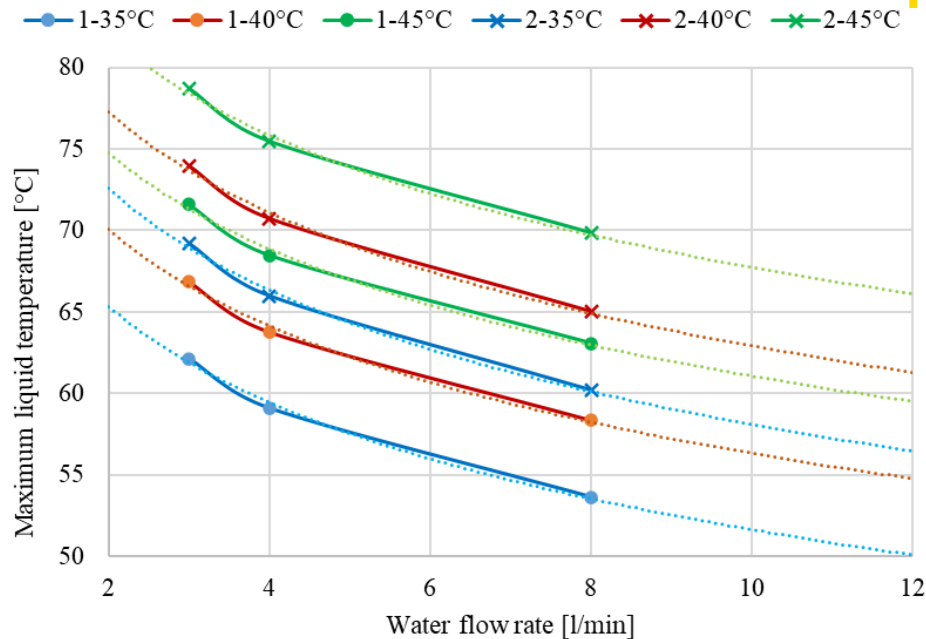
1. Over-evaluated heat generation
2. No natural air flow through the radiator
3. High pressure drops

RAAL[®]
complete cooling solutions

↓
**Custom-made
radiator designed
and evaluated using
Kuli**

Analyzed situations:

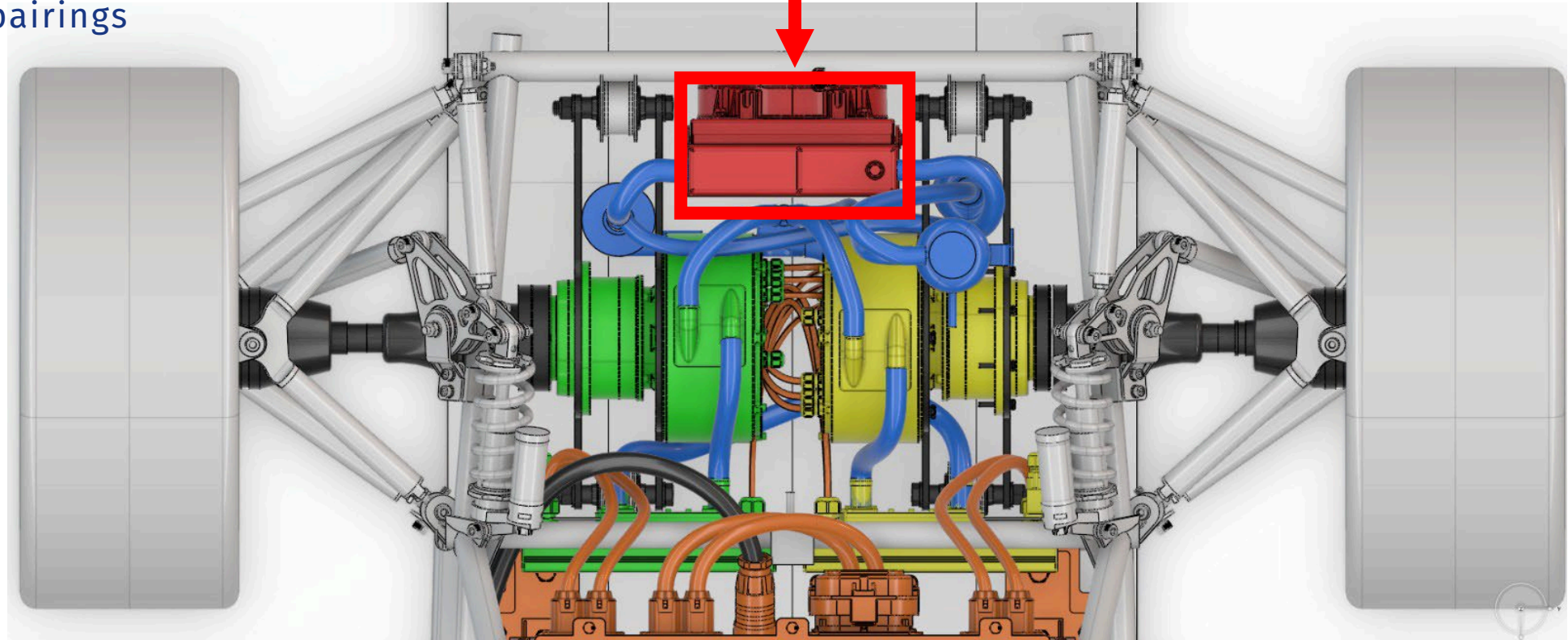
1. Two radiator designs
2. Several ambient temperature values
3. Several liquid flow rate values



3. RADIATOR DESIGN

Evolution

1. More accurate heat generation calculations
2. Updated package limitations
3. New radiator-fan pairings

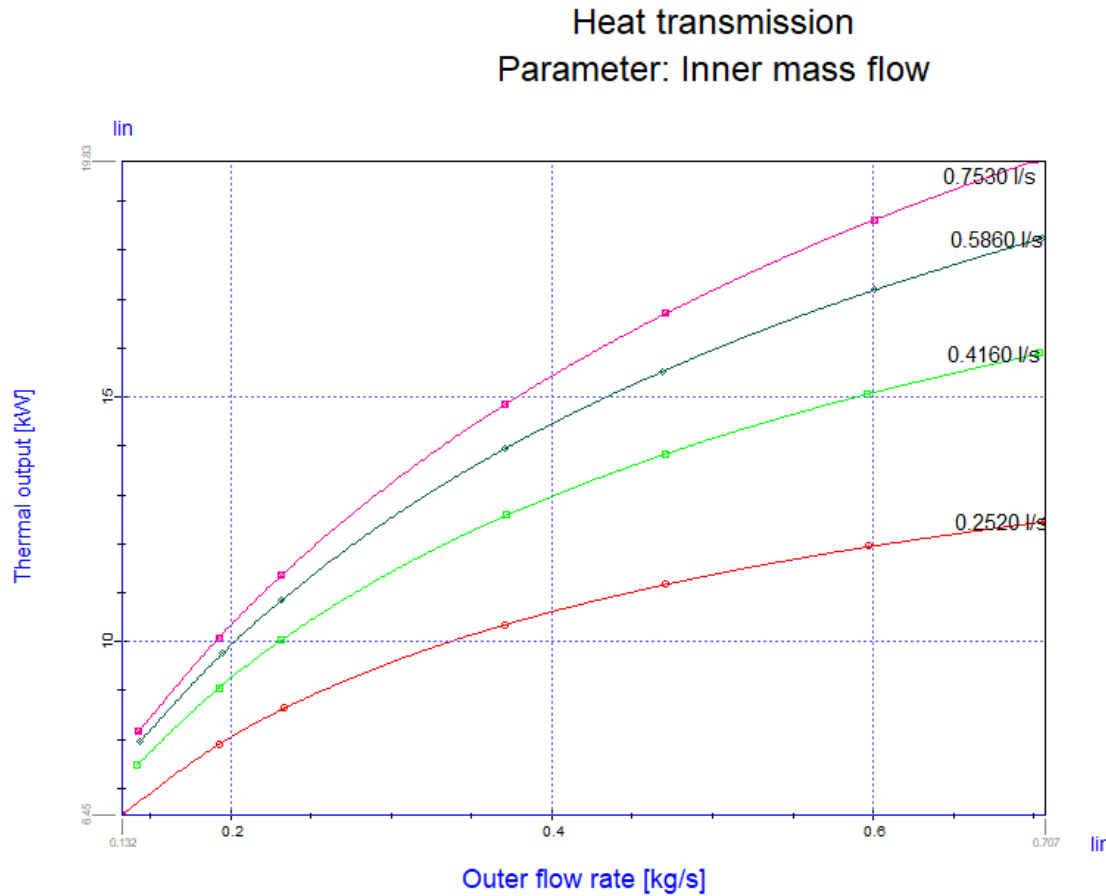


Modeling of a formula student electric vehicle's cooling system

3. RADIATOR DESIGN

Evolution

2nd
gen.



3rd
gen.

4. LIQUID COOLING MODEL

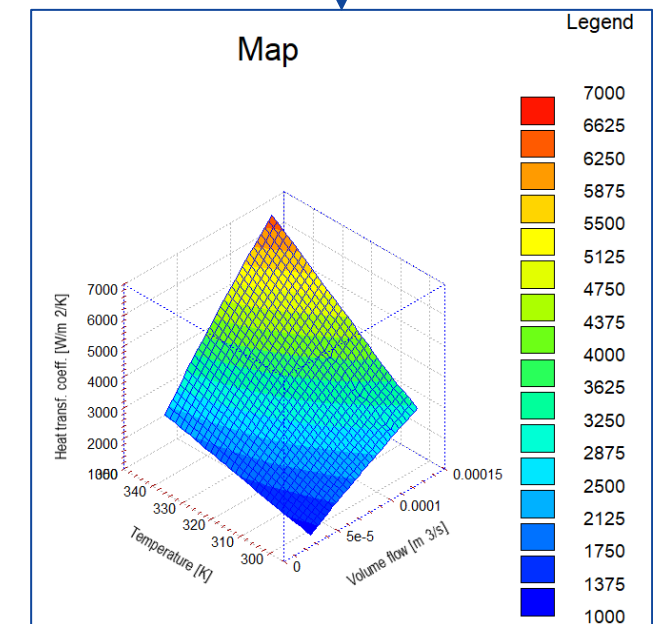
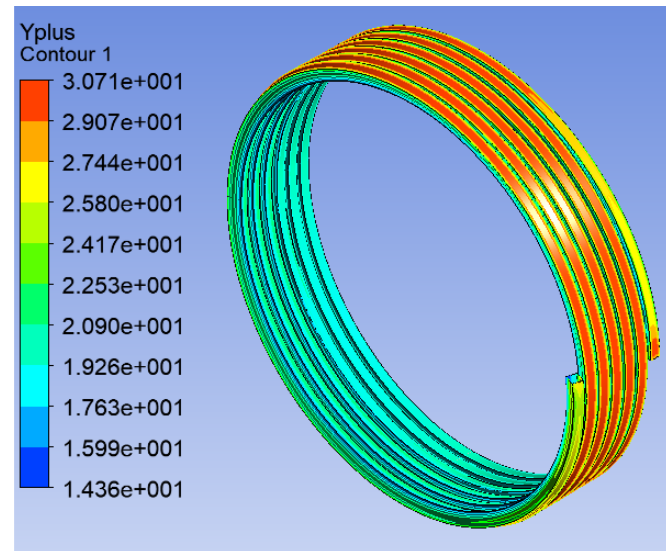
Estimation of unknown values

