



Multifidelity Cosimulation of Hydrogen Fuel Cell Aero Engine



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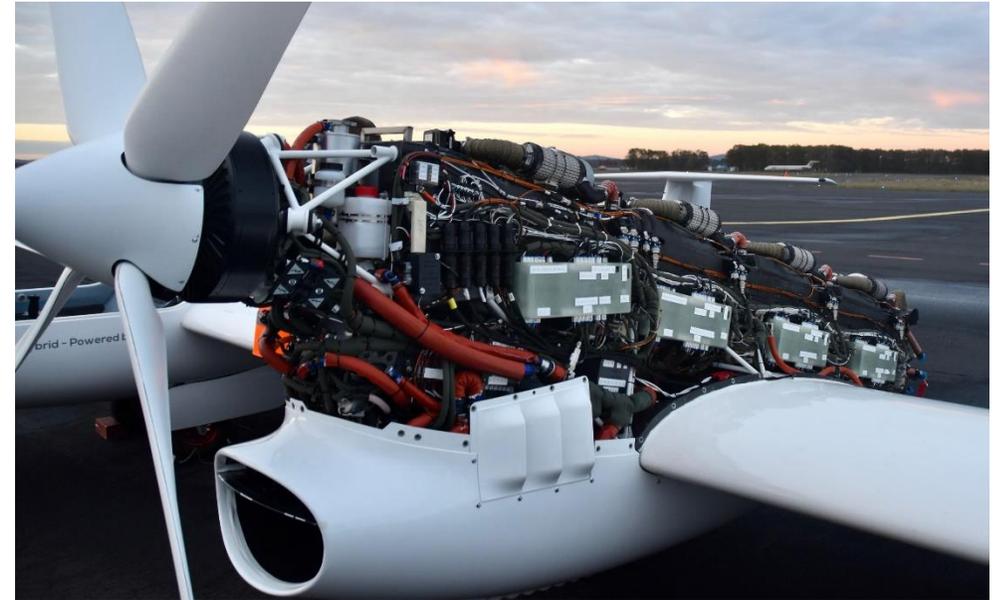
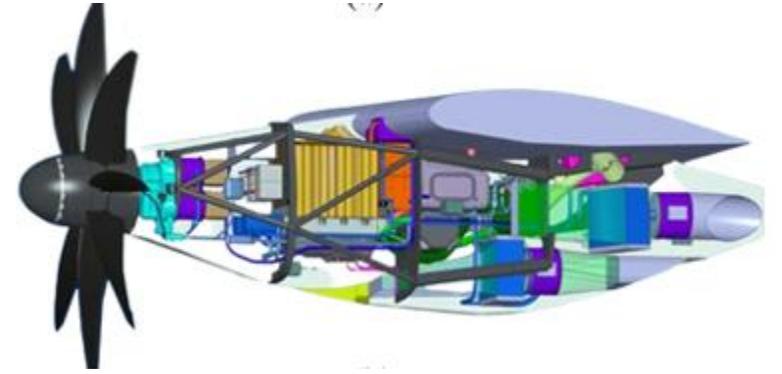
Thermal & Fluids Analysis Workshop
TFAWS 2024
August 26-30, 2024
NASA Glenn Research Center
Cleveland, OH

- Motivation and Purpose for Work
- Overall System Architecture
- Engine Model
- Turbomachinery Flowpath
 - Compressor
 - Turbine
- Fuel Cell Model
- Thermal Management System
 - Fuel Cell Coolant Channels
 - Radiator
- Holistic System Simulation and Control
- Results and Conclusions



Motivation of Work

- Difficulties in modeling full aero engine model
 - 3D Multiphysics Simulations
 - High complexity of fully integrated subsystem models
 - High computational resource demands
 - Challenges with convergence robustness
 - Lack of real-life system data for new technologies
- Benefits of Digital Twin model
 - Performance Evaluation
 - Condition Monitoring
 - System Behavior under Control Inputs





Purpose of Work



- Purpose of work
 - Develop complete and holistic system simulation of hydrogen fuel cell electric aero engine
 - Simulation utilizes multi-fidelity models in an integrated co-simulation
 - Analyze system based on physical boundary conditions and control inputs
 - Boundary conditions
 - Flight velocity
 - Altitude
 - Control Inputs
 - Propfan power input
 - Compressor speed
 - Fuel cell internal average temperature setpoint

