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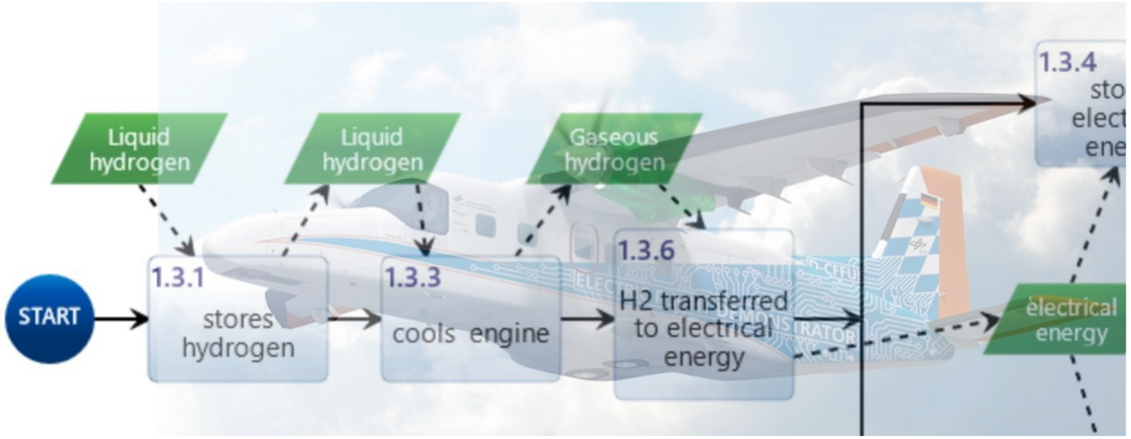

Cryogenic Hydrogen Cooling System for a New Electric Drive System

Prof. Dr.-Ing. André Baeten **06.12.2023**

Affiliation:

Professor of Lightweight Construction, Composite Technology and Technical Mechanics at Augsburg University of Applied Sciences, Germany

Responsibilities:

- Head of the study and research field “composite technology” and “aerospace engineering”
- Head of the test lab “composite materials”
- Point of contact for the Carbon Composites association activities
- Supervisor of PhD candidates
- Research professor in composites technology and fluid structure interaction

Prof. Dr.-Ing. André Baeten

Board of Directors Member of the

International Society of Offshore and Polar Engineers (ISOPE)

Focus: LNG tank design and sloshing analysis

- ISOPE member since 2009
- 15 ISOPE Papers & Presentations
- ISOPE Technical Program Committee (TPC) Member
- ISOPE Sloshing Technical Committee (TC) Chair
- **ISOPE Clean Fuel Symposium Organizer**

The 1st (2022) ISOPE Clean Fuel Symposium

Clean Fuel Production	Clean Fuel Storage	Clean Fuel Transportation	Clean Fuel Standards and Safety Regulations	Clean Fuel Infrastructure	Clean Fuel Sustainability
-wind energy - solar energy - biological processes	-tank design -permeability - gas / liquid	-ship/pipeline -land transport -gas/liquid		-smart grids - local production / central provider	

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Agenda

1. Emission-Free Drive Concepts in Aviation
2. Introducing H2-Cooled Axial Flow Motor
3. Presentation of the Funding Project K-AXFLUX-H2
4. Concept and Technical Realization
5. MBSE-Methodology
6. Cooling with Hydrogen
7. Material Characterization
8. Simulation and Testing
9. Manufacturing
10. Summary and Outlook

Emission-free drive concepts in aviation

Battery electric

Technology easy to control

Low gravimetric energy density/weight of batteries

Synthetic Fuels

CO2-Footprint
Scaling
Price

[Flug Revue]

Hydrogen Direct Combustion

interesting for larger aircraft

e.g.: Airbus ZeroE

Fuel Cell Drive Trains

Future, emission-free and scalable drive system

University and Technical University of Applied Sciences Augsburg:
Projekt K-AXFLUX-H2

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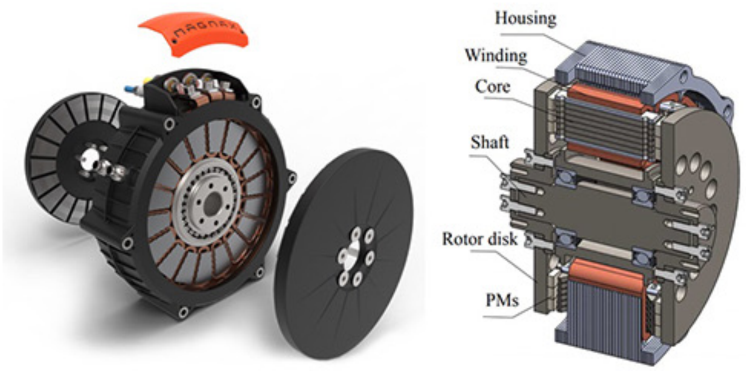
Introducing H2-cooled axial flow motor

Overarching motivation: Sustainable flying using a fuel cell-powered axial flow engine

> Why fuel cell drive?
- Emission-free
- High energy density of LH2

> Why axial flux motor?
- Very high electrical efficiency (approx. 97%)
- Very high overloads possible
- Motor design ideal for internal cooling



[Magnax Motoren]

> Why hydrogen cooling?
- High heat absorption capacity and large T difference; LH2: 20[K] / -253° [C]
- Direct cooling in the windings using hollow conductors

Aim:
Integration of a H2-cooled axial flow motor in a regional distance aircraft

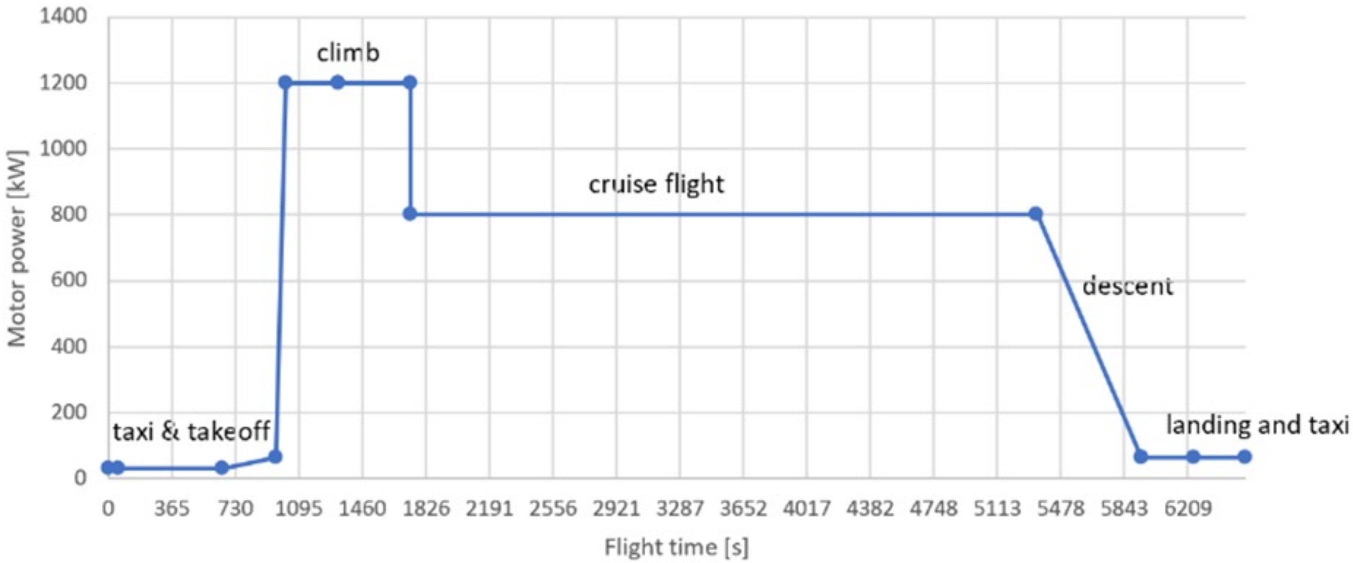
Dornier 228 - research plane of the German Aerospace Center (DLR)

→ Definition of a characteristic flight cycle

→ Definition of the necessary power output

→ Requirement of limited assembly space in the aircraft

→ Target efficiency (electrical) of 97%



Flight profile of the twin-engine DO 228 as the basic requirement

Power output:	600 kW per motor	**Cruise Altitude:**	30,000 ft
Heat dissipation:	14.04 MJ	**Propeller speed:**	1500 rpm

