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DESIGN AND EXPERIMENTAL VERIFICATION OF AN AXIAL MM TURBINE

TAČR KAPPA DEXPAND – FINAL MEETING

JAN ŠPALE

07/03/2024

OUTLINE

1. Motivation
2. Experimental test rig
3. Turbine design
4. Manufacturing, assembly and commissioning
5. Experimental results
6. Future work

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1. MOTIVATION

1. MOTIVATION

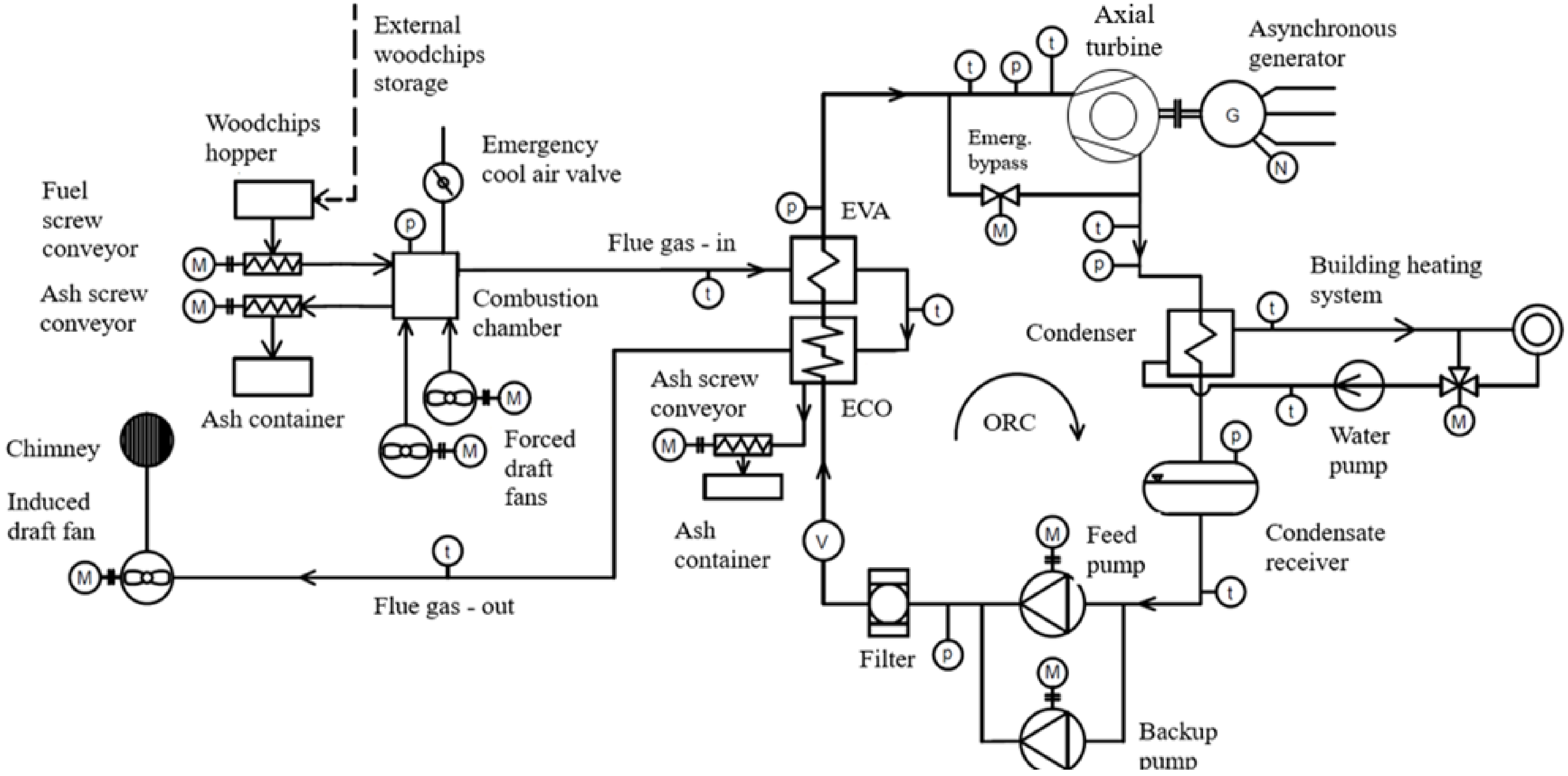
- small-scale distributed energy systems transforming low-temperature external heat sources (waste heat, geothermal heat, solar thermal) or low-grade solid fuels often utilize Organic Rankine Cycle power systems
- usually use volumetric expanders derived/rebuilt from HVAC compressors – robust, but **inefficient** -> replacing it with a turbine is a logical step towards increasing system efficiency
- axial impulse stage is probably the easiest concept to implement, also achieves lowest rotational speeds (bearing issues)

2. EXPERIMENTAL TEST RIG

2. EXPERIMENTAL TEST RIG

Main features

- Woodchips-fired
- 120kWth/8kWel
- Working fluid MM
- Equipped with patented RVE
- RVE to be replaced by an axial impulse turbine
- Direct wf heating
- Several thousands op. hours