- Heat transfer coefficient

⇒ 3D maps from empirical equations Colburn: $Nu = 0.023 \cdot Re_f^{0.8} \cdot Pr_f^{1/3}$

- Pressure drops

⇒ from CFD simulations

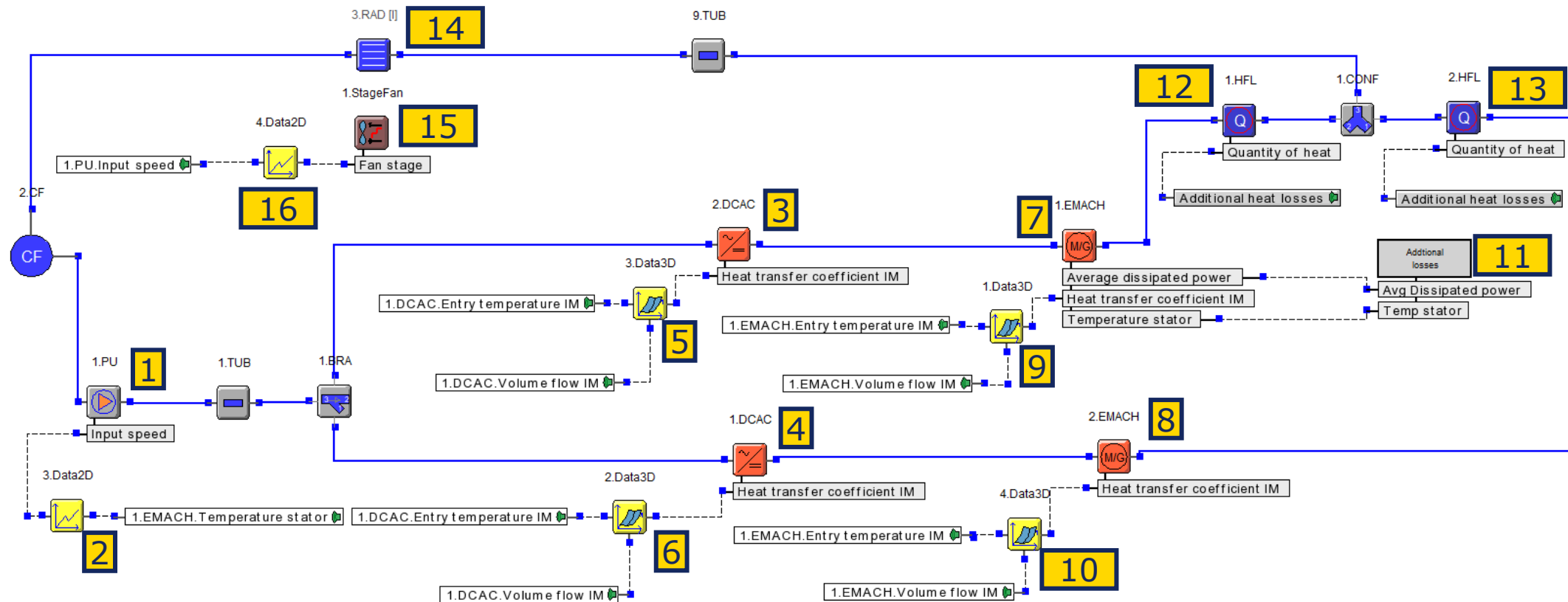


- Change of motor efficiency with temperature

⇒ additional heat from the internal resistance's increase $R = R_{int}[1 + \alpha(T - T_{init})]$

4. LIQUID COOLING MODEL

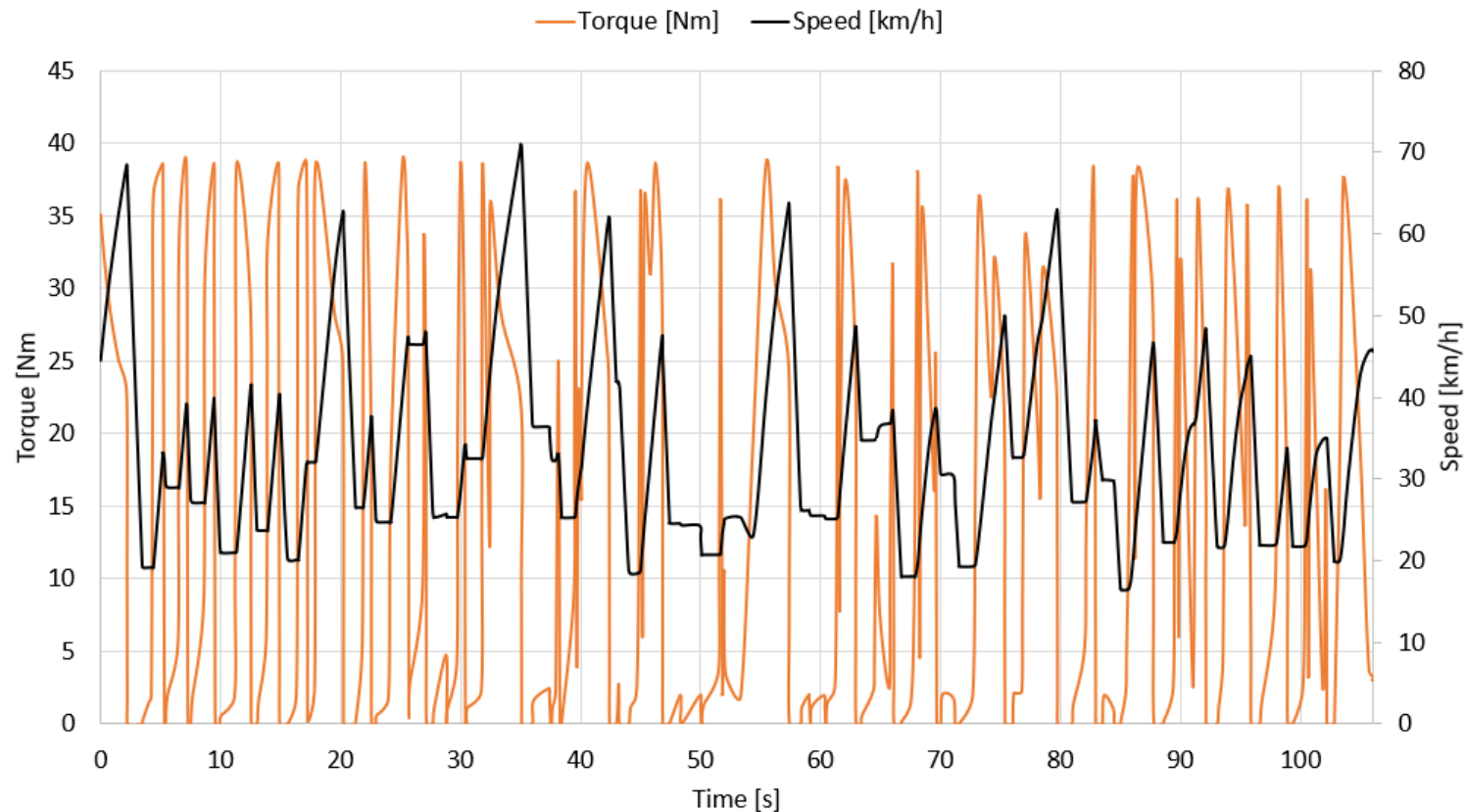
Components



1 – water pump; 2 – water pump control; 3,4 – controllers; 5,6 – controller heat transfer coefficient maps; 7,8 – electric motors; 9,10 – electric motor heat transfer coefficient maps; 11 – motor internal resistance increase calculation; 12,13 – additional heat sources; 14 – radiator; 15 – fan; 16 – fan control

4. LIQUID COOLING MODEL

Simulation parameters



+ engine speed

x22
laps

Simulation
parameters
input data

5. WATER PUMP ANALYSIS

List of requirements

Stator temperature <75°C

Radiator exit/water pump inlet temperature <65°C

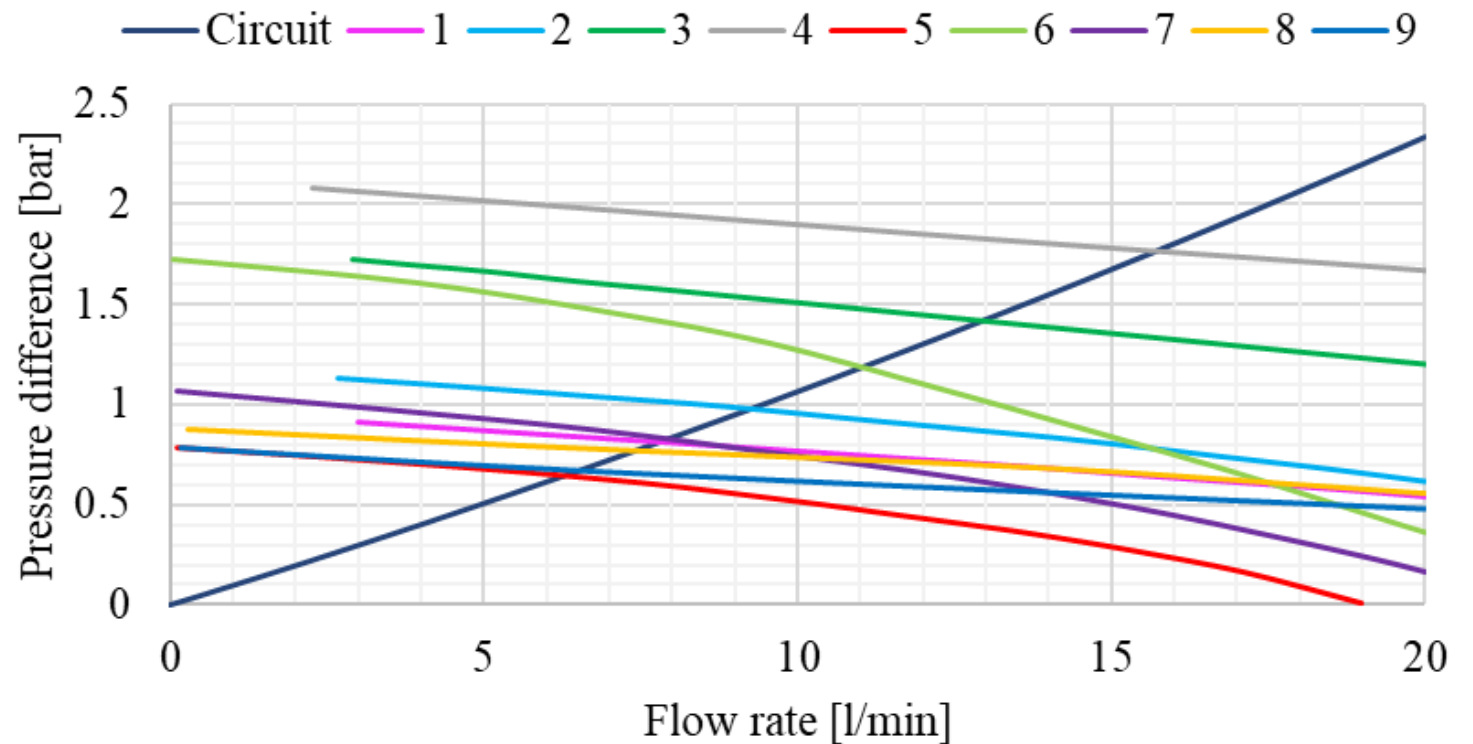
Maximum controller inlet pressure <2 bar