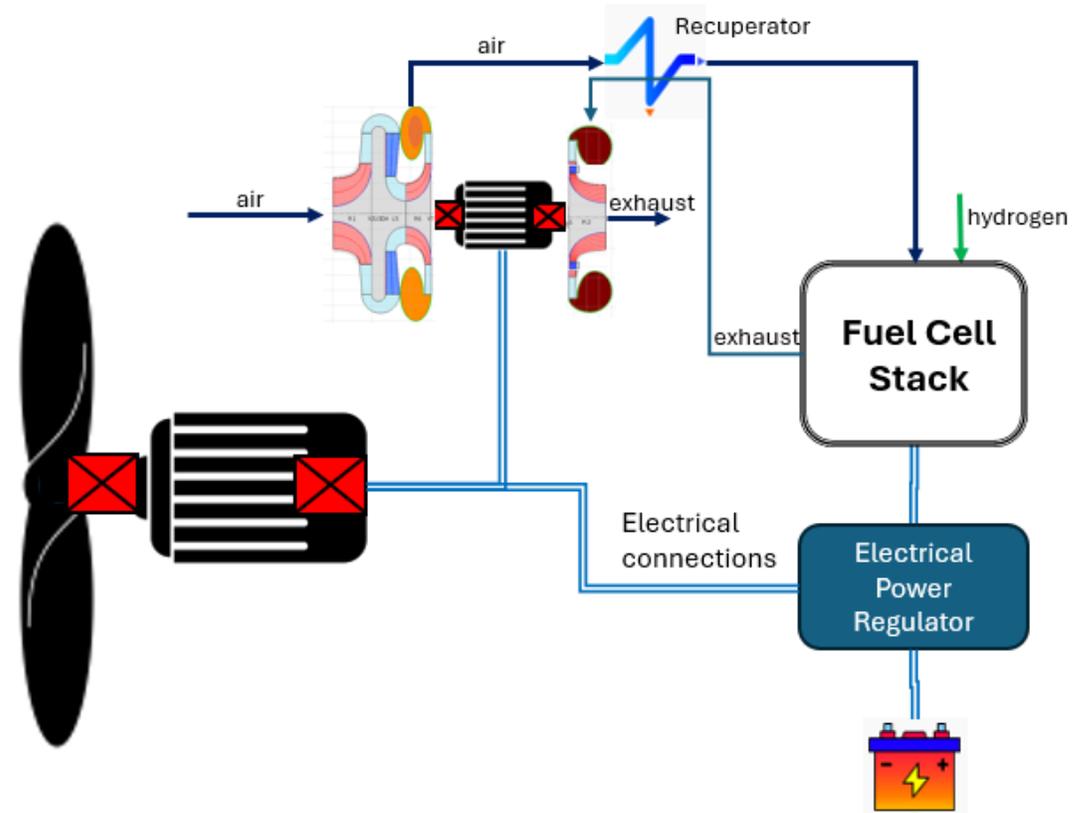


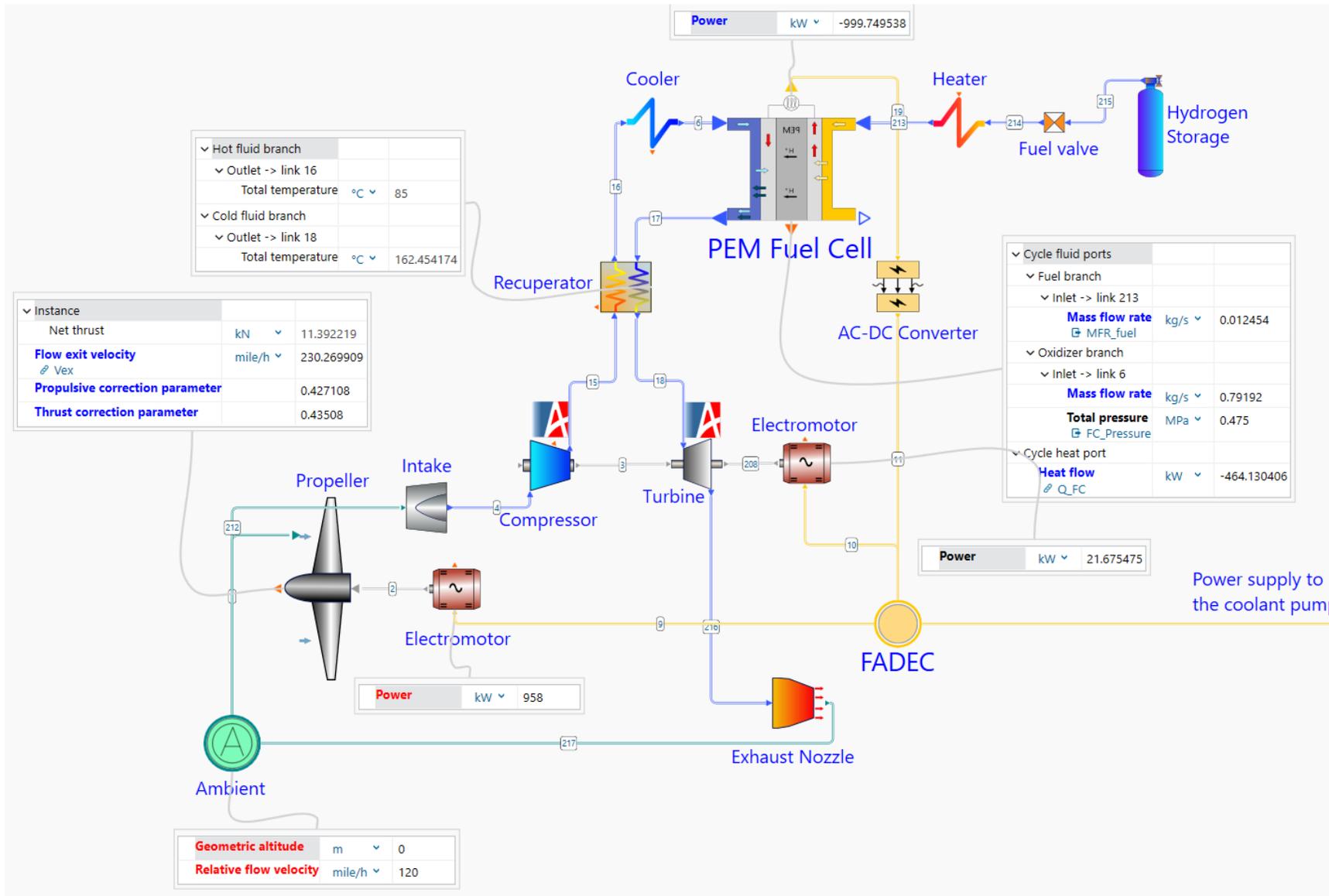
Overall System Architecture



- Subsystems
 - Engine Model
 - Lumped-parameter (0D) thermofluid cycle/system model
 - Turbomachinery components (turbocompressor)
 - 1D throughflow model utilizing loss component models
 - Thermal Management System
 - 1D model
 - Heat transfer (Nusselt correlations)
 - Pressure loss (Moody correlations)
- Subsystems are coupled such that their interrelations are modelled in overall system model

- PEM Fuel Cell
 - Nominal temperature: 80 °C
 - Nominal electric power: 1 MWe
- Prop Drive Motor
 - Power: 958 kW
 - Corresponds to PT6 engine for Beechcraft 1900
- Turbocompressor
- Recuperator
- Power Regulator and Battery Storage
 - Not included in system model





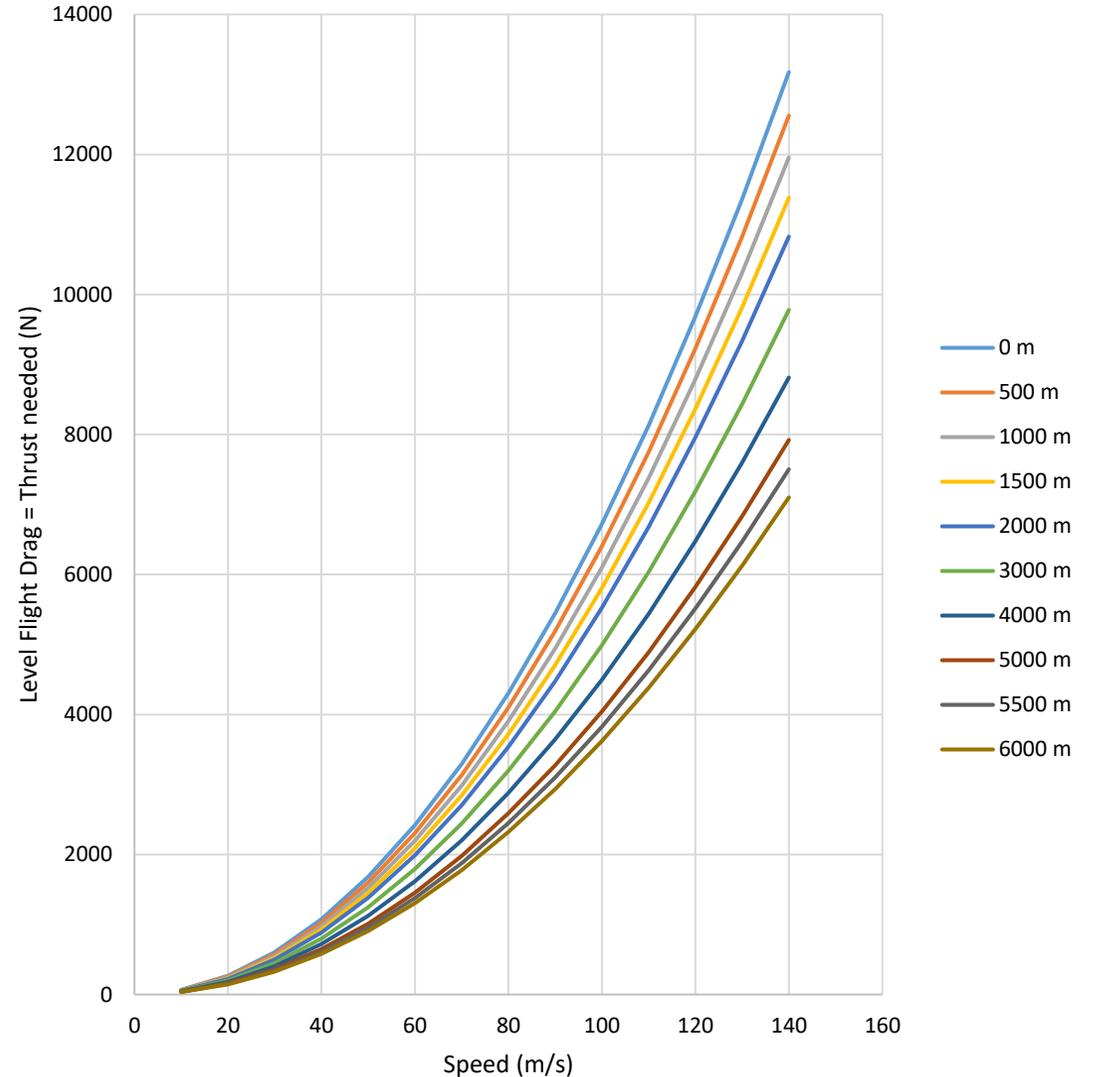
Aircraft Engine Performance – Multiple Operating Conditions

	Take Off	Low Altitude Cruise	High Altitude Cruise
Altitude [m]	0	50	5400
Atmospheric Pressure [kPa]	101.3	100.7	51.23
Atmospheric Temperature [°C]	15	14.7	-20.1
Flight Speed [m/s]	54	103	134
Drag [kN] *reference value only	1.9	6.9	6.9
Engine Power [kW]	958	958	958

- Thrust Calculation

- Wing Surface Area: 28.8 m²
 - Based on Beechcraft 1900
- Drag Coefficient: 0.038
 - Based on Boeing 737-800, Airbus A320

