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Modelling and simulation of the Stralis Bonanza A36-HE hydrogen-electric aircraft

emission free aircraft

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Bonanza A36-HE
technology demonstrator

Bonanza A36-HE

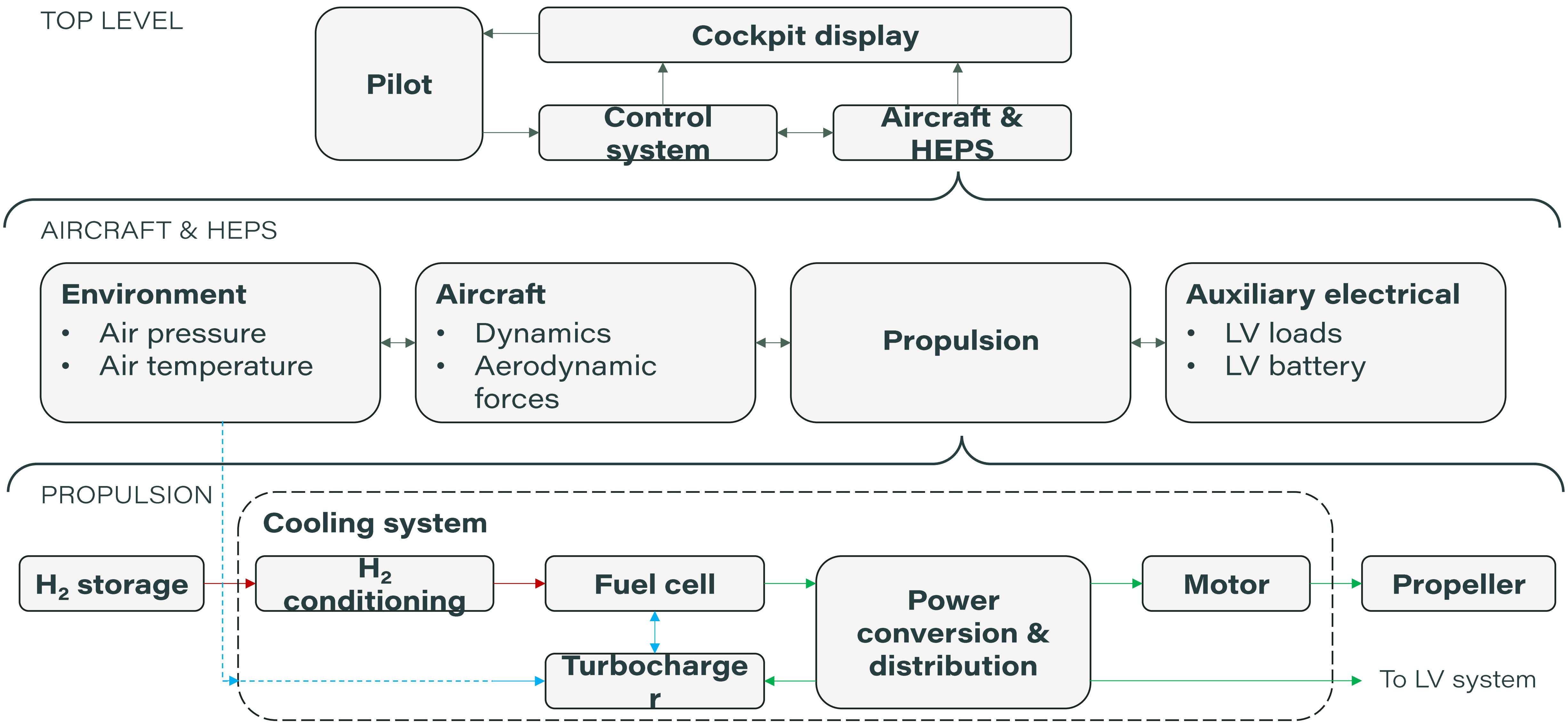
- Beechcraft Bonanza A36 retrofitted with Stralis hydrogen-electric propulsion system
- 26 kg LH_2 carried in wing-tip tanks
- 180 kW electric motor with integrated drive
- 2x 110 kW HT-PEM fuel cells
- 10,000 ft operating altitude
- 156 kt cruise speed
- 500 km range

Flying test bed "Bonnie"

Iron-bird "Clyde"

Modelling the Bonanza A36-HE

System architecture



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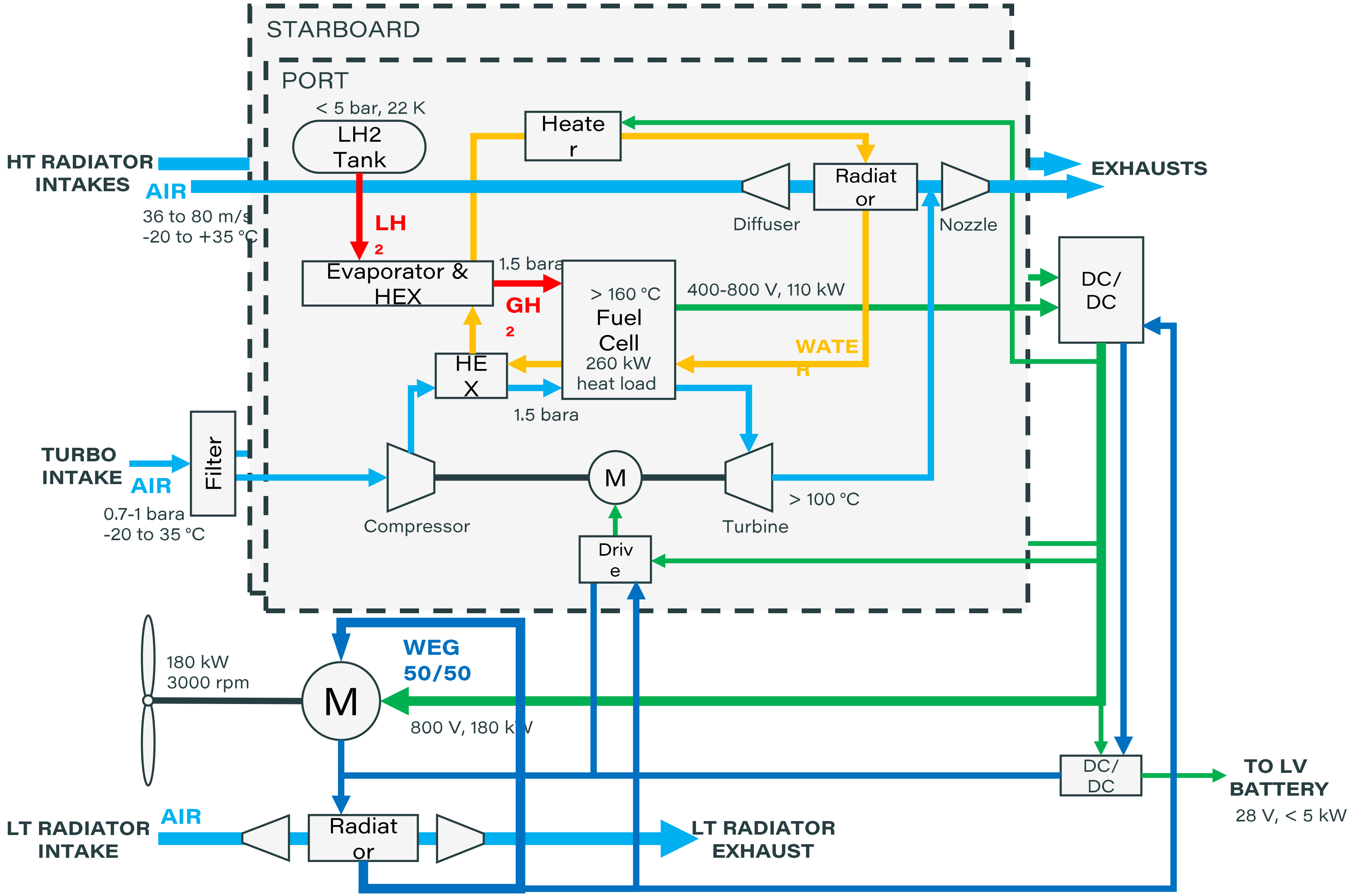
Propulsion system overview



