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DEVELOPMENT OF ADDITIVELY MANUFACTURED CRYOGENIC HEAT EXCHANGERS FOR HYDROGEN-ELECTRIC AIRCRAFT PROPULSION

11.07.2023 | DR.-ING. MARCO VIETZE | CEC/ICMC 2023 | C2OR2B-03

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

AdHyBau
Lufo VI-1

Project "AdHyBau" → hydrogen-electric propulsion system for aviation

Engineering Design	• Efficient coil design and optimized cooling systems through additive manufacturing for high power density electric machines ► 10 kW/kg • Cryogenic hydrogen as cooling medium and energy source • New lightweight design of hybrid structures with fiber reinforced composites and additively manufactured metal components
Simulation	• Digitalization in product development ► design and simulation process based on a digital twin of electric machines
Materials	• Investigation of cryogenic material properties of additively manufactured test specimens • Influence of hydrogen on additively manufactured materials

SIEMENS

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Fraunhofer IWM

KIT Karlsruher Institut für Technologie

Institut für Leichtbau und Kunststofftechnik

Project partners at CEC/ICMC 2023

Date Time	Room	Title	Speaker	Session ID
Monday 9:30 AM	Emalani 320	Additive Manufacturing and hybrid materials in high power…	Ch. Weidermann	J1 Or 1A
Monday 5:45 PM	Emalani 320	New concept for cryogenic gaseous hydrogen-cooled lightweight electric engine	M. Pohl	M1 Or 3G
Tuesday 11:30 AM	315	Development of additively manufactured cryogenic heat exchangers for hydrogen-ele…	M. Vietze	C2 Or 2B
Wednesday 10:30 AM	318	Cryogenic material testing with gaseous hydrogen for hydrogen-electric aircraft prop…	F. Ebling	M3 Or 1A
Wednesday 11:00 AM	318	Cryogenic thermo-physical properties of additive manufactured…	K.-P. Weiss	M3 Or 1A
Wednesday 11:20 AM	318	Additive Manufacturing of Cryogenic Materials	Olaf Rehme	M3 Or 1A

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AdHyBau Lufo VI-1

"Development of additively manufactured cryogenic heat exchangers for hydrogen-electric aircraft propulsion" *Marco VIETZE & Cenk EVRIM*

AGENDA

- System analysis & requirements derivation for subsystems and components
- Development of analytical optimization tool for heat exchanger design
- In-depth design and analysis loops
- Outlook: cryogenic component testing
- Summary

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This work is supported by the Federal Ministry for Economic Affairs and Climate Action of the Federal Republic of Germany. Grant-No.: 20M1904B.

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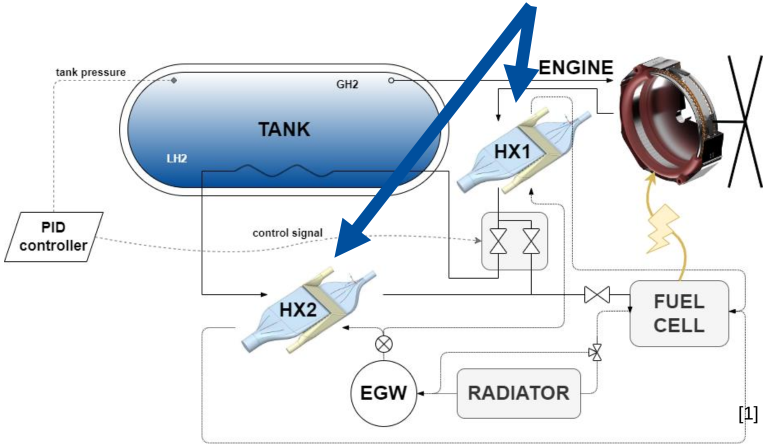
AdHyBau Lufo VI-1

System analysis & requirements derivation for subsystems and components

- 1D thermo-fluidic modelling of relevant subsystem characteristics to resolve interactions and interdependencies between subsystems

- Analyze and derive requirements for subsystems and components from…
  - Mass flow rates
  - Energy transport
  - Pressure & temperature development

Heat exchangers to be developed



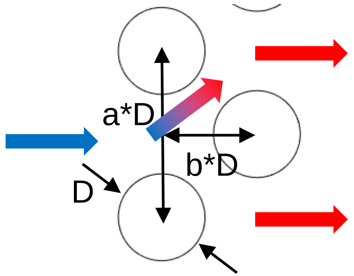
[1]