Minimum flow rate >7 L/min

Limit motor internal resistance increase

Reduced power consumption

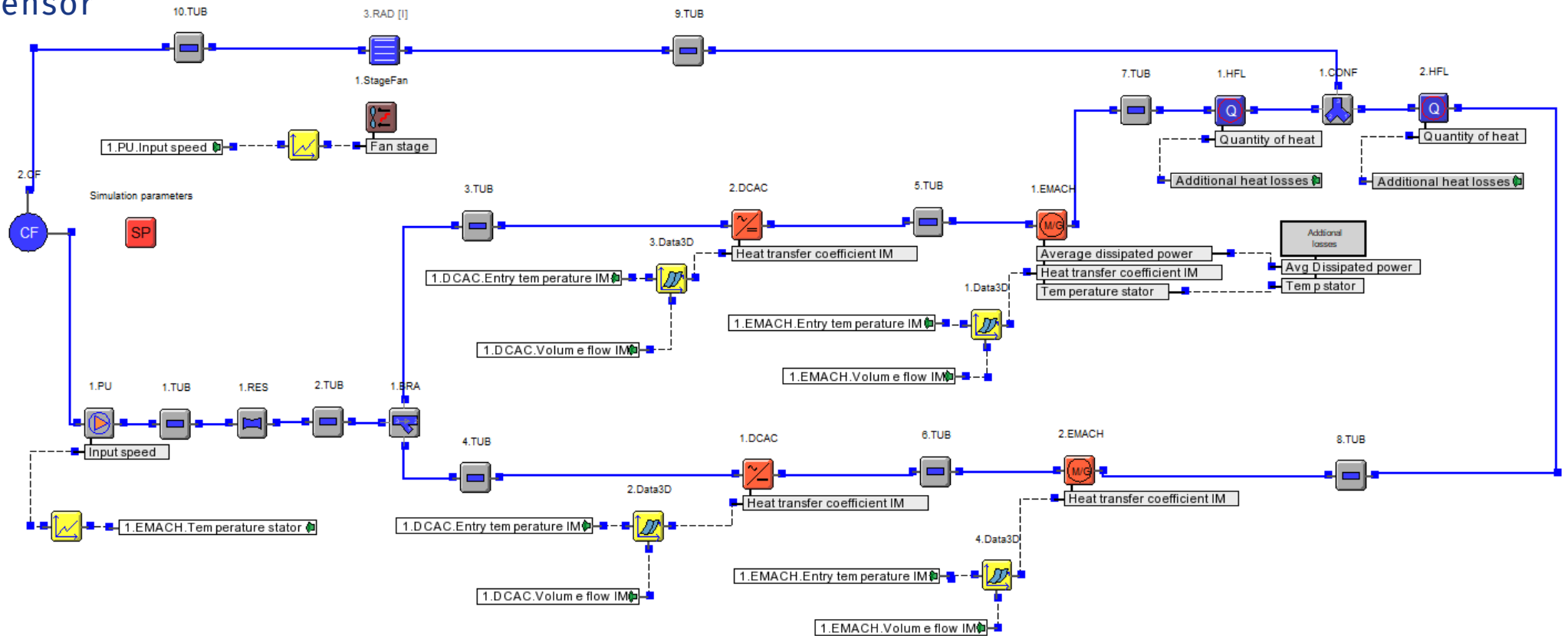
Possibility for PWM control



5. WATER PUMP ANALYSIS

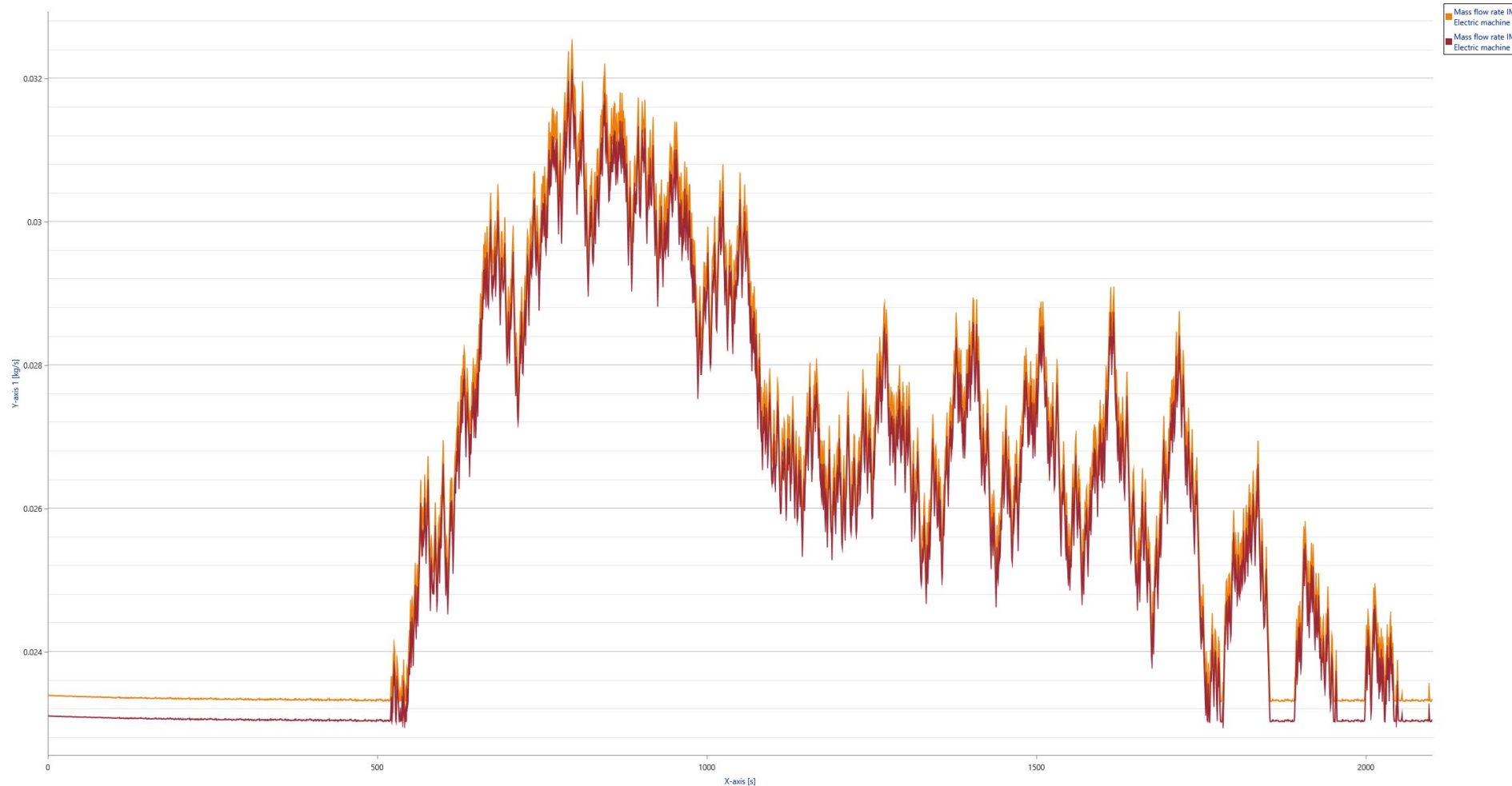
Completed simulation model

- + all tubes and bends from final CAD routing
- + flow rate sensor



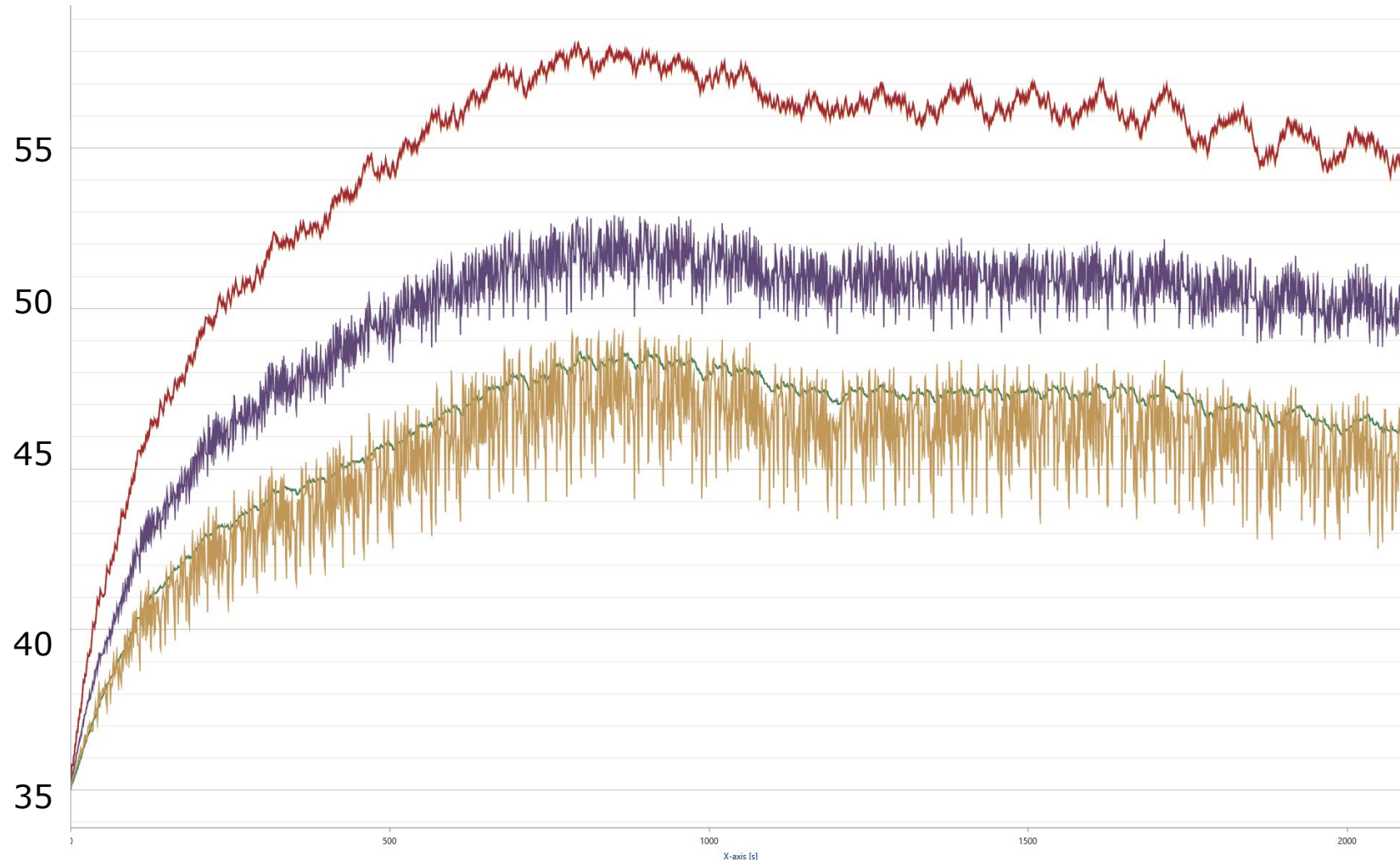
5. WATER PUMP ANALYSIS

Results – Thermal imbalance



5. WATER PUMP ANALYSIS

Results – Temperature requirements



Stator temperature

Radiator inlet temperature

Radiator exit temperature

Inverter temperature

6. BATTERY MODEL