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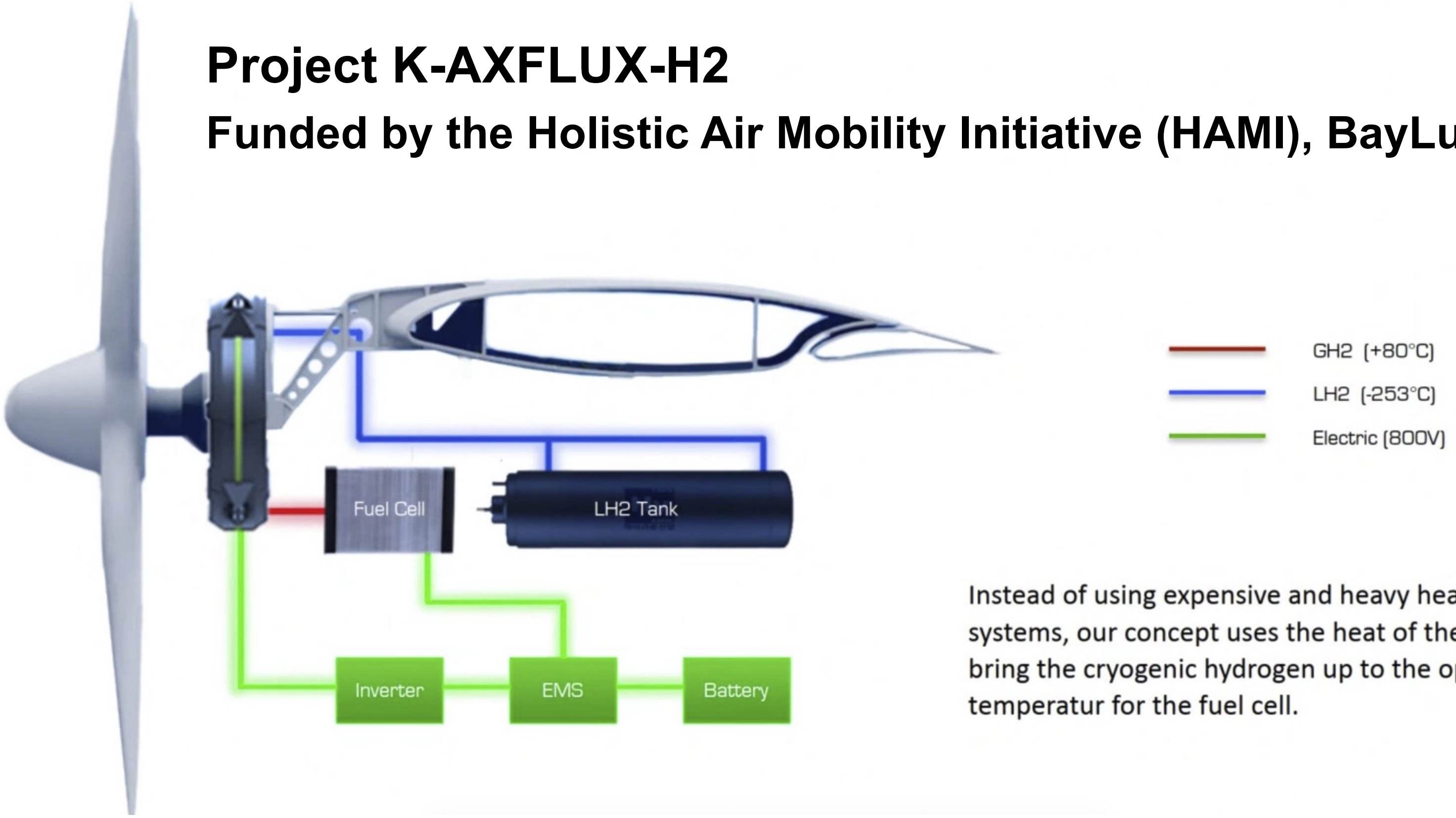
Project K-AXFLUX-H2

Funded by the Holistic Air Mobility Initiative (HAMI), BayLu25



Instead of using expensive and heavy heat exchange systems, our concept uses the heat of the E-motor to bring the cryogenic hydrogen up to the operating temperatur for the fuel cell.

Universität Augsburg University
Hochschule Augsburg University of Applied Scie
Gefördert durch:
Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie

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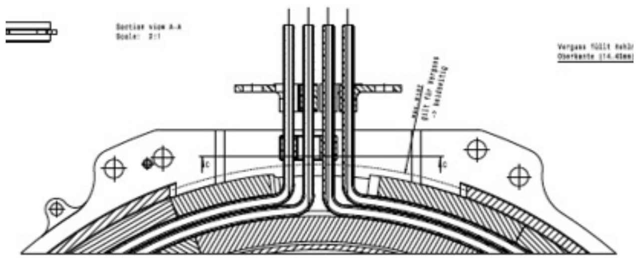
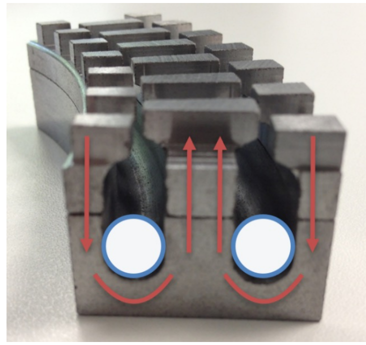
Cryogenic hydrogen flows through the tubes for cooling



[Josef Schnöll]

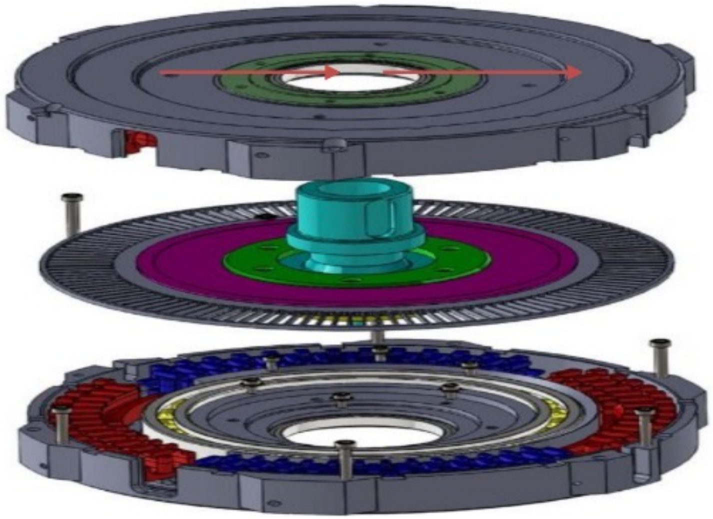


[Josef Schnöll]

Continous hydrogen flow

Phase transition

Heat transition



[Josef Schnöll]

Temperature range

Thermal material expansion

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Aircraft (DO228): flight profile (aircraft specifications and flight phases defined by duration, altitude, speed, etc.)

Resulting requirement: engine performence

Axial Flux Engine: For the climp phase, the engine must deliver an output of 600 kW for a duration of 13 min

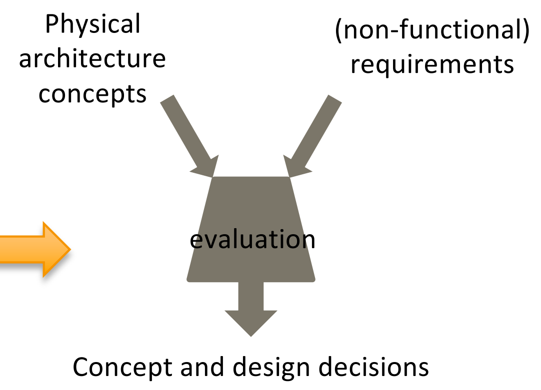
Resulting requirement : cooling performance

Cooling System: The cooling system must be able to dissipate a heat quantity of 3.93 kWh (14.04 MJ) in a period of 13 minutes

Requirements analysis

Functional analysis:
Thermal transfer
using hydrogen as
transport medium

Cooling element:
3.3 kg of hydrogen must be transported through the cooling tubes within 13 minutes