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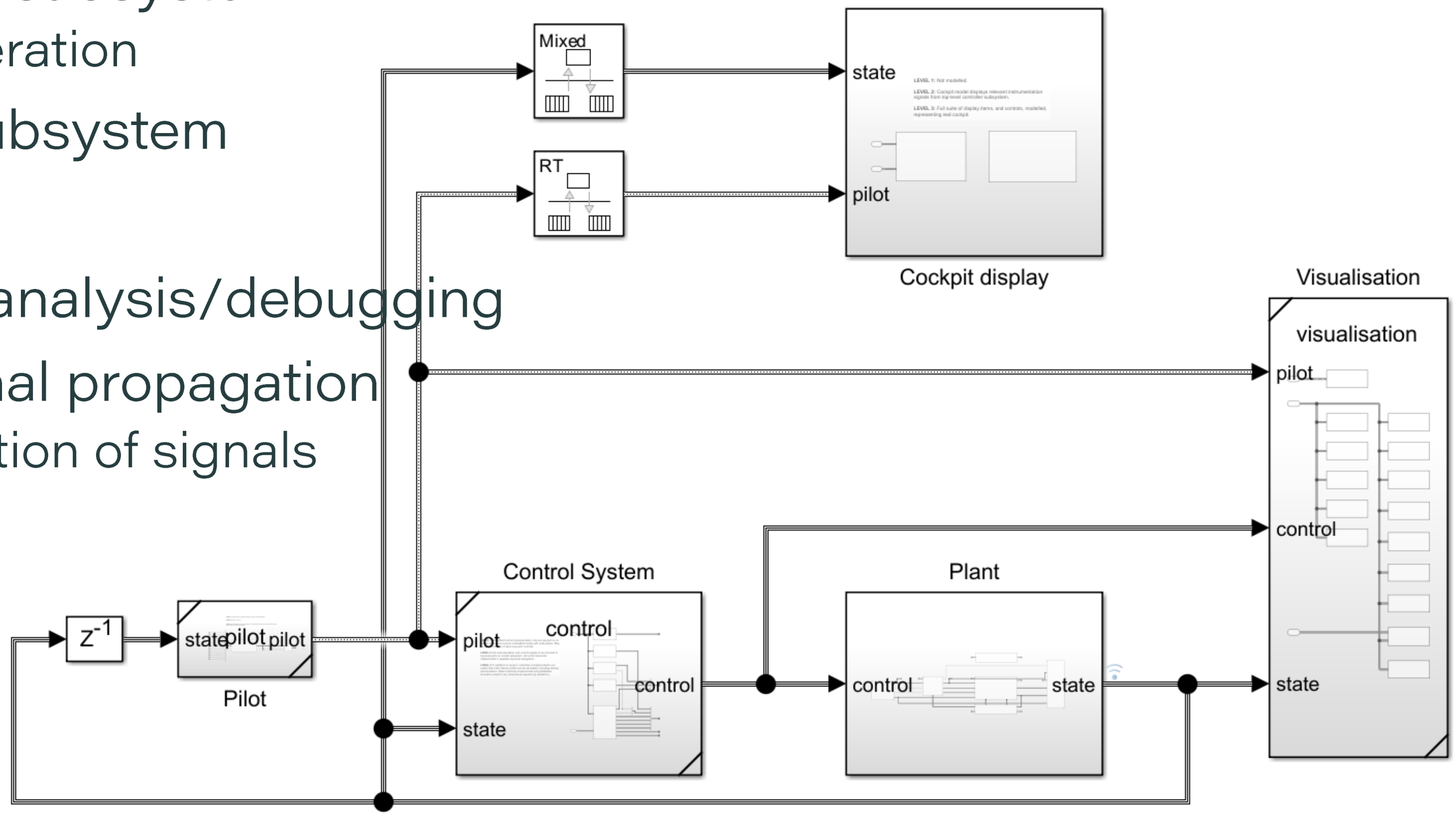
Modelling approach

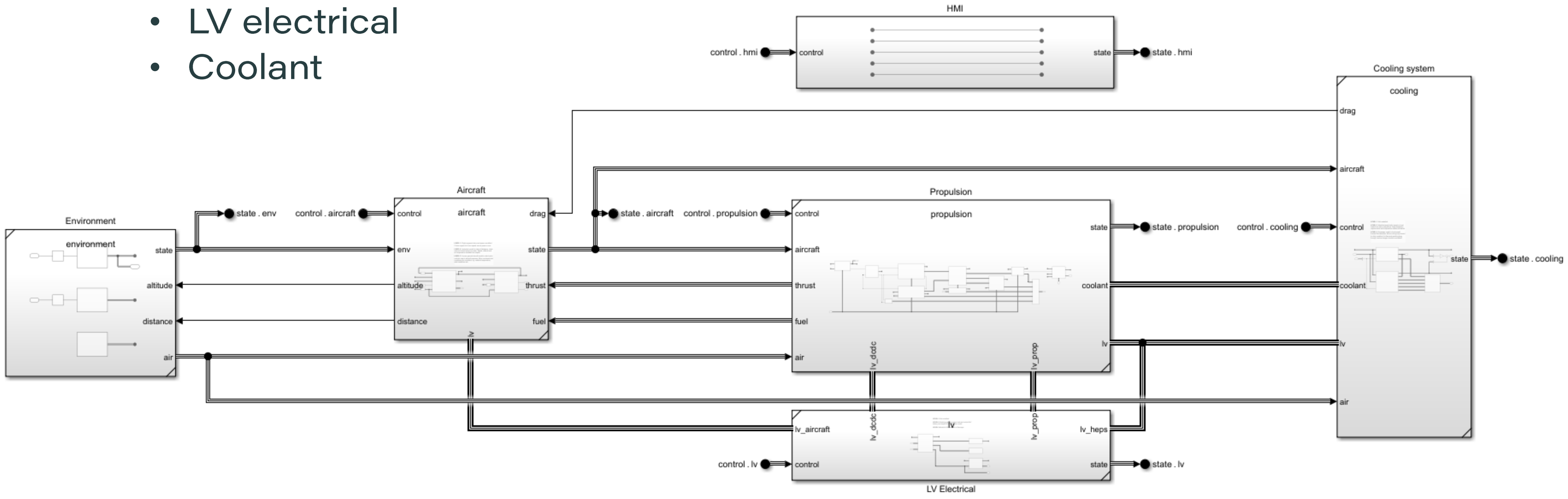
- Simulink time-domain model
- Ultimately suitable for real-time simulation
  - Fixed time step
  - Only components that support code generation
- Incremental approach
  - Subset of systems initially; systems added over time
  - Analytical models transitioned to physical Simscape networks
- Modelled based on public domain component data
  - Individual components and systems validated using test benches
  - Overall model validated using aircraft mission profile

Top-level model structure

- Plant takes control action as input and produces state signals as output
- Control in separate top-level subsystem
  - Facilitates future code generation
- Pilot modelled in separate subsystem
- Cockpit visualization
- Visualisation subsystem for analysis/debugging
- Simulink buses used for signal propagation
  - Rapid prototyping and addition of signals



- Simscape busses used to collect physical networks into single ports
  - LV electrical
  - Coolant