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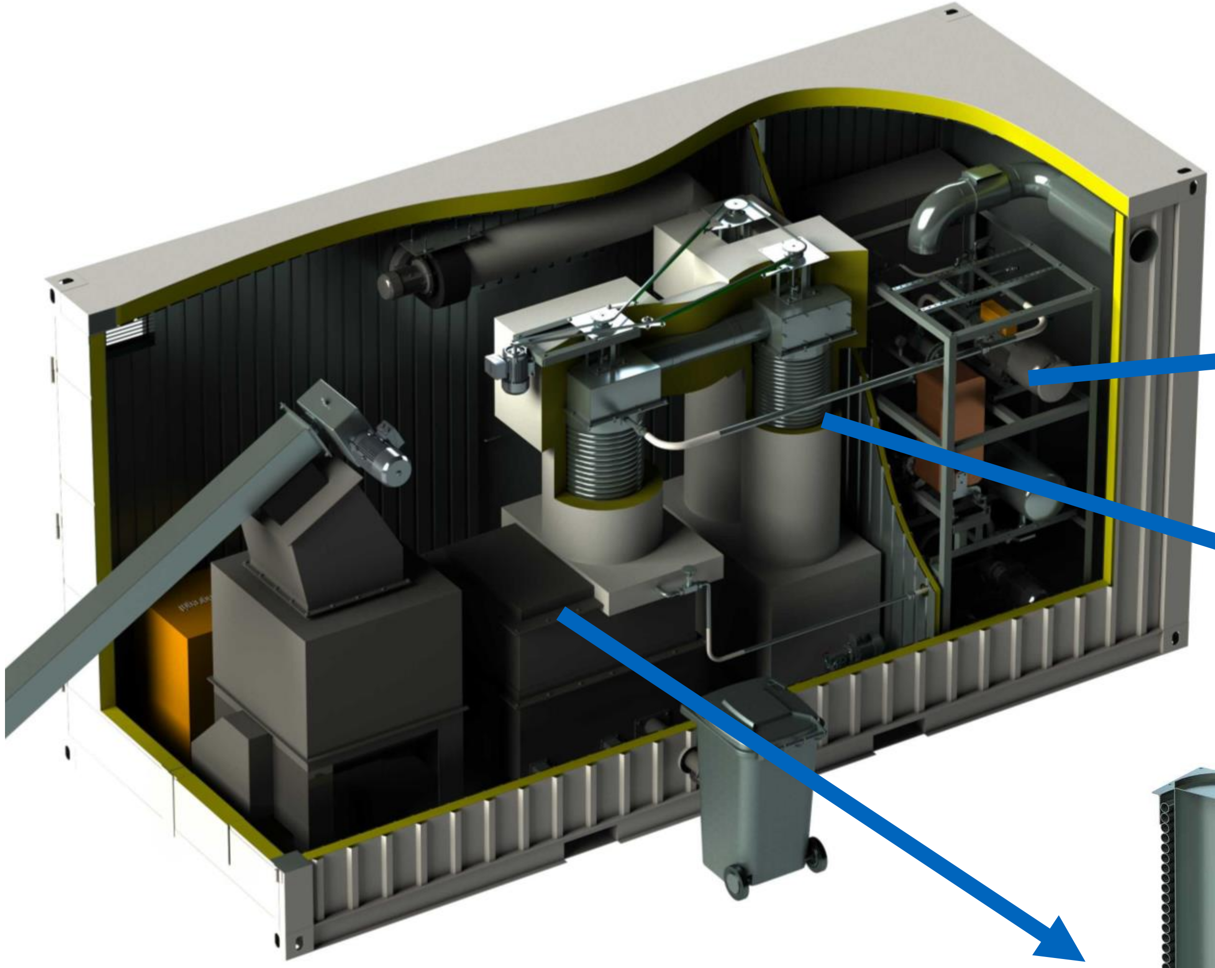
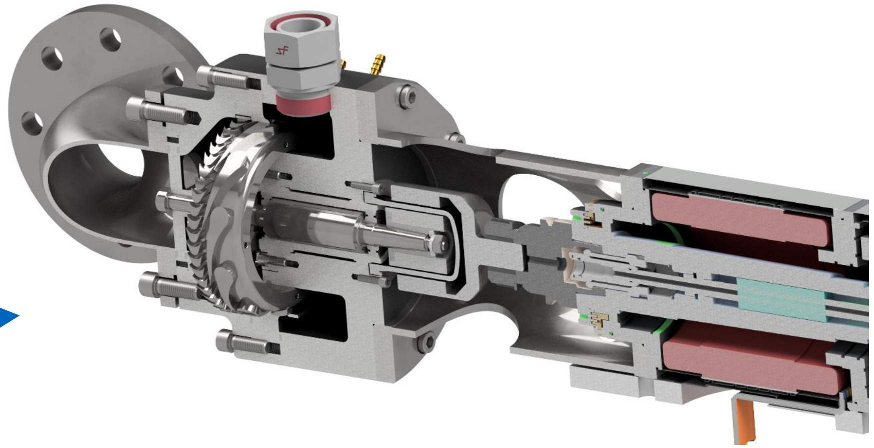
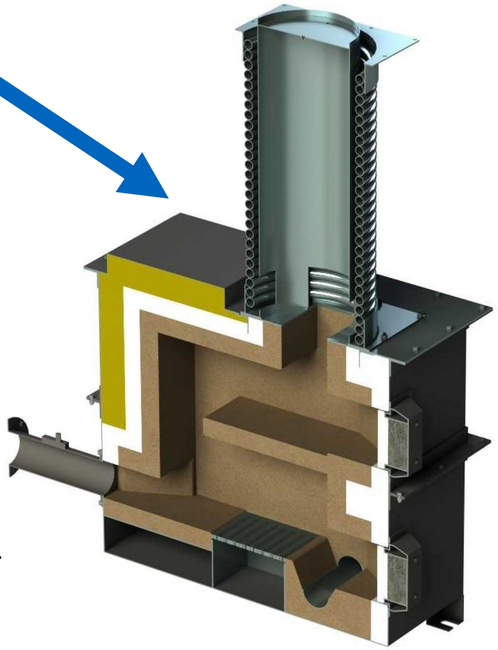




In-house developed **rotary vane expander**

Whole CHP ORC unit fit in a container



Robust combustion chamber designed to meet emission limits even for low-quality biomass equipped with a **moving grate** for slag desintigration

Custom **flue gas** helical wound **heat exchangers** with automatic cleaning mechanism

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2. EXPERIMENTAL TEST RIG

Steady state operation

Parameter	50 kW_{th} unit	120 kW_{th} unit	Units
Flue gases			
Evaporator inlet temperature	650	**1400***	°C
Economizers outlet temperature	164	**132**	°C
Thermal power input to the ORC	46.7	**121**	kW
ORC			
Expander inlet pressure	553	**522**	kPa
Expander inlet temperature	182	**180**	°C
Expander outlet pressure	58	**46**	kPa
MM mass flow rate	0.125	**0.3**	$kg \cdot s^{-1}$
Auxiliaries			
Expander rotational speed	3026	**3034**	rpm
Gross electrical power output	3100	**7565**	W
Net electrical power output	1990	**6200**	W
Expander isentropic efficiency	61	**56**	%
Total net CHP efficiency	84	**89**	%

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3. TURBINE DESIGN

Current author's progress with the thesis

Parameter	Value	Units
Expander inlet pressure p_1	650	kPa
Expander inlet temperature T_1	190	°C
Expander inlet superheating T_{SH}	10	K
Expander outlet pressure p_3	55	kPa
Working fluid	MM	–
Working fluid mass flow rate $\dot{m}_{wf}$	0.3	$kg \cdot s^{-1}$

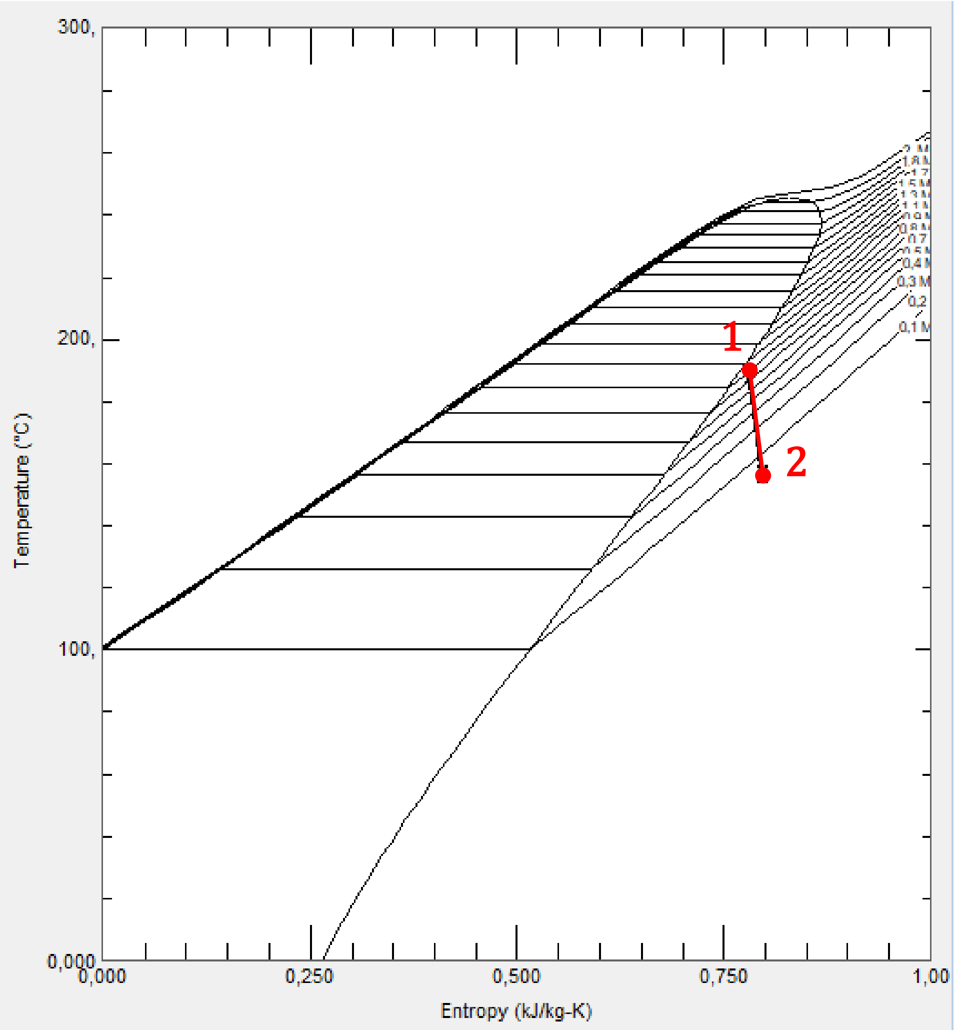
- Very **high molar mass and molecular complexity**