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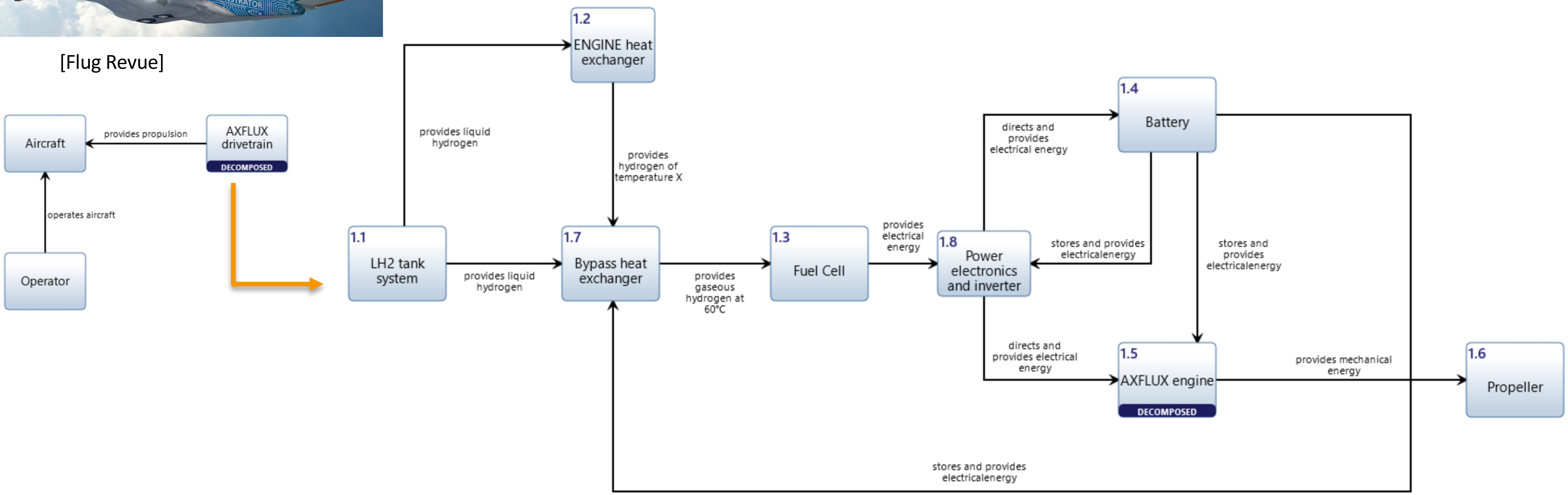
Model-Based Systems Engineering (MBSE) Approach for the design and verification of the drive train including the cooling system

[Flug Revue]

Powertrain system layout (functional)



