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Sensitivity analysis of the air compression system for a fuel cell-powered regional aircraft

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DLR

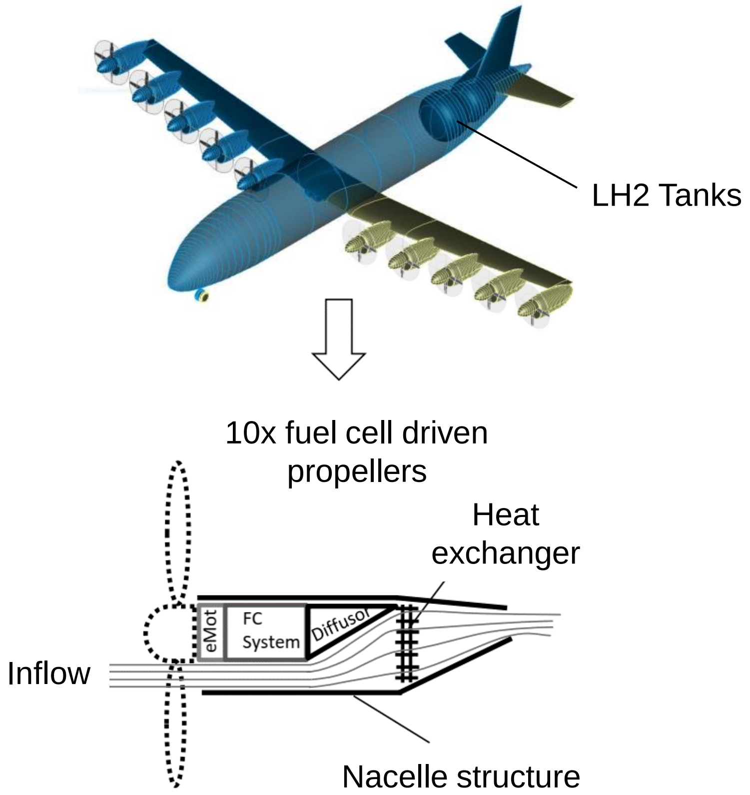
Introduction

DLR is investigating various hydrogen aircraft concepts that can reduce emissions in aviation, e.g.

- Short-range aircraft with hydrogen-burning gas turbines
- Fuel cell-powered regional aircraft
- Hybrid concepts (hydrogen burning gas turbines and fuel cell auxiliary power unit)

This talk focusses on a 70 passenger aircraft where fuel cells provide the entire propulsive power.

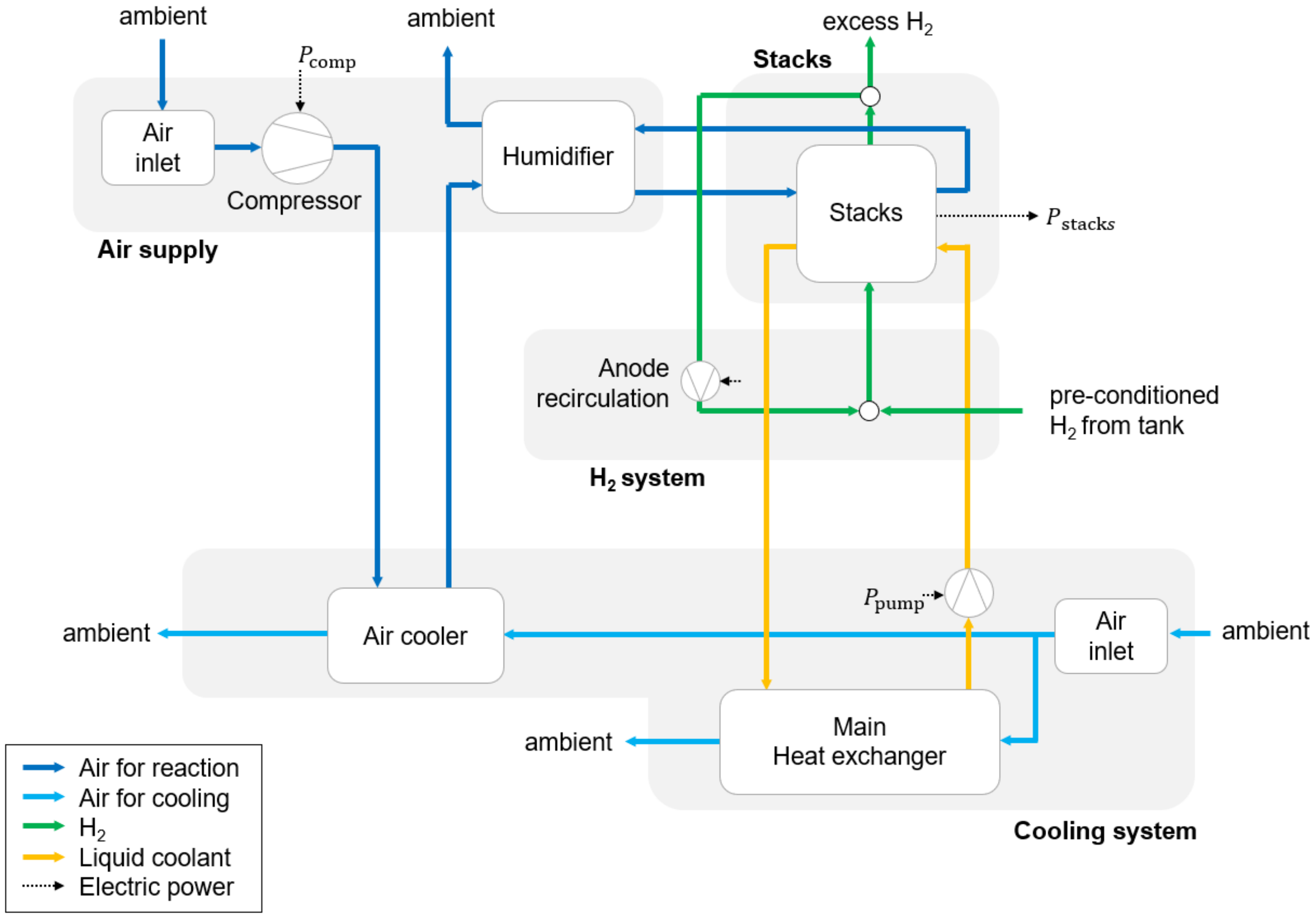
Aircraft Property	Value
Passengers	70
Cruise Speed	Ma. 0.55
Cruise altitude	8840 m
Design range (design target)	1850 km
Max. takeoff weight (design target)	26 tons
Electric power demand at sea level	3.12 MW