=>low enthalpy drops along the expansion

=>very low speed of sound

=>**supersonic turbomachinery**

=>extremely non-ideal compressible fluid flow



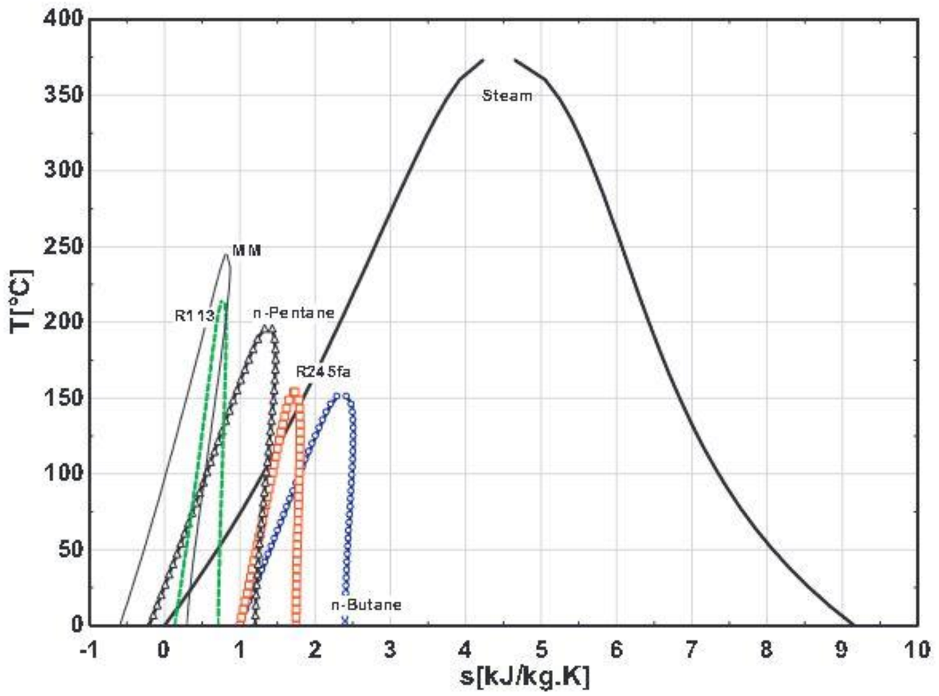
=>1D loss correlations often fail

Current author‘s progress with the thesis

Name: Hexamethyldisiloxane (MM)

Formula: $C_6H_{18}OSi_2$

Property (unit)	Value
MW (kg/kmol)	162.37752
$T_{TP}(\mathrm{K})$	204.93
$T_c(\mathrm{K})$	518.75 ± 0.40
$P_c(\mathrm{MPa})$	1.939 ± 0.02
$v_c(\mathrm{m^3/kmol})$	0.629 ± 0.03
Tb (K)	373.67 ± 0.10
dh_vap at Tb (kJ/kg)	192.5
Acentric factor	0.419



Current author‘s progress with the thesis

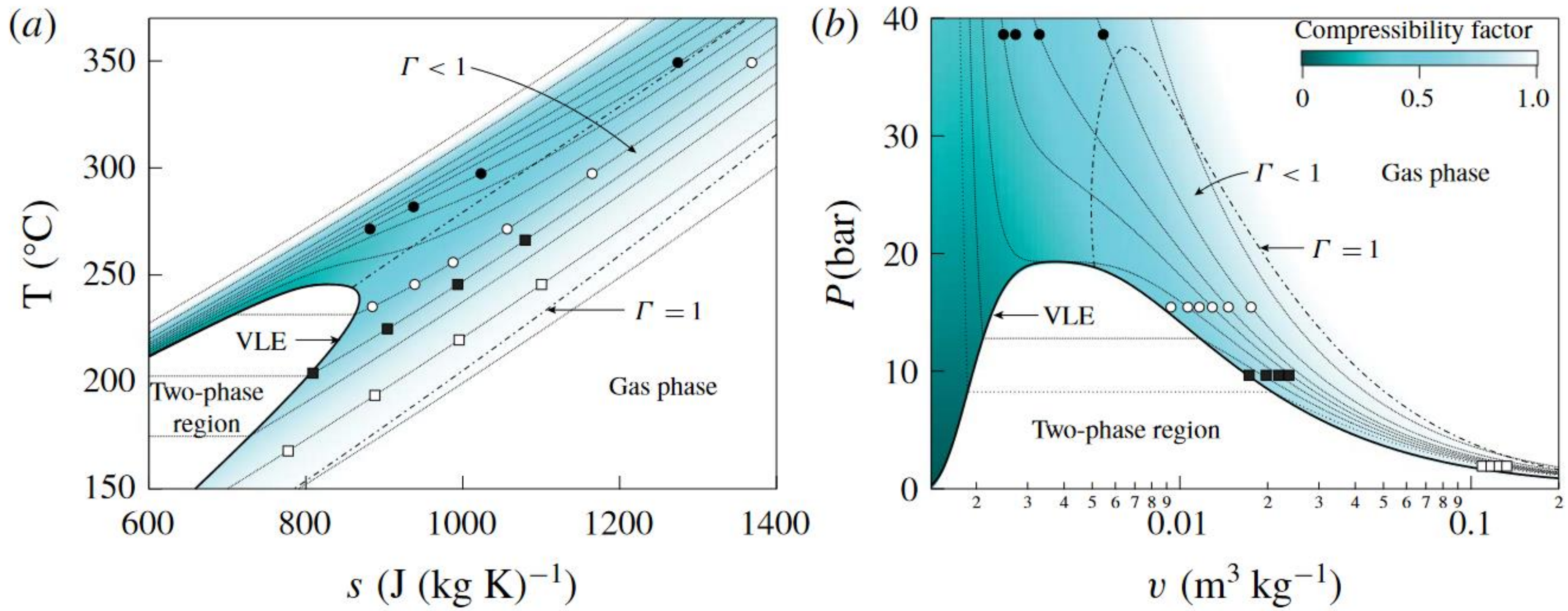
- Accounting for compressibility effects – Z and Γ

$$Z_T = \frac{P_T}{T_T R \rho(T_T, P_T)}$$

- Bethe-Zel‘dovich-Thompson (BZT) fluid which exhib non-ideal behaviour in single phase vapour region.