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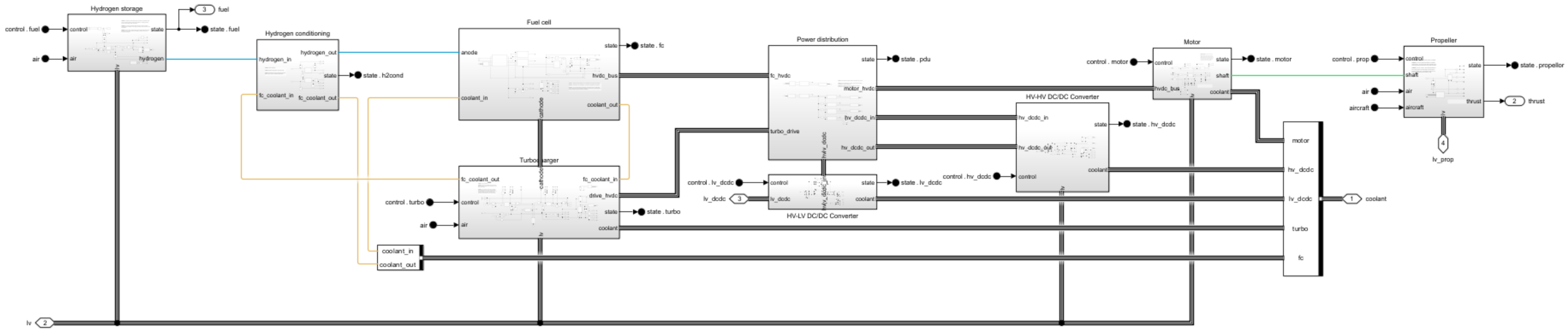
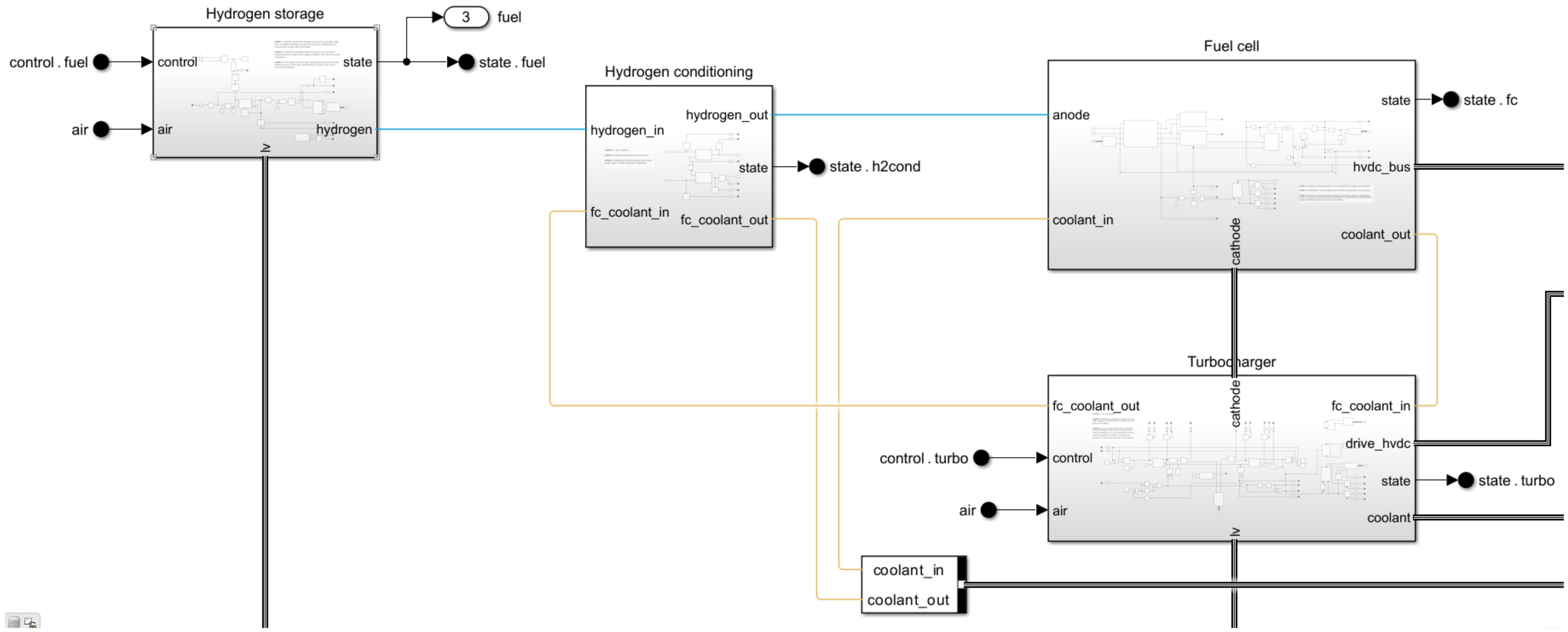
Propulsion system model



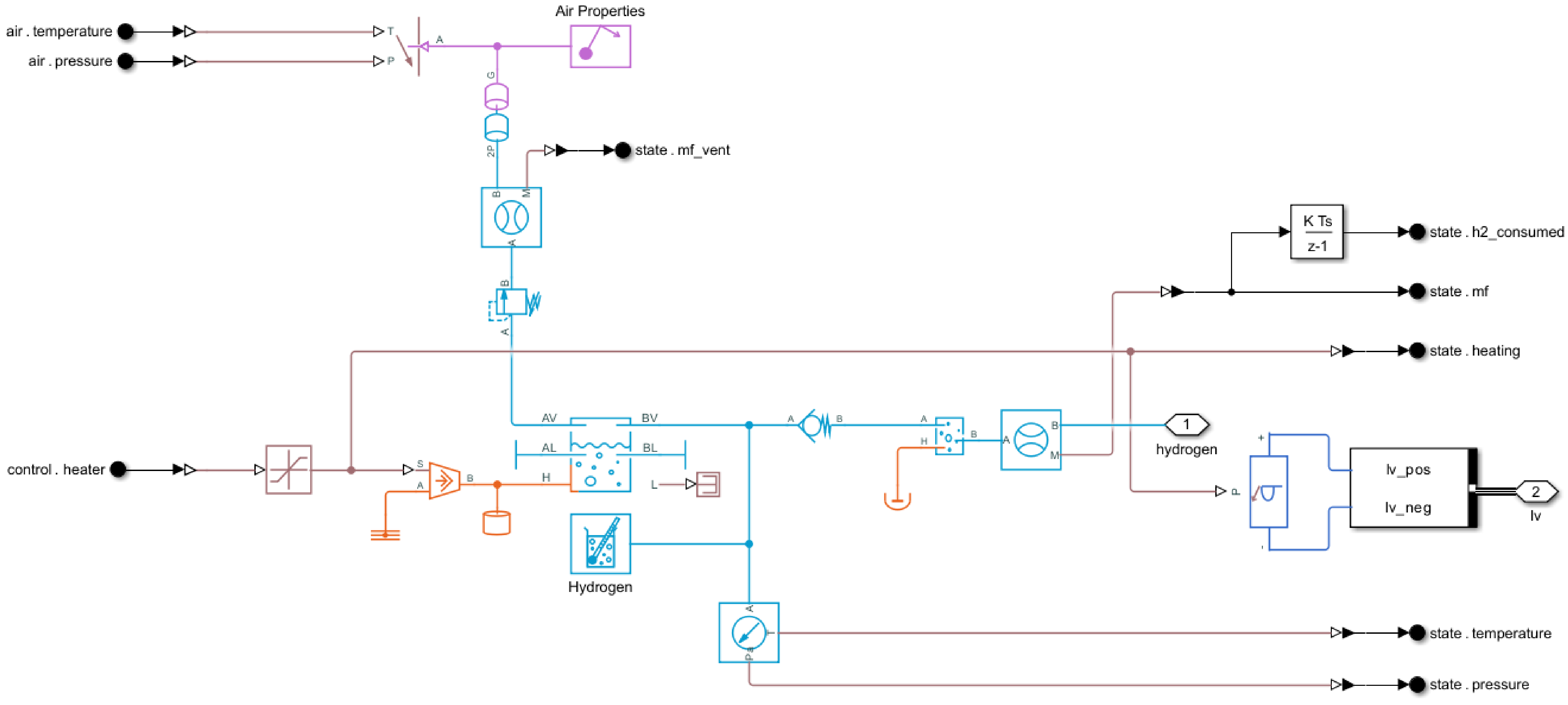
Single coupled Simscape physical network, 10 ms simulation timestep

- Hydrogen: Two-phase fluid network (hydrogen)
- Electrical: HV (800 V), LV (28 V)
- Cathode air supply: Gas (air) and moist air (nitrogen, oxygen, water vapor) fluid networks
- High-temperature cooling: Thermal liquid (water)
- Low-temperature cooling: Thermal liquid (water/ethylene glycol)
- Air cooling: Gas (air)
- Motor & propeller: Mechanical