Fuel-cell powered regional aircraft concept by G. Atanasov et al. (DLR-SL)

Fuel cell system layout

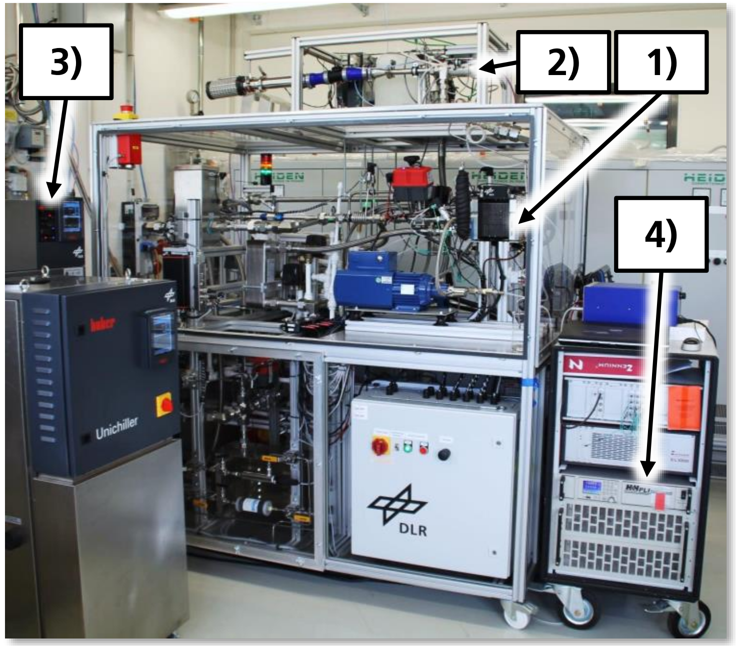
Several auxiliary systems are required in order to operate fuel cell stacks under harsh environmental conditions and at high altitudes.

