Modelling a Low Temperature PEM Fuel Cell in KULI

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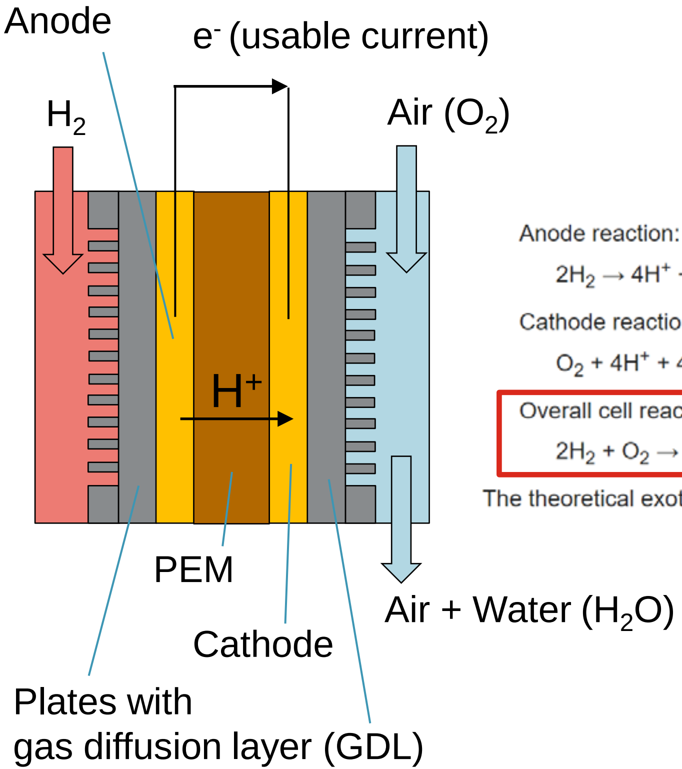
Introduction – Fuel Cell Basics

PEM Fuel Cell Basics



Anode reaction:

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Cathode reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

Overall cell reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat} + \text{electrical energy}$$

The theoretical exothermic potential is +1.23 V overall.

Source: Wikipedia

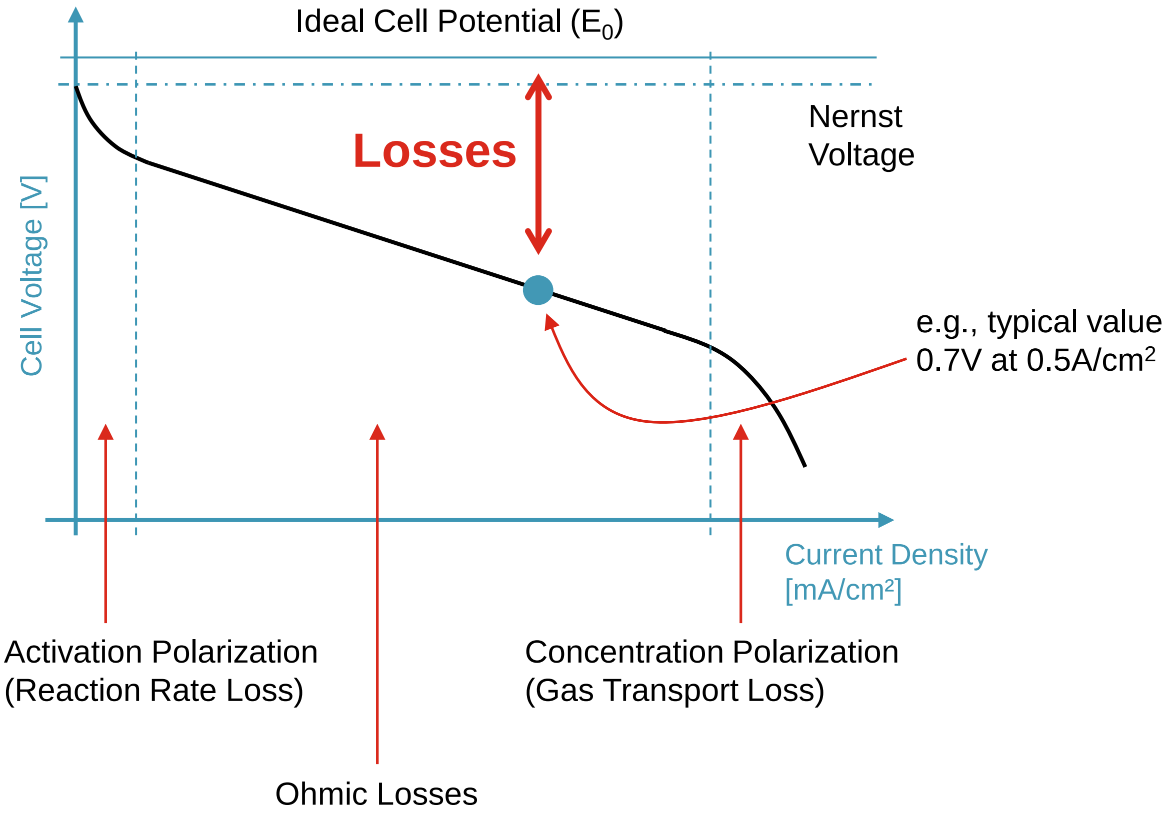
A PEM fuel cell…

… consumes **H_2** (from a tank)
… and **O_2** (from the air)
… and generates **electric energy**
… and **waste heat**

The performance is (mainly) influenced by

- **H_2 supply**
- **O_2 supply**
- Power draw (**current**)
- Cell **temperature**
- **Membrane humidity**

Usable Power, Stack Size, Losses…



A simplified calculation leads to an „order of magnitude“ estimation…

- 50A require 100cm²

70V require a stack of 100cells

3.5kW electric power

- Losses:
(1.23V - 0.7V) * 100 * 50A

2.65kW losses

Example: Toyota Mirai Gen 1 (data and pic from Wikipedia)

Fuel cell volume: ~36.8l
Fuel cell power: 114kW

370 cells stacked (e.g. ~260V @ 0.7V per cell)