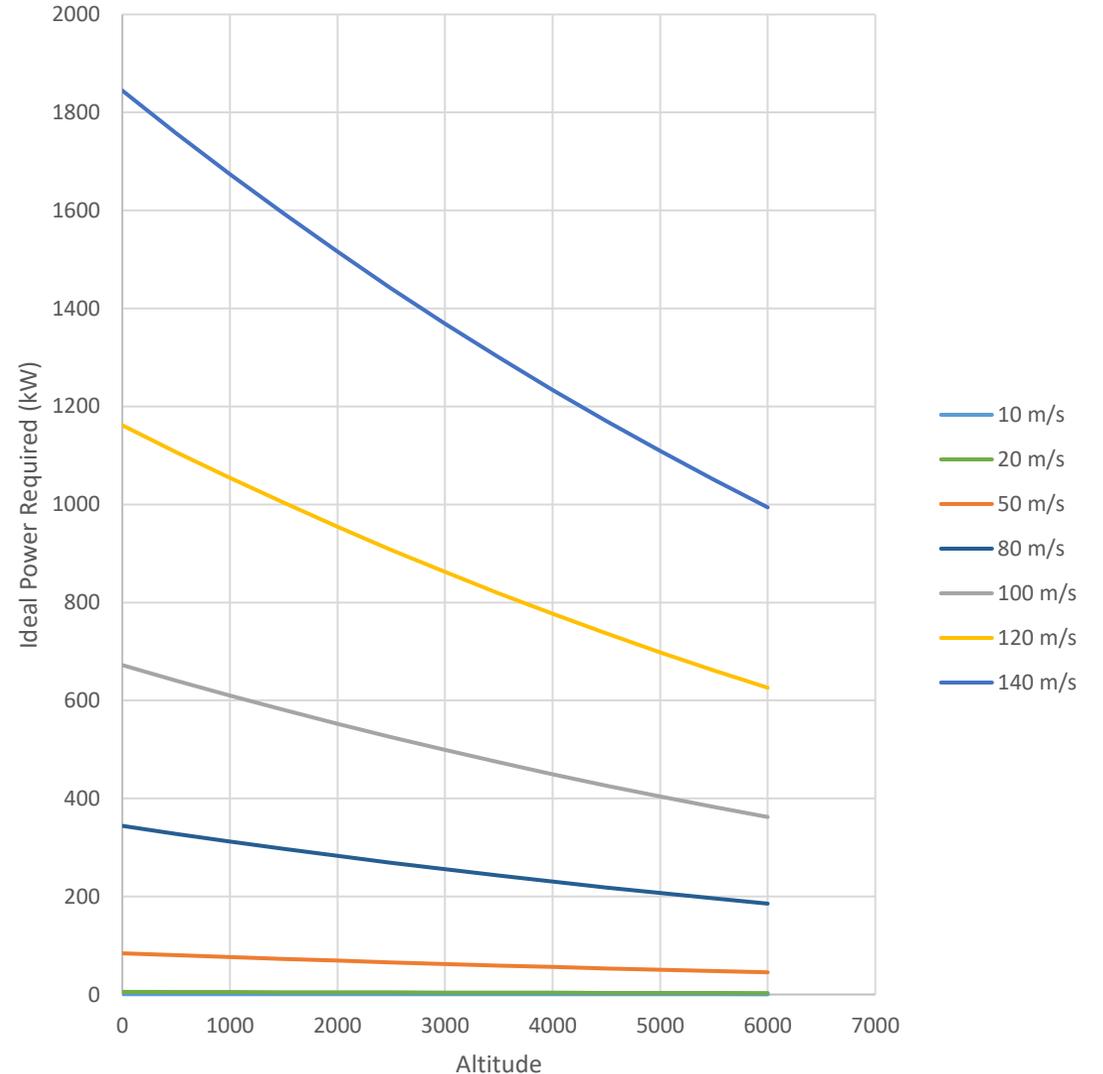
$$F_d = \frac{1}{2} C_d A_{wing} \rho_{air} v_{\infty}^2$$



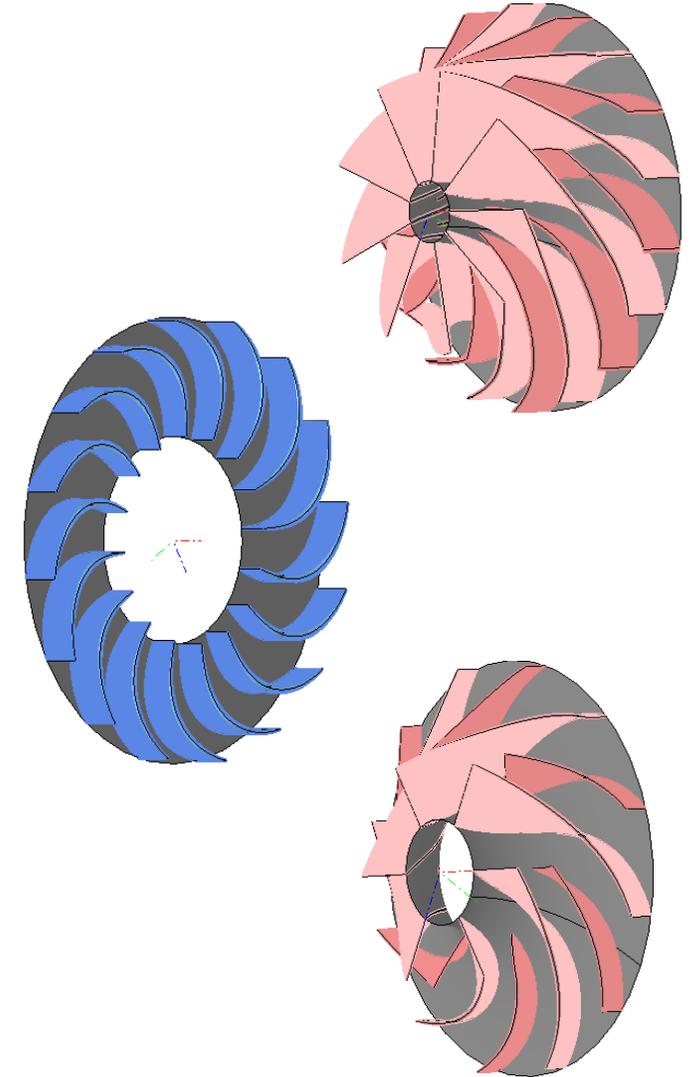
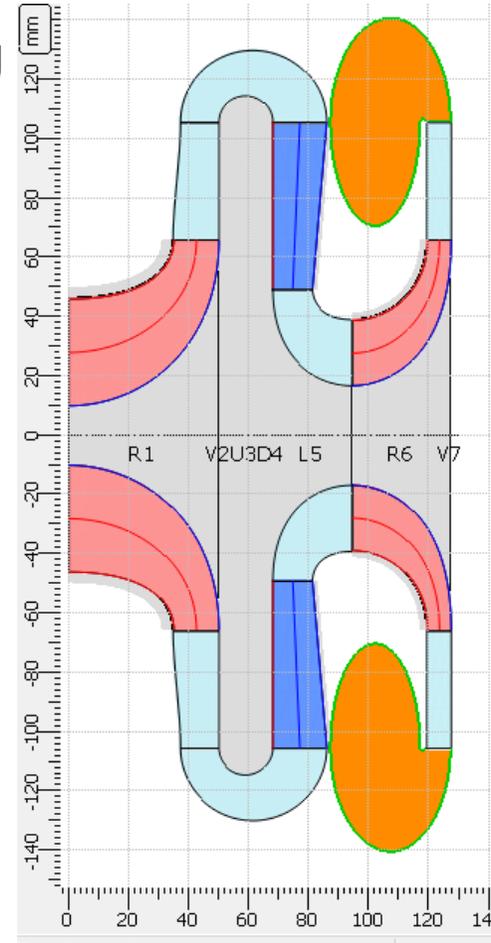
- Ideal power to drive propellor and maintain level flight
 - Plot assumes 100% propulsor efficiency
- Typical propulsor efficiency:
 - 60%-70%

$$\eta_p = \frac{2}{2 + \frac{\Delta V}{V_\infty}}$$

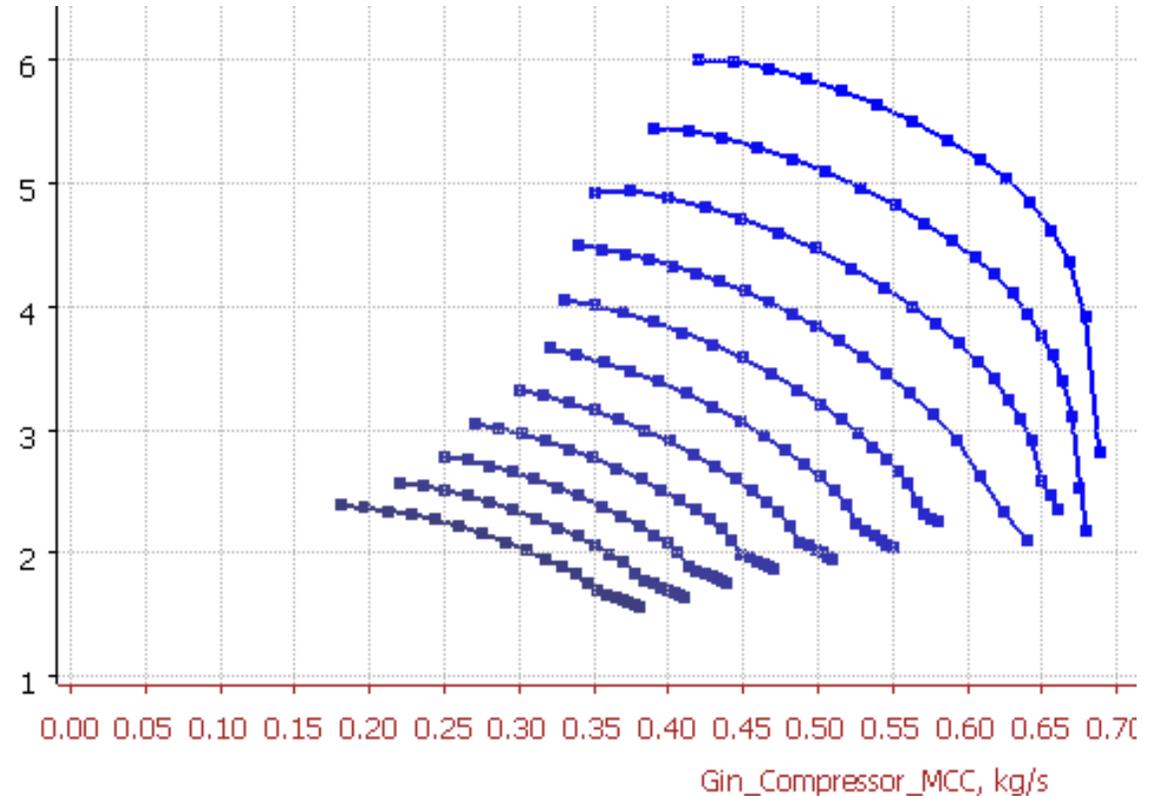
- High altitude cruise conditions
 - 134 m/s, 5400 m
 - 1200 kW thrust power available to aircraft