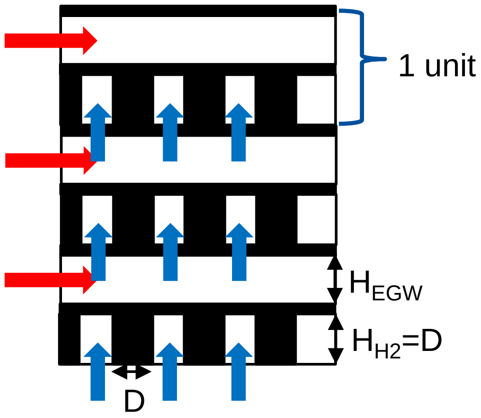
Concept → System-Modell → Requirements derivation → Component design

[1] „System analysis and requirements derivation of a hydrogen-electric aircraft powertrain “, International Journal of Hydrogen Energy, 10.1016/j.ijhydene.2022.09.052

Development of analytical optimization tool for heat exchanger design

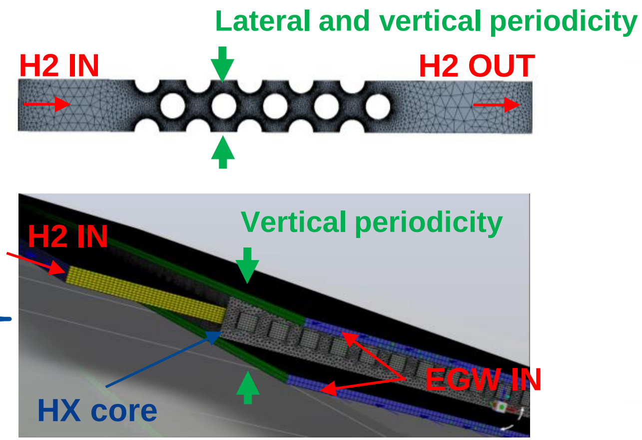
- Additive manufacturing allows for advanced internal heat exchanger geometries
- Analytical method for heat transfer and pressure drop based on lateral incident flow on tube bundles
- Optimizer applied to analytical method
  - Target function: HX core mass
  - Constraints
    - Minimum H2 outflow temperature → > 290 K
    - Maximum allowable pressure in H2 core → < 1000 Pa
  - Variables
    - *Pin/tube diameter* and *channel height*
    - *Lateral* and *depth distance* of pins
    - *Number of pins per row* and *number of rows*
    - *Number of units/plains* to build a stack

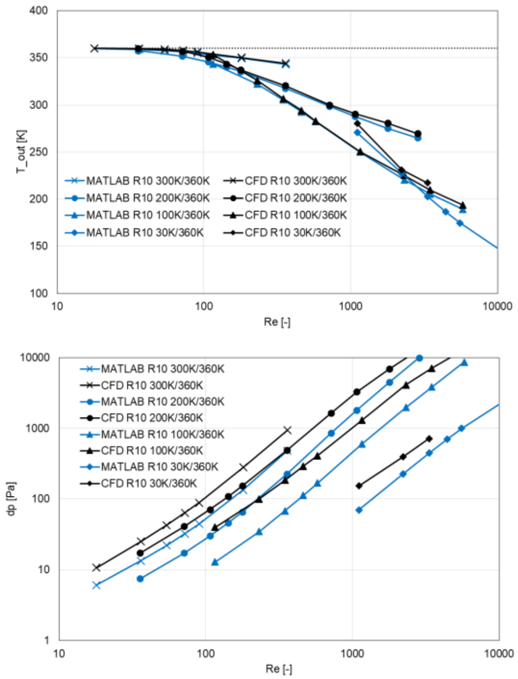




Development of analytical optimization tool for heat exchanger design

- Two-step validation with CFD
  - 2-directional periodic unit cell
    - Only H2 as medium
    - Fixed wall temperature
  - 1-directional periodic unit cell (one plane of the HX including primary and secondary side)
    - Cross flow arrangement of H2 and EGW
    - Heat conduction through HX-wall is being considered