Proposed experiments

Objective

- + Internal resistance maps
- + Specific heat capacity maps

3 testing cells

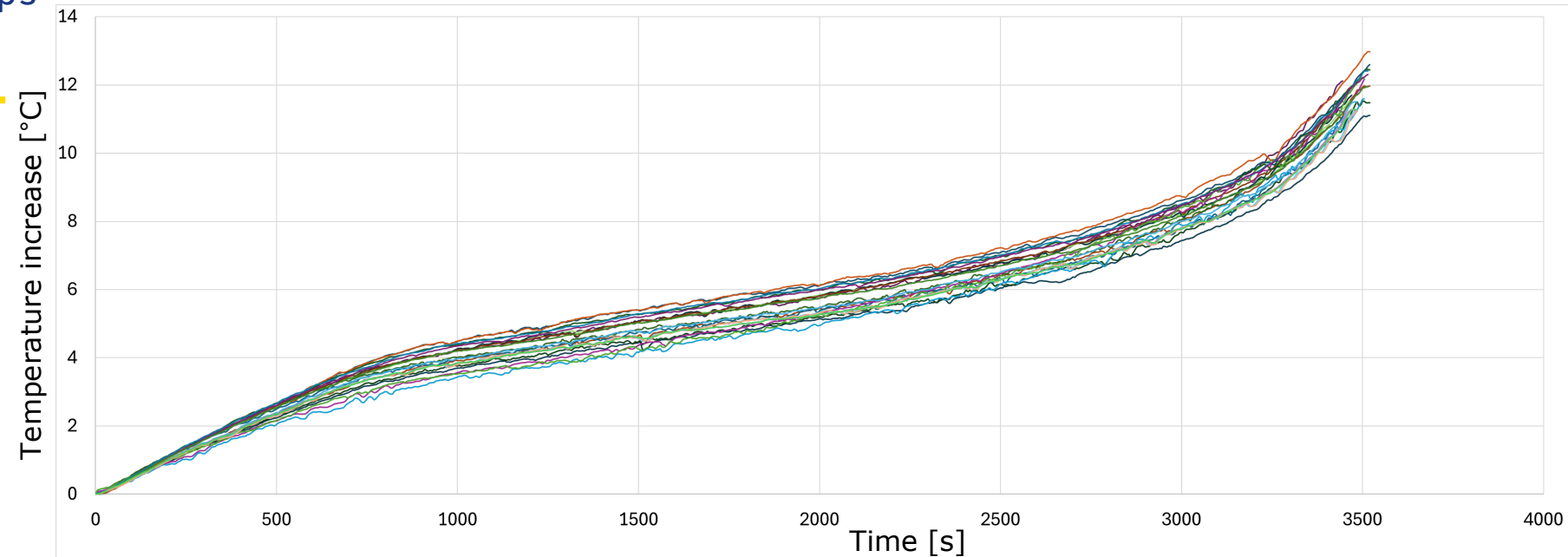
3 temperature measuring points/cell

4 discharge rates

3 repeats/test

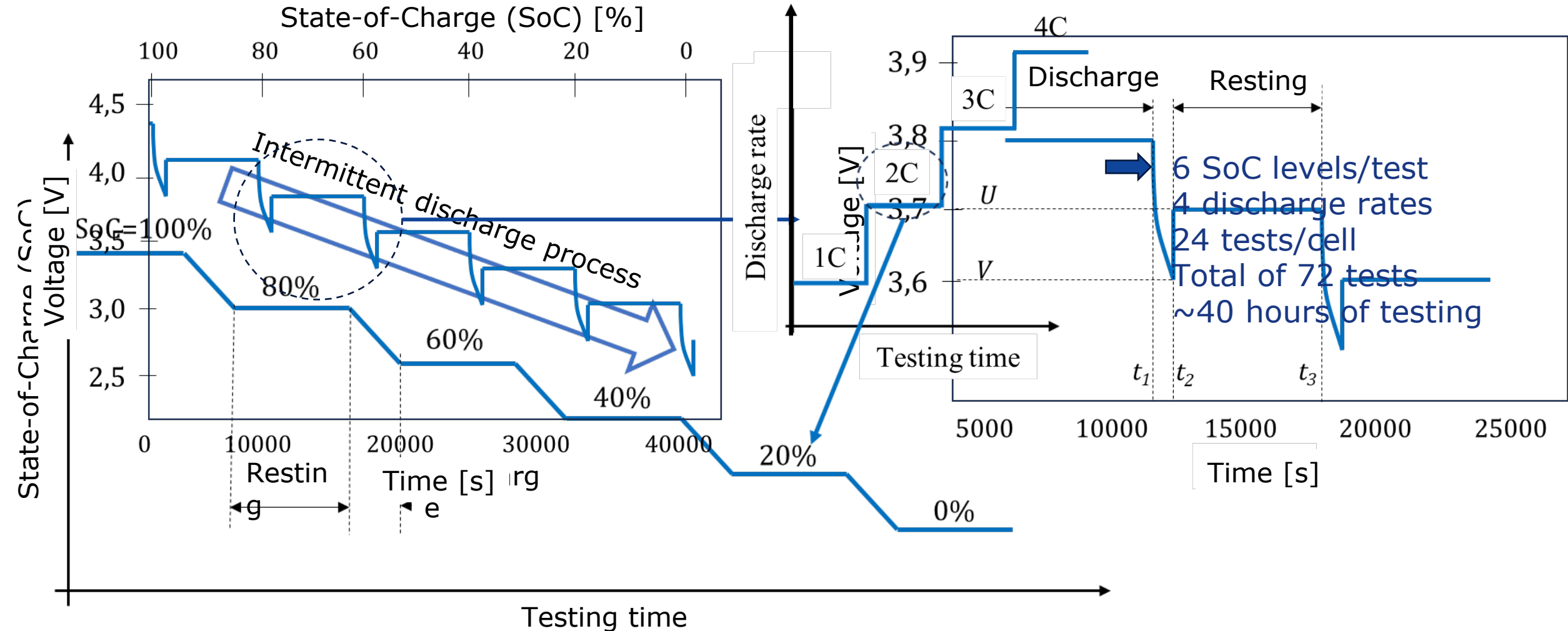
Methodology

- + Temperature increase
 - + Heat generation
- at different discharge rates



6. BATTERY MODEL

Experimental methodology - heat generation



6. BATTERY MODEL

Simulink model validation

Discharge time

Temperature increase

Heat generation rate

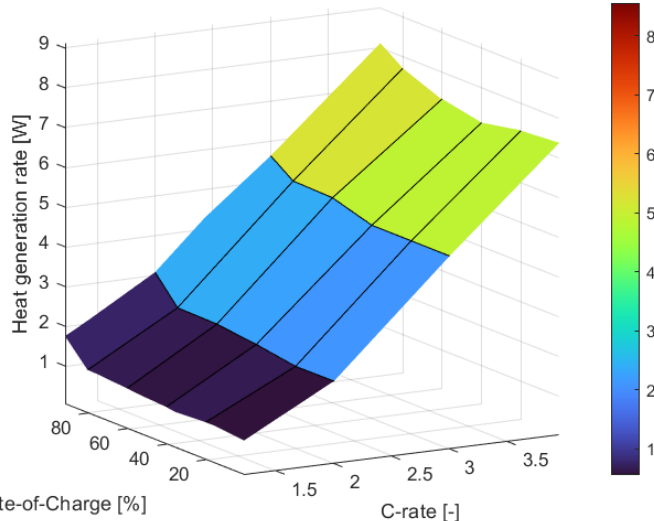
Natural
convection
thermal