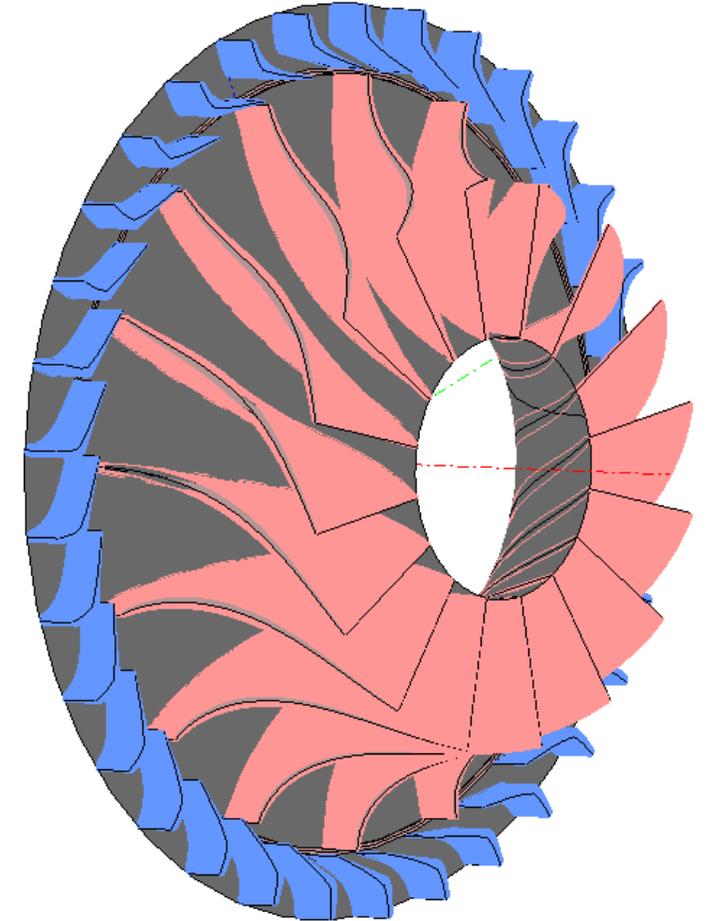
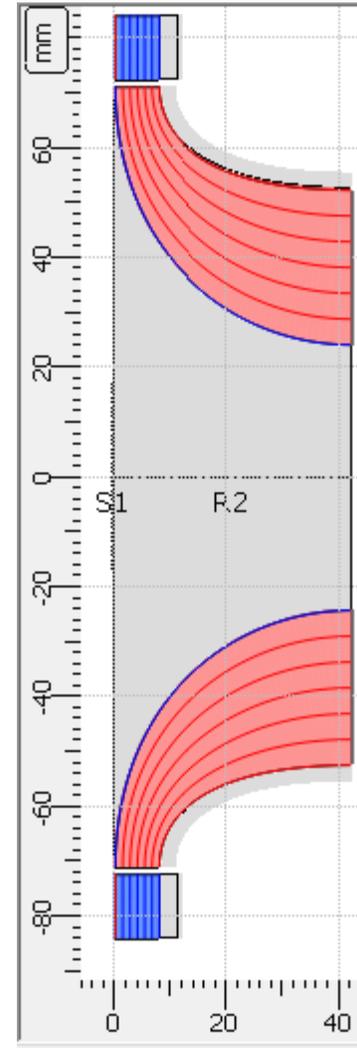
- Compressor
 - 1D model designed and analyzed using AxSTREAM®
 - Geometry
 - 2-stage centrifugal configuration
 - Design Point Performance
 - Suction parameters based on near cruise altitude rated condition
 - Inlet Total Temperature: -8 °C
 - Inlet Total Pressure: 61.1 kPa
 - Rotational Speed: 56000 rpm
 - Total-Total Pressure Ratio: 4.1
 - Isentropic Efficiency: 79%
 - Mass Flow Rate: 0.63 kg/s



- Compressor performance map at design inlet conditions
 - Total-Total Pressure Ratio vs Mass Flow Rate
 - Set of speedlines
 - 38000 – 58000 rpm
 - 2000 rpm increments

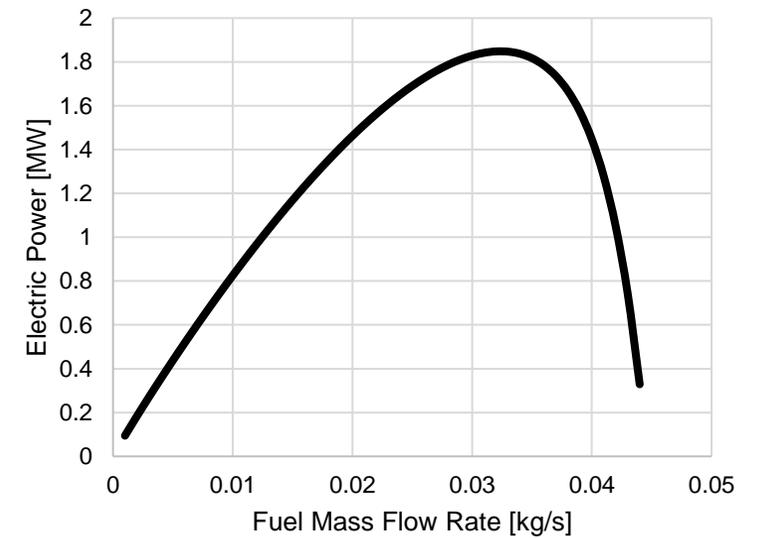
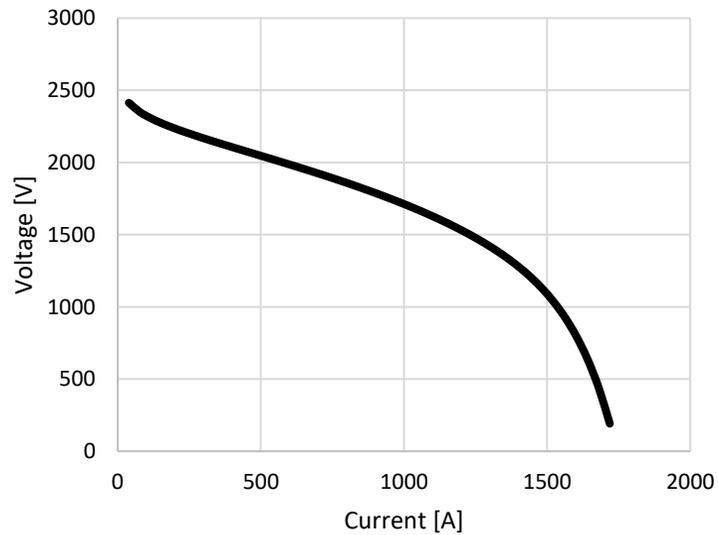
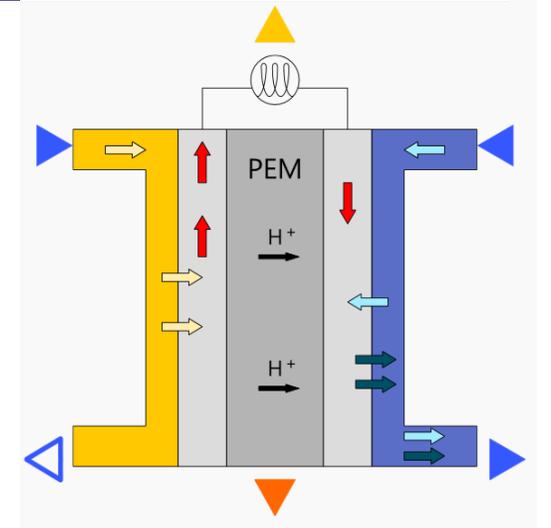