$$\Gamma = 1 + \frac{a}{c} \cdot \left(\frac{\delta a}{\delta p}\right)_{is}$$

- *Speed of sound* increases along the expansion =>



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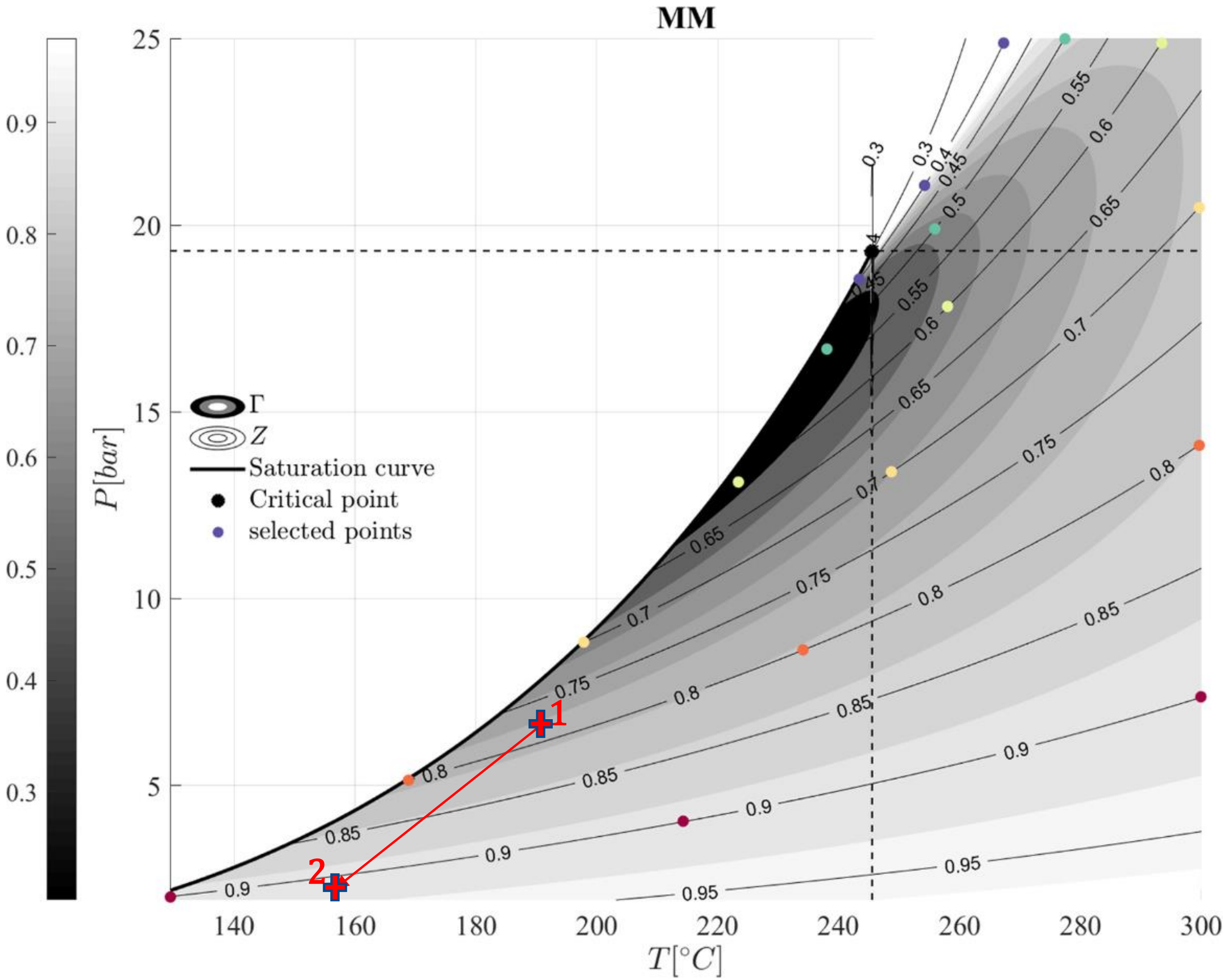
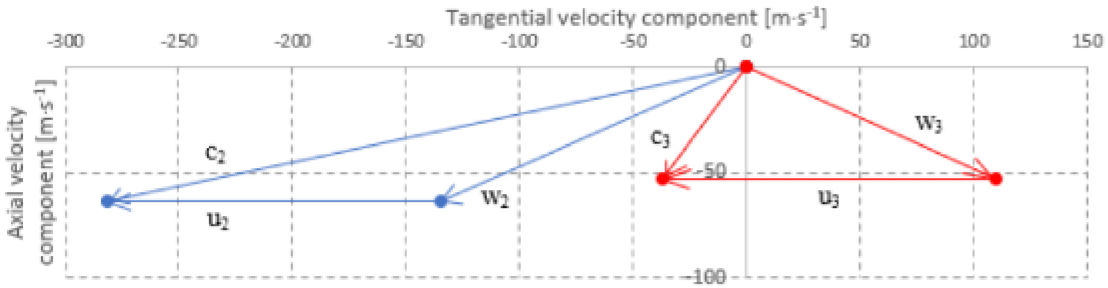


Current author‘s progress with the thesis

Turbine design parameters, initially chosen from 0D maps, later optimized

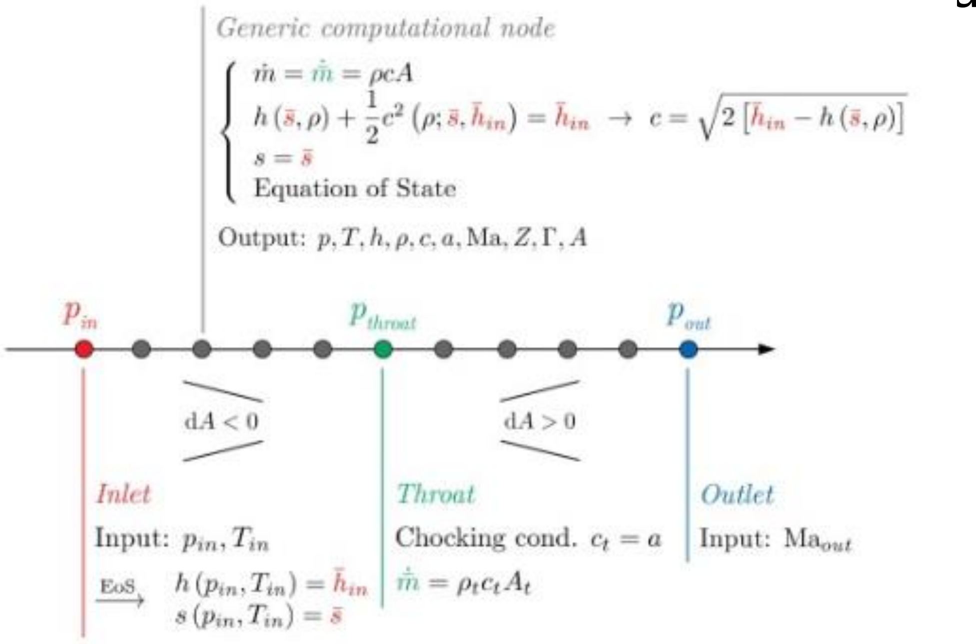
Parameter	Initial value	Units
Rotational speed n*	24000(28000)	rpm
Midspan diameter Dmid	100	mm
Nozzle outlet flow angle $\alpha 2$	13	o
Isentropic efficiency guess	70	%
Partial admission guess e*	58.5(97.5)	%
Blade height ratio	0.1(0.055)	–
Minimum blade height h min	5	mm
Rotor blades aspect ratio AR	2	–
Mechanical power output P_{mech}	11	kW