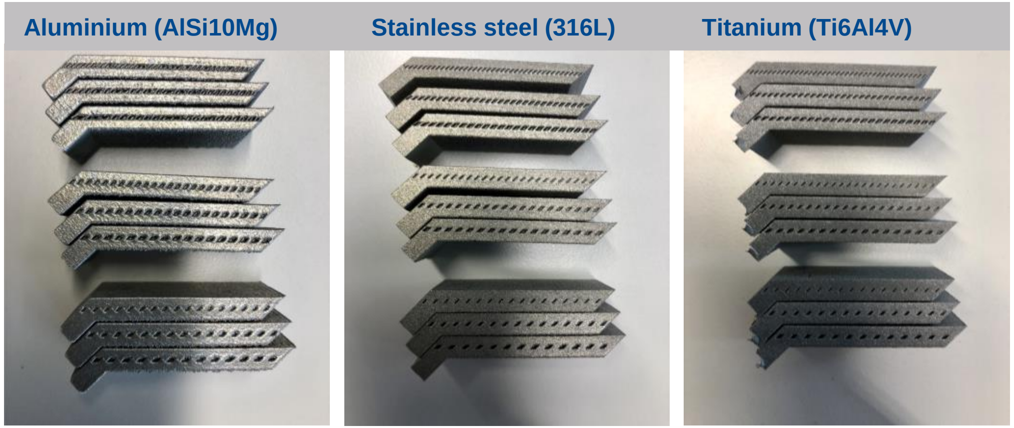


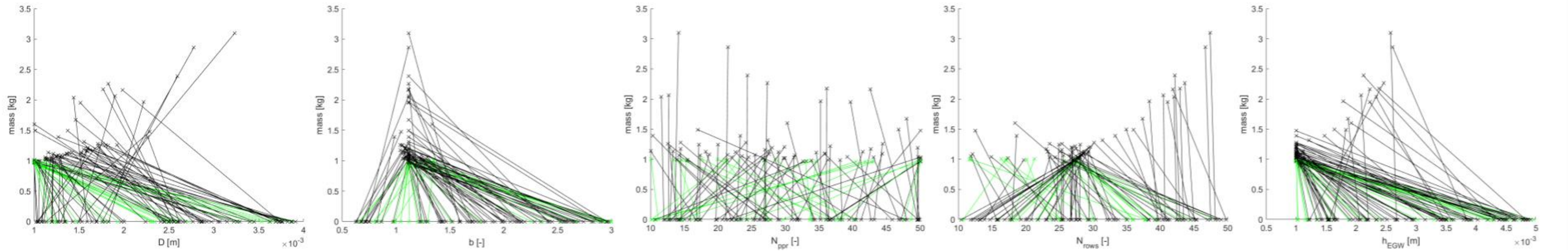


- Results for various temperature levels and flow velocities show …
  - Good agreement of fluid exit temperature prediction
    - <u>Error less than 2% in relevant flow regime</u>
  - Acceptable agreement of pressure drop prediction
    - <u>Predictable difference can be accounted for with correction factor</u>

Development of analytical optimization tool for heat exchanger design

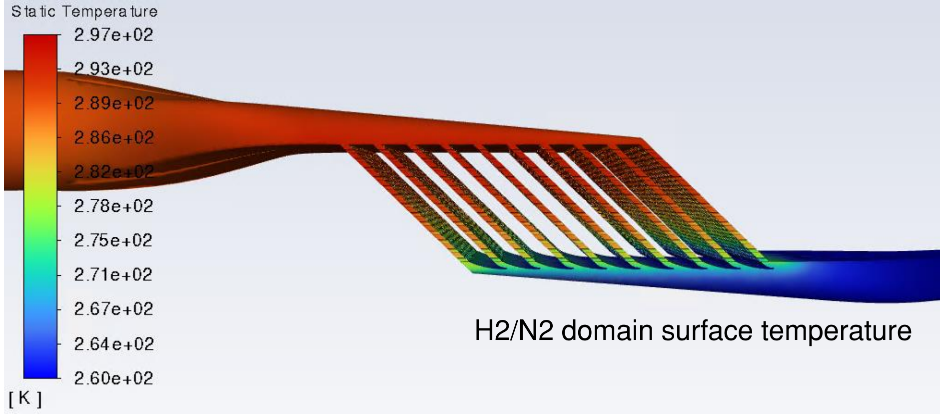
- AM parameter study for to establish manufacturing limits for…
  - min. pin diameter
  - min. pin distance
- Manufacturing limits constitute boundaries for optimization
- Optimization results show:
  - Some variables have a distinct global minimum (e.g. D, b, H_{EGW})
  - Some variables have no distinct global minimum, as they interact (e.g. trade <u>pins per row</u> for <u>number of units</u>)