➡ ~400A needed for rated power

Each cell has a thickness of 1.34mm

➡ Stack height ~0.5m

Cell area ~750cm² ➡ ~0.53A/cm²

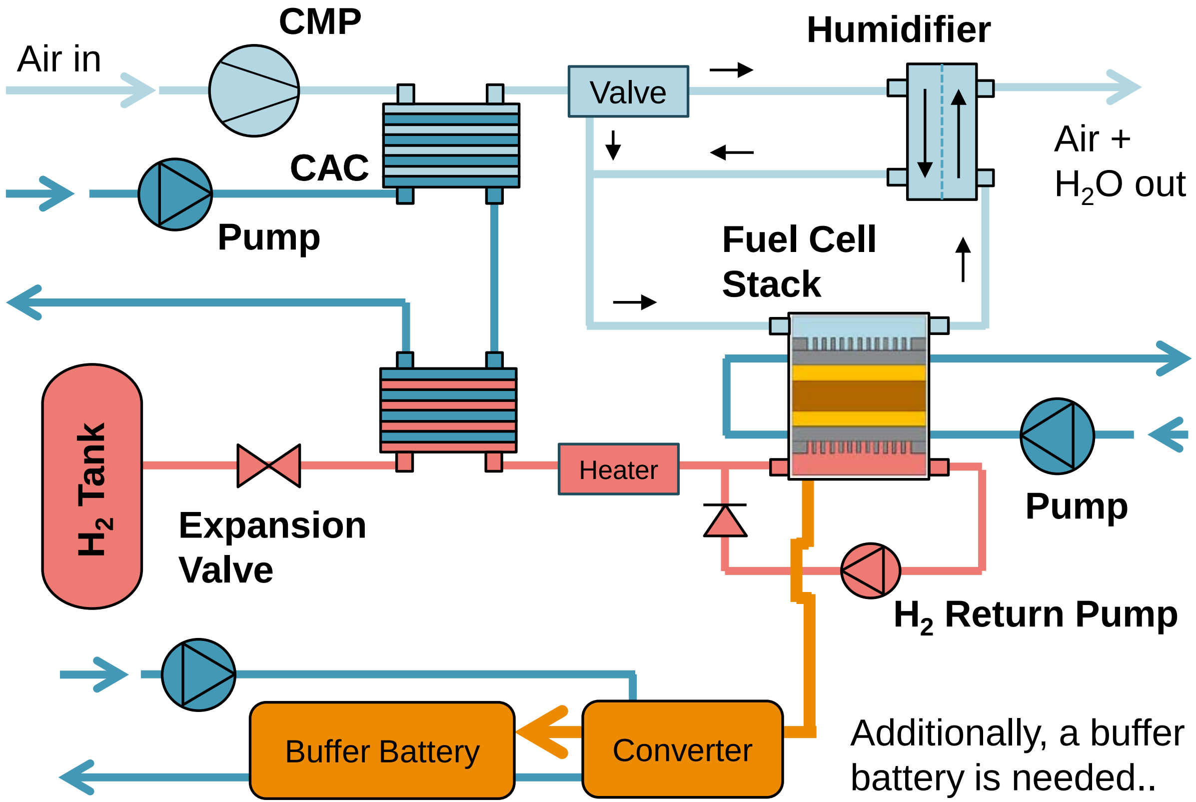
Picture source: Wikipedia.com

See operating point from previous slide (0.7V at 0.5A/cm²)

Battery: 245V, 1.6kWh capacity (NiMH)

Motor: 113kW

A typical architecture for a PEM fuel cell system (VTM-relevant components only)



Additionally, a buffer battery is needed..

- FC Anode needs to be supplied with H2 from tank
- Tank pressure (e.g. 700bar) needs to be reduced to ~7bar
- Expansion cools down the gas, so it needs to be heated
- Either electrically or by HX
- Unused H_2 needs to be re-circulated
- FC Anode needs O_2 (from air)
- To provide sufficient O_2, the air must be compressed
- Warm-up from compression requires charge air cooling
- To keep the membrane humid, H_2O from waste-air is returned to the suction air
- Waste heat is removed to the cooling system…

Thermal Model of the Fuel Cell

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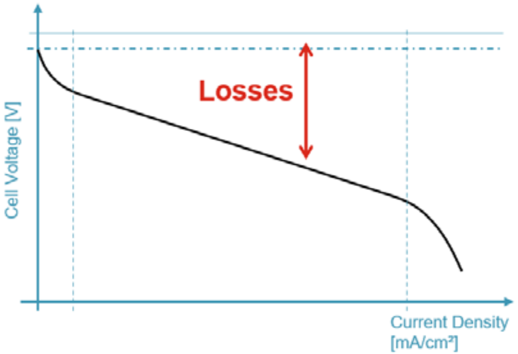


Based on voltage vs. current correlation and the cell operating point, the **losses** can be calculated.

The voltage vs. current correlation will depend on the **cell temperature** and **humidity** (→membrane resistance) and on supplied **H_2** and **O_2**.

Cell temperature is evaluated from the energy balance considering

- **Cell losses,**
- Heat from air supply (**O_2**),
- Heat/cold from **H_2** supply and
- **Heat rejected to the cooling system**