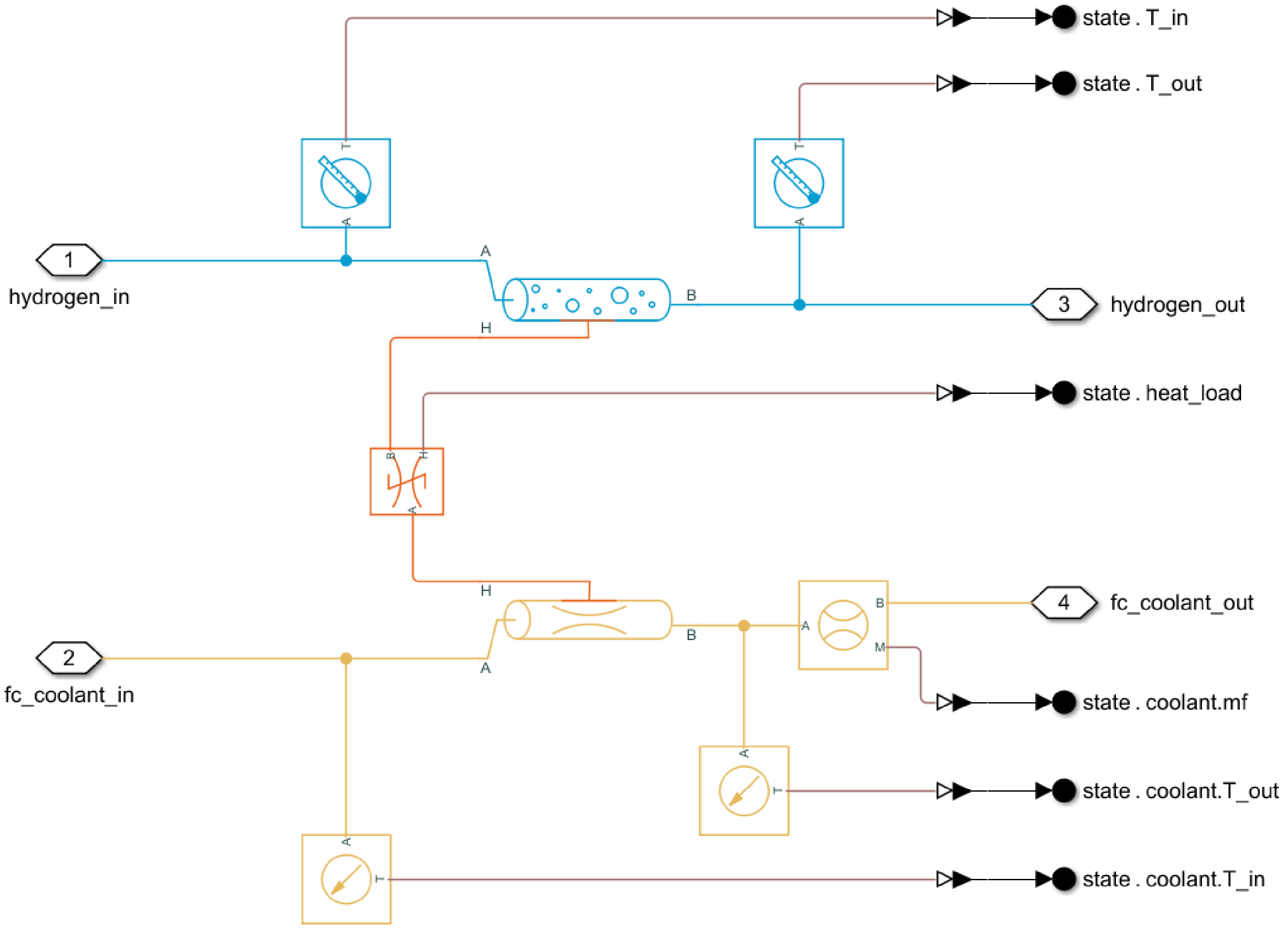
Hydrogen and fuel cell systems



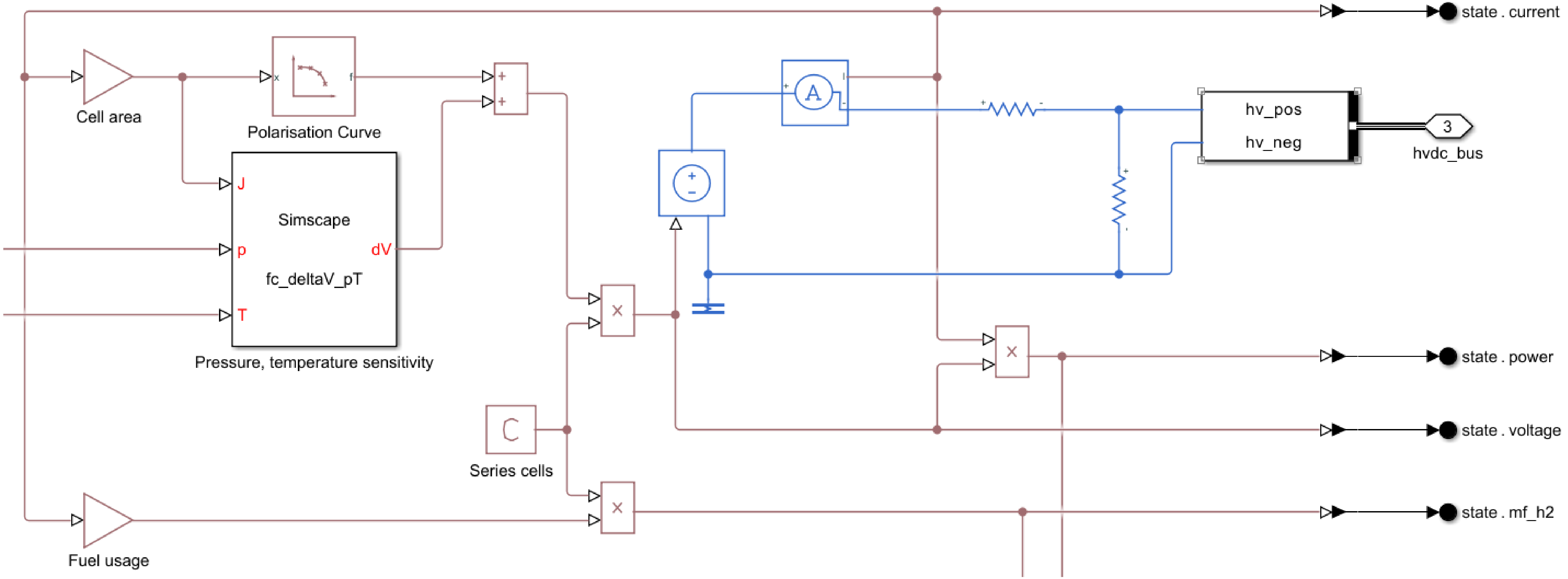
Hydrogen storage



Hydrogen conditioning



Fuel cell: Electrical

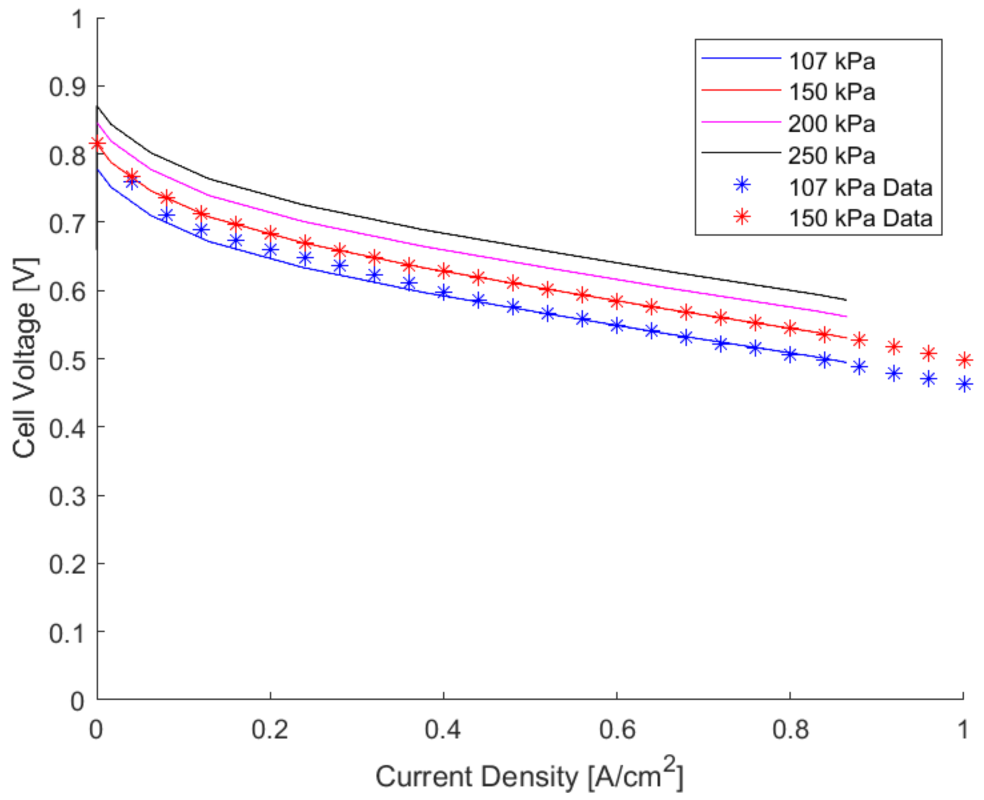


$$\Delta V_T = (c_T + a_T \cdot J^{b_T})(T - T_{\mathrm{ref}})$$

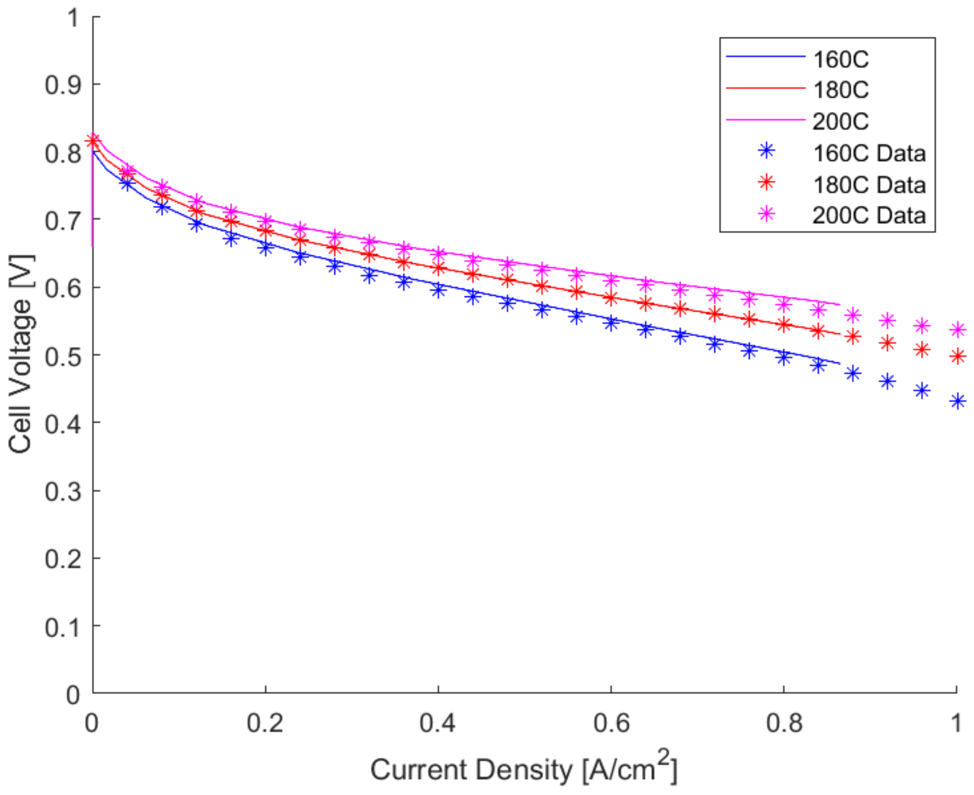
$$\Delta V_p = (c_p + a_p \cdot J^{b_p}) \ln \frac{p}{p_{\mathrm{ref}}}$$