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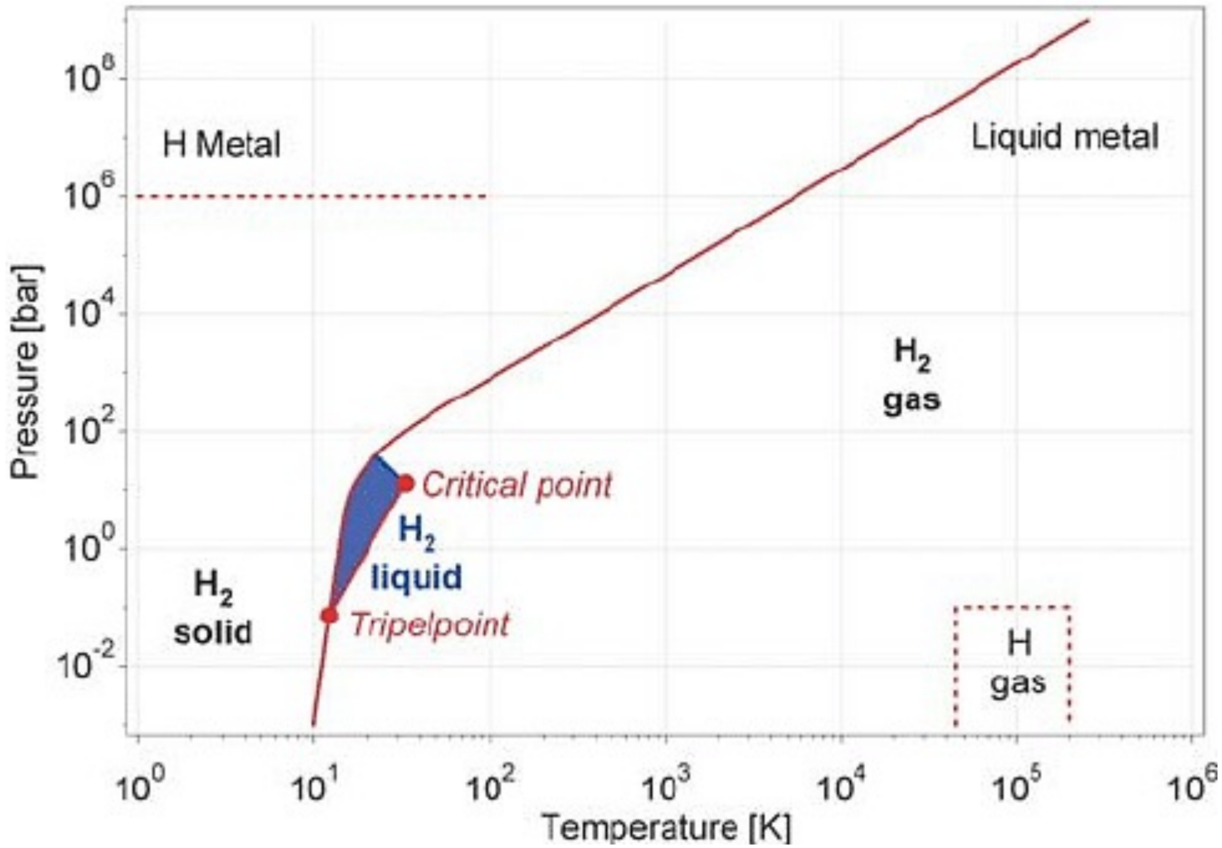
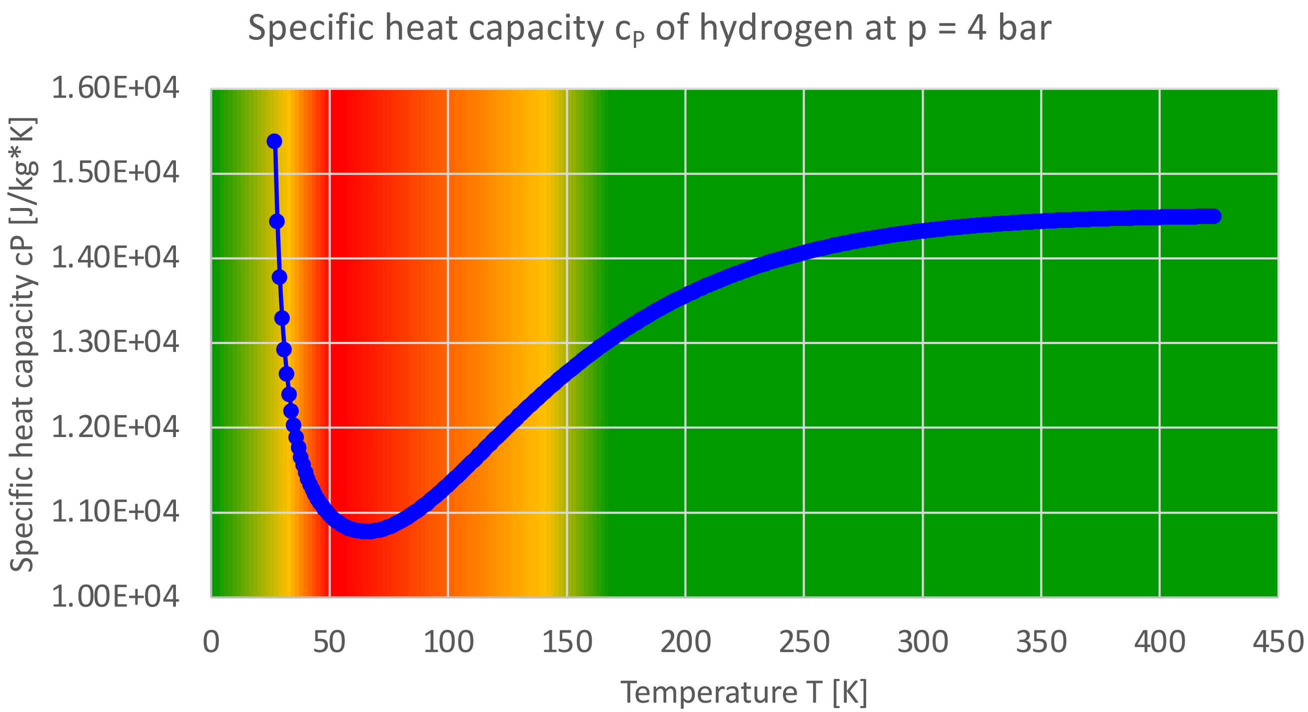
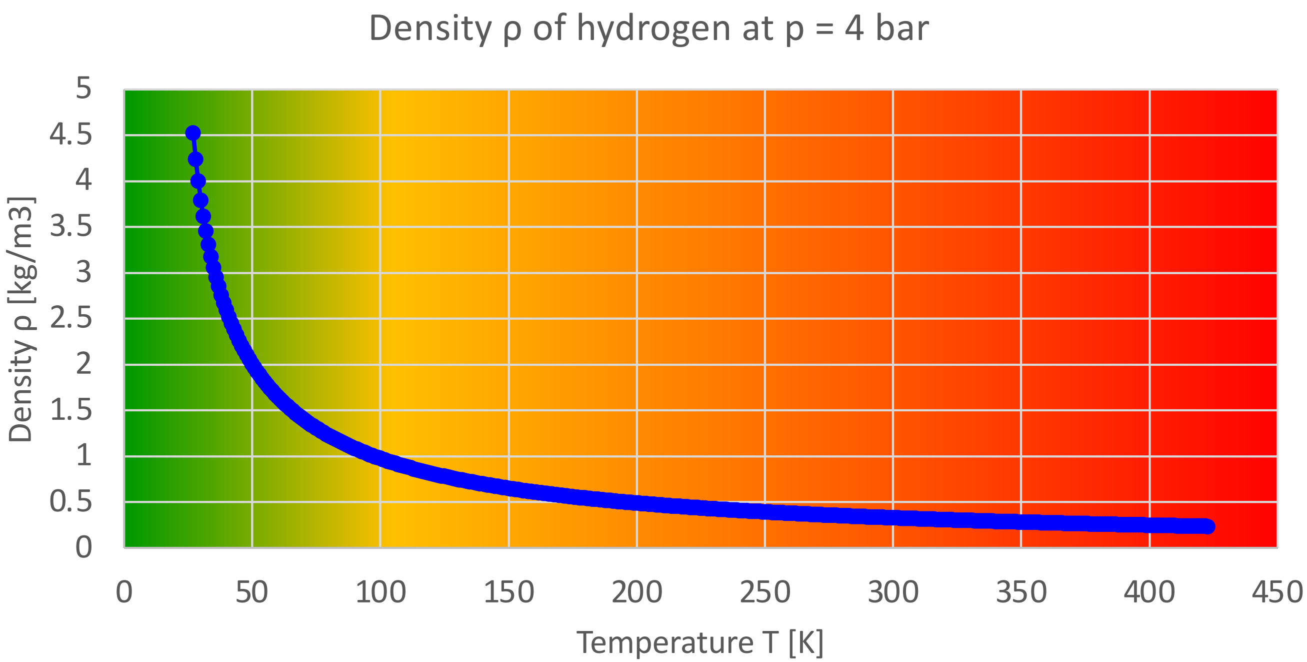
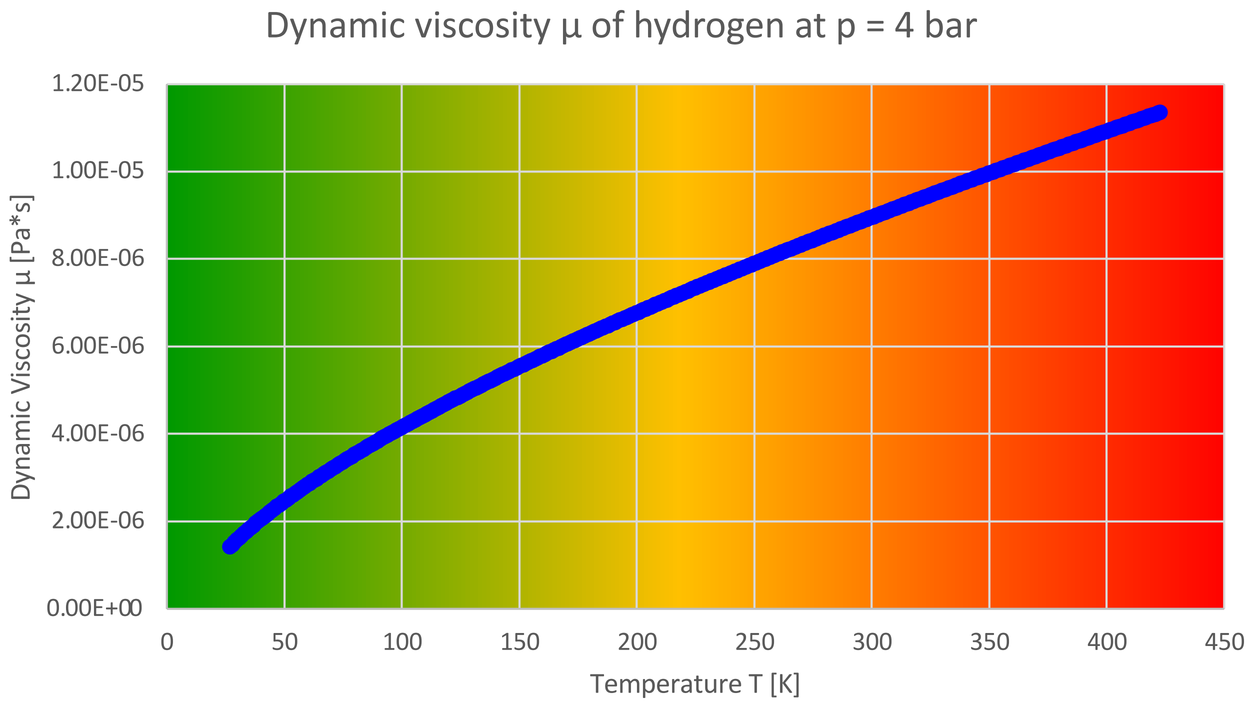