Current author‘s progress with the thesis

Nozzle design – supersonic convergent-divergent de Laval nozzles

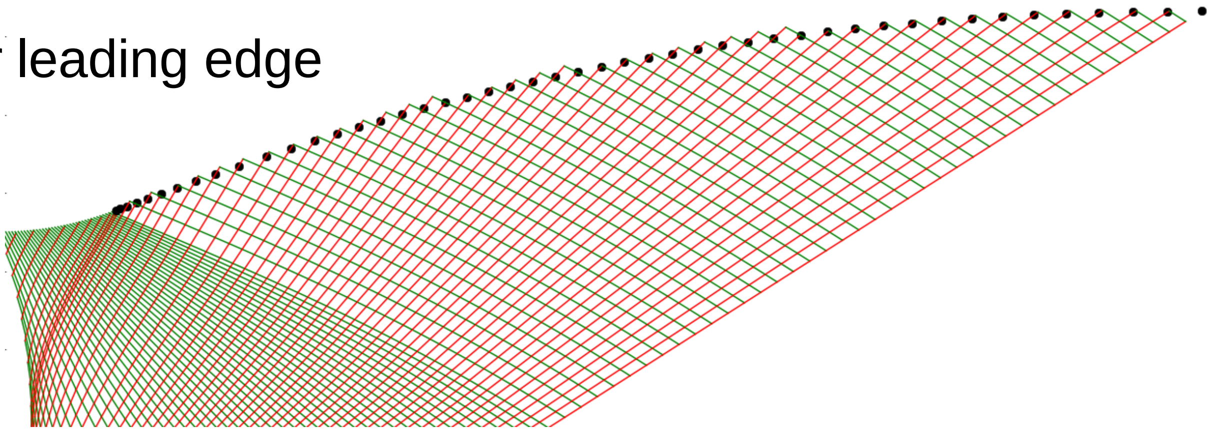
- Utilizes ve … urbopumps



Rotor design – purely impulse stage, constant channel width buckets with desired flow deflection angle

3. TURBINE DESIGN

- Developed a 1D meanline design tool based on velocity triangles and celocity coefficient loss correlations
- Designed as an impulse single stage axial turbine with supersonic nozzles with a geometry calculated using Method of Characteristics (MoC) – Mach 2 outlet
- prismatic short blades (l_blade = 5.5 mm)
- high aerodynamic loading of the rotor blades
- Detached bow shockwave at the rotor leading edge
- boundary layer separation issue



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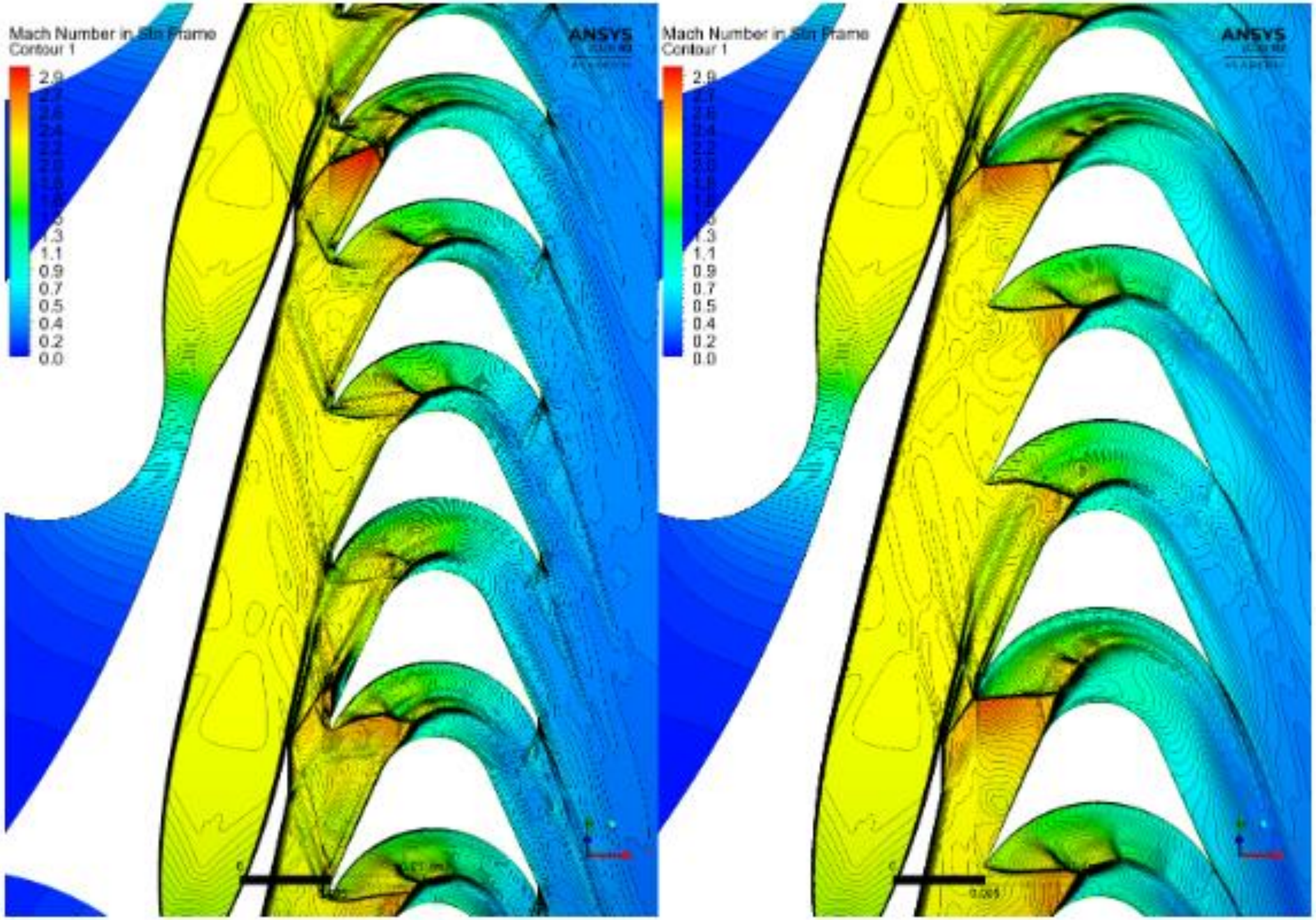
3. TURBINE DESIGN