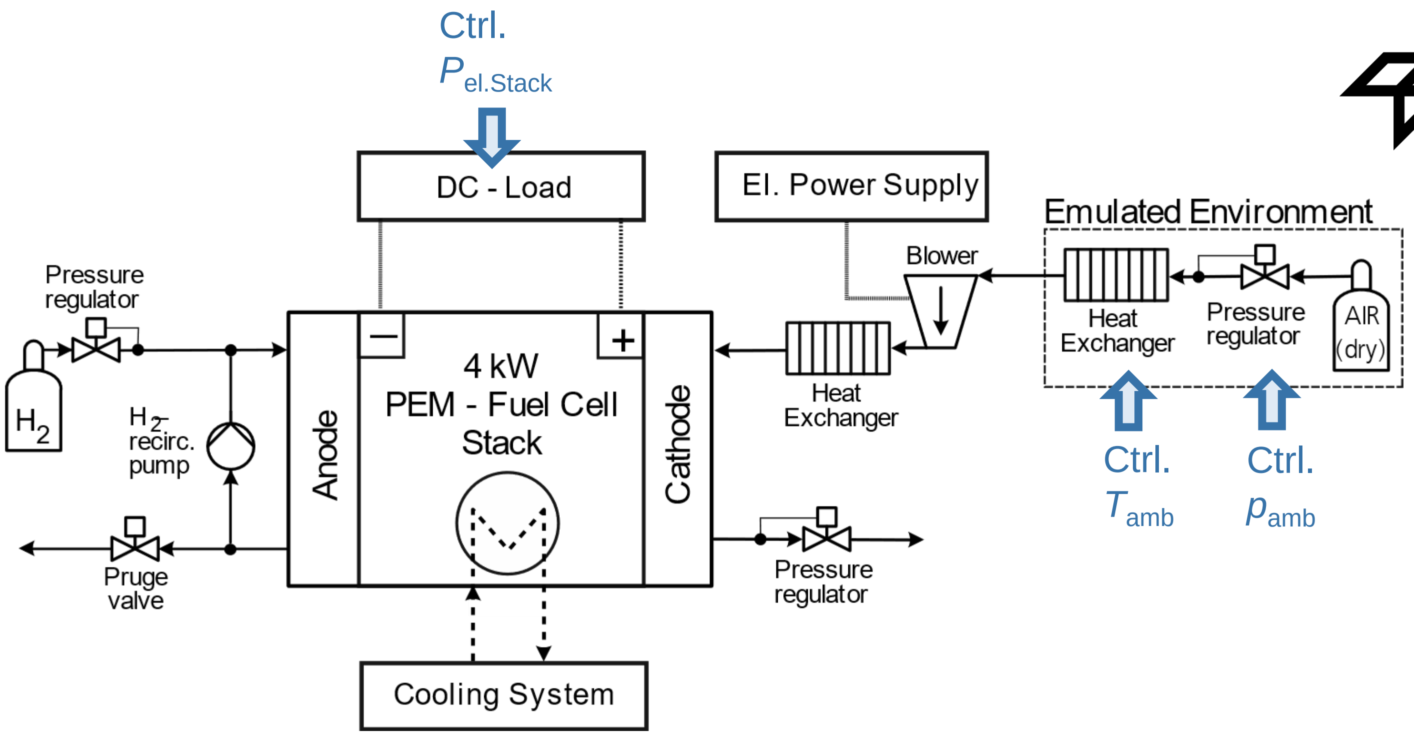


- To achieve sufficient efficiencies at cruise altitude, the fuel cells need to be supplied with compressed and humidified air
- However, the compressor decreases the system's effective power output and limits the feasible operating range
- **Here, we investigate the impact of the compressor on the overall system performance**
  (A) Experimental investigations on a lab-scale centrifugal compressor
  (B) Up-scaled simulations for one pod (312 kW) of the regional aircraft

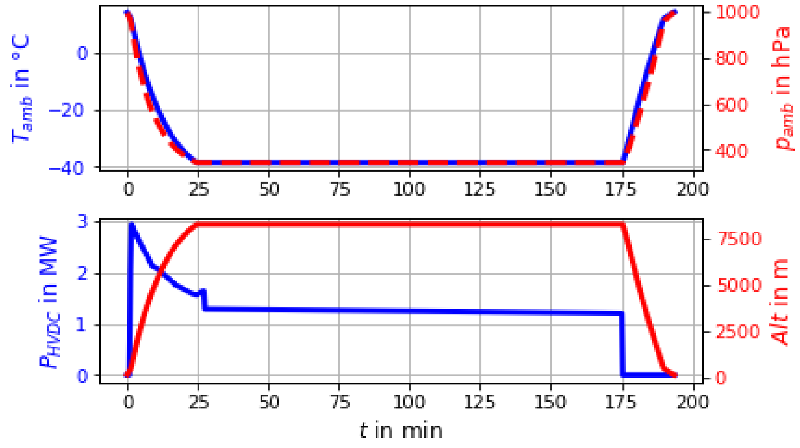
Experimental setup

No.	Component	Description
1)	FC-Stack	*Hydrogenics HyPM® HD4*
2)	Compressor	*Celeroton CT-17-700*
3)	Stack cooling	*Huber Unistat 615W*
4)	DC-Load	*H&H PLI6412*