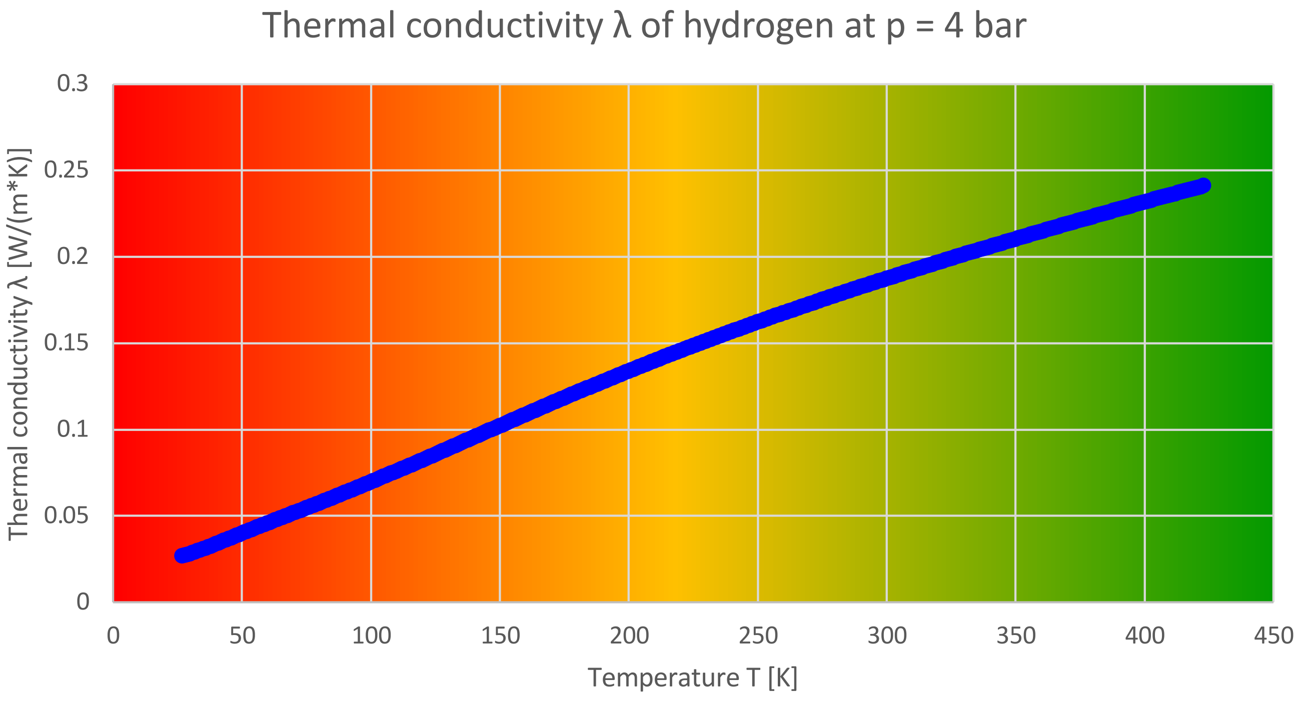
Hydrogen heat transfer Depends on

- Phase transition
- Boil-off Rate
- Turbulence
- Compressibility effects


Specific heat capacity cP of hydrogen at p = 4 bar
Specific heat capacity cP [J/kg*K]
1.60E+04
1.50E+04
1.40E+04
1.30E+04
1.20E+04
1.10E+04
1.00E+04
0
50
100
150
200
250
300
350
400
450
Temperature T [K]


Density ρ of hydrogen at p = 4 bar
Density ρ [kg/m3]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
Temperature T [K]


Dynamic viscosity µ of hydrogen at p = 4 bar
Dynamic Viscosity µ [Pa*s]
1.20E-05
1.00E-05
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
0
50
100
150
200
250
300
350
400
450
Temperature T [K]


Thermal conductivity λ of hydrogen at p = 4 bar
Thermal conductivity λ [W/(m*K)]
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Temperature T [K]

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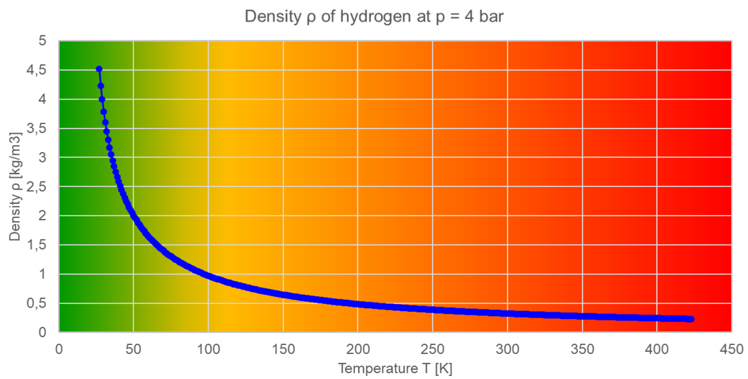
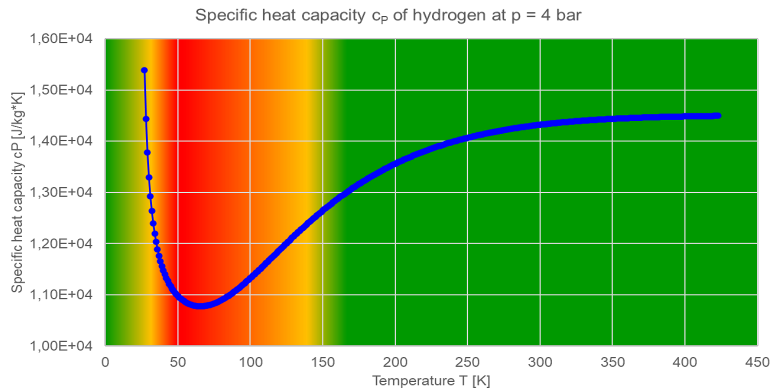
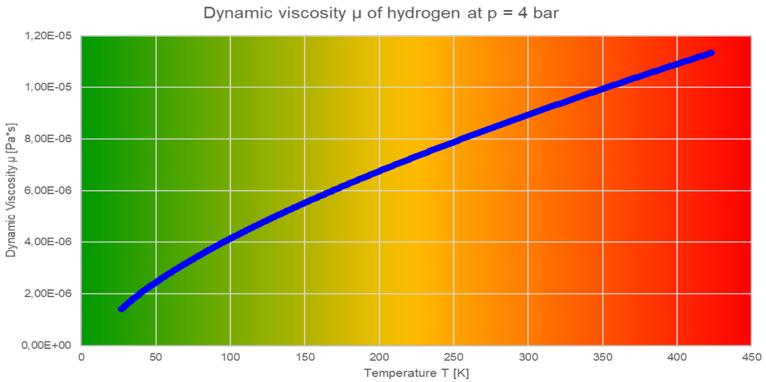
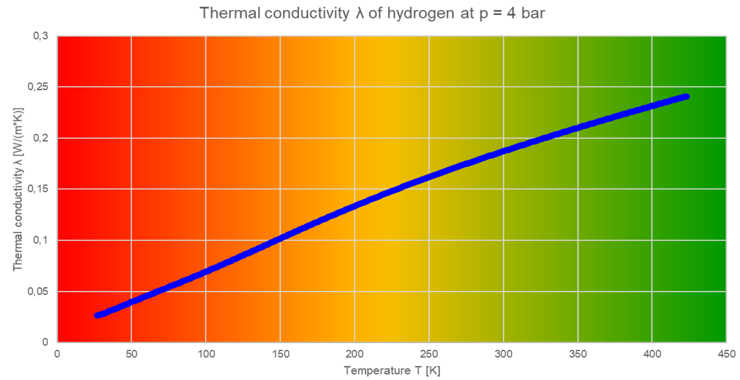
Ideal temperature scope for hydrogen in a cooling system is between 150 K and 250 K









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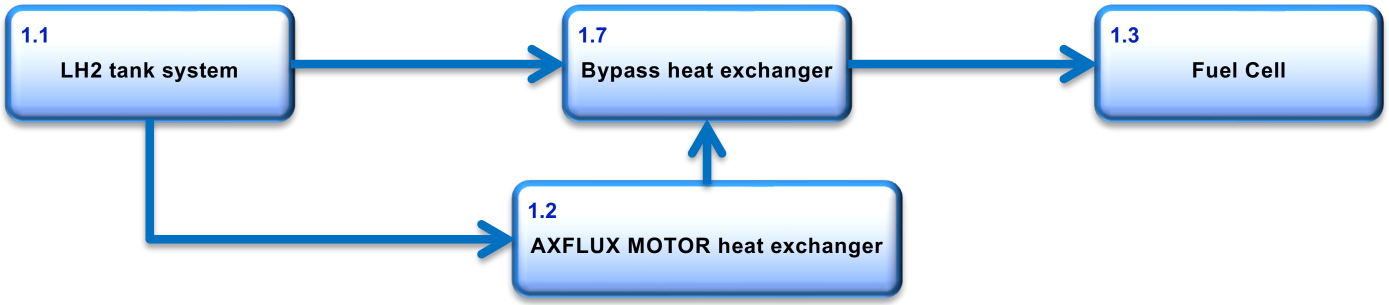
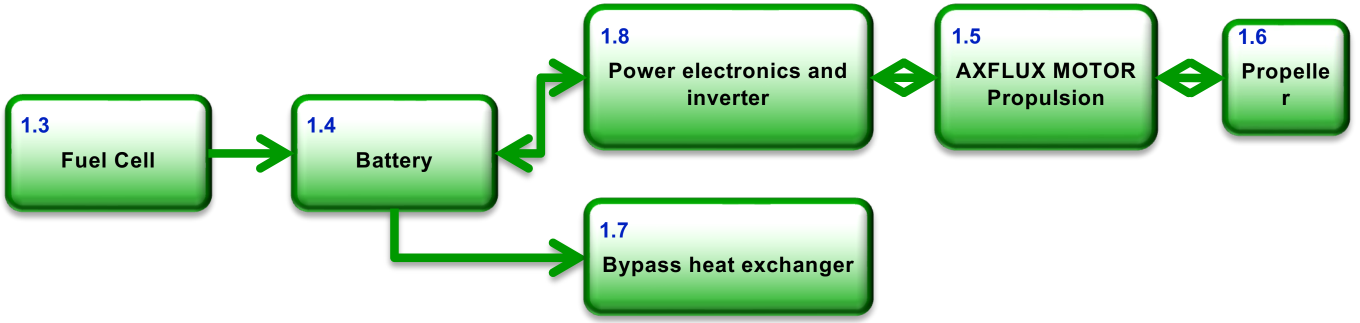