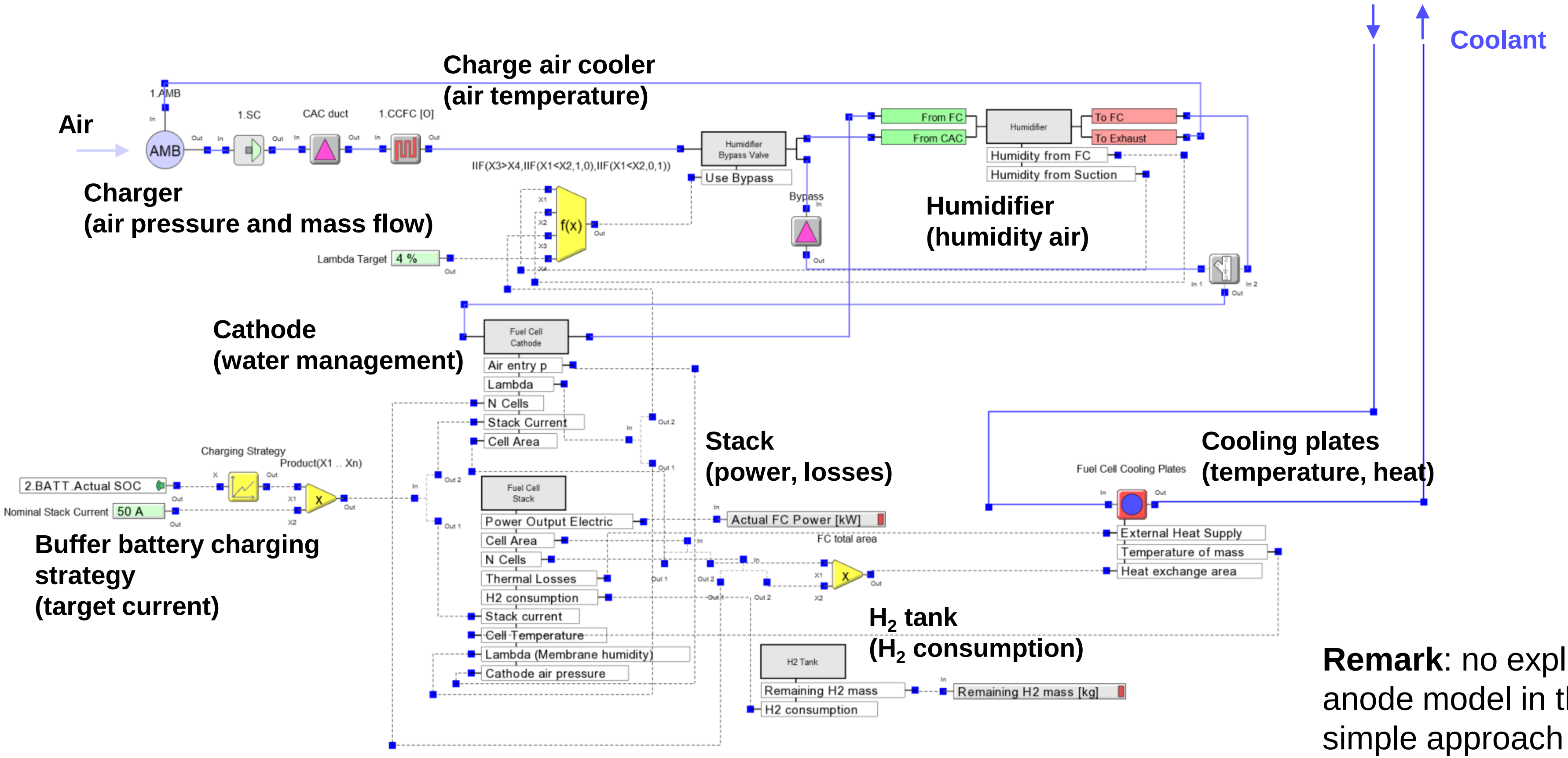
Humidity will be calculated from

- H_2O generated from the fuel cell reaction
- H_2O being stored in the membrane and
- **H_2O gathered from or dissipated to the air supply (evaporation…)**

The cell interacts with the rest of the system via heat and H_2O rejection

Modelling Fuel Cells in KULI

KULI Simulation Model (principal parts)



Remark: no explicit anode model in this simple approach

Focus on the Stack…

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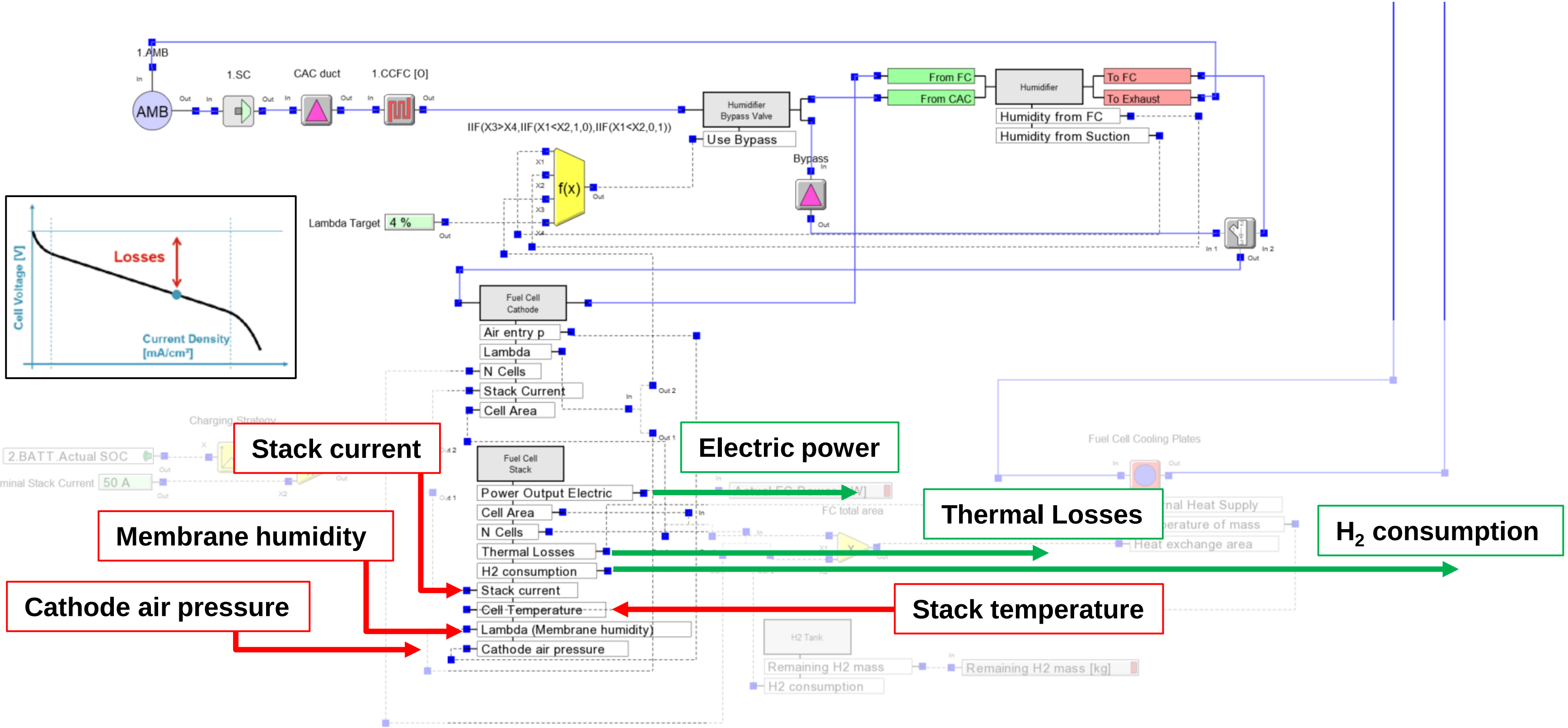