model

Specific heat capacity

Temperature estimation

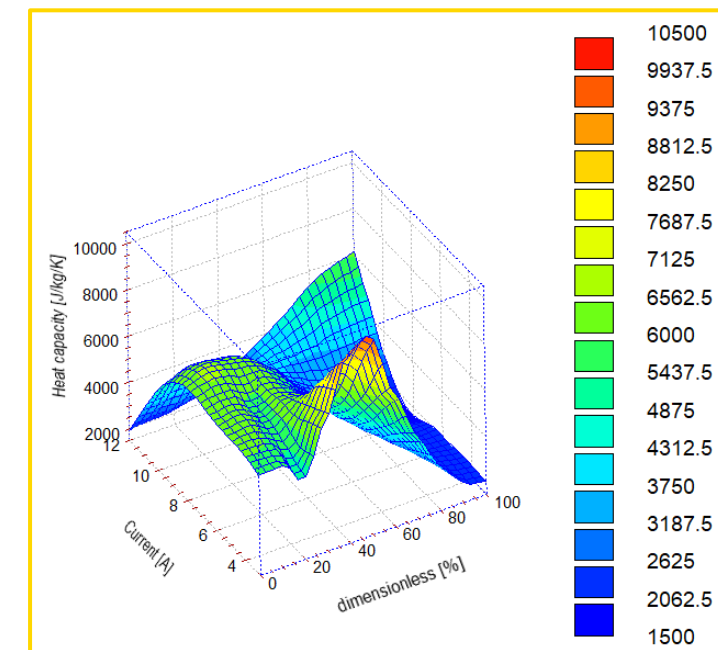
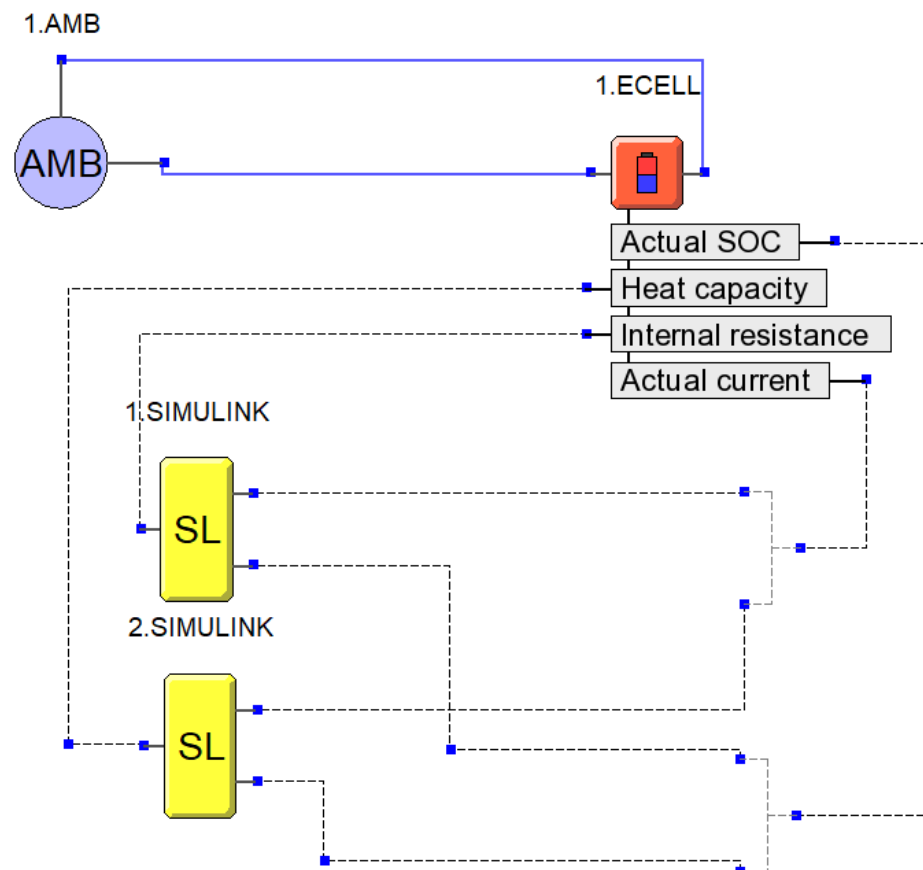
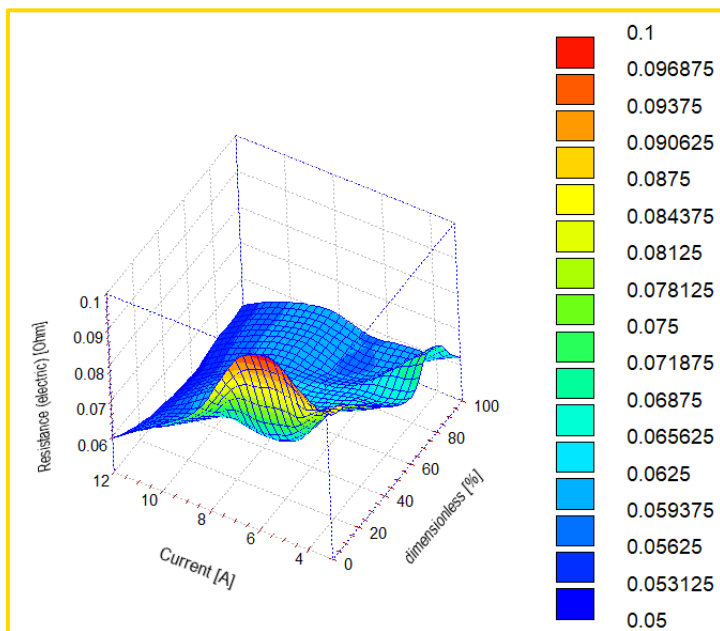
Data used
in battery
thermal
models

Heat generation map



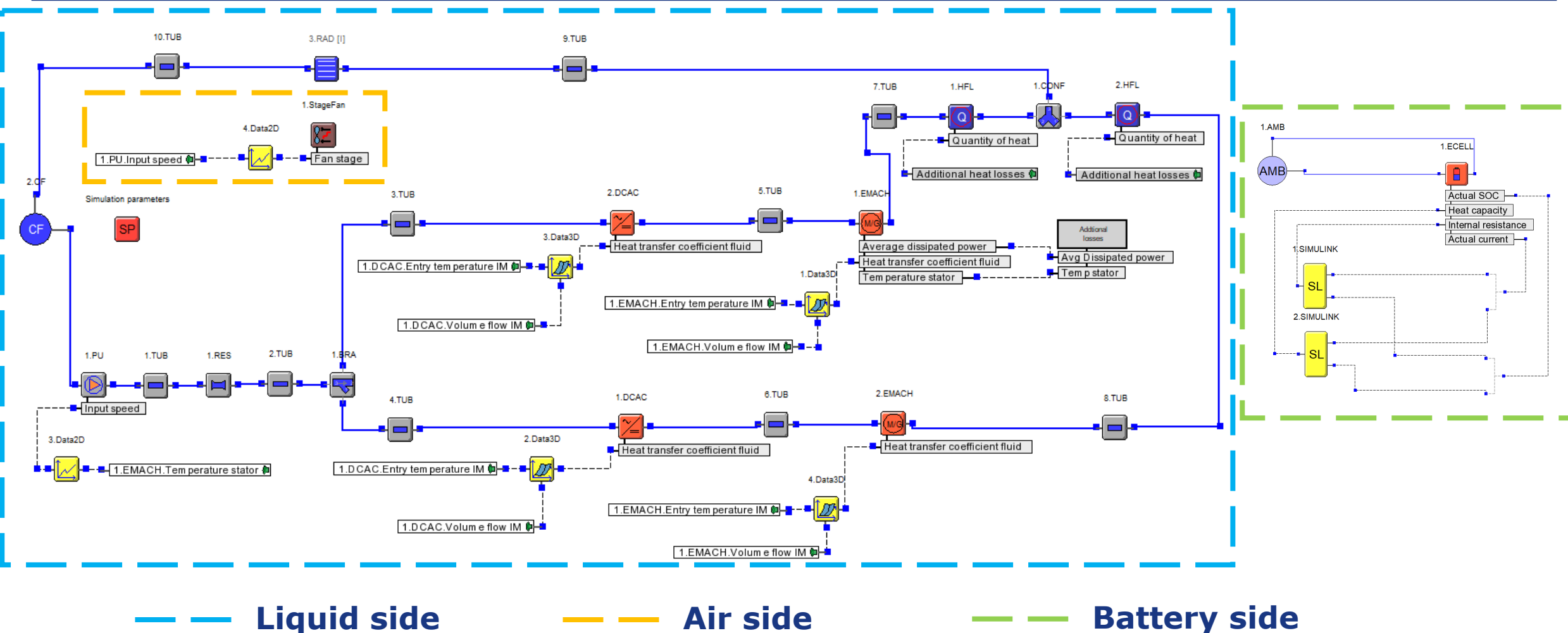
6. BATTERY MODEL

Implementation in Kuli



7. OVERALL VEHICLE THERMAL MODEL

Circuits and components



8. CONTROL ALGORITHMS

Test scenarios

OBJECTIVE

Reduce energy consumption

METHOD

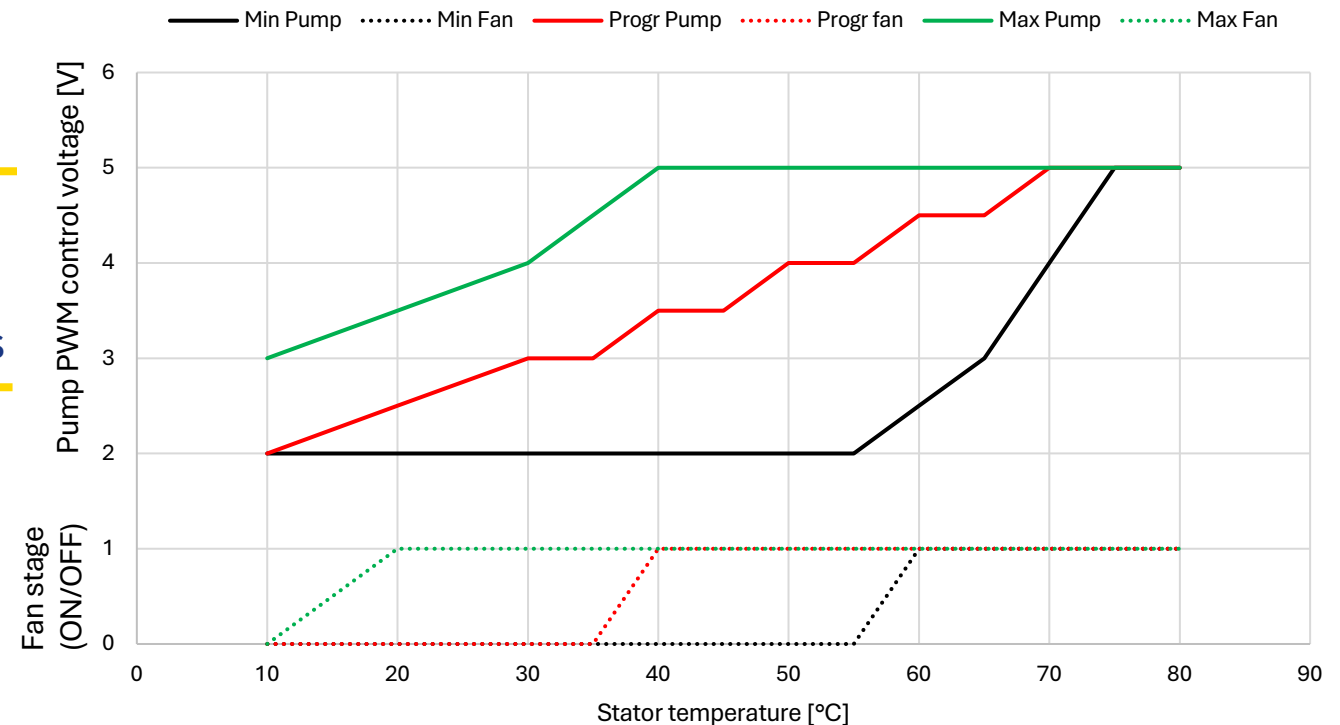
Water pump and radiator fan control algorithms

TEST SCENARIOS

- 3 control algorithms:

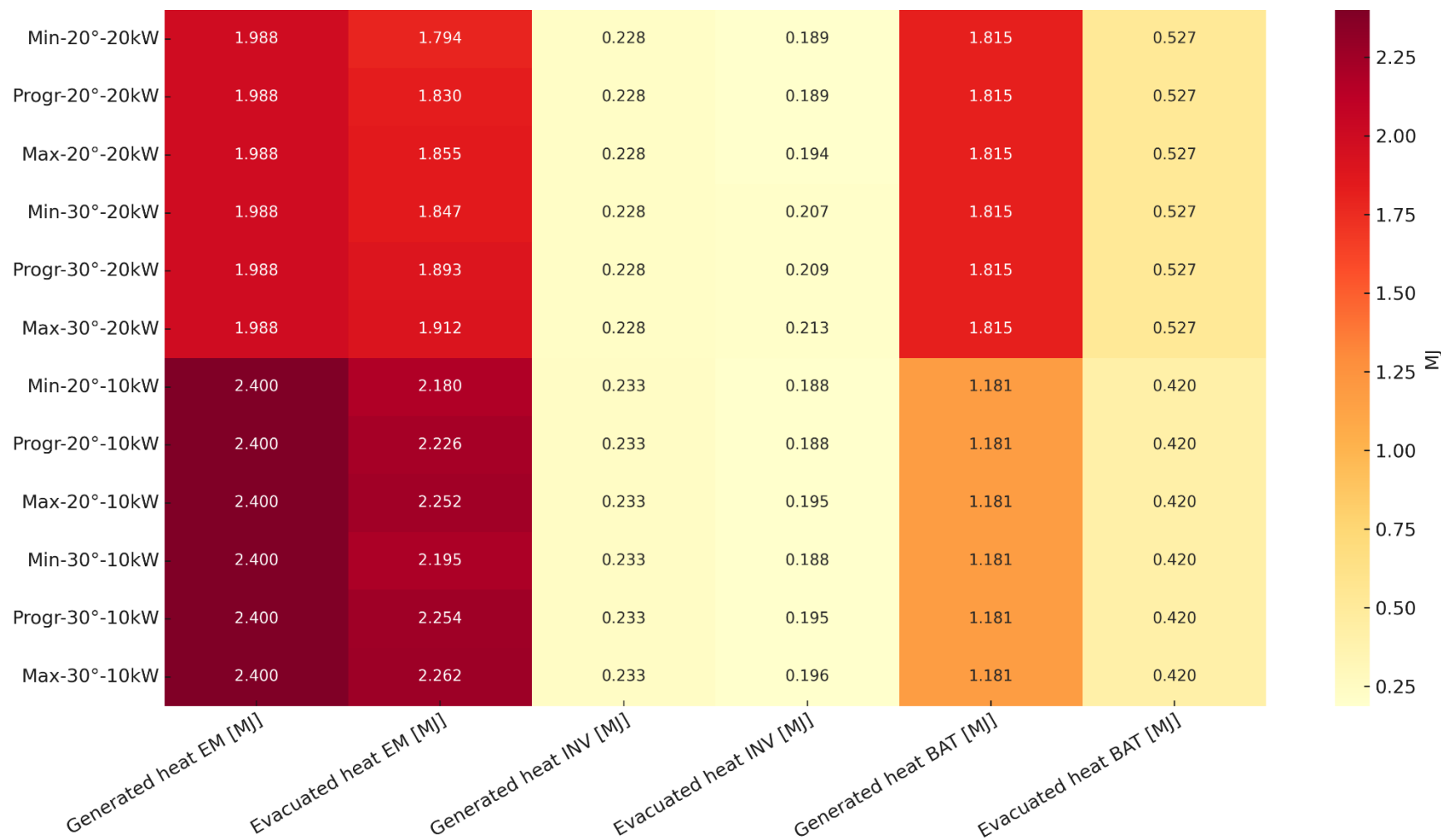
Minimum, Progressive, Maximum cooling

- 2 ambient temperature cases: 20-30°C
- 2 maximum power outputs: 10-20 kW



8. CONTROL ALGORITHMS

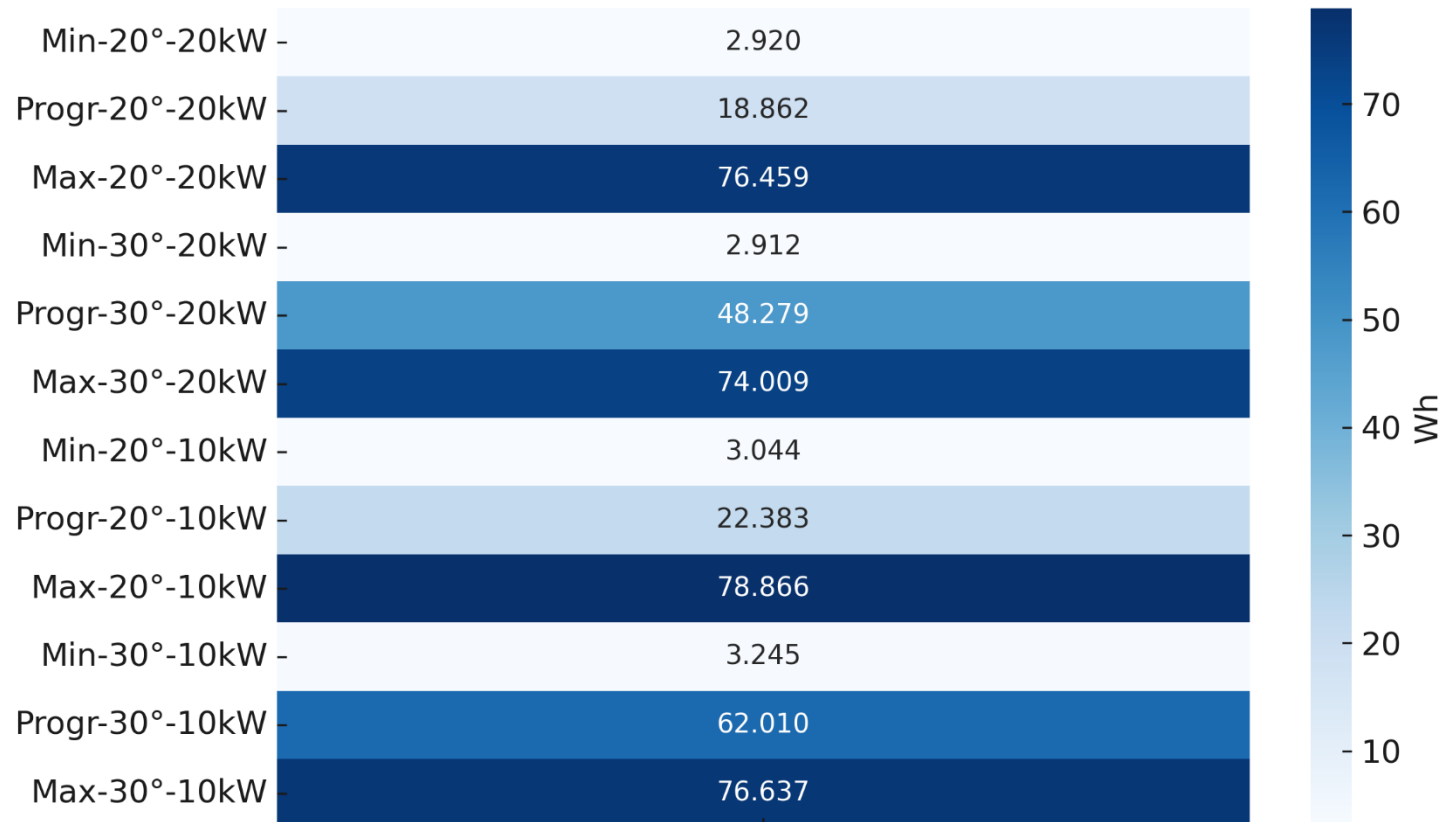
Results' overview – Generated and evacuated heat