Energy flow system



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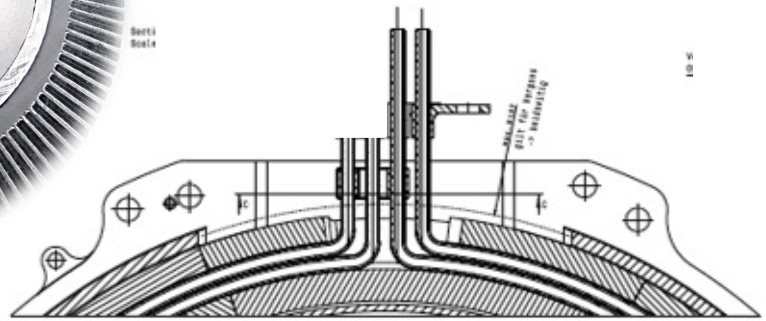
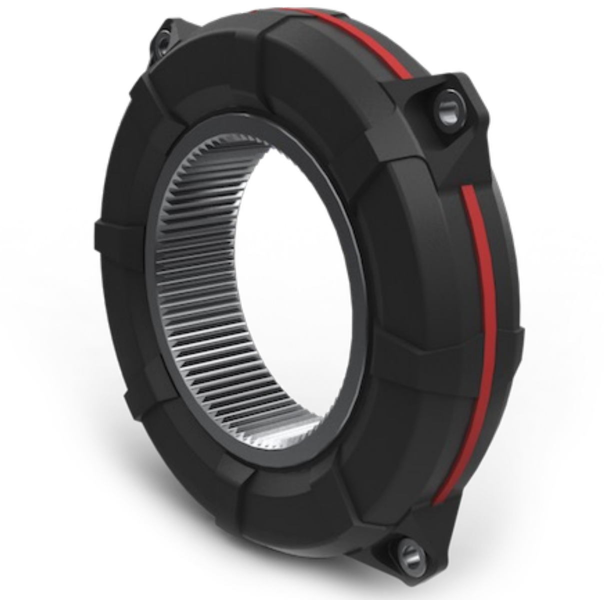
Housing:

- Engine suspension
- Shielding to the outside
- Lightweight construction





Rotor / Stator:

- Lightweight rotor, high stiffness
- Excellent magnetic properties
- Lowest possible thermal expansion
- Heat transfer in minimal installation space

Electrical and thermal insulation of the hollow conductors:

- Sealing function against hydrogen
- High electrical currents
- Multi-pole design with a very high packing density

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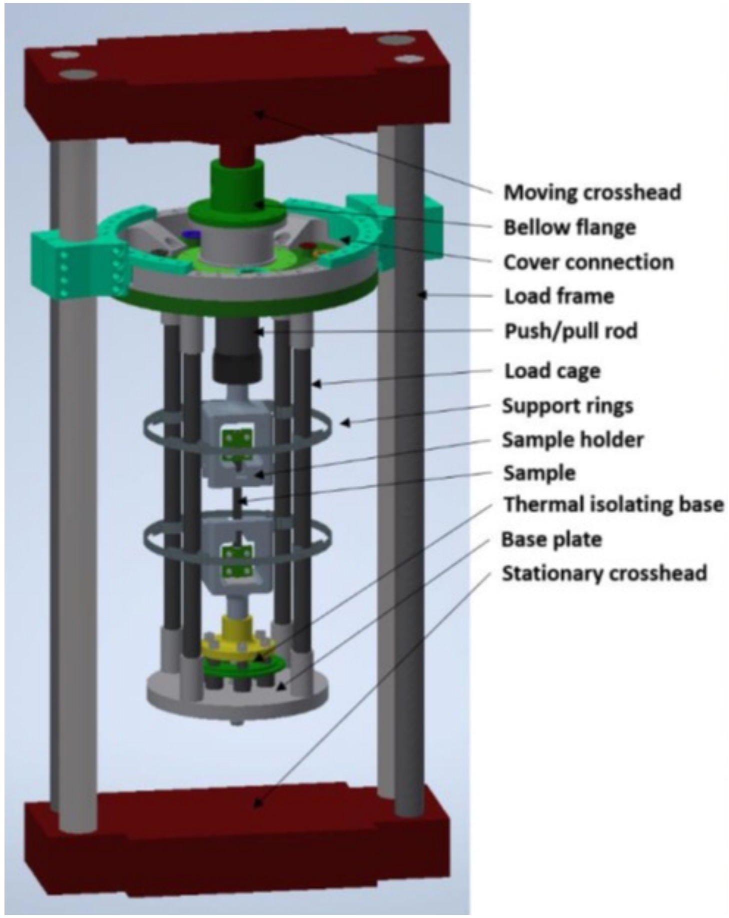
Immersion cooling



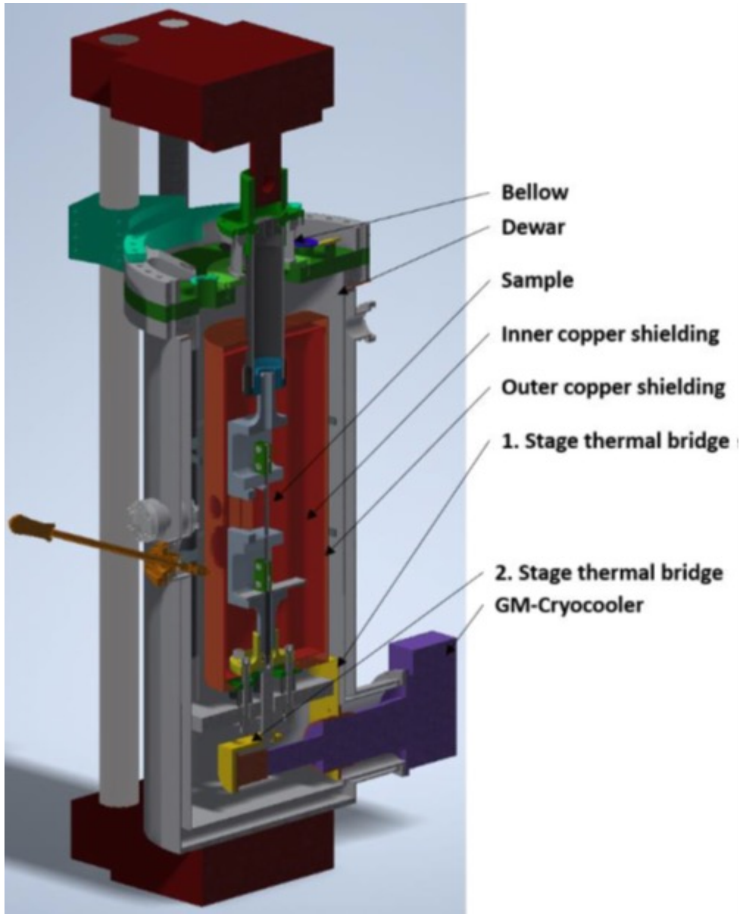
- Proven and easy method
- Immersion of the entire specimen
- Subsequently clamping and testing

Drawback

- Limited to the boiling temperature of hydrogen
- Rapid reheating of the sample
- No exact values at specified temperatures

Improvement

- Cooling the sample directly in the test device
- Cooling in an insulated chamber



Cryocooler

- Closed cooling circuit
- Gifford-McMahon cooler
- Determination of characteristic values at defined temperatures