Fuel cell: pressure & temperature

Pressure

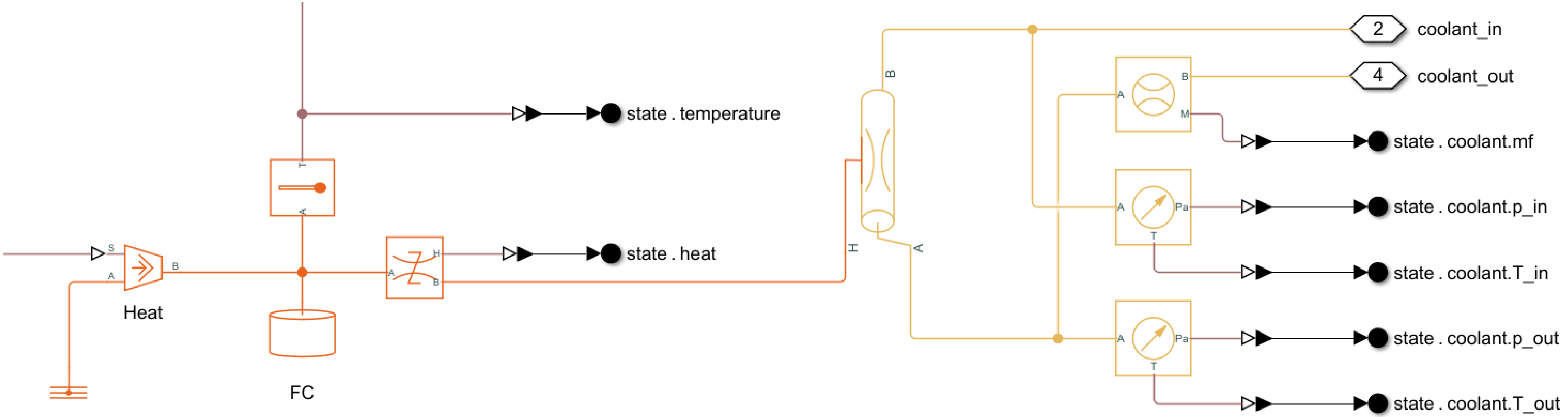


Temperature

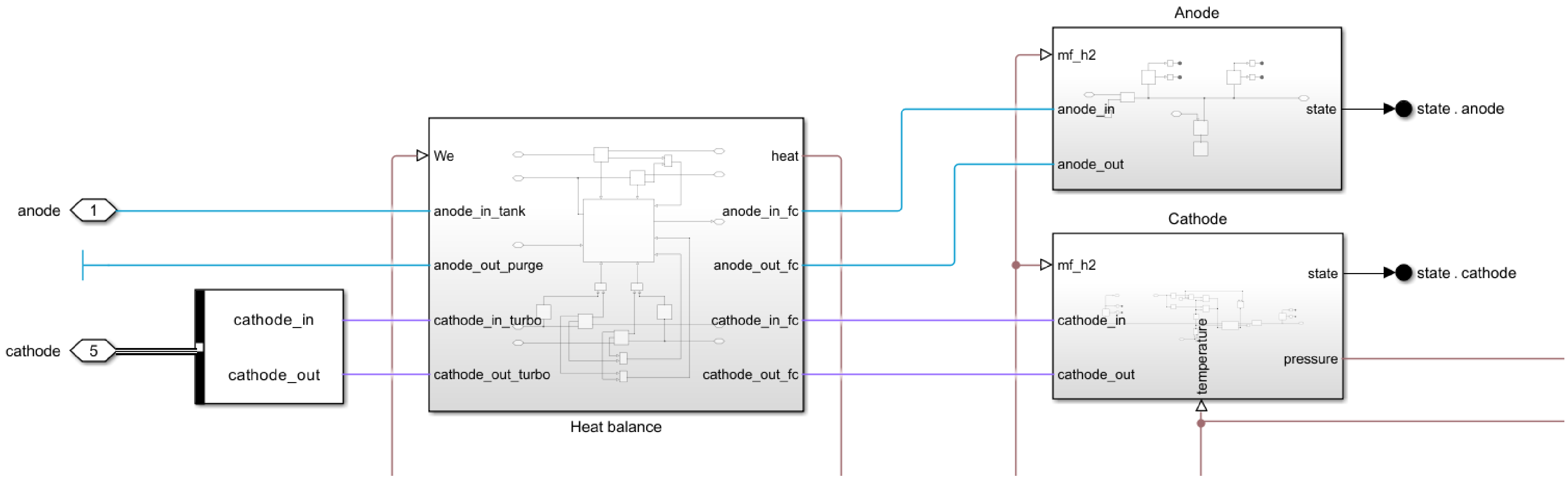


https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review20/fc320_hibbs_2020_o.pdf
https://data.epo.org/publication-server/rest/v1.0/publication-dates/20220928/patents/EP4064397NWA1/docu