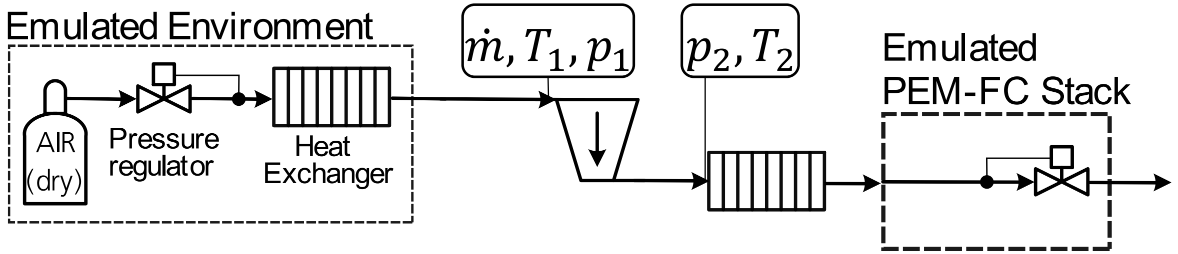




Exemplary mission profile

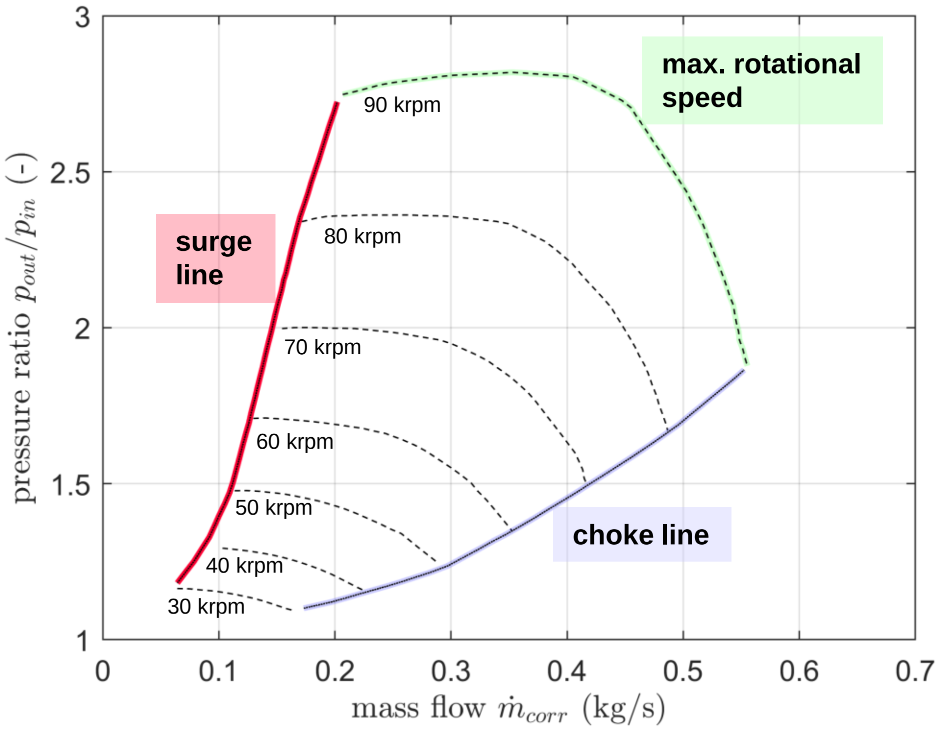


Experimental setup



$$P_{el,Blower} = \frac{\dot{m} \cdot c_p \cdot T_1}{\eta_{\mathrm{is}} \cdot \eta_{\mathrm{el}} \cdot \eta_{\mathrm{mech}}} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]$$

Exemplary compressor map [1]

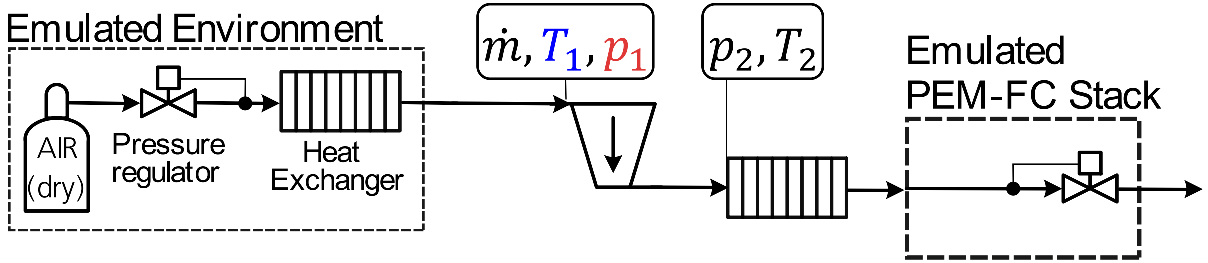


Objective of experimental studies:
Characterisation of a radial compressor under aeronautical operating conditions

- Shift of compressor map
- Shift in efficiency and el. power demand of compressor

→ Establishment of a component model for radial compressor
→ Extension of fuel cell system model for simulative investigation