- Turbine
 - 1D model designed and analyzed using AxSTREAM®
 - Geometry
 - Single stage radial-inflow configuration
 - Design Point Performance
 - Suction Parameters
 - Inlet Total Temperature: 159 °C
 - Inlet Total Pressure: 4.66 bar
 - Total-Total Pressure Ratio: 4.6
 - Rotational Speed: 56000 rpm
 - Rotational Speed Range:
 - 38000 – 62000 rpm
 - Power Output: 124 kW
 - Isentropic Efficiency: 92%

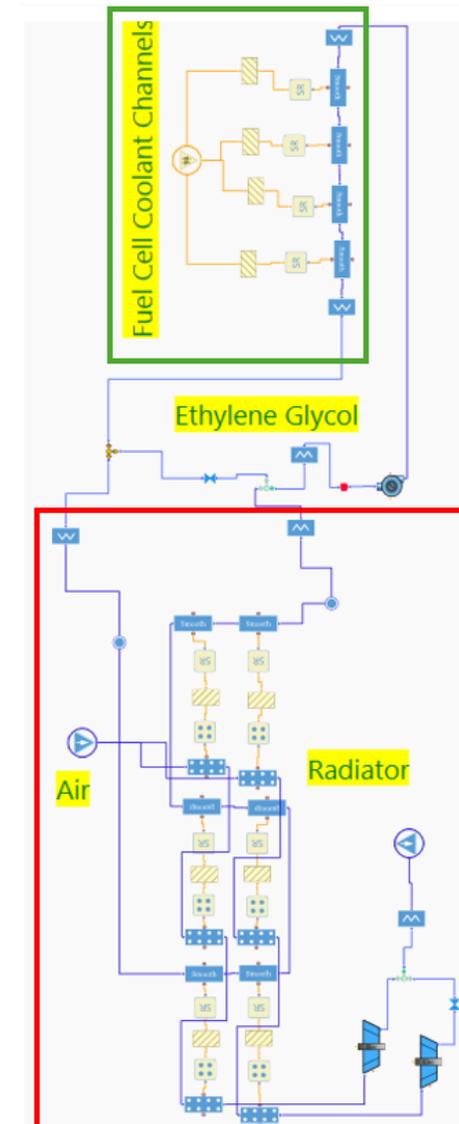
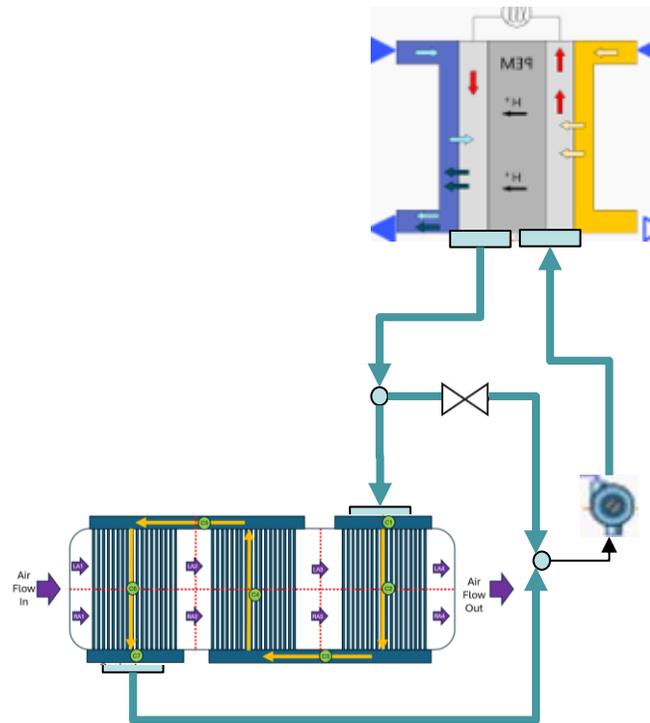


Property	Value
Fuel Cell Temperature [°C]	80
Fuel/Air Equivalence Ratio	< 1
Single Fuel Cell Area [m ²]	0.1
Catalyst-Specific Area [cm ² /mg]	1000
Catalyst Loading [mg/cm ²]	0.5
Membrane Humidity Level	100% Humidified
Membrane Thickness [mm]	0.178
Cell Number - Stack	2450

- Fuel Cell IV Characteristic at Nominal Conditions
 - Fuel cell pressure: 0.475 MPa
 - Oxygen Utilization: 0.542

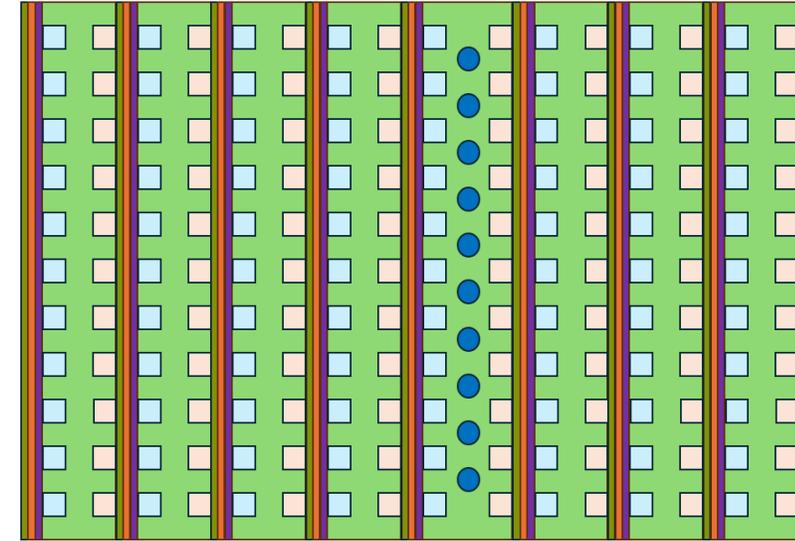


- Liquid cooling architecture
- Controlling fuel cell internal average temperature to setpoint value (80 °C)
- Singular control input is radiator bypass (coolant split)
- Constant volume flow coolant pump and air
- Enables small ΔT in fuel cell channels (minimize thermal stress)
- Reliable thermal operation up to 34 °C external temperature

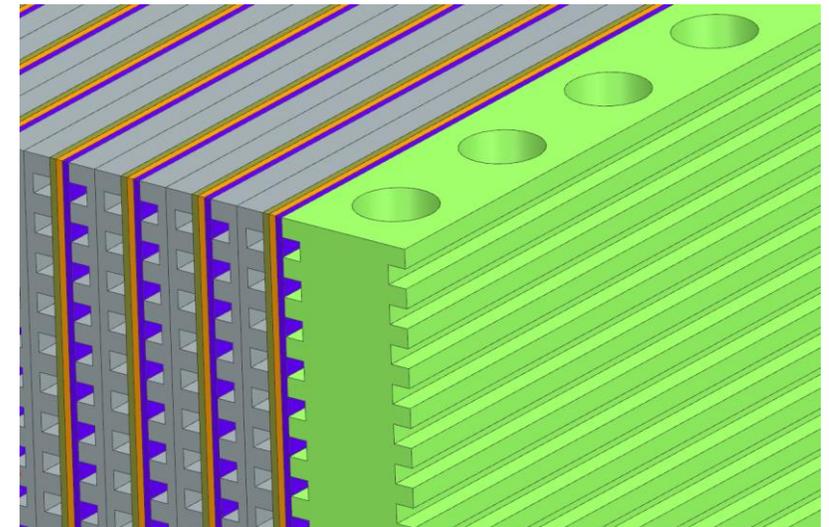


Fuel Cell Coolant Channel Properties

Property	Value
Fuel Cell Area [m ²]	0.1
Fuel Cell Width [mm]	316
Fuel Cell Height [mm]	316
Number of Coolant Channels	3500
Cooling Channel Width [mm]	2
Cooling Channel Height [mm]	2
Cooling Channel Length [mm]	316
Spacing Between Cooling Channels [mm]	2
Cooling Channels per Cooling Plate	79
Minimum Number of Cooling Plates	45
Number of Fuel Cells in Stack	2450
Fuel Cells Cooled per Cooling Plate (approx.)	55