8. CONTROL ALGORITHMS

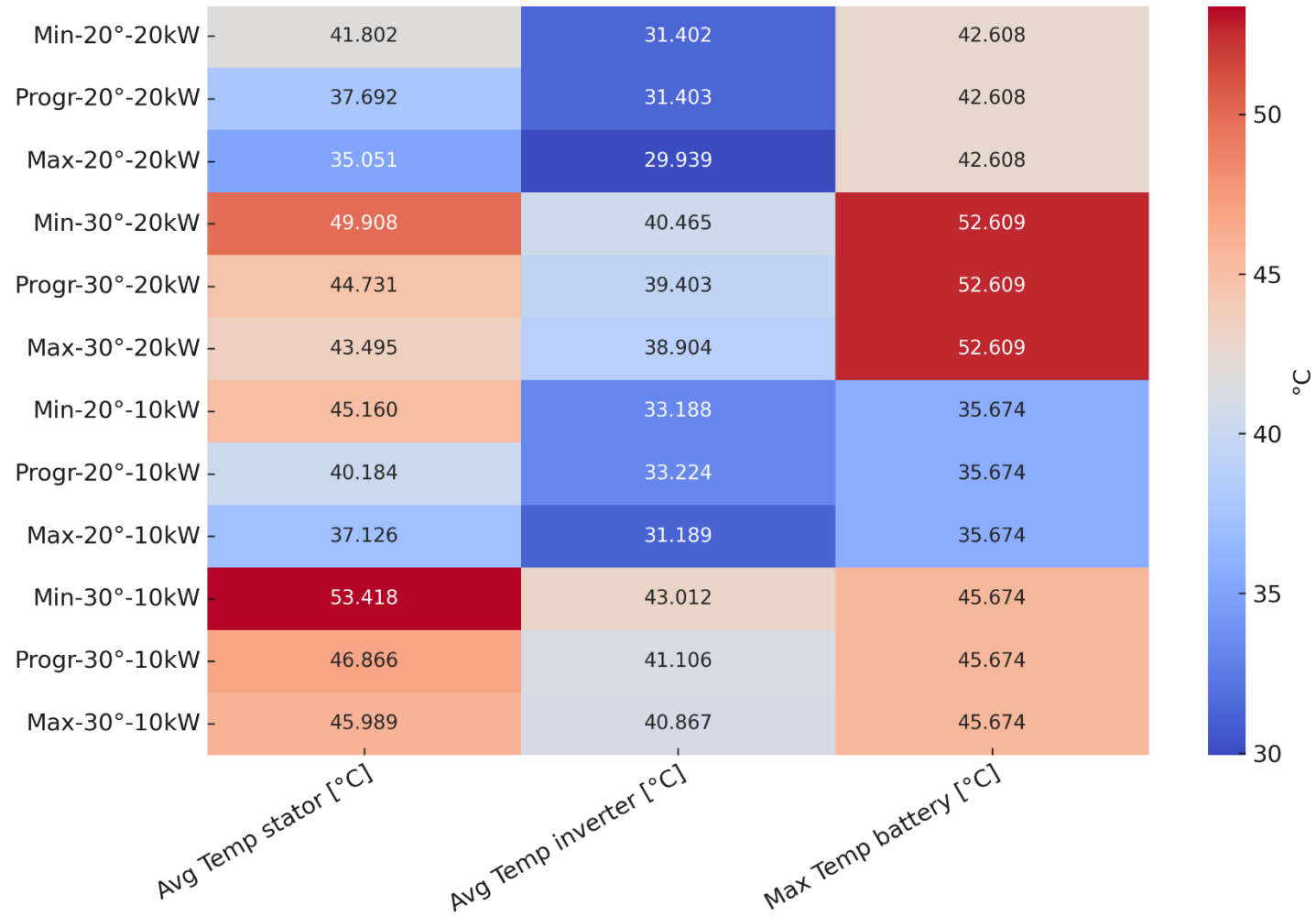
Results' overview – Energy consumption

Water pump + Radiator fan energy consumption



8. CONTROL ALGORITHMS

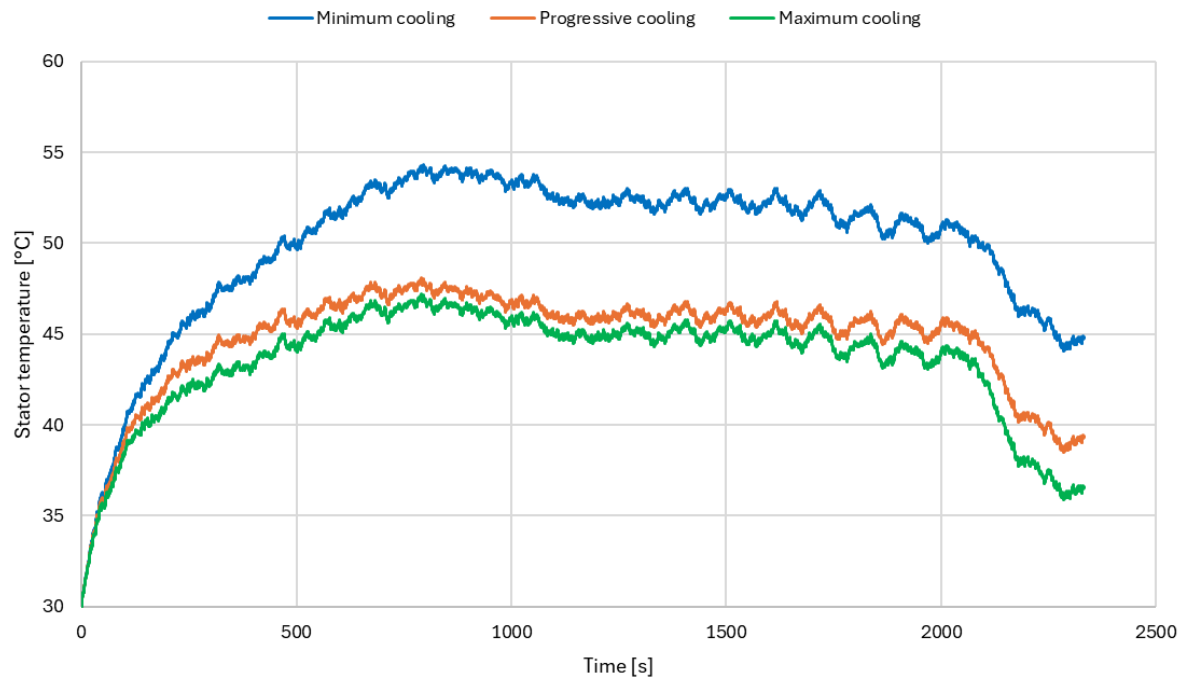
Results' overview – Temperatures



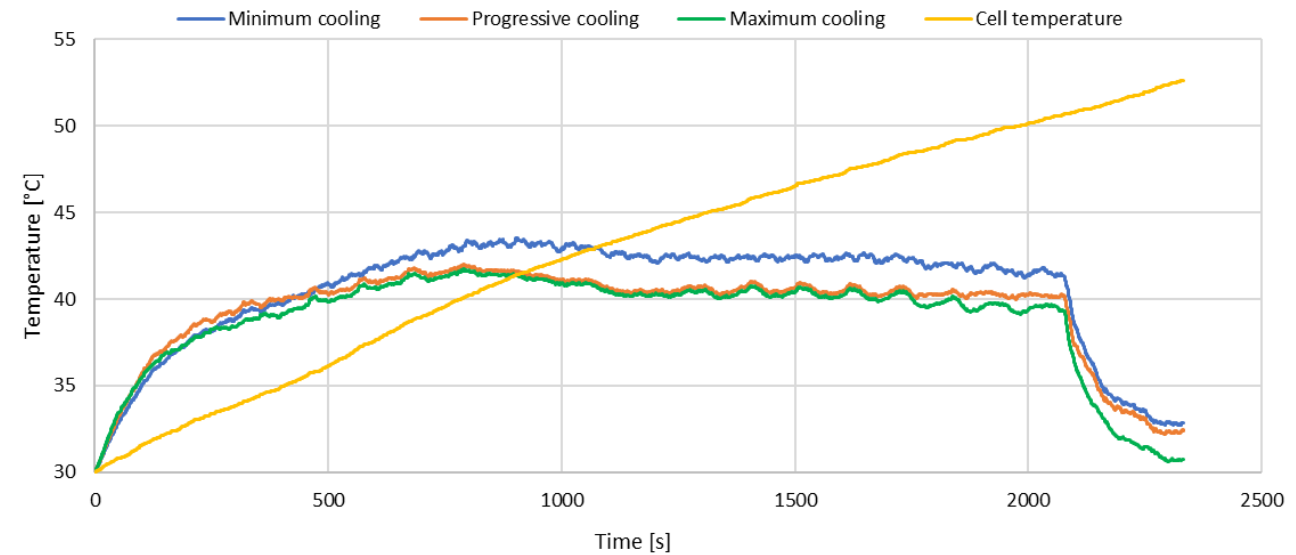
8. CONTROL ALGORITHMS

Temperature evolutions

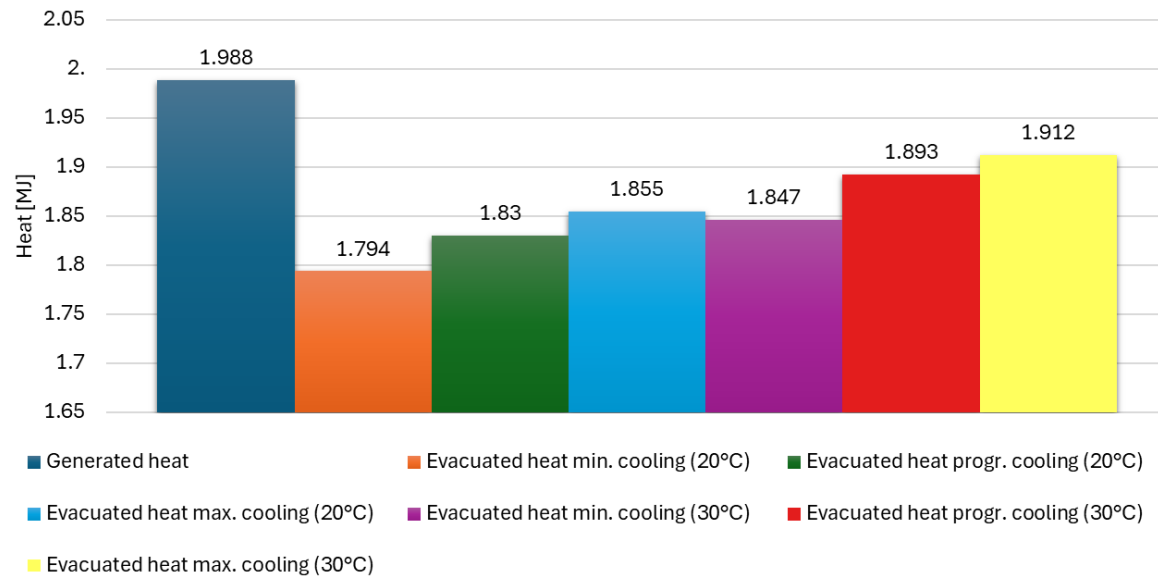
Stator temperature at 30°C ambient temperature, 20 kW power limit



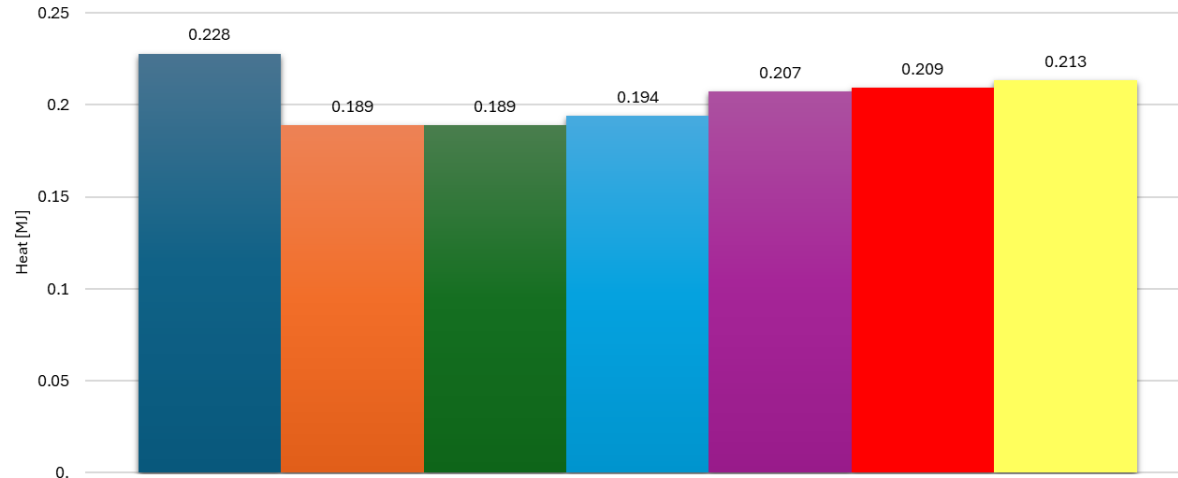
Inverter and battery cell temperature at 30°C ambient temperature, 20 kW power limit