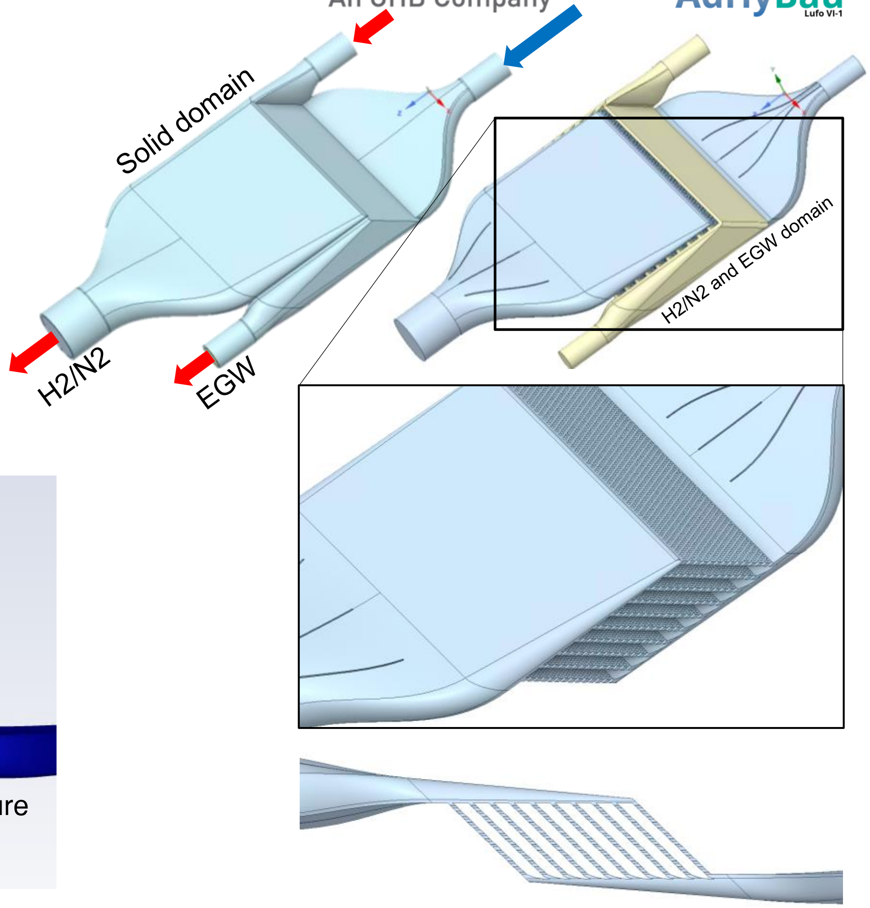


In-depth design and analysis loops

- CFD analysis with entire model
  - around 126 mio. elements
  - Three domains (H2, EGW, Ti)
  - Material data of Ti6Al4V provided by KIT
  - Temperature dependant material and fluid data
  - Four H2 cases (system analysis), one N2 case (cryo-test)
  - Turbulence model: K-ω SST

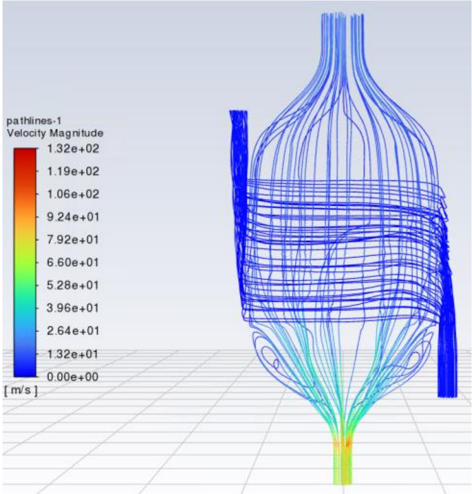


H2/N2 domain surface temperature



In-depth design and analysis loops

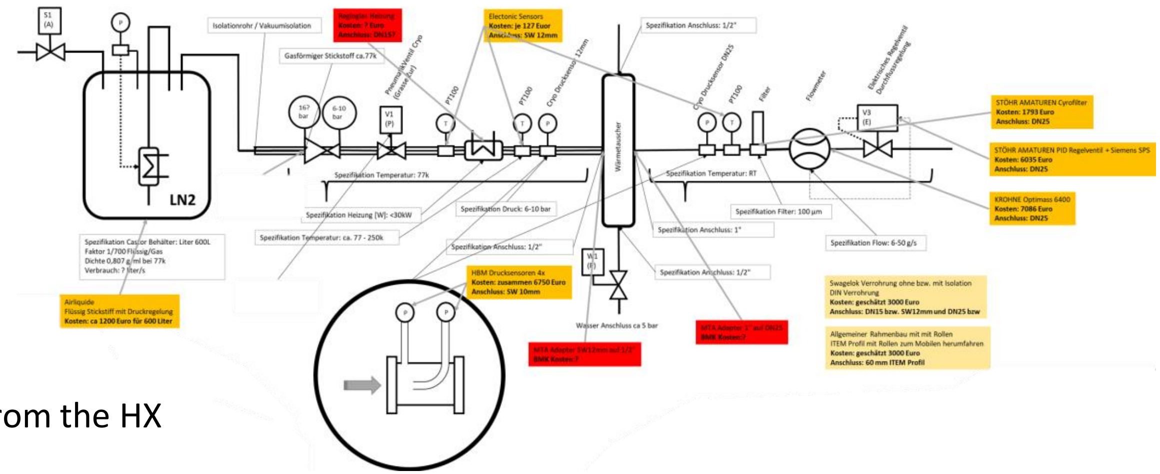
- Predictions of analytical method are met
  - $T_{H2,OUT}$ of all cases are at or above requirement
    - Prediction error of analytical tool is < 3%
  - Pressure drop in core within limits (working pressure 5 bar)
    - Total incl. intake and outlet: < 2000Pa for gas domain
    - HX core/layer only: < 1000 Pa for gas domain
- Minimum surface temperature (T_{min} = 238K) on EGW side is not undershot