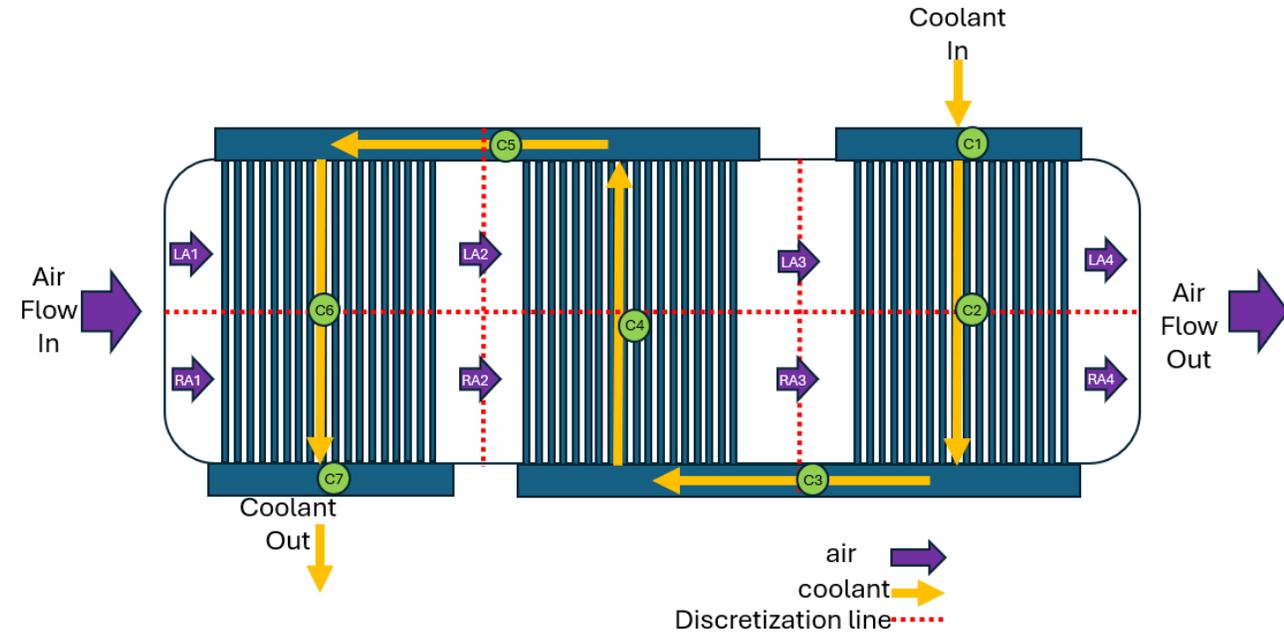


- Anode
- PEM
- Cathode
- Oxidizer (Air)
- Fuel (Hydrogen)
- Coolant (Ethylene Glycol)



Radiator Properties

Property	Value
Number of Tubes	15000
Tube Length [mm]	1000
Tube Inner Diameter [mm]	2
Tube Outer Diameter [mm]	2.5
Tube Longitudinal Pitch [mm]	5
Tube Cross Pitch [mm]	5
Tubes Across Air Flow	250
Tubes Along Air Flow	60





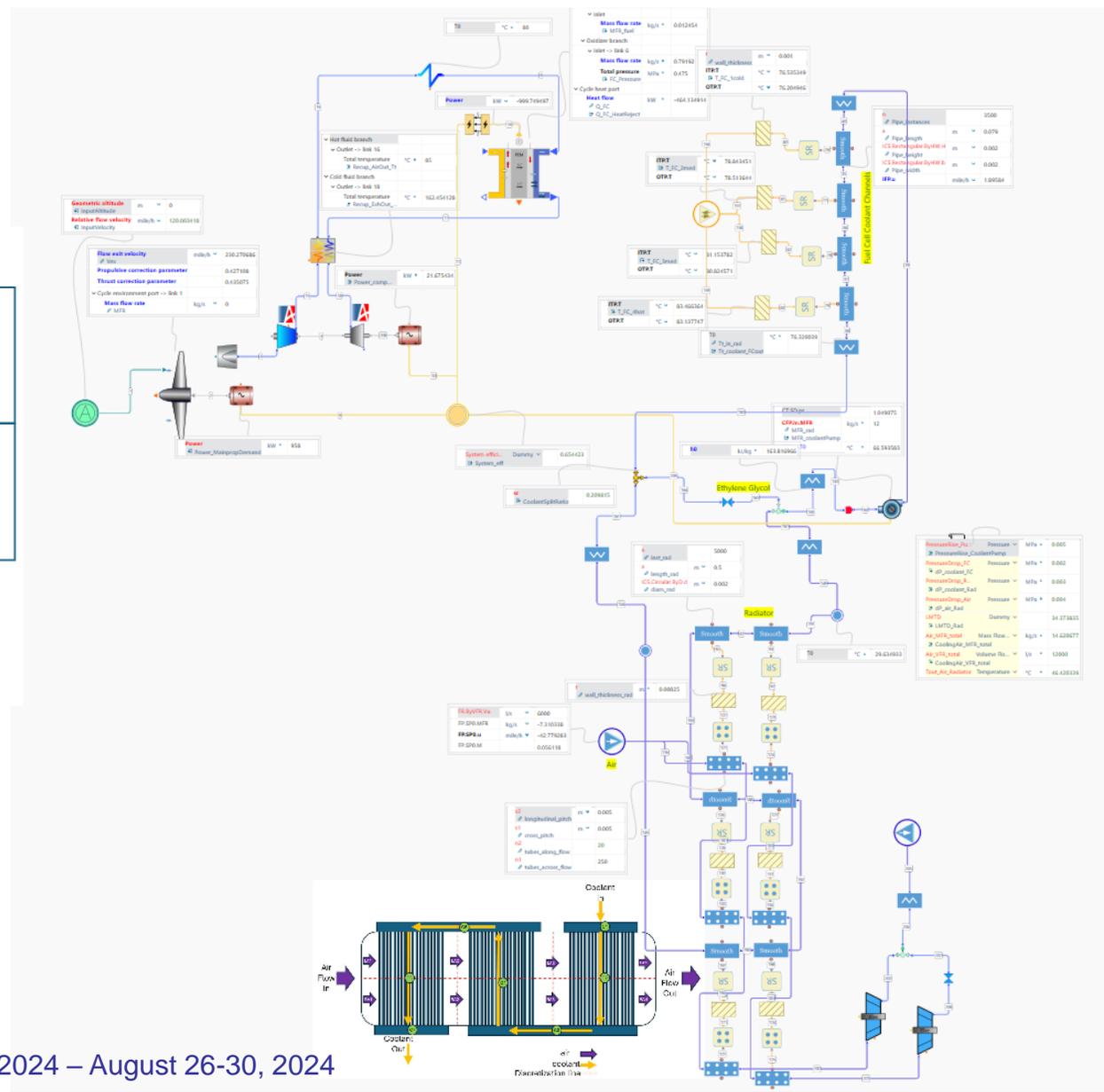
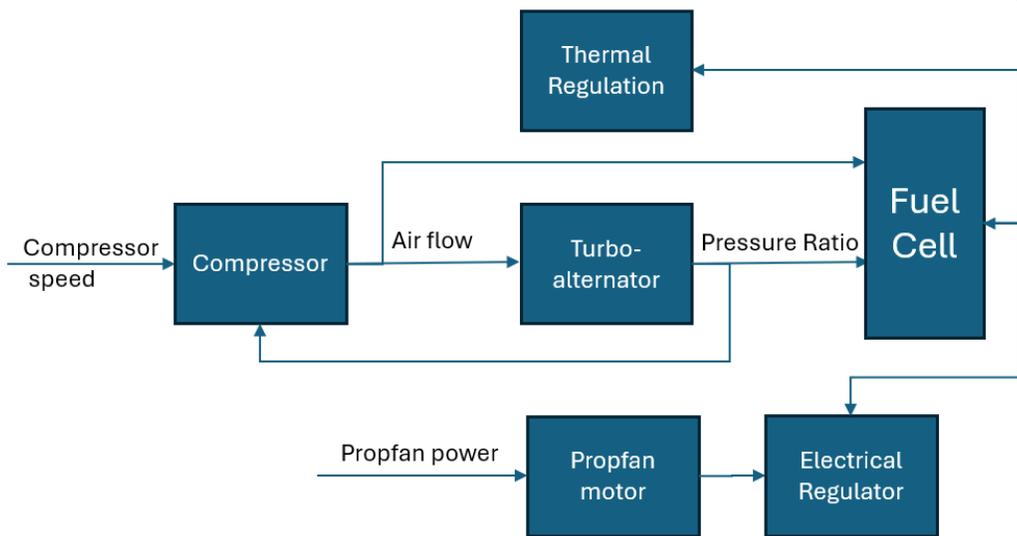
Thermal Management System