Drawback

Increased costs

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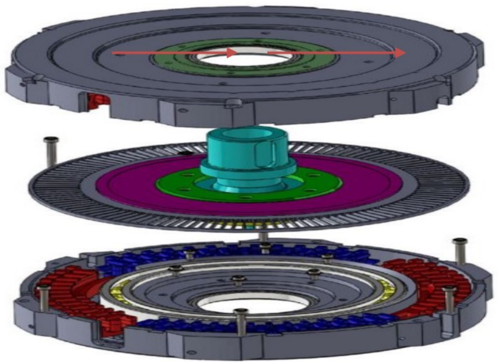
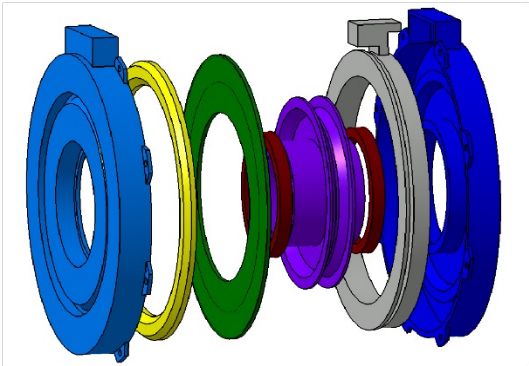
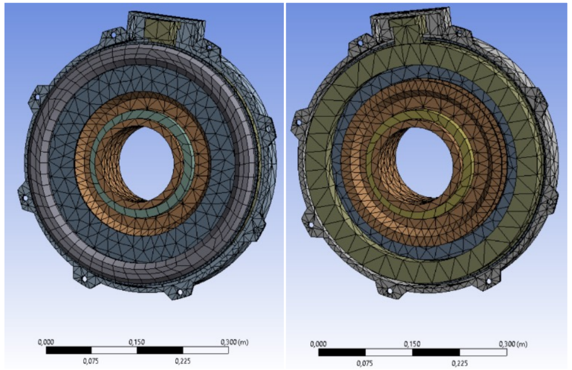


Basic CAD model



Simplified CAD model



Tetrahedrally meshed CAD model

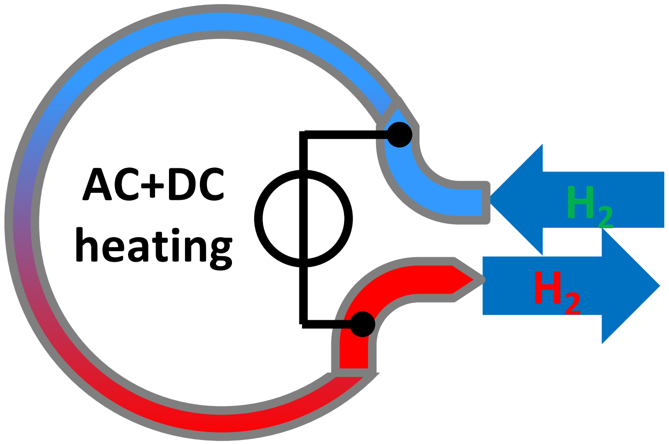
No overlapping of the eigen frequencies

Boundary Conditions:

- Housing-tabs as fixed support
- Shaft as cylindrical support with rotational freedom

Mass flow $\dot{m}$, fluid flow velocity v and waste heat $\dot{Q}$ at Input & Output constant => Main parameter

Changing heat transfer into the hydrogen



Output parameters:

- X H2 $\mathbf{T_2}$ at the exit
- X H2 $\mathbf{p_2}$ at the exit

Calculation of futher parameters (density, velocity, volume flow) at the Input

↓

Charaterisation of the fluid flow behaviour (turbulent/laminar) with the Reynolds number for tubes

↓

Calculation of the pressure loss at the entrace caused by the tube

↓

Determining of the exit temperature with the thermal efficiency of the motor

Heat flux calculation

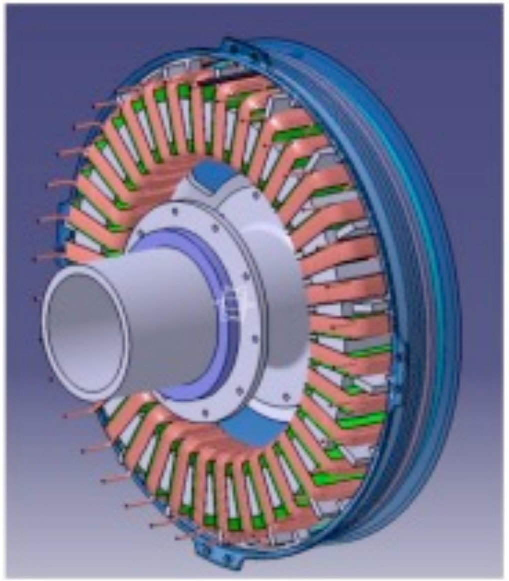
- Wall surface of the ring conductor: $S = d_{tube} * \pi * l_{tube}$
- Assumption: All of the unseable energy is converted to heat

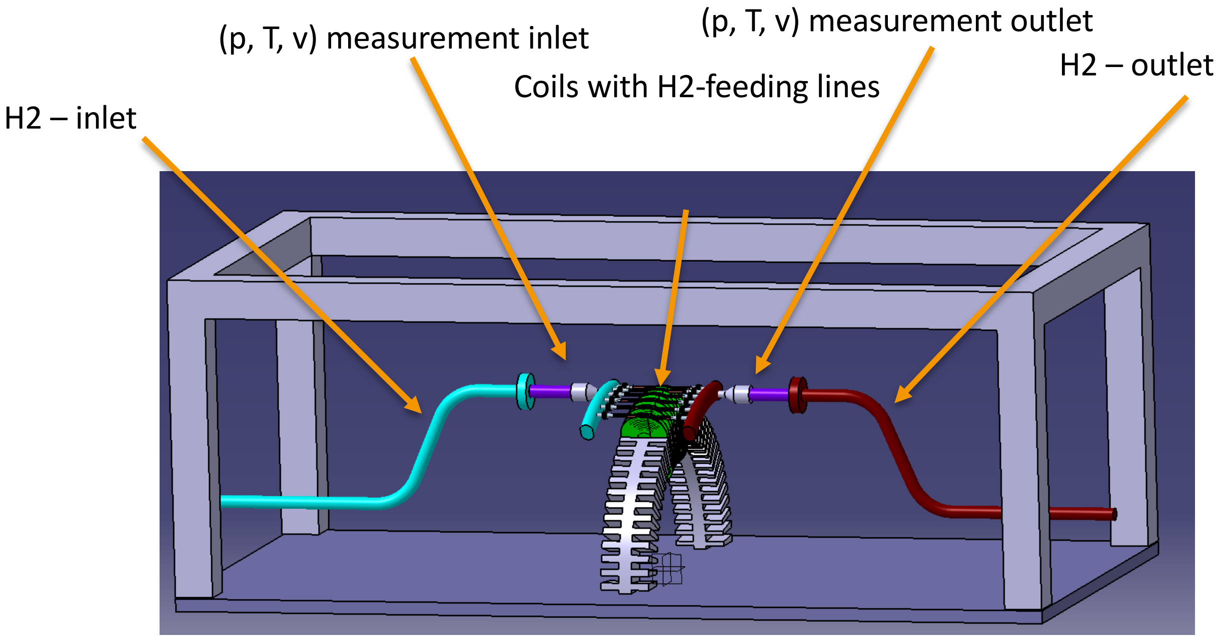
$$\dot{Q} = P_{Motor} * (1 - \eta_{Motor}) \quad \Rightarrow \Phi_q = \frac{\dot{Q}}{S}$$

Motor data for calculation	
P_{motor}	200 [kW]
η_{motor}	95 [%]
d_{tube}	3.2 [mm]
L_{tube}	1106 [mm]

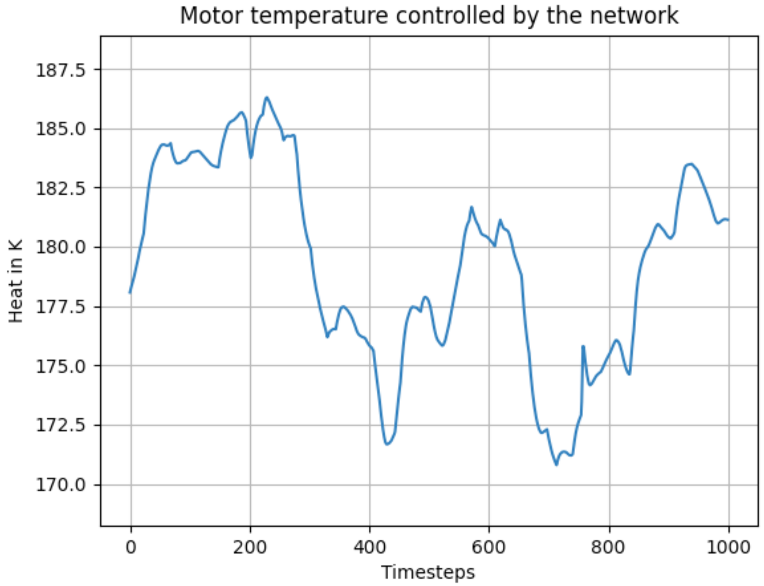
Fluid flow data	
p_{Inlet}	4 [bar]
T_{Inlet}	30 [K]
$\dot{m}_{hydrogen}$	0.0005 [kg/s]