Theoretical Considerations

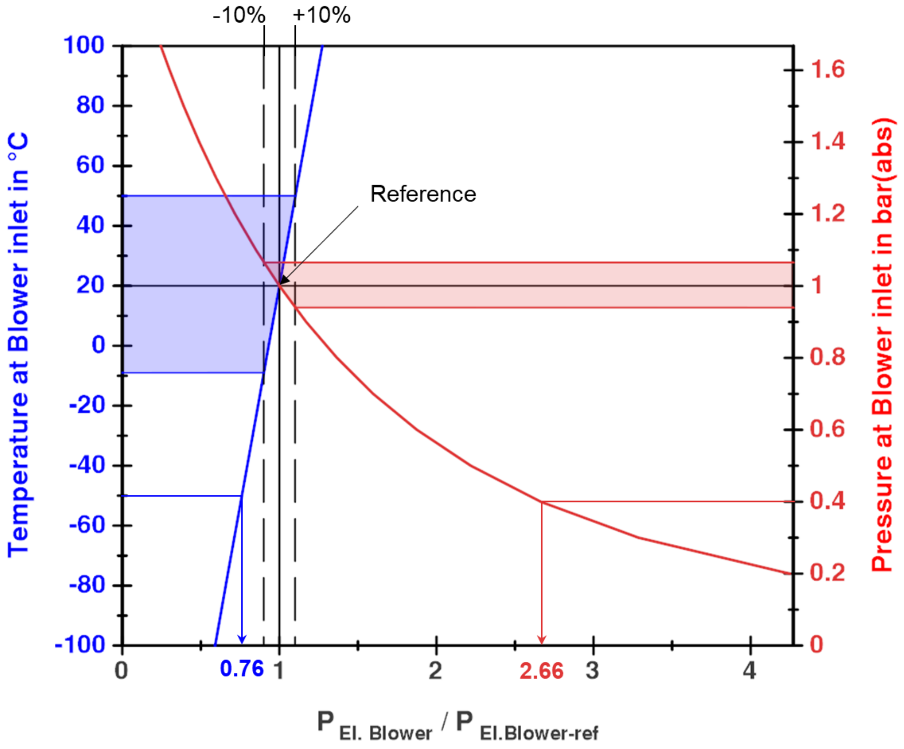


$$P_{el,Blower} = \frac{\dot{m} \cdot c_p \cdot T_1}{\eta_{\mathrm{is}} \cdot \eta_{\mathrm{el}} \cdot \eta_{\mathrm{mech}}} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]$$

Exemplary operational point: $T_1 = -50°C, p_1 = 0{,}4\ bar(abs)$

- Decrease of T_1 from 20°C to -50°C at $p_1 = 1{,}0\ bar(abs)$
  → 24% decrease in el. power demand of blower
- Decrease of p_1 from 1,0 bar(abs) to 0,4 bar(abs) at $T_1 = 20°C$
  → 166% increase in el. power demand of blower
- Total change in el power demand of blower:
  $(0{,}76 \cdot 2{,}66) - 1 = 2{,}03 - 1 = \mathbf{103\%}$

Sensitivity of el. power demand regarding T_1 and p_1

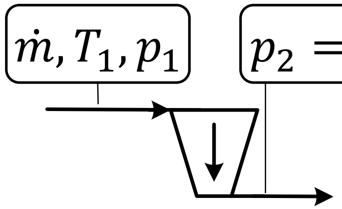


Reference Point:
$p_1 = 1.0$ bar absolute
$p_2 = 2.0$ bar absolute
$T_1 = 20$ °C

Assumption:

$$\frac{\dot{m}}{\eta_{\mathrm{is}} \cdot \eta_{\mathrm{el}} \cdot \eta_{\mathrm{mech}}} = const.$$