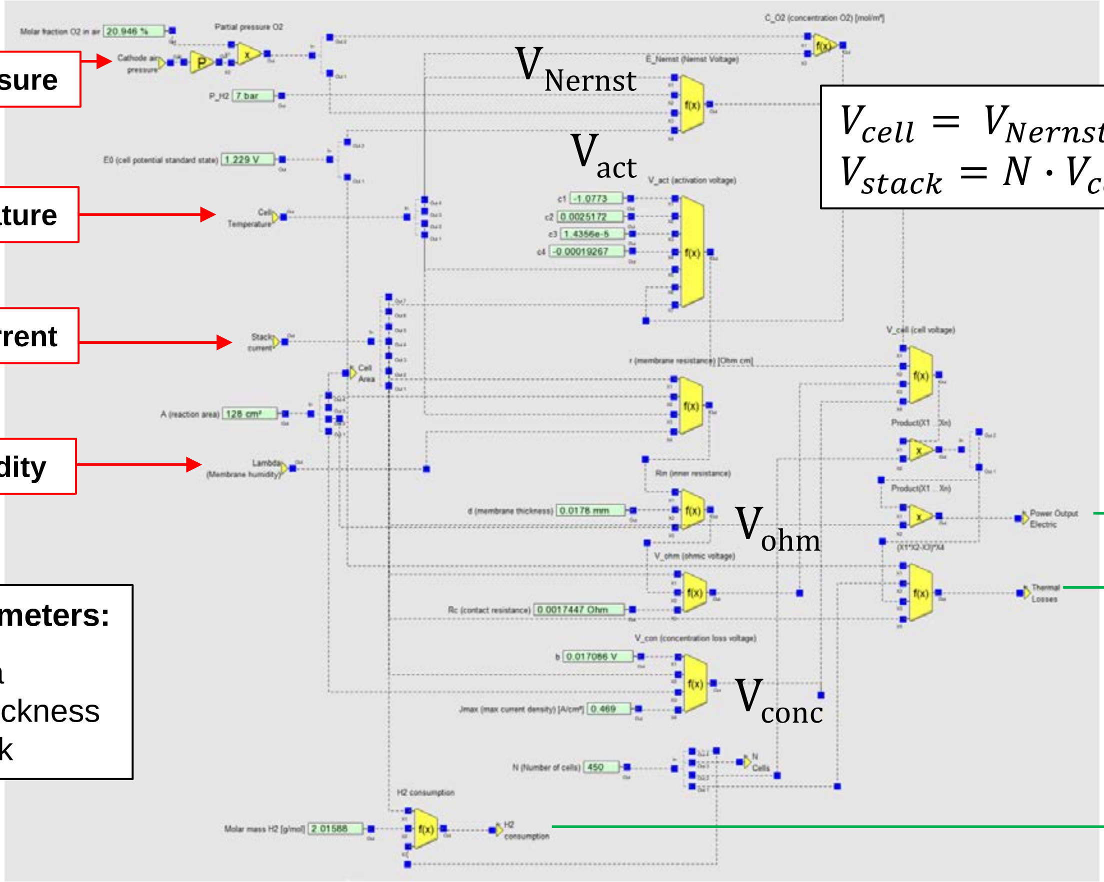
An Even Closer Look at the Stack

Cathode air pressure

Stack temperature

Stack current

Membrane humidity



$$V_{cell} = V_{Nernst} - V_{act} - V_{Ohm} - V_{conc}$$
$$V_{stack} = N \cdot V_{cell}$$