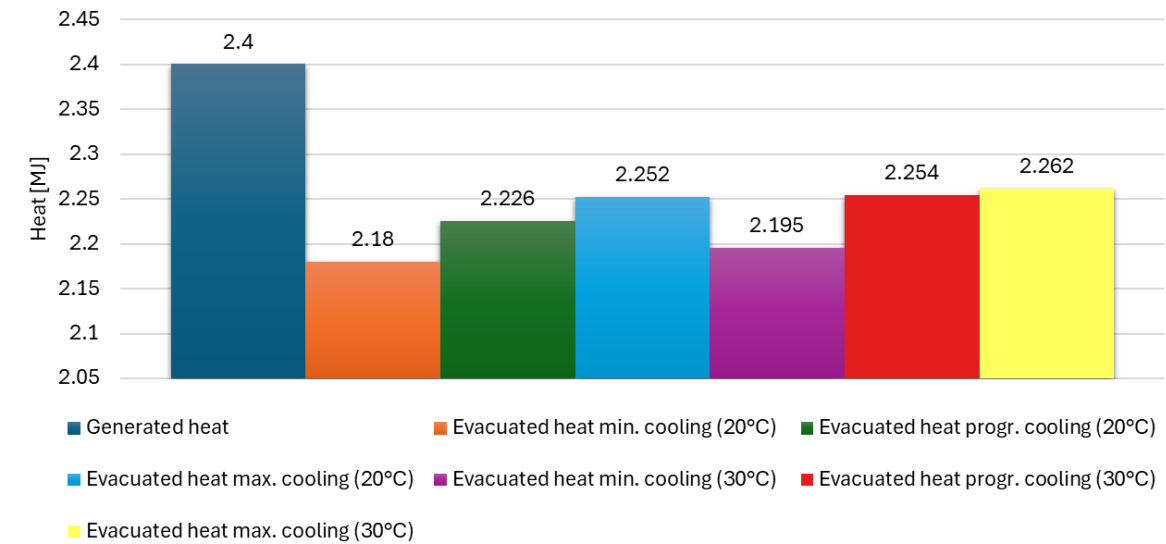
Motors at 20 kW power limit



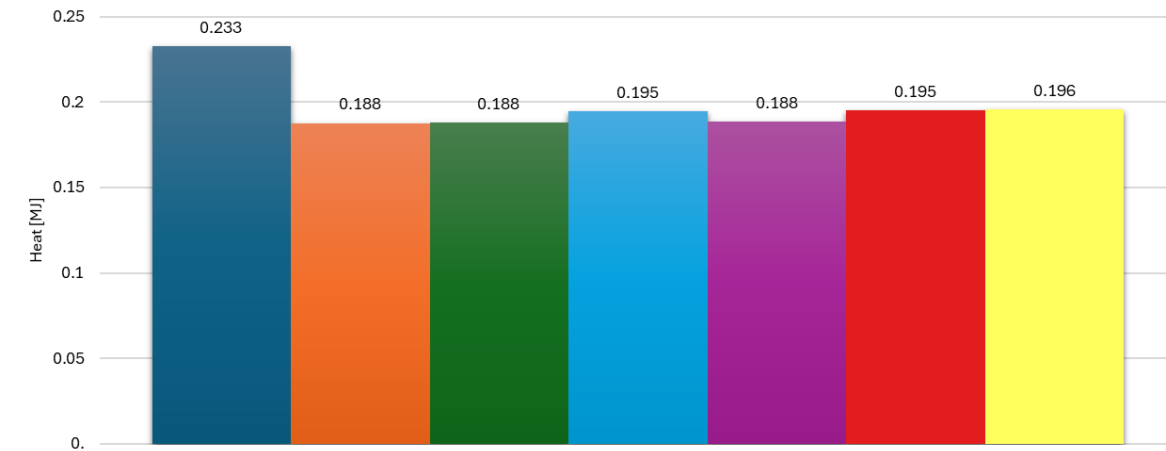
Inverters at 20 kW power limit



Motors at 10kW power limit



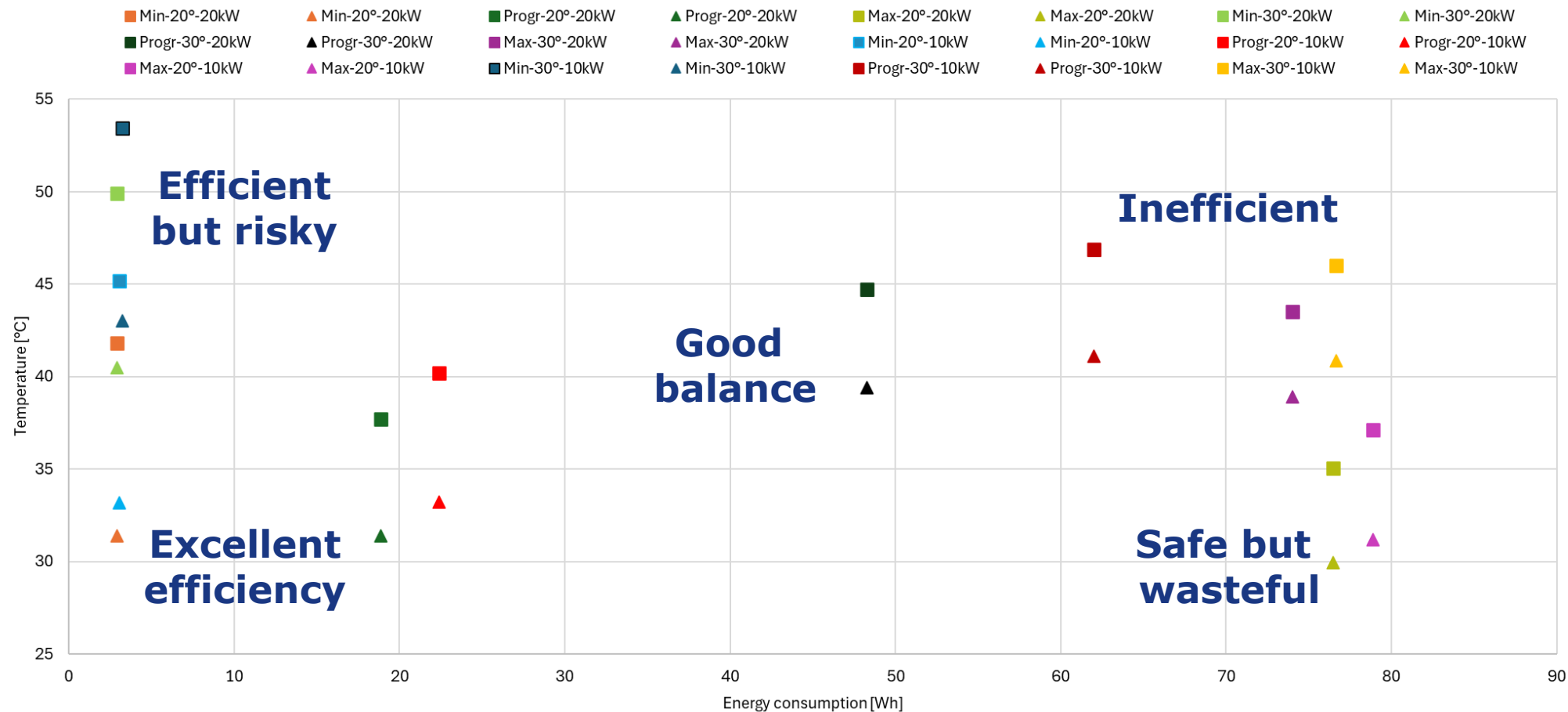
Inverters at 10kW power limit



8. CONTROL ALGORITHMS

Efficiency vs Safety trade-off map

Average motor $\square$ and inverter $\triangle$ temperatures



9. FUTURE DEVELOPMENTS

Additional tests and validations

- Data acquisition from the liquid cooling circuit through on-track testing
- Validation of additional components and maps
- Further experiments with the battery cells – forced convection situation
- Validation of the extended Simulink model - added heat transfer coefficient map in function of air flow rate
- Model the entire battery pack in the Kuli environment with added forced air convection
- Simulate test scenarios, with added control algorithm for the battery fans
 - ➡ balancing temperatures in the various components considering reliability, energy consumption and lap time

9. FUTURE DEVELOPMENTS

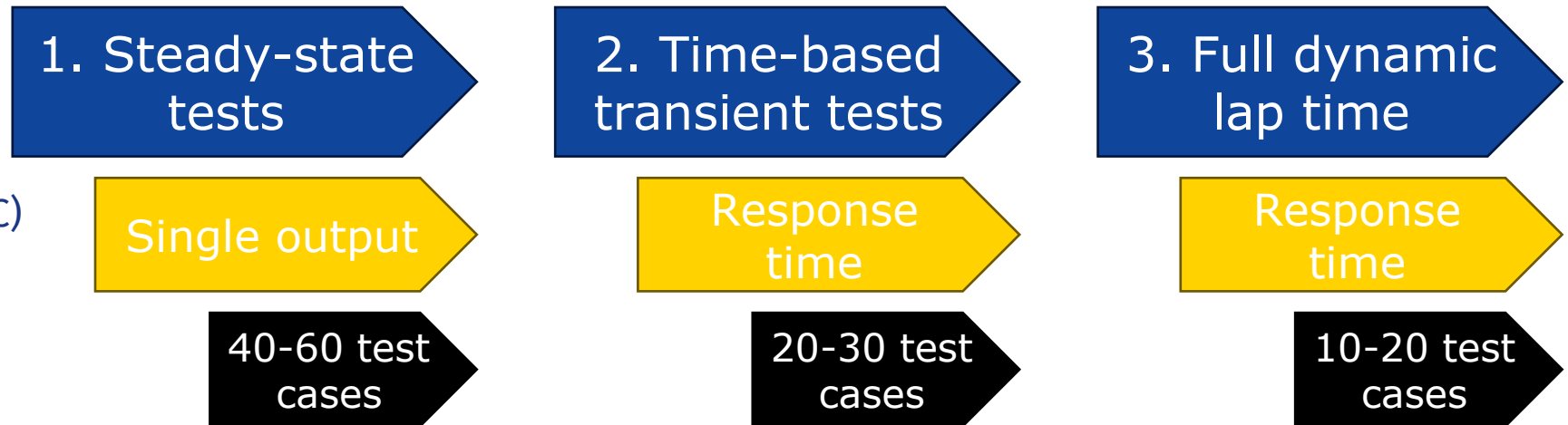
Create dataset for artificial intelligence models

Dataset variables:

- PWM voltage (0:5:100%)
- Radiator fan state (on/off)
- Speed (0:10:Vmax)
- Ambient temperature (10:5:40 °C)
- Power limit (5:5:30 kW)

Outputs:

- Motor temperature
- Controller temperature
- Battery cells' temperature
- System pressure
- Power consumption



9. FUTURE DEVELOPMENTS

Create dataset for artificial intelligence models

- Integrate AI techniques for:
 - Improving energy efficiency
 - Optimize how power is used (control of pump, fans) to balance speed and thermal management
- Improving lap time – AI-assisted driving strategy (real-time dashboard) that suggest real-time adjustments to the driver based on:
 - Track sector analysis: where high loads can cause overheating
 - System temp trends: predict future overheating risks based on: current SoC, sector speed, power demand, cooling performance

=> recommendations: Push hard in Sector 2 – system cool enough to increase power;

Reduce acceleration in sector 3 – avoid overheating before next high-load section



THANK YOU FOR YOUR ATTENTION!

Thomas Imre Cyrille Buidin

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