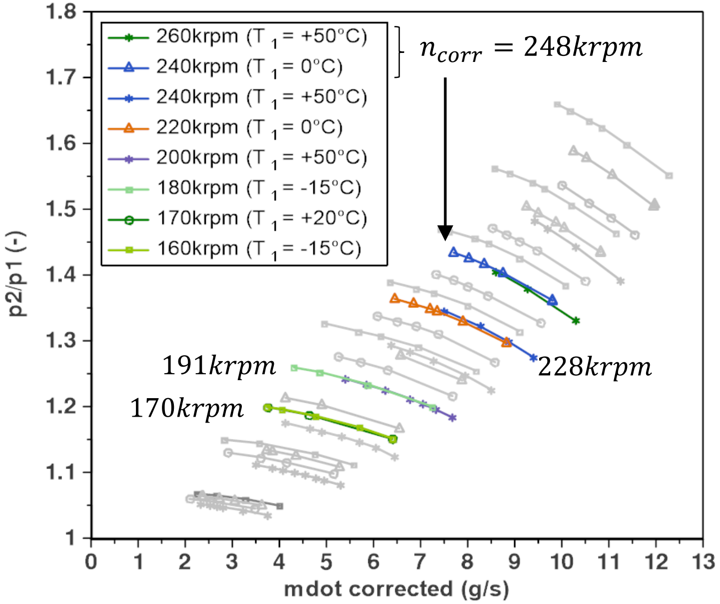
Experimental Results



Measurement data

$$\dot{m}_{corr} = \dot{m}\frac{p_{ref}}{p_1}\frac{\sqrt{T_1}}{\sqrt{T_{ref}}}$$

$$n_{corr} = n\frac{\sqrt{T_{ref}}}{\sqrt{T_1}}$$



By correction of mass flow ($\dot{m}$) and rotational speed (n) of the blower, the measurement results become comparable

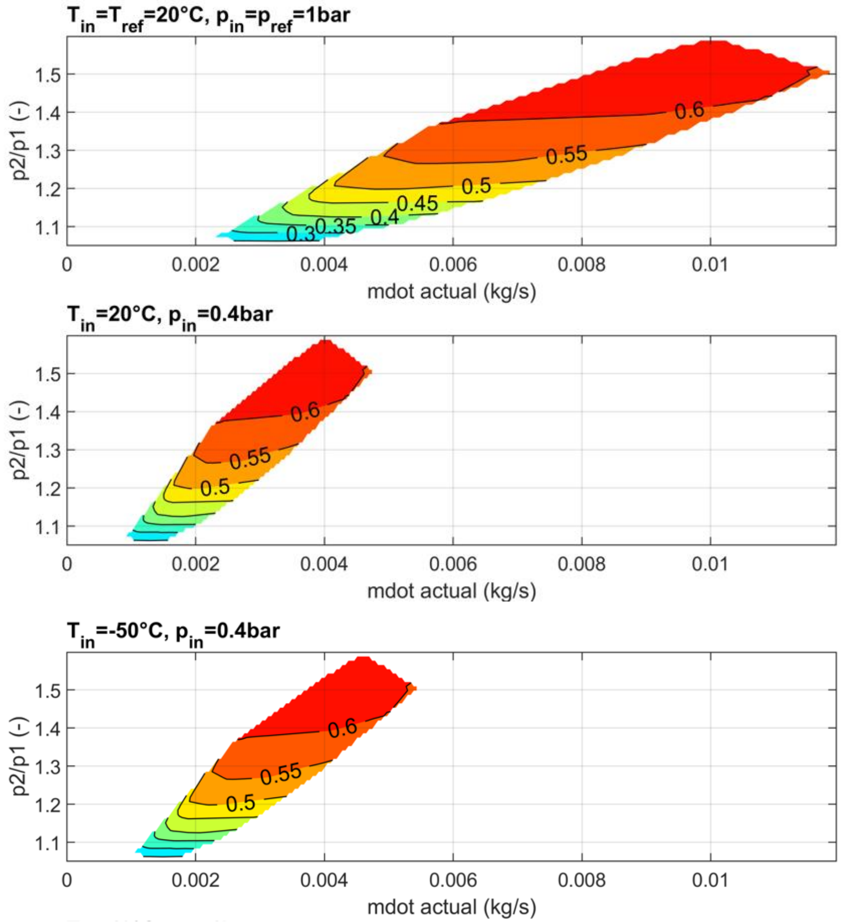
→ Validated method
(Also suitable for axial compressors)