PIN 10/32 Ti64 H2			CASE1 (Ti64)		CASE2 (Ti64)		CASE3 (Ti64)		CASE4 (Ti64)	
			max. heat transfer		cruise power		max. H2 mass flow		min. H2 inlet temp	
			H2	EGW	H2	EGW	H2	EGW	H2	EGW
dp_total		Pa	939,3	12649,0	471,6	13417,2	1477,5	13993,3	6,5	14106,4
dp_layer		Pa	592,2	2420,0	312,5	2942,0	809,1	3340,0	3,8	3405,0
T	IN	K	213	315,5	209	304,7	259,8	296,9	**30,0**	295,0
T	OUT	K	303,6	311,9	299,9	302,65	290,5	295,6	295,0	294,7
T analytical vs. CFD	**OUT**	**%**	**-2,6%**	**0,7%**	**-1,8%**	**1,4%**	**-0,8%**	**0,2%**	**-2,7%**	**-2,5%**
T	MIN	K	212,95	**242,29**	208,96	**239,77**	259,77	**269,46**	30,001	**257,477**
m_dot	IN	kg/s	0,00259375	0,3125	0,0016875	0,3125	**0,0031875**	0,3125	0,00009375	0,3125
Q_dot=q*A		W	**3105,7**	2963,5	2027,3	1934,5	1304,7	1245,0	299,5	285,9

Outlook: cryogenic component testing

- Setup with cryogenic nitrogen to test HX at different
  - Mass flow rates
  - Inlet temperatures
  - Inlet pressures

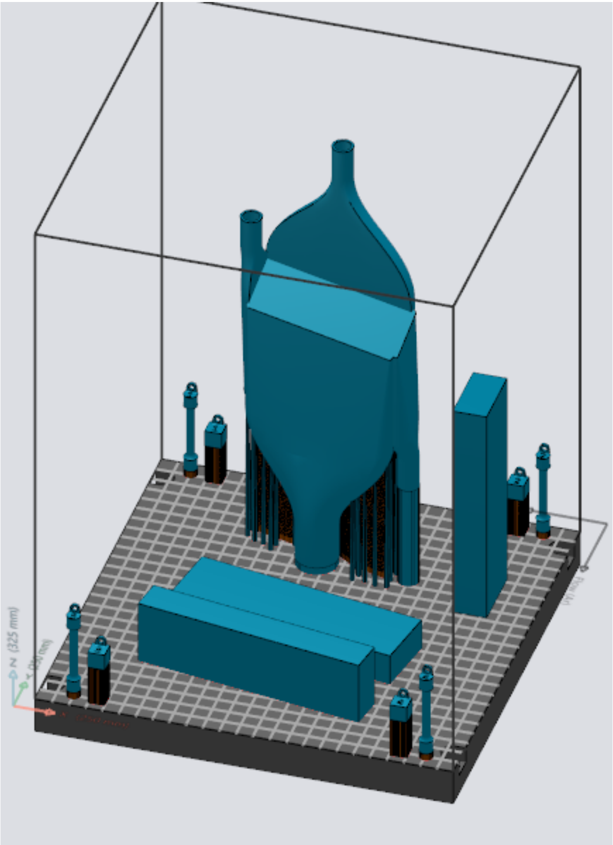


- Measure
  - Temperature increase of gas
  - Pressure drop of gas
  - Potential particles originating from the HX

- Results will be used to validate analytical model and CFD simulations

Summary

- **Requirements for heat exchanger derived** from system analysis
- Analytical **heat exchanger design tool developed and verified** with CFD
  - Shows good and predictable results
- **Design limits established** e.g. by manufacturing tests
- **Optimization of geometry** in accordance with requirements
- CFD **simulation of detailed design**
  - Minor adjustments implemented
- **Heat exchanger manufactured**
- Preparations for cryo testing initiated



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