Electric power

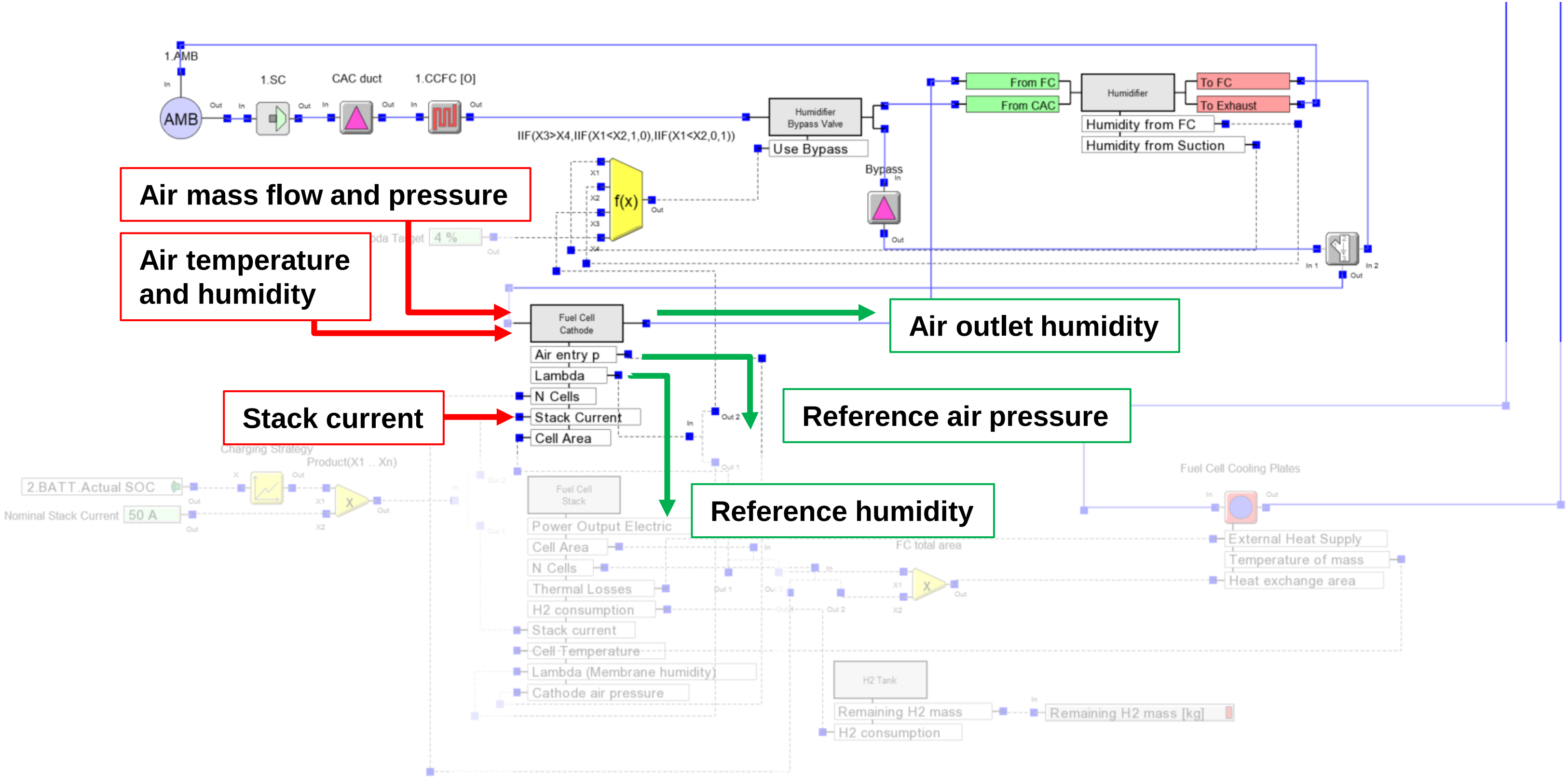
Thermal Losses

H_2 consumption

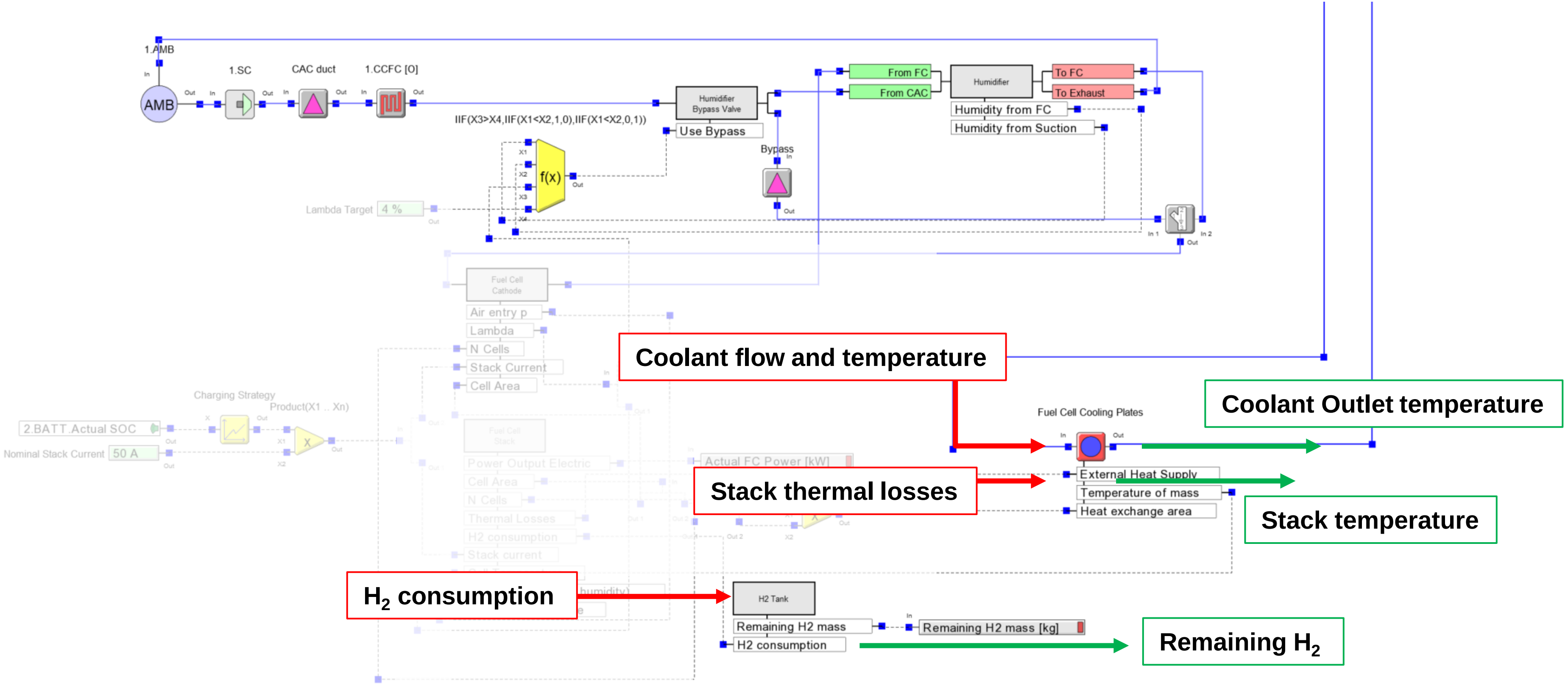
Important Parameters:

- Reaction area
- Membrane thickness
- # cells in stack

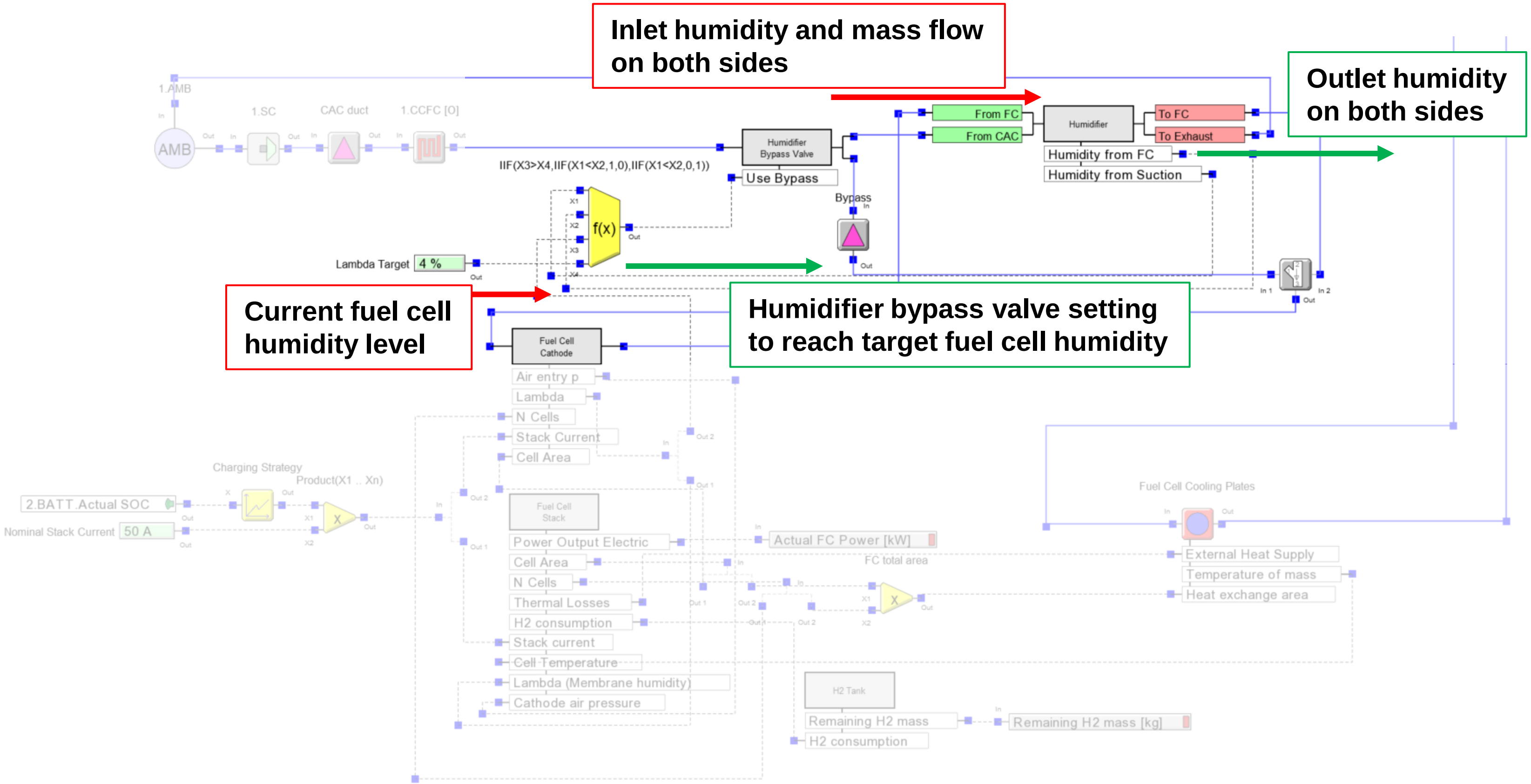
Focus on the Cathode…



Focus on Cooling Plates and H_2 Tank



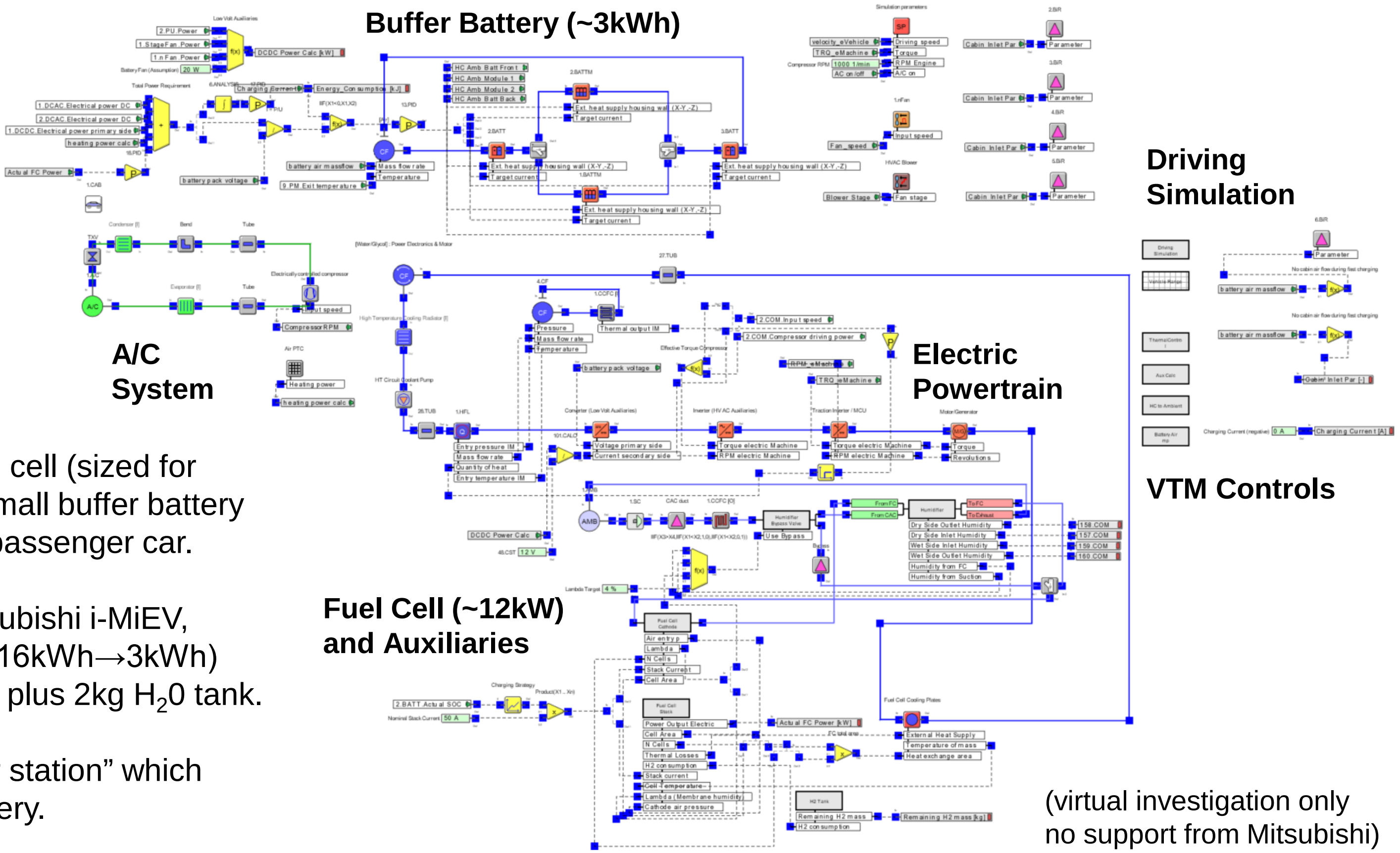
Focus on the Humidifier



Virtual Vehicle Integration

Virtual Integration of a Fuel Cell
From i-MiEV to Hy-MiEV

Mitsubishi i-MiEV



Task:

Virtually integrate a small fuel cell (sized for average cycle loads) and a small buffer battery (for peak loads) into a small passenger car.

Our base model was the Mitsubishi i-MiEV, we reduced the battery size (16kWh→3kWh) and installed a 12kW fuel cell plus 2kg H_20 tank.

The fuel cell acts as a “power station” which constantly recharges the battery.

(virtual investigation only no support from Mitsubishi)

Further Changes to VTM System

- **Twice (!) the radiator size** needed for cooling fuel cell + powertrain (an alternative would have been a separate FC cooling loop)

- **Stronger coolant pump** needed to provide higher flow-rates (can require bypasses/branches, if maximum coolant flow rates for other powertrain components are exceeded, not considered here)

- **Battery cooling concept** (air-cooled battery in vehicle underbody) should be adapted (e.g. compact coolant-cooled battery pack) for a more detailed analysis… but this has been neglected in this model.

Simulated Boundary Conditions

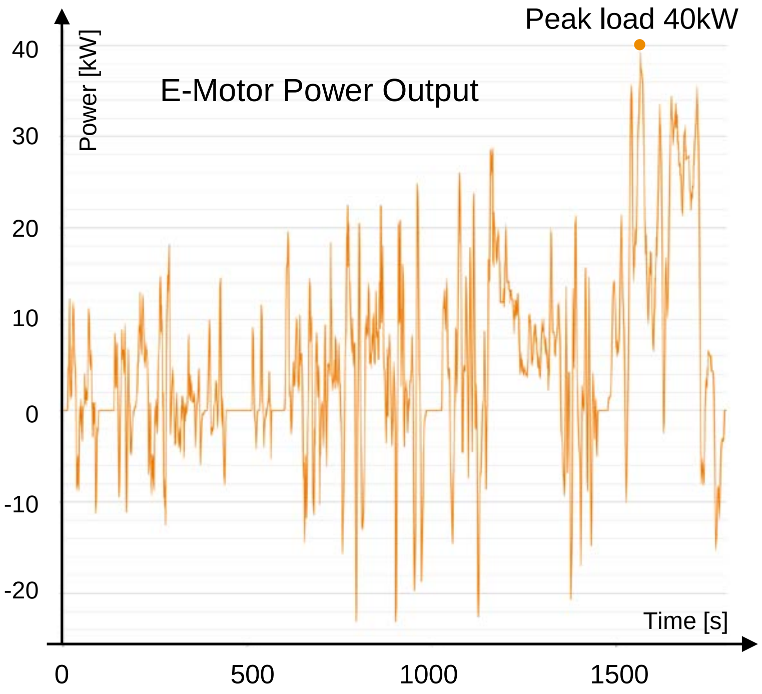
Drive Cycle:

WLTC Class 3 → Quite ambitious for this car (fast accelrations, top speed > 120kph)
Should push the vehicle close to the limit…

45kW Motor
(Mitsubishi i-MiEV)

Driving Simulation

Cycle ok for this motor…



Ambient Conditions:

21degC, 40% humidity, 1013hPa
Solar Intensity 900W/m², 85% cabin recirc.