→ Component model for radial compressor established

- Shift of compressor map

- Shift of efficiency

→ Scaling possible



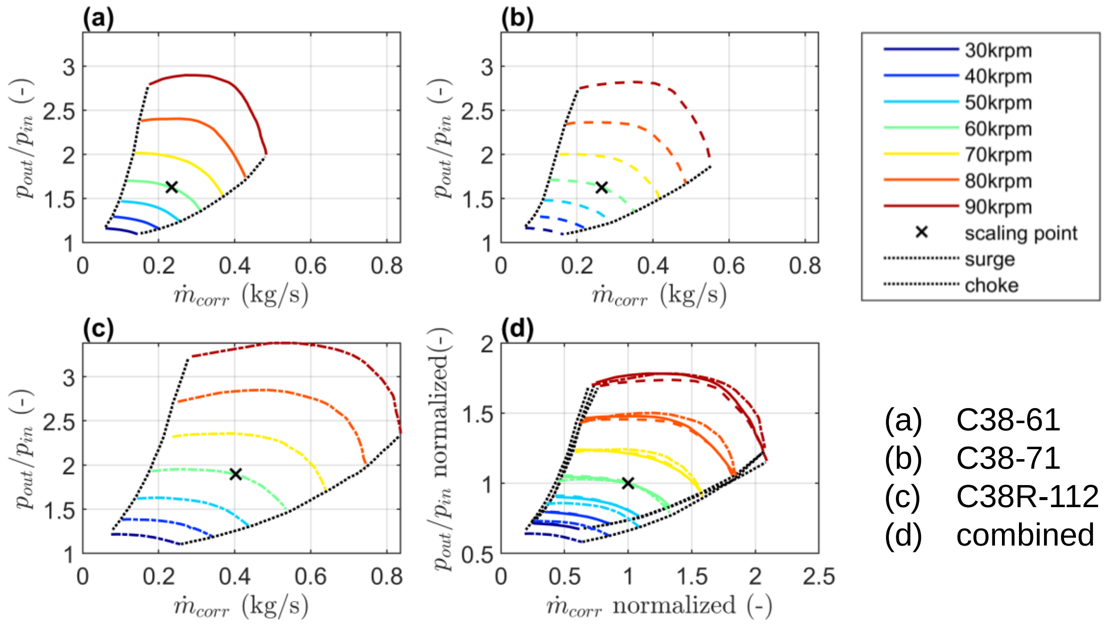
Mach similarity

Simulation - Modeling approach

Compressor model

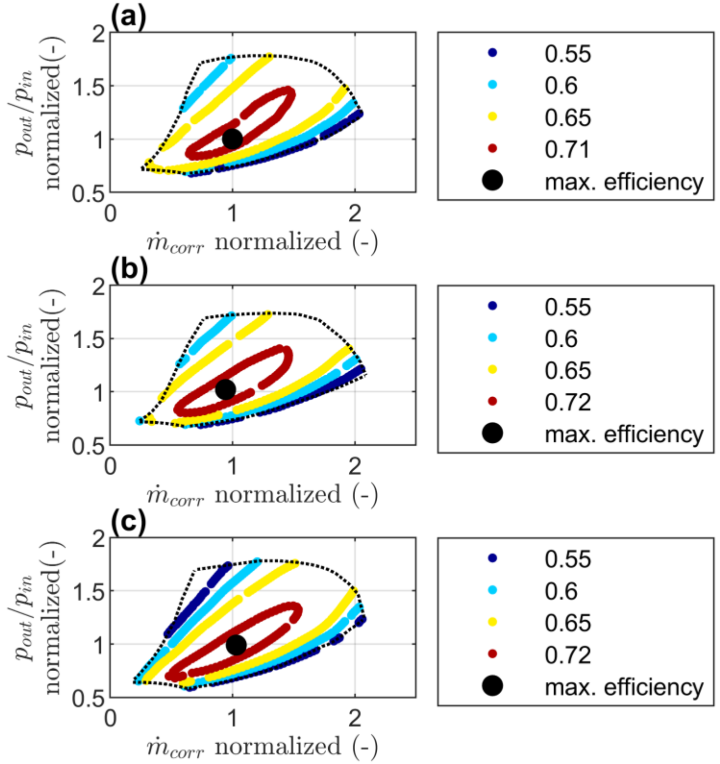
- The experimentally validated approach based on **Mach similarity** is used to predict compressor performance at varying flight altitudes
- Moreover, **geometric similarity** is used to obtain an approximate model for the effect of different compressor sizes (Data from Refs. [1-2]).

Scalable compressor map (rotational speed)*



(a) C38-61
(b) C38-71
(c) C38R-112
(d) combined

Scalable efficiency map*



(a) C38-61
(b) C38-71
(c) C38R-112

*Data is normalized with respect to the point of maximum efficiency:

$$\dot{m}_{corr} = \dot{m}\frac{p_{ref}}{p_1}\frac{\sqrt{T_1}}{\sqrt{T_{ref}}}, \quad \dot{m}_{corr,norm} = \frac{\dot{m}_{corr}}{\dot{m}_{corr}(\eta_{max})}$$

Simulation results

Overall system model:

- The compressor model based on data from Refs. [1-3] is combined with a detailed fuel cell system model developed by DLR [4]

System sizing:

- Each component is sized for the respective critical point during the aircraft's design mission
  - Take-off (312 kW per pod, 0 m, Mach 0.0)
  - Cruise (273 kW per pod, 8840 m, Mach 0.55)