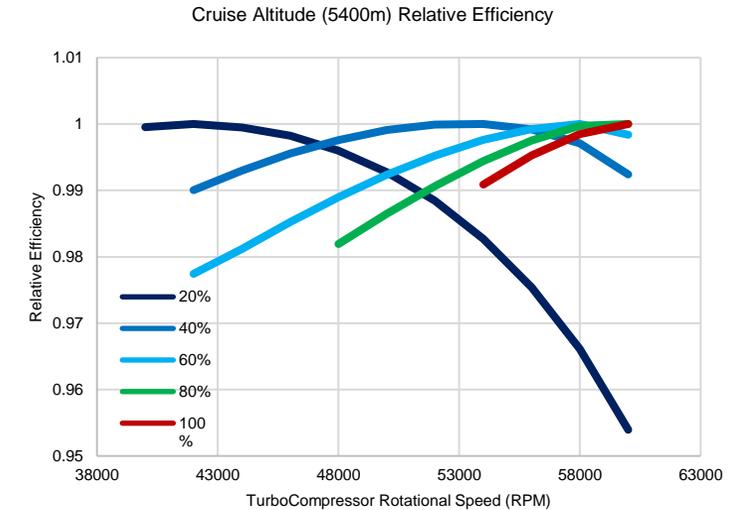
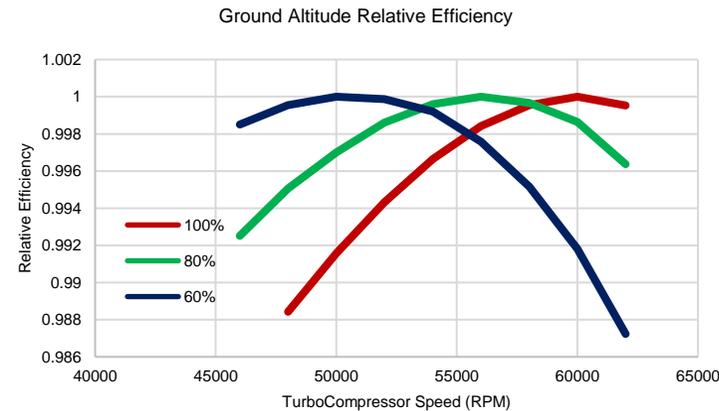
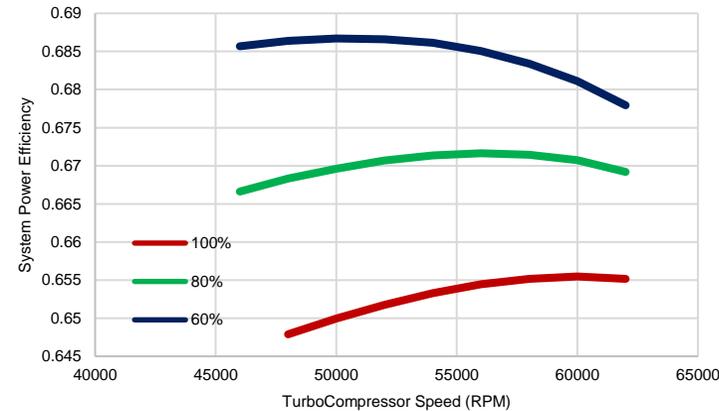
Thermal Management System Performance – Multiple Operating Conditions

	Take Off	Take Off- Hot Climate	Low Altitude Cruise	High Altitude Cruise
Operating Conditions				
Altitude [m]	0	0	50	5400
Atmospheric Pressure [kPa]	101.325	101.325	100.726	51.226
Atmospheric Temperature [°C]	15	34	14.7	-20.1
Fuel Cell				
Aspiration Air Flow Rate [kg/s]	0.849	0.772	0.861	0.549
Heat Rejection [kW]	466	475	464	515
Coolant Pump				
Mass Flow Rate [kg/s]	12	12	12	12
Inlet Temperature [°C]	66.5	66.3	66.6	65.1
Fuel Cell Coolant Channels				
Coolant Inlet Temperature [°C]	66.6	66.3	66.6	65.1
Coolant Outlet Temperature [°C]	76.3	76.2	76.3	75.9
Coolant Split Ratio	0.211	0.945	0.208	0.175
Radiator				
Coolant Mass Flow Rate [kg/s]	2.53	11.34	2.50	2.09
Coolant Pressure Drop [kPa]	3.37	13.11	3.35	3.30
Coolant Outlet temperature [°C]	29.8	65.7	29.3	13.4
Air Outlet Temperature [°C]	46.5	68.2	46.2	40.6
Air Volumetric Flow Rate [m ³ /s]	12	12	12	12
Air Mass Flow Rate [kg/s]	14.63	13.72	14.55	8.41
Log Mean Temperature Difference	34.3	14.1	34.6	54.5

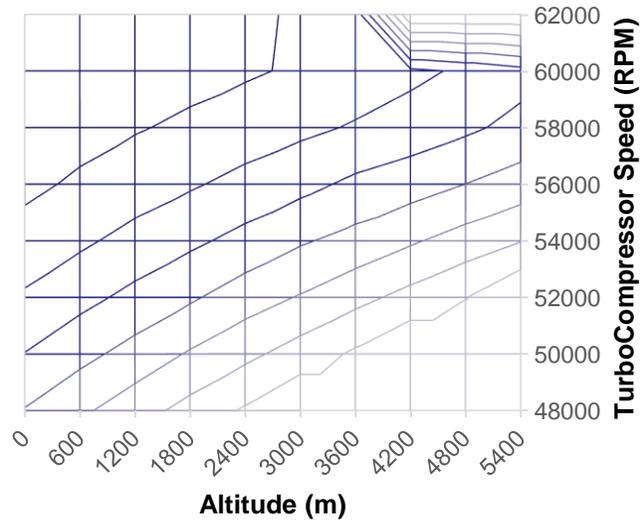




- Simulated number of cases with variation in turbo speed (RPM), load, and two altitudes
- Shows optimum engine efficiency can be determined and programmed into FADEC
- Competitive power system efficiency
- Good stability and operability demonstrated – able to simulate most reasonable steady-state operating conditions with all equipment within operational regime

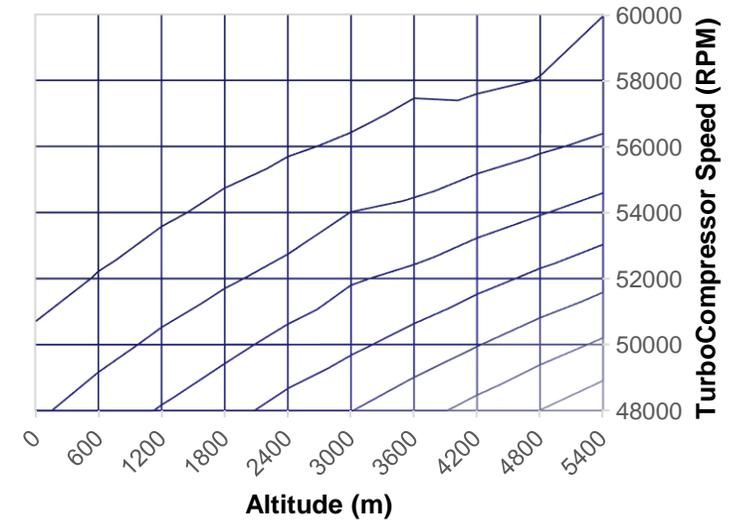


100% Power



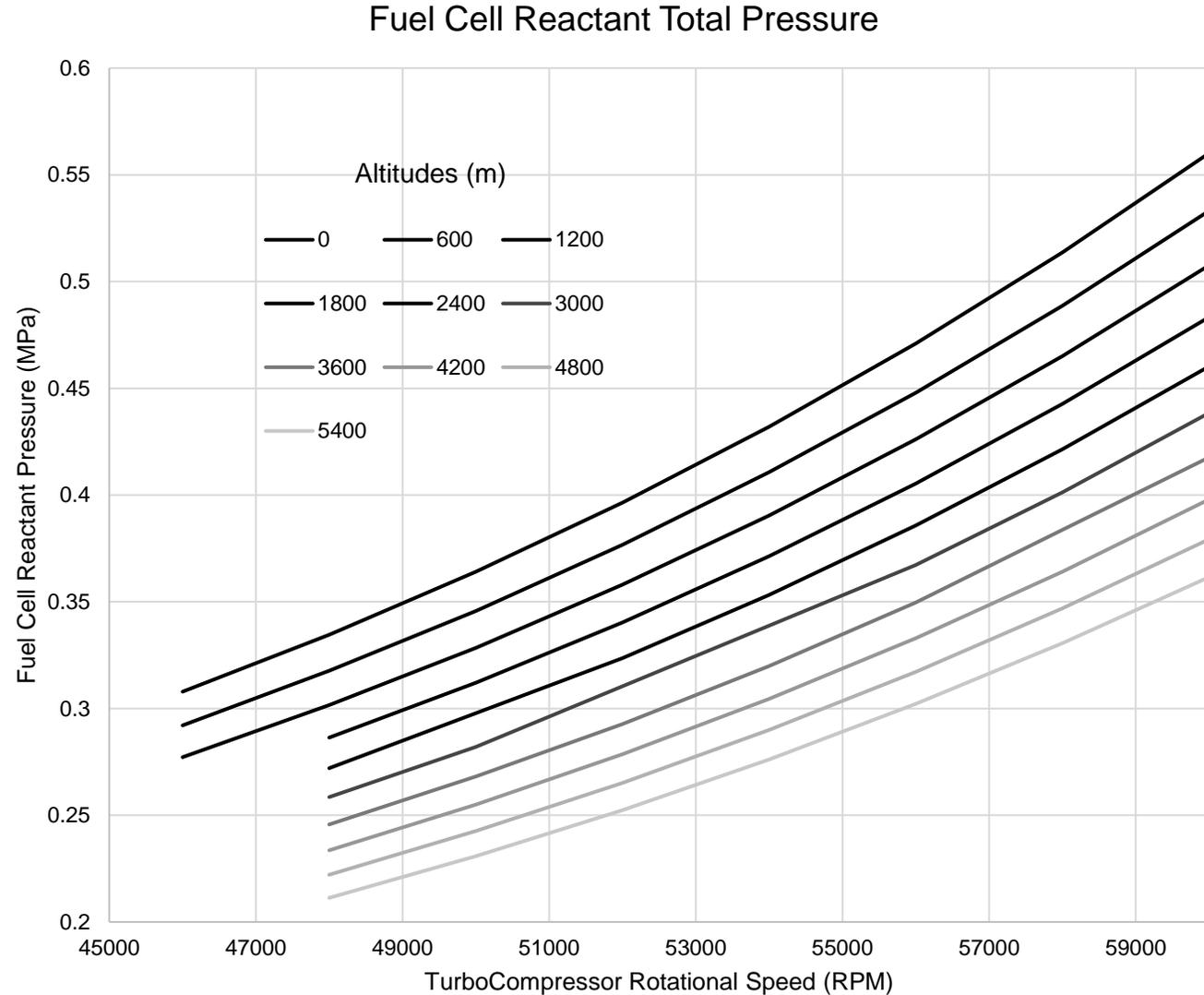
0.64-0.642
 0.642-0.644
 0.644-0.646
 0.646-0.648
 0.648-0.65
 0.65-0.652
 0.652-0.654
 0.654-0.656