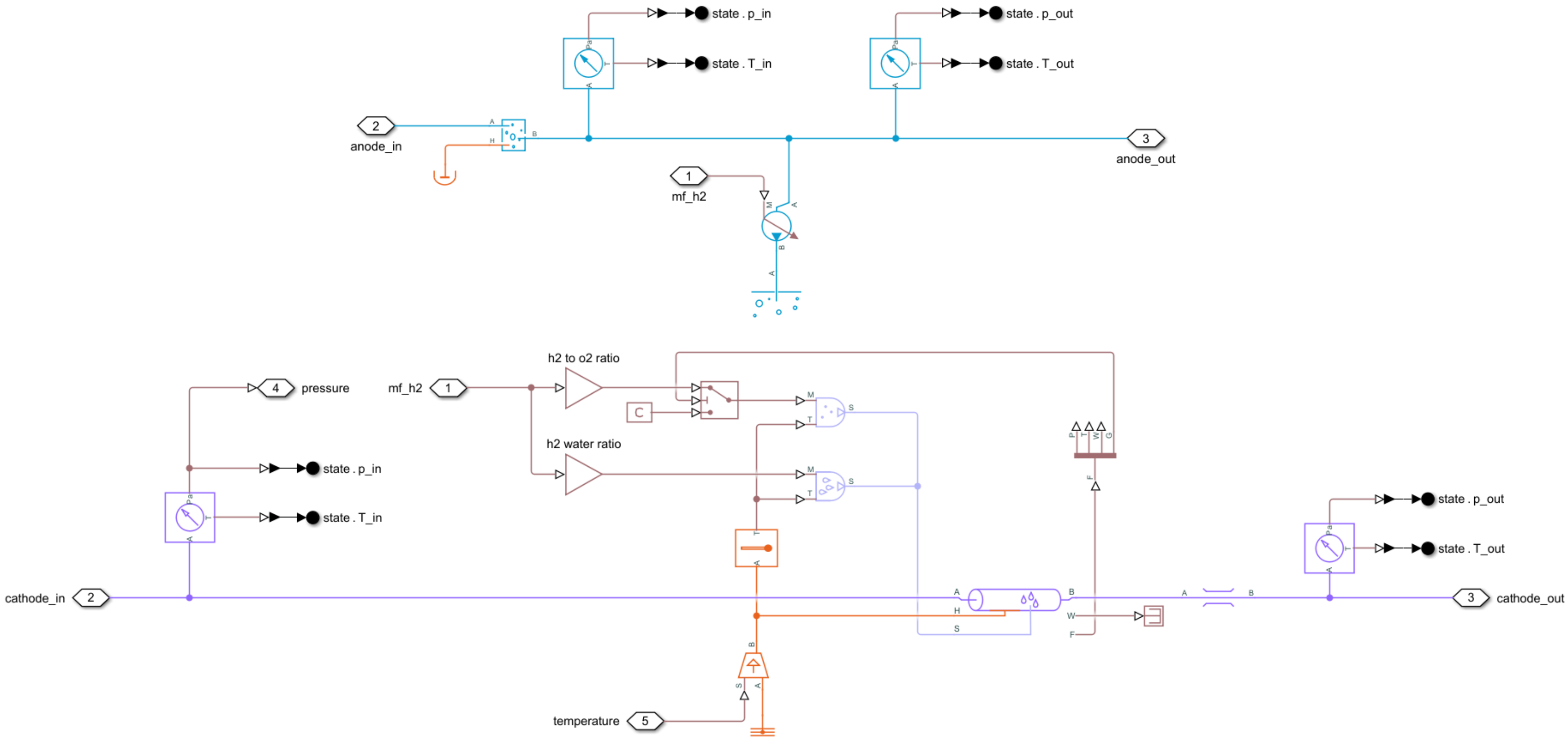
Fuel cell: Thermal



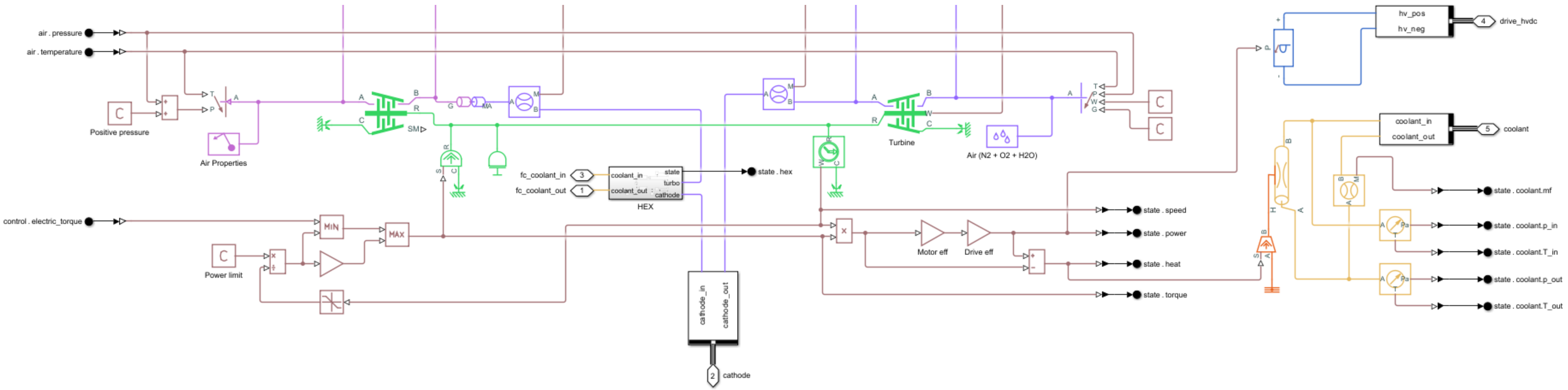
Fuel cell: anode & cathode



Fuel cell: anode & cathode

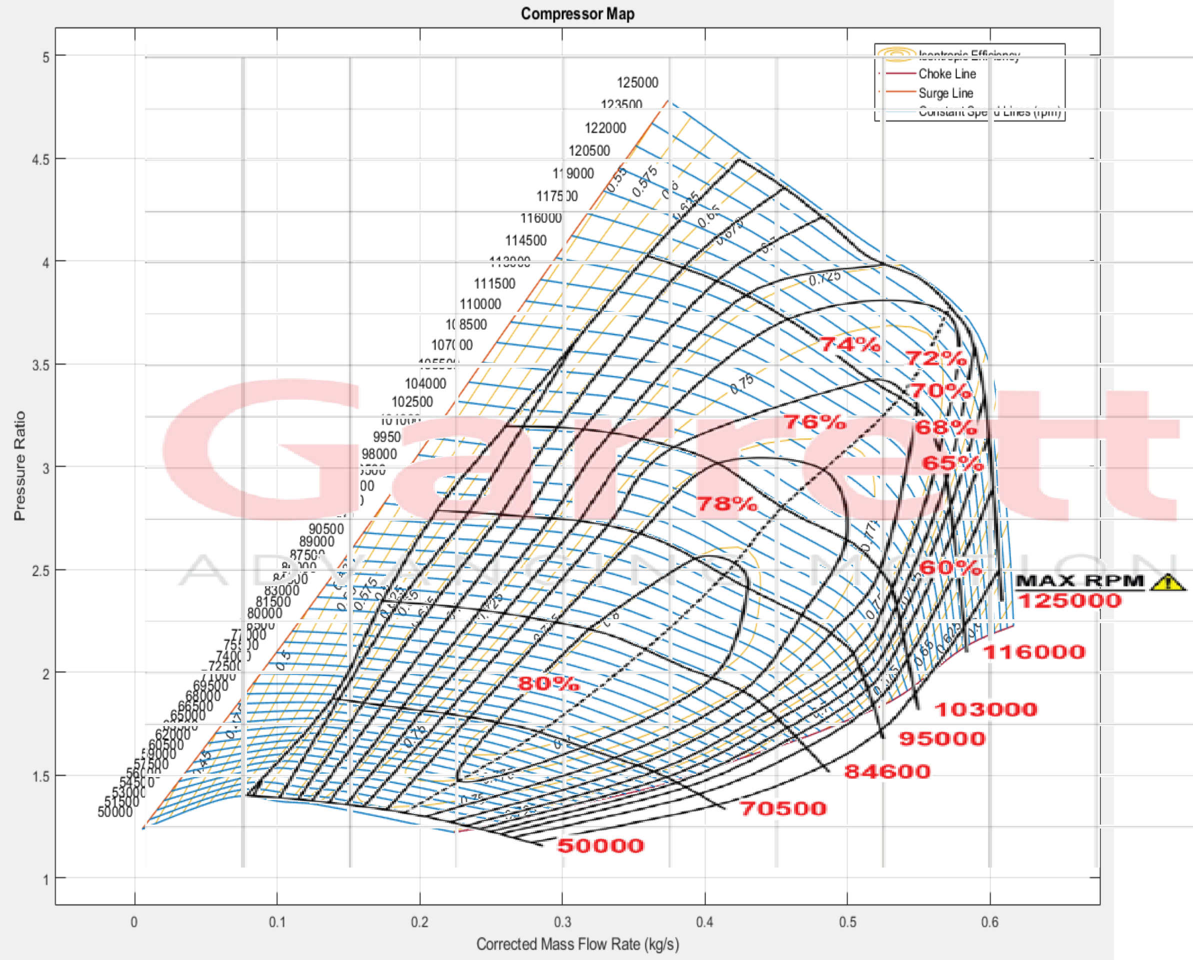


Turbocharger

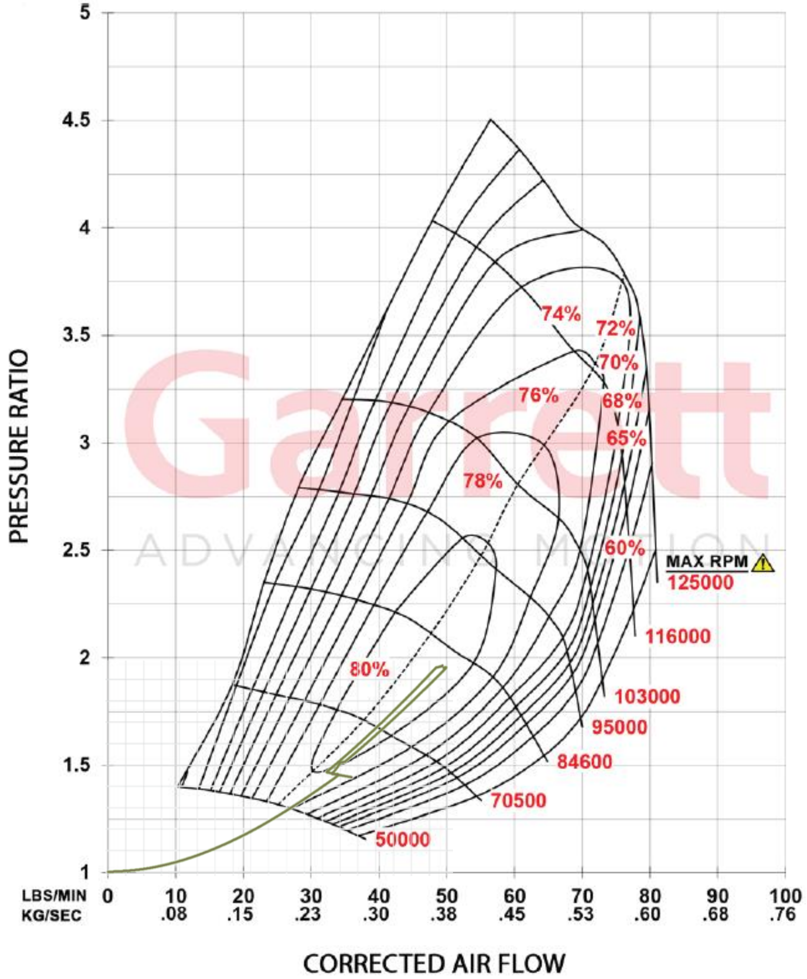


Turbocharger: compressor modelling

Compressor map matching

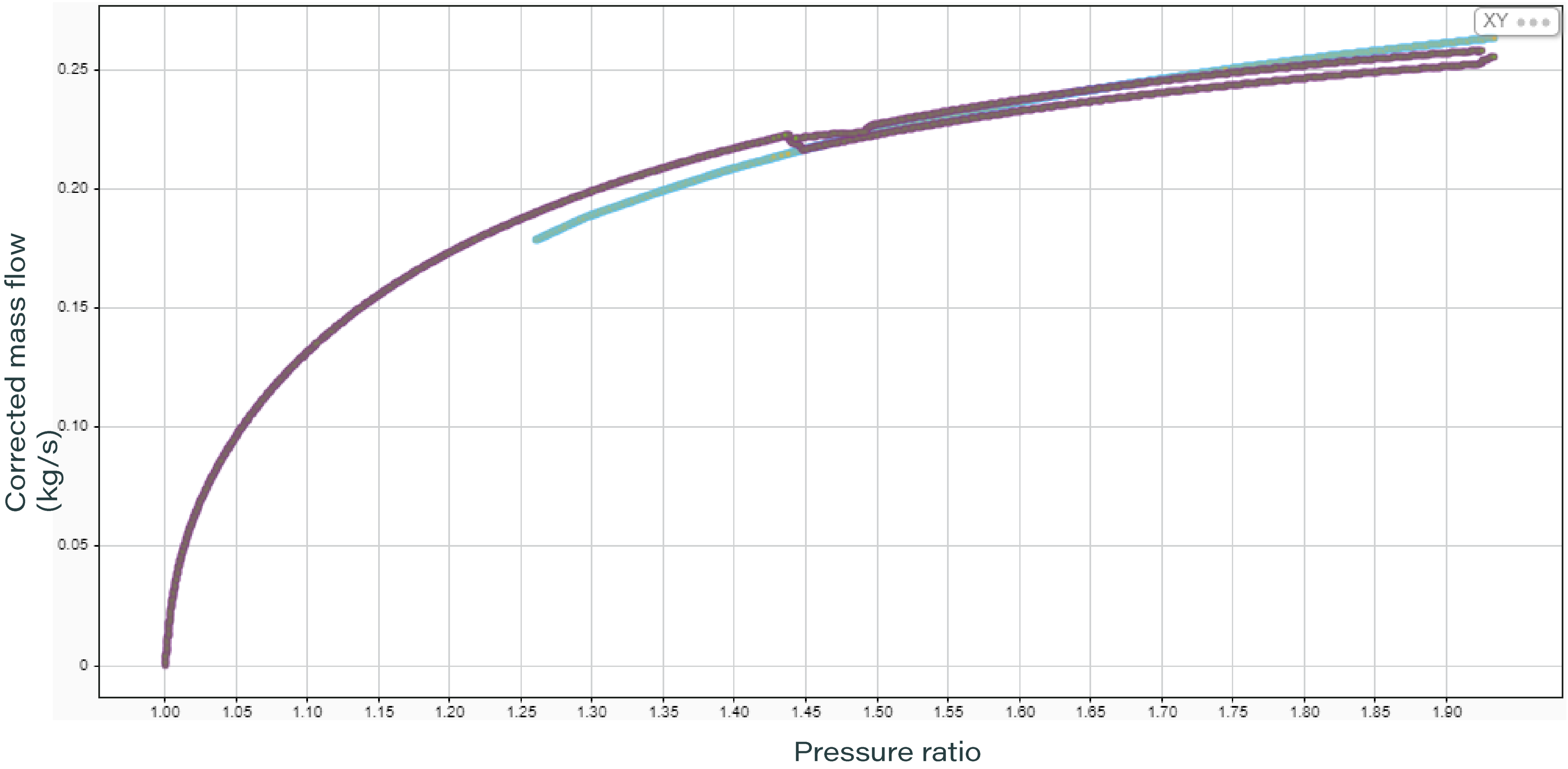


Compressor operating point



Garrett G40-900 84 trim T4 1.06 A/R. https://www.garrettmotion.com/wp-content/uploads/2022/07/Garrett_Performance_Catalog_Volume-9_2022.pdf

Turbine operating point (vs. Garrett G40-900 84 trim T4 1.06 A/R)



Garrett G40-900 84 trim T4 1.06 A/R. https://www.garrettmotion.com/wp-content/uploads/2022/07/Garrett_Performance_Catalog_Volume-9_2022.pdf

Outcomes

Model features

Environment
- Air temperature, pressure with altitude
- Weather (wind speed, air temperature)
- Route (latitude, longitude, heading)

Aircraft
- Lift & drag, including flaps & gear position
- 3-degree-of-freedom dynamics
- Longitudinal stability
- Dynamic fuel mass
- Single point gear interaction with ground