Electric Energy Balance

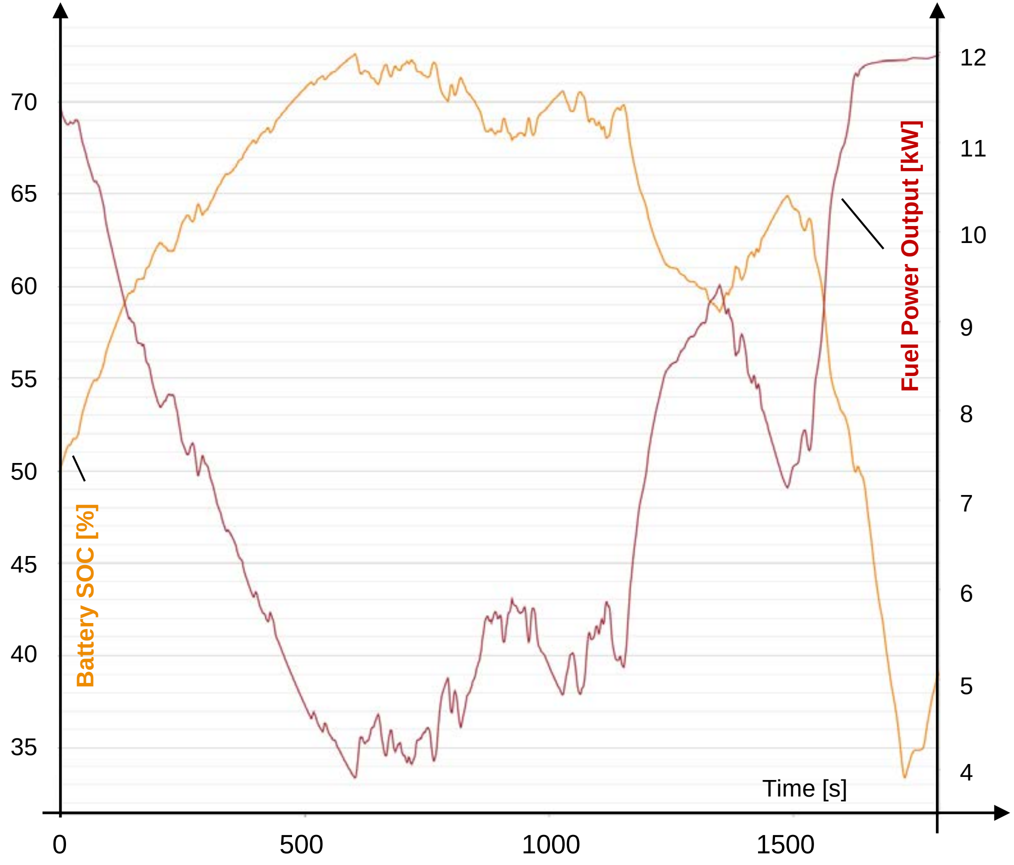
Very simple fuel cell operation strategy implemented:

- No battery charging above 80% SOC
- Full FC power below 50% battery SOC
- Linear scaling of FC output in between (based on battery SOC)

Results:

- Initial battery SOC of 50% leads to 40% SOC after the WLTC
- Can be higher, if FC power is not scaled down during high SOC phase (first 1400s)

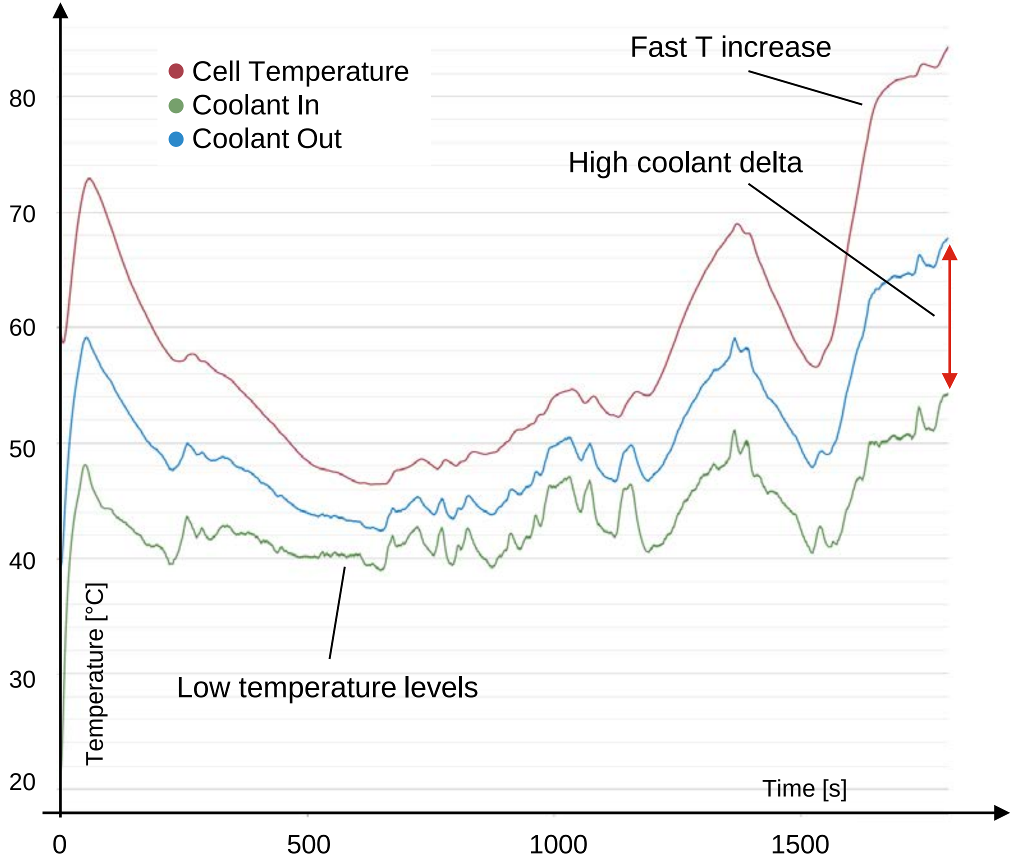
- **FC is strong enough to operate this vehicle.**
- **Battery sizing OK.**



Fuel Cell Temperature Levels

Results:

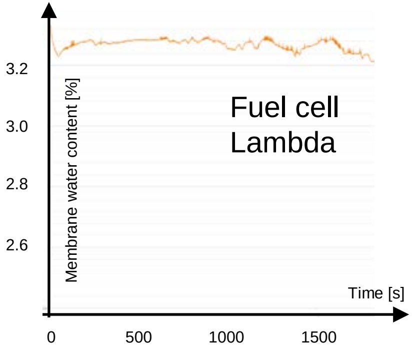
- Temperature levels during peak power increase sharply and could become a problem for sustained high loads.
- During the simulated cycle temperature levels are ok, even a little bit low (could be solved with a more refined VTM control strategy)
- Coolant temperature delta over fuel cell exceeds 10K in peak load… coolant mass flow rate should not be lower
- **FC is strong enough to operate this vehicle.**
- **Battery sizing OK.**