- Design parameters

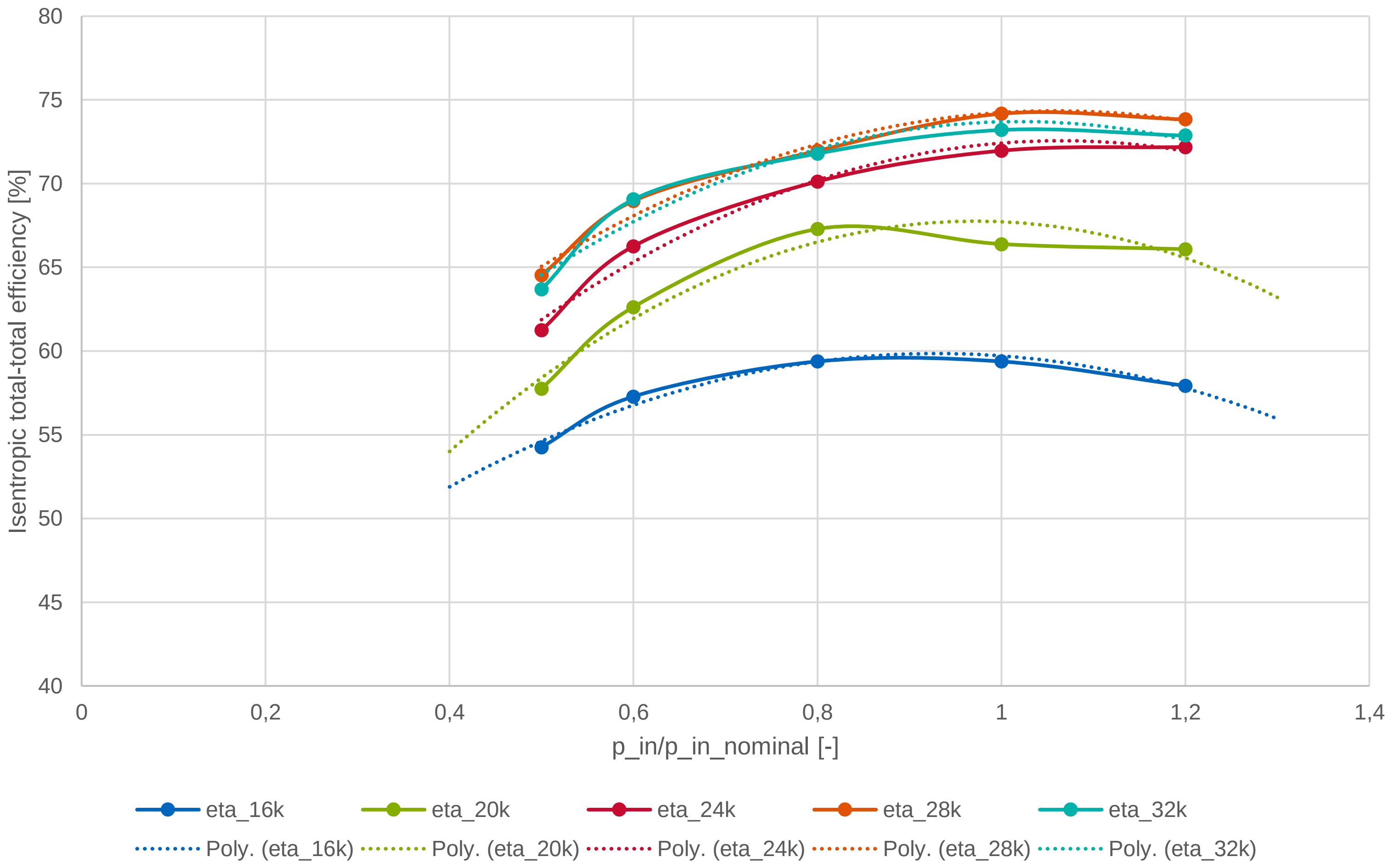
3. TURBINE DESIGN

Ansys CFX full stage simulation – effect of blade edge thickness; identifying shockwave structures and secondary loss sources



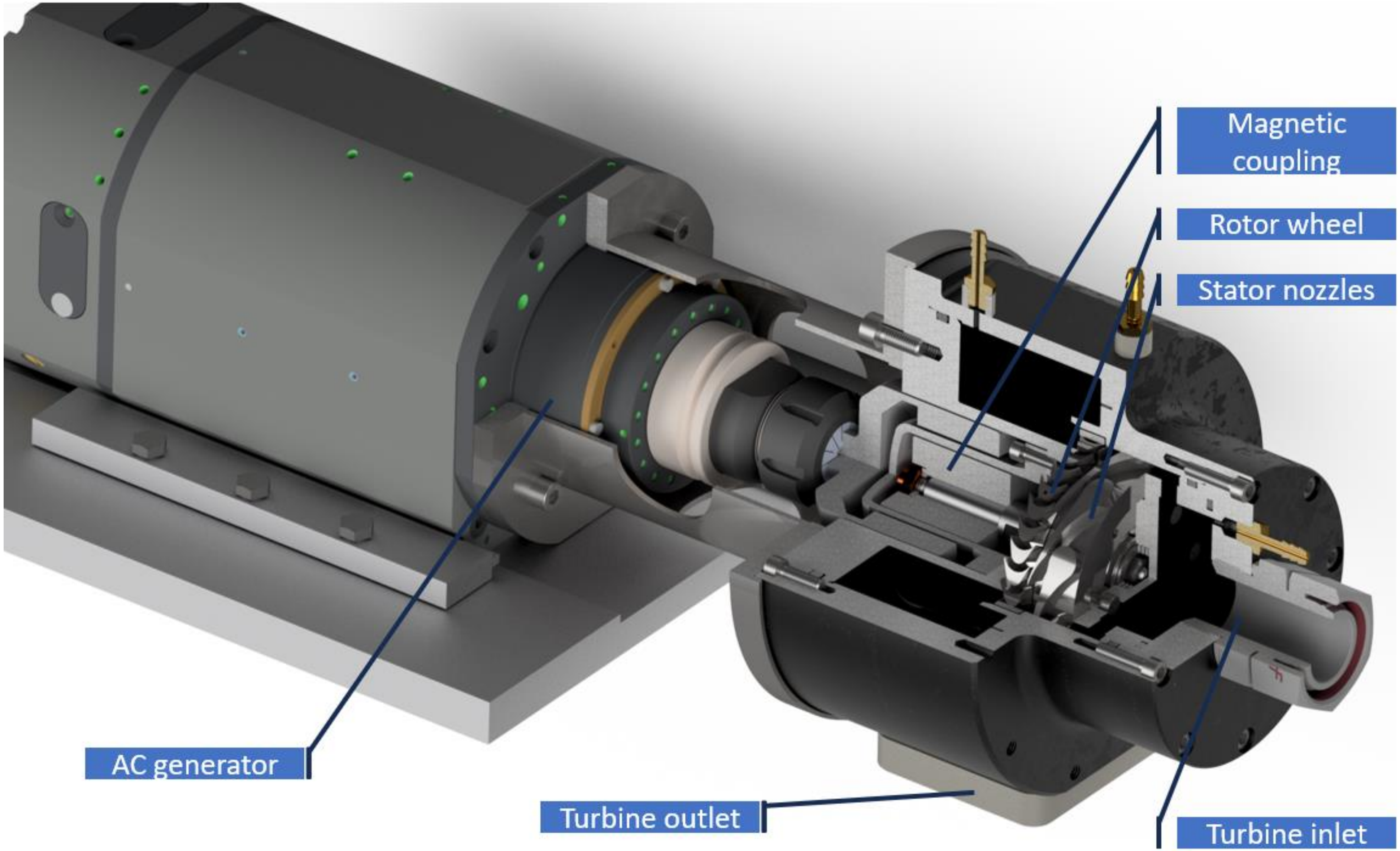
3. TURBINE DESIGN

Ansys CFX full stage simulation – off-design operating charateristics of the machine – different pressure ratios and rotational speeds