AI-supported virtual and real testing

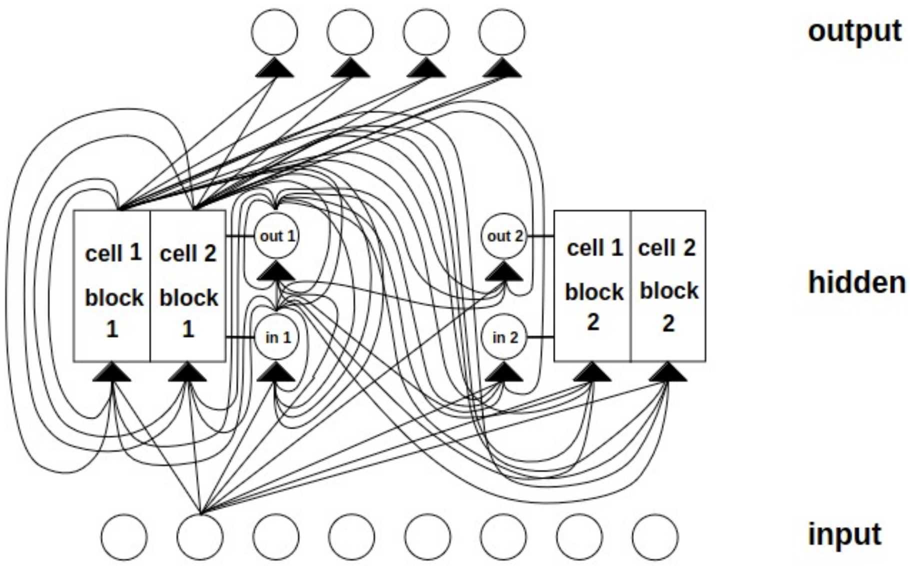




AI-based control loop for the H2 cooling system



Long-Short-Term-Memory (LSTM) Neuronal Network



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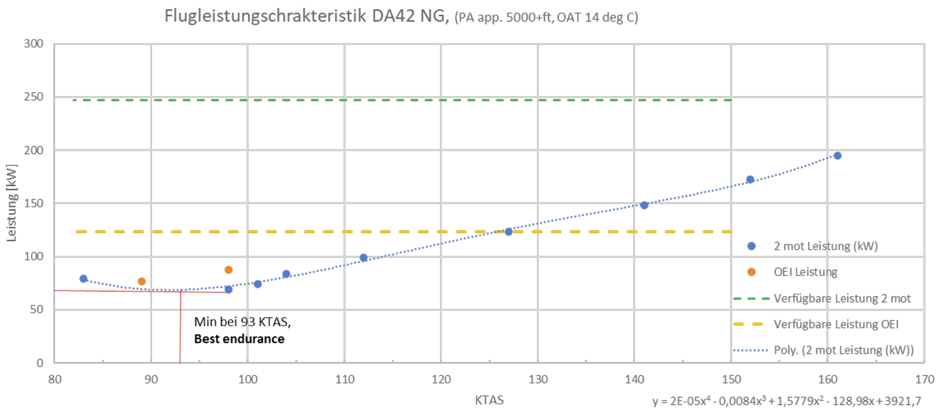
AI-based Operational Testing

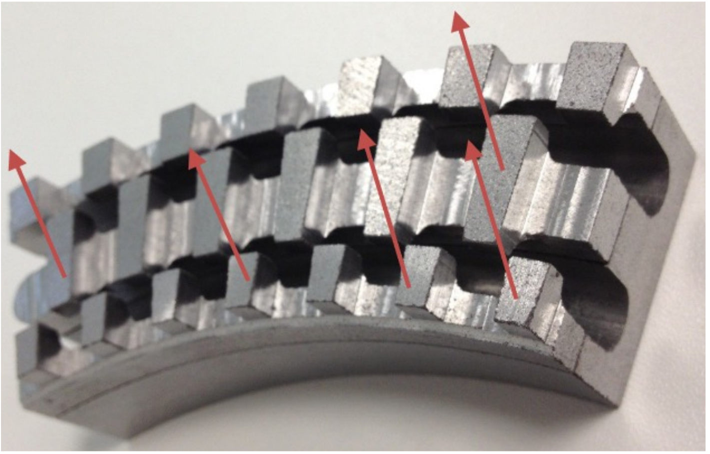


Aim:

Integration of the H2-cooled E-motor in theDLR flying test bed Do 228

Way ahead:

Evaluation of measurement flights with the DA 42NG aircraft and training of MBL-algorithms, extrapolation to Do 228



Additive manufacturing

- grants more design freedom
- manufacturing of challenging geometries
- optimal usage of the limited installation space

Component	Stator	Housing, Insulators	Rotor
Challenge	Challenging geometry	Lightweight	Stiffness, Lightweight
Technology	Metal 3D-printing (EBM, SLS, DMLS)	Polymer 3D-printing (FDM)	CFRP Additive Manufacturing (FPP)

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Equipment in the new MRM research building

3D-Printer (1 m^3),
Fiber Patch Placement system,
Multi-function composite draping cell)
Autoclave (2m x 1m)

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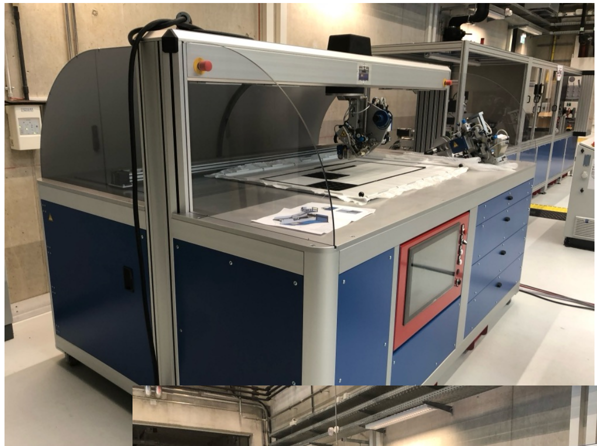
Equipment in the new MRM research building



Tape production machine (C-fibers, bio-based fibers)
Cross layer: 2D – 3D tape layer dry fibers / prepregs

Faculty of Mechanical Engineering – Research group HSA_comp

Level: Bachelor Degree, Master Degree, Thesis or Group Project

Concept Study of a Cryogenic Hydrogen Cooled Axial Flux Engine for Aerospace Applications

In this project a concept study for a lightweight cryogenic hydrogen cooled axial flux motor is developed. The concept is based on a hybrid material design to fulfill the electro-magnetic, thermal, chemical, and mechanical requirements for a high-performance electrical drive train for Urban Air Mobility (UAM) applications. The concept study focuses on the virtual pre-design of the rotor stator combination and the cooling system using composites and ferromagnetic materials. FE and electro-magnetic performance simulation results based on trade studies will be performed. Additionally, a Design of Experiment (DoE) will be derived for the thermal and chemical material characterization of the cooling system operated with cryogenic hydrogen.

Scope of the internship is to get familiar with high-technology simulation and testing tools used to design a complex electrical motor cooled with cryogenic hydrogen. The internship covers:

- Support of the Design of Experiment for H2-cooled axial flux engines
- Support of the development of an AI-based thermodynamical control loop of the cooling system
- Hydrogen safety assessment
- CFD / FE simulations and electromagnetic simulations of an axial flux engine
- Model-Based Systems Engineering (MBSE): Set up of model functions for the hydrogen cooling system

Summary

- As an energy source, hydrogen is an essential part of the solution for the mobility of the future
- Significant reduction of thermal losses in the drive train by utilizing the heat capacity of cryogenic hydrogen
- Result: Lightweight, compact, highly efficient and scalable powertrain
- As part of the K-AXFLUX-H2 funding project, design methodologies are being developed that help to significantly reduce the very high costs for the design and production of hydrogen-based drive technologies (MBSE)

Outlook

- Functional demonstrator with integrated H2 cooling system in the 300 kW power range, available in 2024 and ready for testing in aircraft

Prof. Dr.-Ing. André Baeten

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