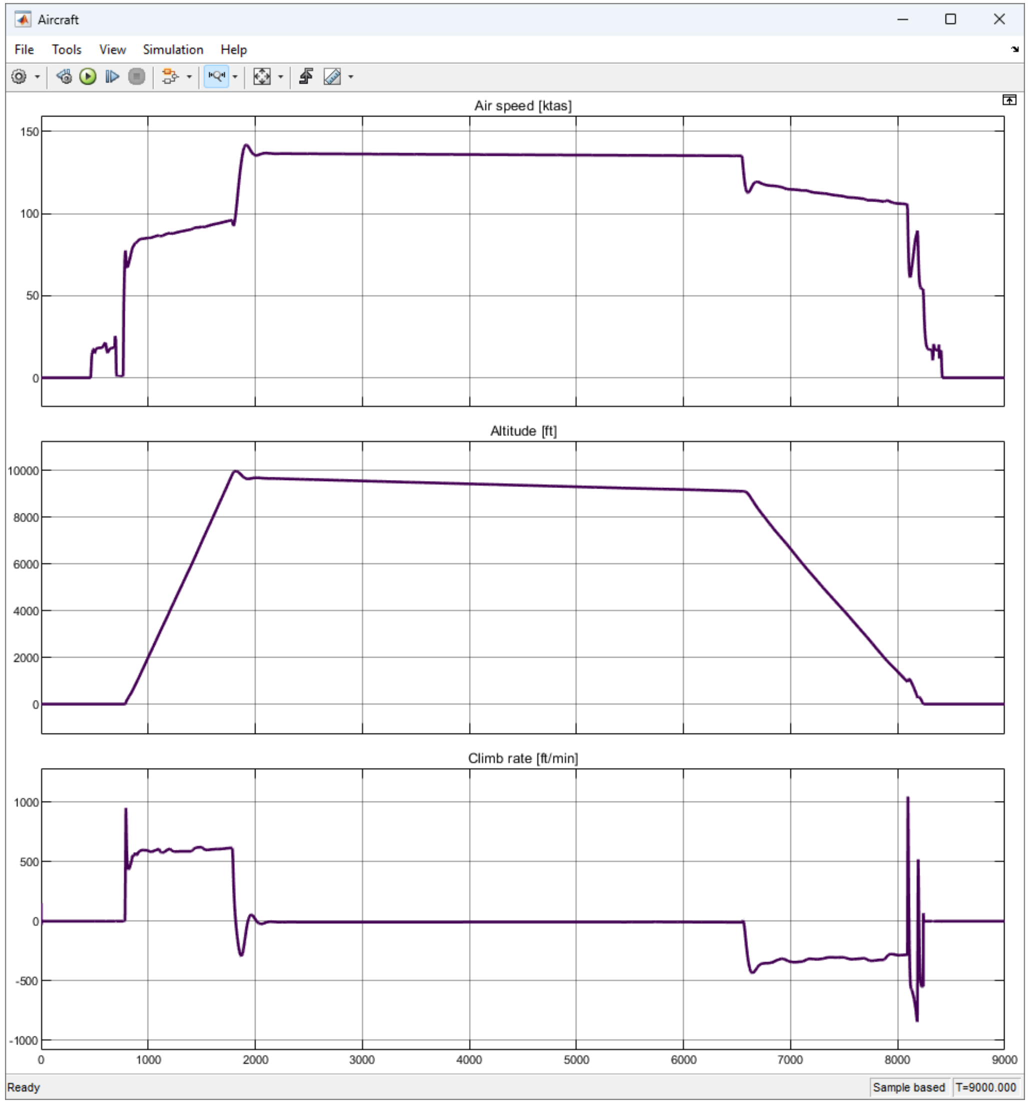
Visualization
- Full analogue of cockpit with instruments
- 3D visualization with capacity for satellite imagery

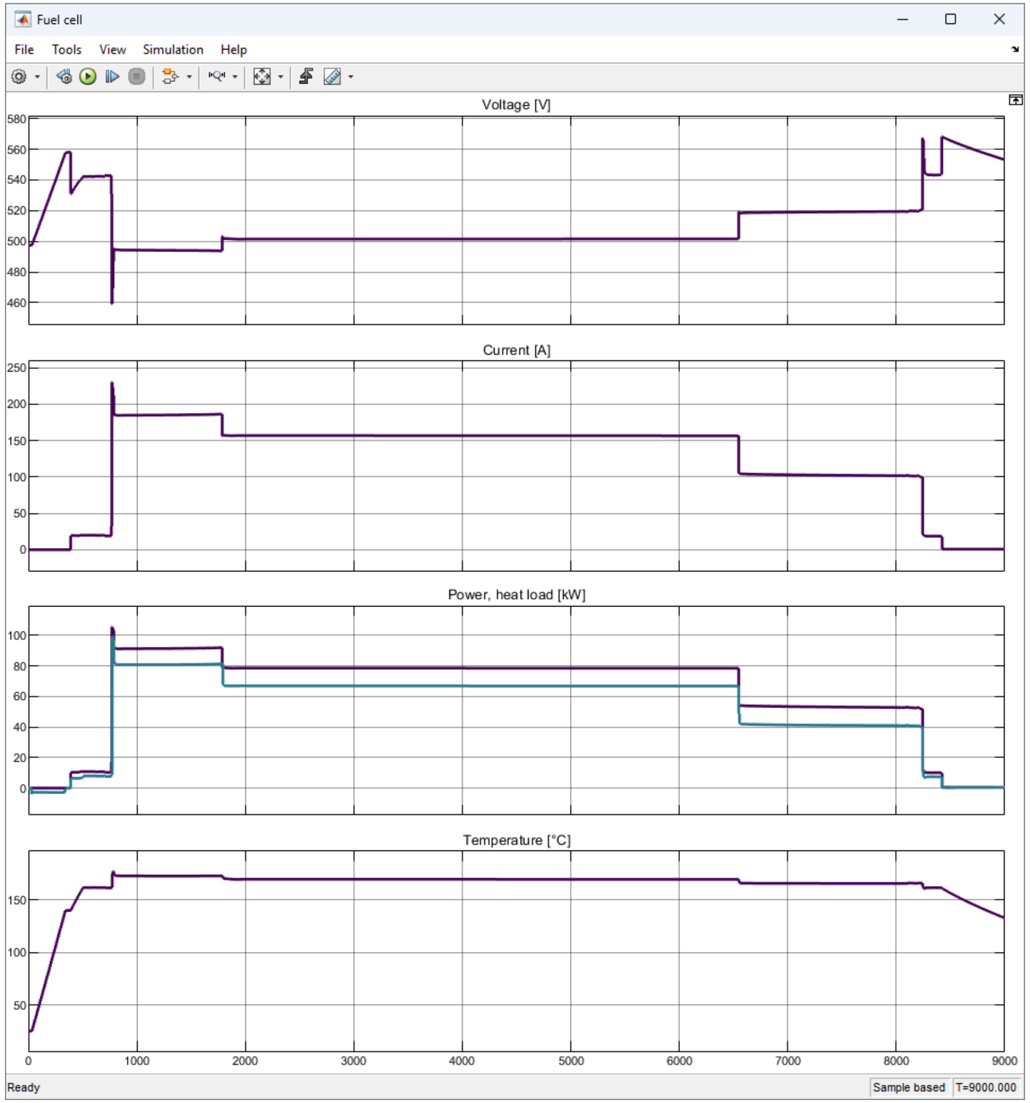
Propulsion
- LH_2 tank with electric heater
- Hydrogen conditioning from FC coolant
- Turbocharger based on manufacturer performance maps
- HV-HV and HV-LV DC/DC converters
- Propulsion motor with efficiency map and voltage sensitivity
- Propeller model based on manufacturer performance map
- Electrically actuated propeller pitch
- Low- and high-temperature coolant loops
- Radiator modelling including ram air and propeller wash

Cockpit visualisation

3D visualisation

Simulation outputs





Insights

1. Fixed pitch vs constant speed propeller
   - Determined early in the project that a fixed pitch propeller would not be sufficient to meet the target performance of the aircraft
   - Implemented constant speed propeller with electric actuator for final model

2. Fuel cell voltage constraints
   - Pressure/temperature sensitivity of fuel cell voltage highlighted voltage constraints
   - Fuel cell must be at temperature for take-off; may need engine run-up under brakes

3. Fuel cell thermal management during idle/taxi
   - Determined that under low power conditions, cathode air supply alone exceeded fuel cell cooling requirements
   - Required cathode air flow to be throttled for idle/taxi (via turbo)

Challenges, opportunities, and next steps

Challenges

- Large model; single Simscape physical network & solver
  - Runs better than real-time, but barely
  - Solution of initial condition is fragile
  - Small changes can result in crashes
  - Some issues of scale (Simulink to Simscape signal conversion)
- Available input data
  - Fuel cell characteristics
    - Sensitivity to oxygen partial pressure
    - Independent anode/cathode pressures
  - Turbine maps
  - Heat exchangers
  - Aircraft aerodynamics
- DC-DC converter modelling
  - Issues with initial condition solution
  - Missing current/power limit behavior

Opportunities

- Partition model
  - Multiple, smaller, physical networks with independent solvers
  - Opportunity to set different timescales for different modelling domains
  - Simulation can leverage parallel processing
- Fuel cell
  - Model sensitivity to oxygen partial pressure in cathode
  - Voltage behavior during startup/shutdown
- Decouple visualization from simulation
  - Simulation data playback
  - 3D scene visualisation

Next steps

- Improve model performance, targeting hard real-time simulation
- Enhance fuel cell model
  - Model sensitivity to oxygen & water vapor partial pressures
  - Model anode and cathode pressure sensitivity independently
- Revisit aircraft modelling
  - Flight control surfaces
  - Longitudinal stability
- Trade studies to support design process
  - Parameter sweeps
  - Mission profiles
  - Optimisation studies

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Questions?