80% Power

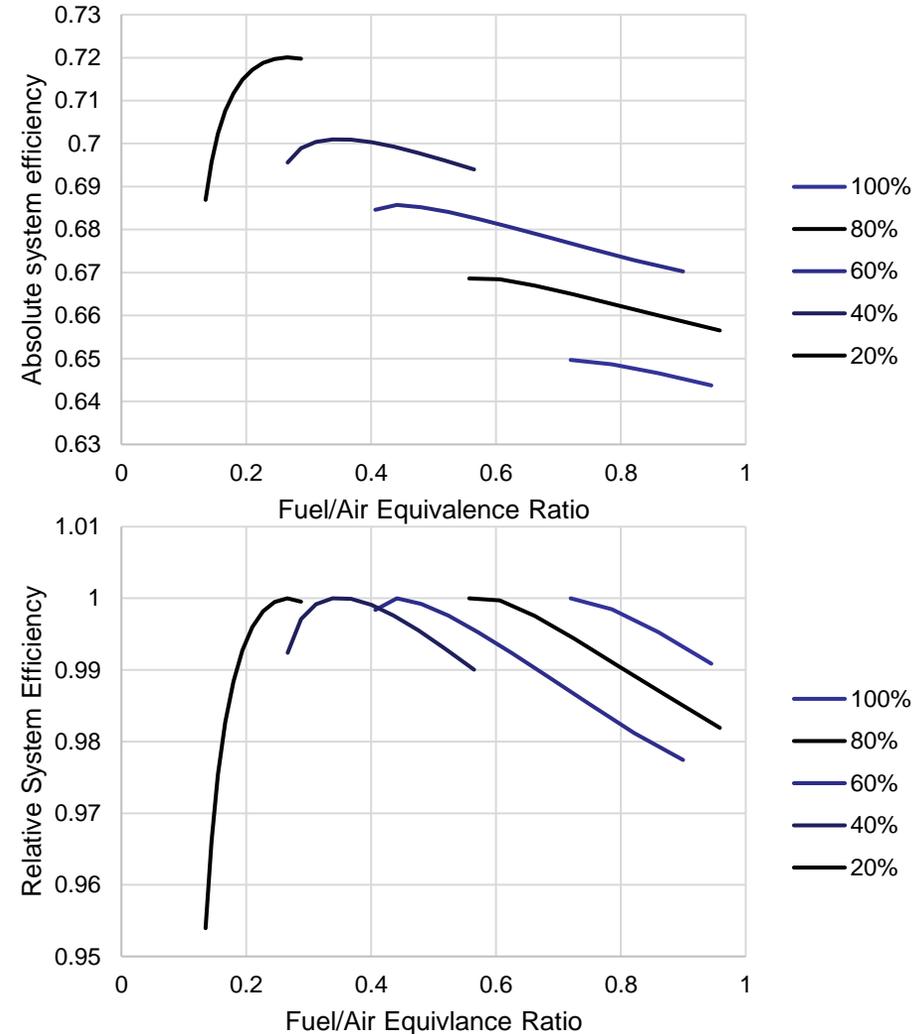


0.65-0.652
 0.652-0.654
 0.654-0.656
 0.656-0.658
 0.658-0.66
 0.66-0.662
 0.662-0.664
 0.664-0.666
 0.666-0.668
 0.668-0.67
 0.67-0.672

- Some inferences on internal operational parameters of system
- Pressure ratio is nearly constant for each speed (due to machine characteristic)
- Reactant pressure effects efficiency of the fuel cell
- Much different results if architecture did not include recovery



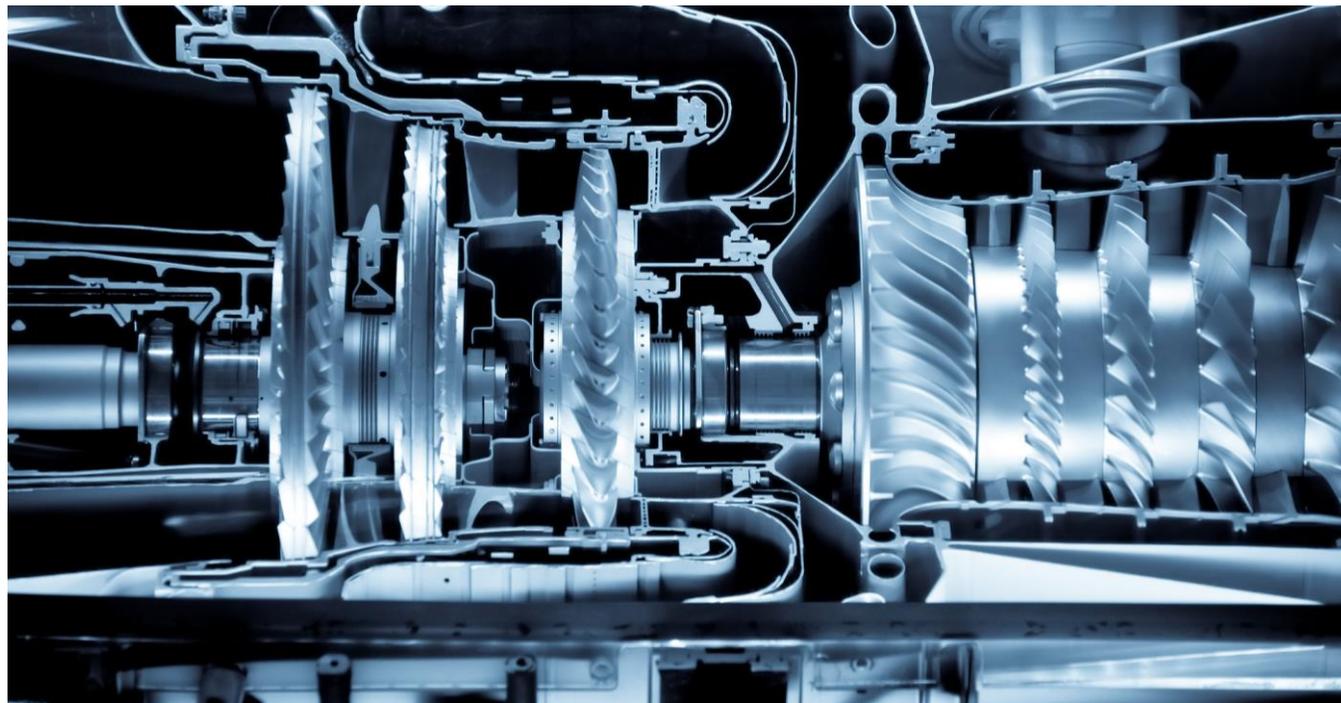
- Cruise Altitude = 5400m Analysis
- Instead of representing the data as a function of turbo RPM, we use fuel/air equivalence ratio
- Note that higher equivalence ratios mean less air and therefore lower turbo RPM
- Shows fairly stable region of operation
- Can be used for feedback control in a correction to feedforward control function





Conclusions

- Demonstrated a holistic system model that incorporates fidelity refinement in sub-components of key influence and interest
- Integrated thermal management system and aspiration/energy recovery turbomachinery
- Demonstrated high efficiency fuel cell electric architecture for zero emission aircraft propulsion
- Simulation results show system can be simulated in a similar manner to the way it is controlled
- Process useful to a MBSE approach to novel technology design



Thank you

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