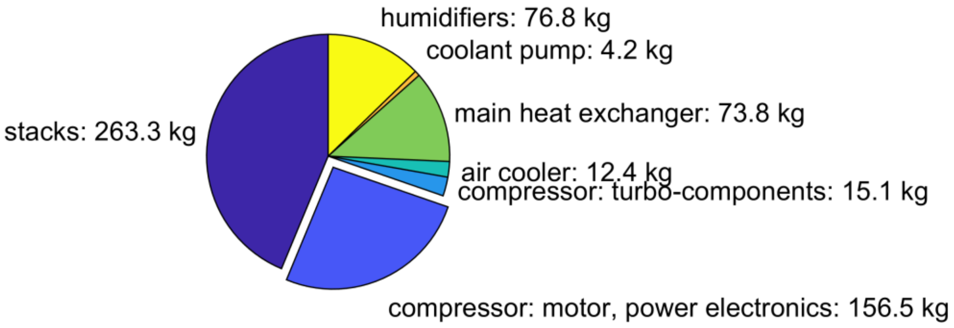
Results:

- When sizing the compressor so that the stacks are operated at 1 bar(abs) and 0.75 A/cm^2 at cruise altitude, the compressor unit becomes the heaviest auxiliary component of the system

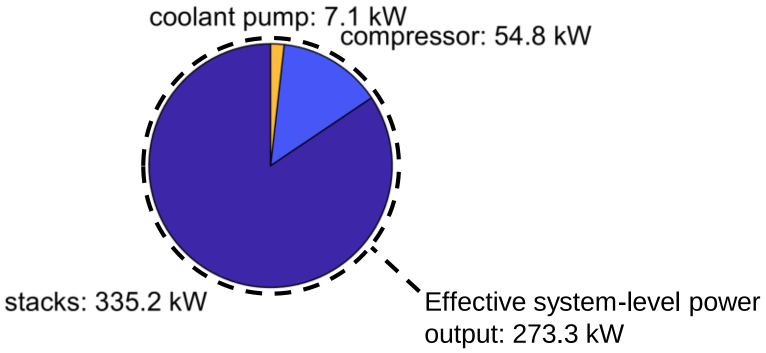
- Higher stack pressures at cruise altitude would likely require multi-stage compressors

- The air cooler mass is negligibly small when designing it for an ambient temperature of 35 °C.

Mass breakdown of the main system components (one of 10 pods)



Power supply/consumption (one of 10 pods)



Conclusions

Methodology:

- The concept of **Mach similarity** was experimentally validated and can accurately predict compressor performance at varying inlet pressures and temperatures

- The concept of **geometric similarity** can be used to approximate maps for different compressor sizes

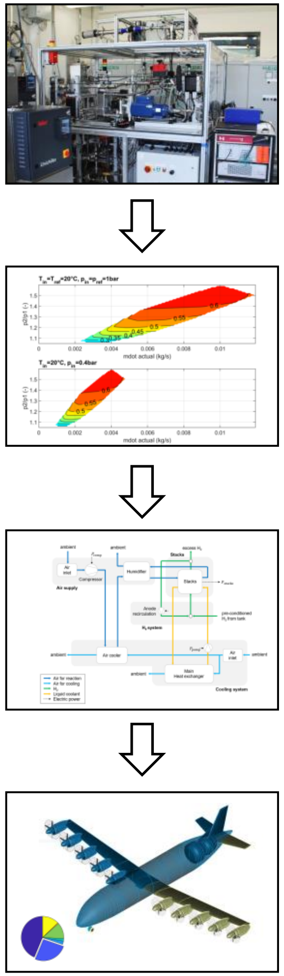
Technology:

- For regional aircraft applications, the compressor unit can become the heaviest auxiliary component in a fuel cell propulsion unit

    - The **high mass of currently available electric compressors** is mainly caused by the **motor and power electronics.** Optimization of these components can significantly improve the overall system’s performance

    - Somewhat decreasing the cruise altitude could improve the overall system performance further (trade-off with aerodynamics)

- In order to achieve higher fuel cell operating pressures (and hence higher efficiencies), multi-stage compressors and/or expansion of the fuel cell exhaust in a turbine stage could improve the performance further



Thank you for your attention

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[2] Rotrex A/S. "ROTREX C-range C38R supercharger." https://www.rotrex.com/wp-content/uploads/2022/01/Rotrex-Technical-Datasheet-C38R-Rev2.0.pdf (accessed Jul 28, 2022)

[3] Rotrex A/S. "Rotrex EK40 Fuel Cell Compressor." https://rotrex-fuel-cell-compressor.com/wp-content/uploads/2022/05/Rotrex-Technical-Datasheet-EK40-Rev1.2.pdf (accessed Jul 28, 2022)

[4] M. Schröder, F. Becker, J. Kallo, and C. Gentner, "Optimal operating conditions of PEM fuel cells in commercial aircraft," International Journal of Hydrogen Energy, vol. 46, no. 66, pp. 33218-33240, 2021, doi: https://doi.org/10.1016/j.ijhydene.2021.07.099