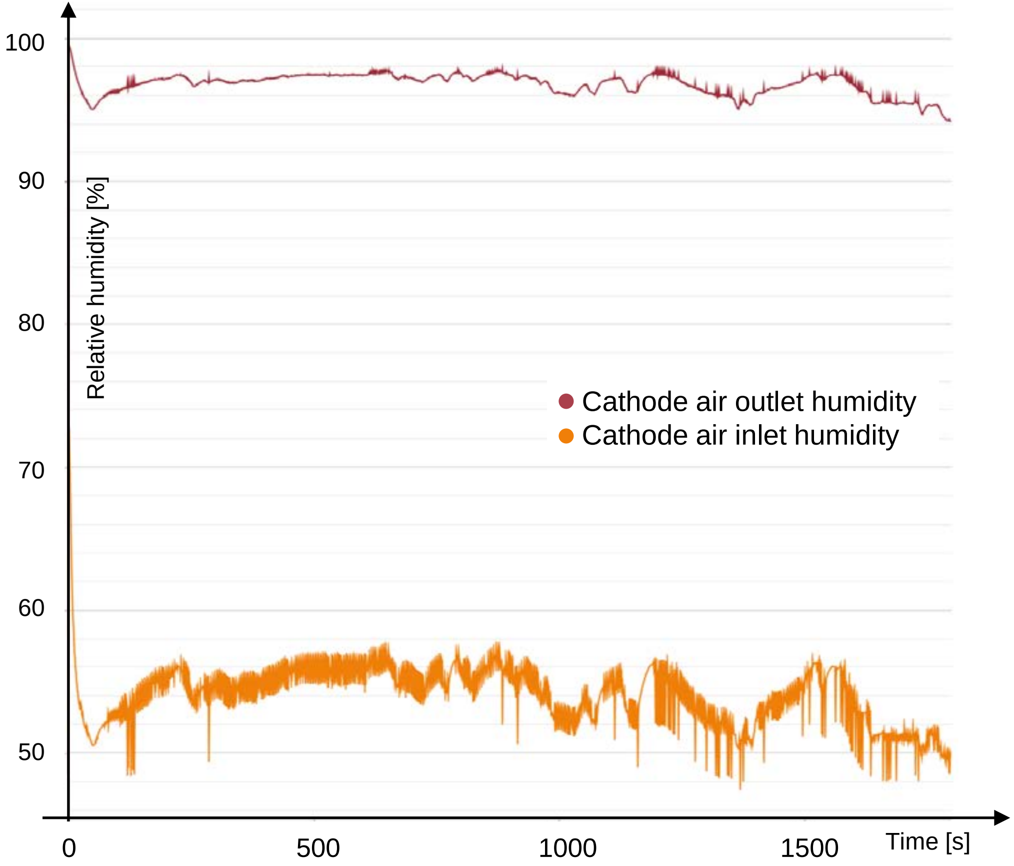


Fuel Cell Humidity

Results:

- Even though the humidifier is constantly active (bypass not used), a lot of H_2O is rejected to the air flow.
- A reasonable humidification of the fuel cell membrane can be ensured (lambda ~3.3% is a reasonable value)
- Higher lambda could be achieved by additional humidification of the H2 side (currently not implemented)

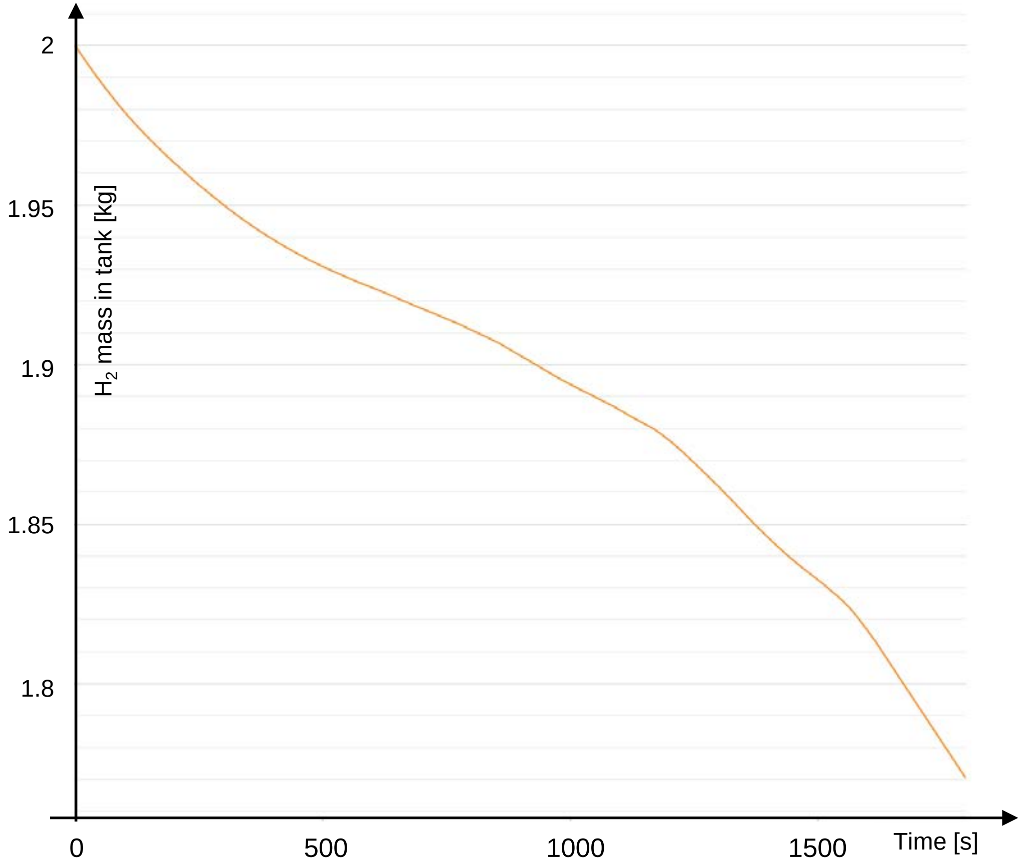




H2 consumption and range

Results:

- For the complete WLTC cycle, a total amount of 0.229kg of H_2 are consumed.
- Considering the driving distance of the cycle (23.25km), this yields a total range of ~203km.
- This value fits well to the “rule of thumb” range of 100km per kg H_2.



Summary

Summary

- We have shown
  - How a PEM fuel cell generally works and what infrastructure is needed in a car to operate it
  - Which aspects of a fuel cell are relevant from a thermal management point of view and how to model them in KULI
  - How a PEM fuel cell can be integrated into an overall vehicle model… and which results can be derived.
- KULI supports the modelling of fuel cells… and especially in combination with it´s system simulation capabilities this can provide valuable insights.
- **We invite you to discover the possibilities together with us!**

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INSPIRING **INNOVATION.**