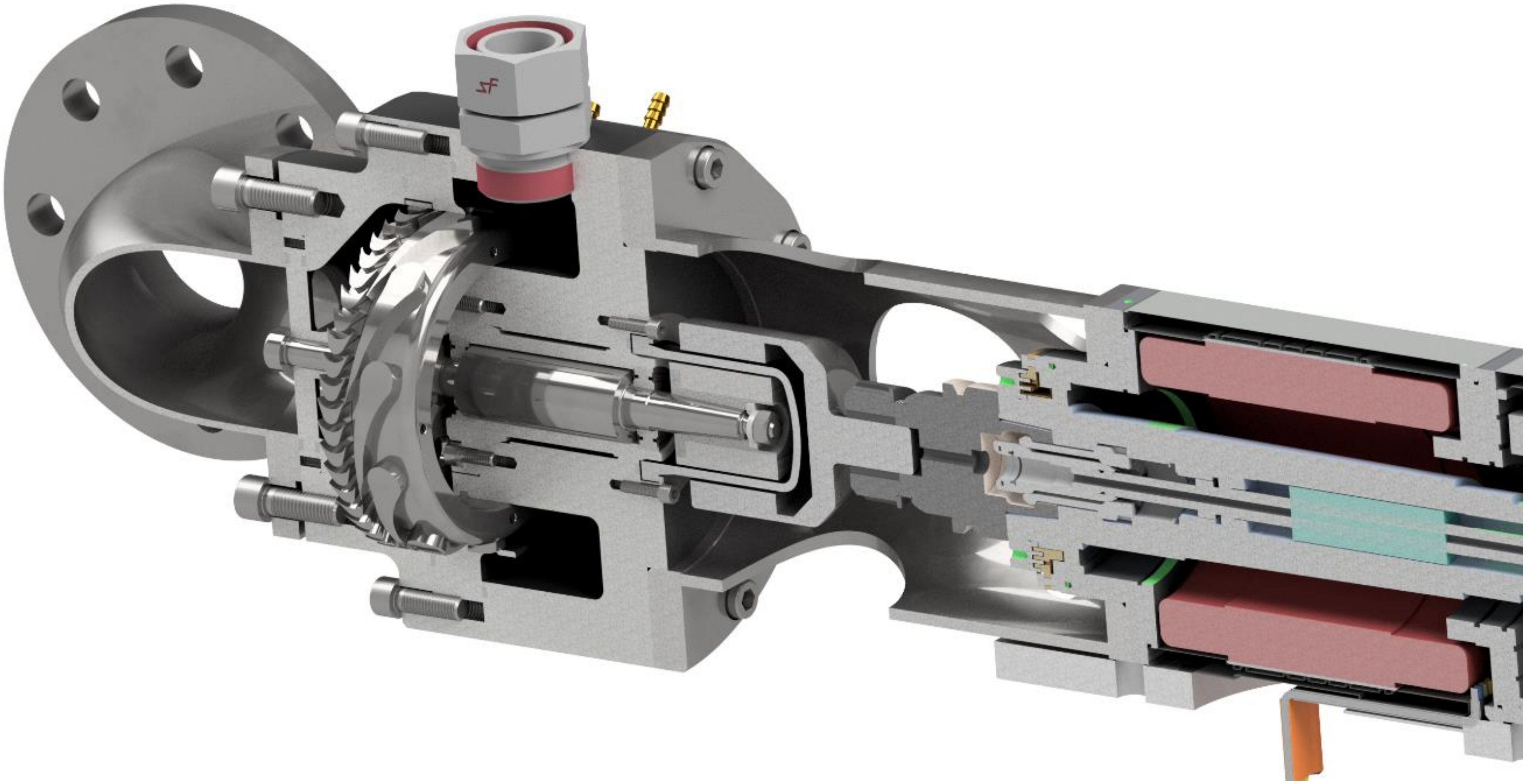
3. TURBINE DESIGN

v1 assembly



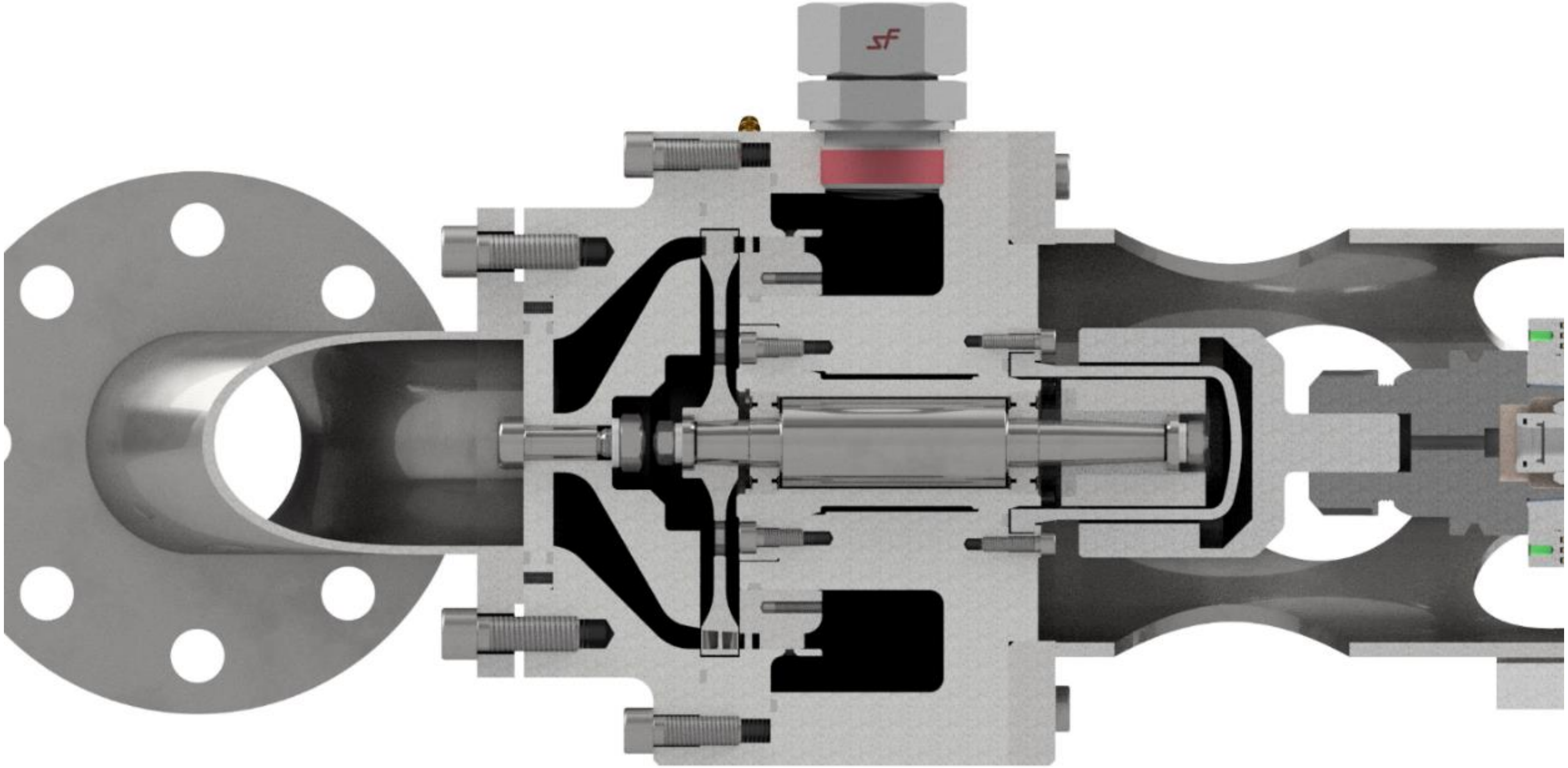
3. TURBINE DESIGN

v2 assembly



3. TURBINE DESIGN

v2 assembly



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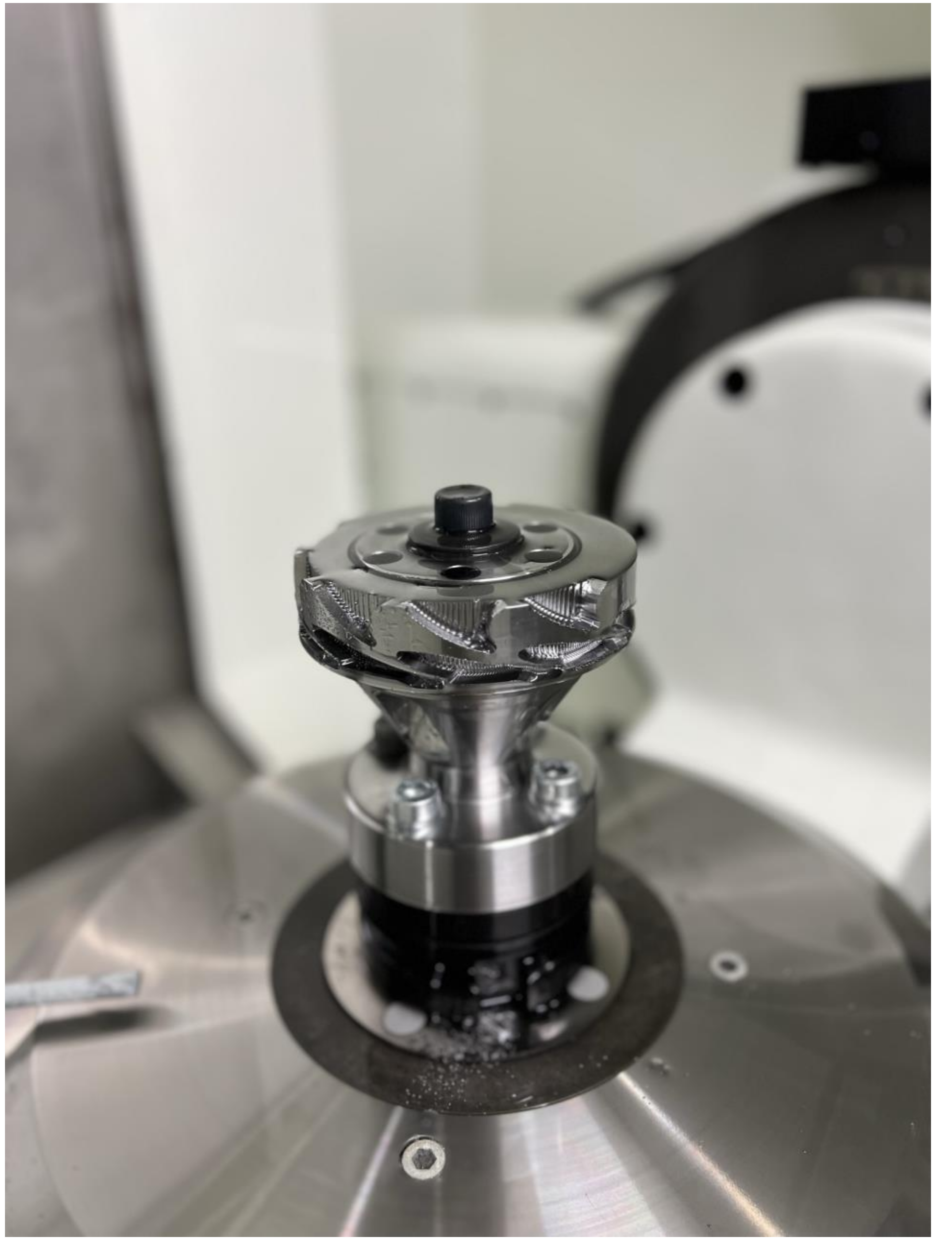
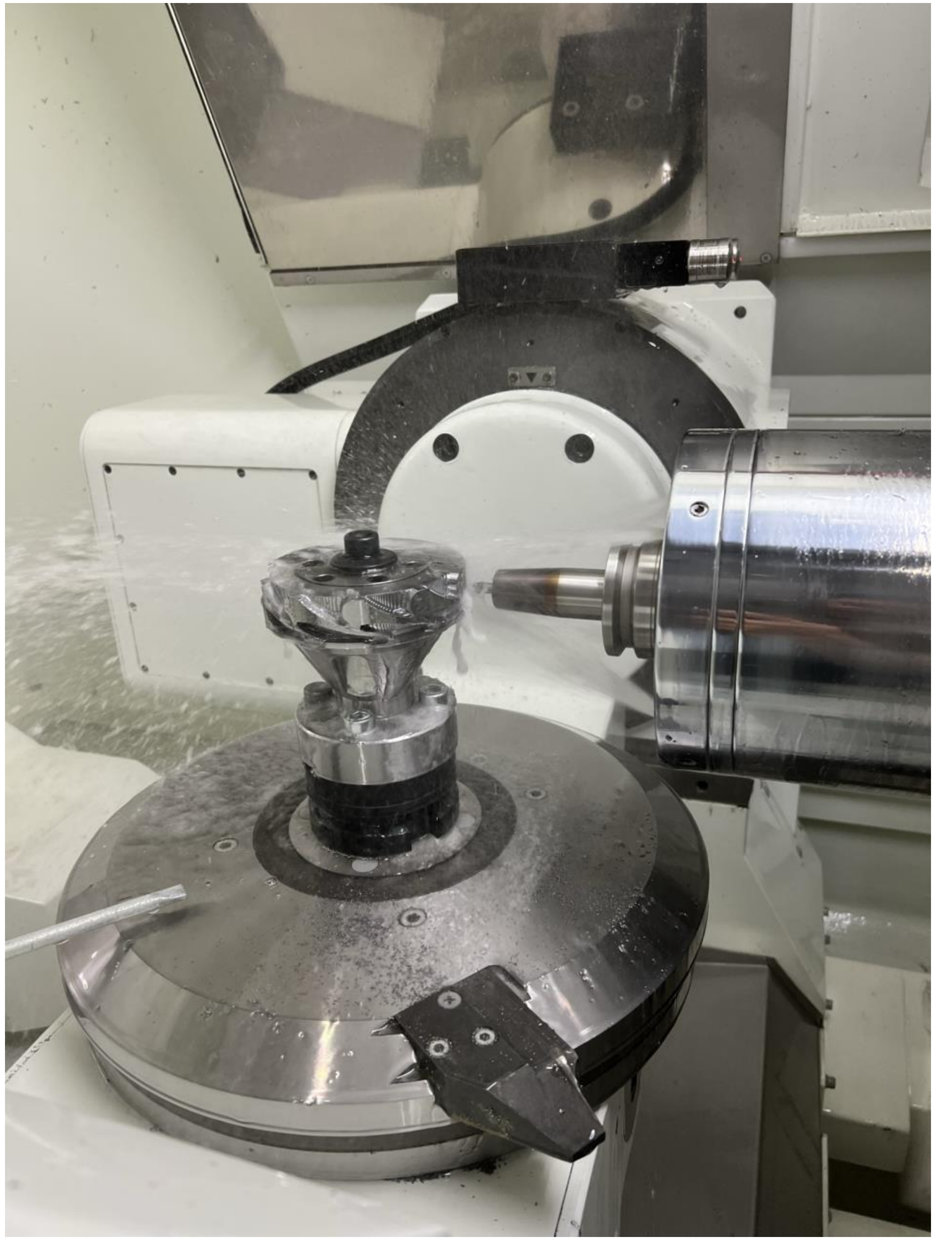
4. MANUFACTURING, ASSEMBLY AND COMMISSIONING

4. MAN., ASS. AND COMM.





4. MAN., ASS. AND COMM.

4. MAN., ASS. AND COMM.

In experimental research, not everything goes according to your plan all the time…

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5. EXPERIMENTAL RESULTS

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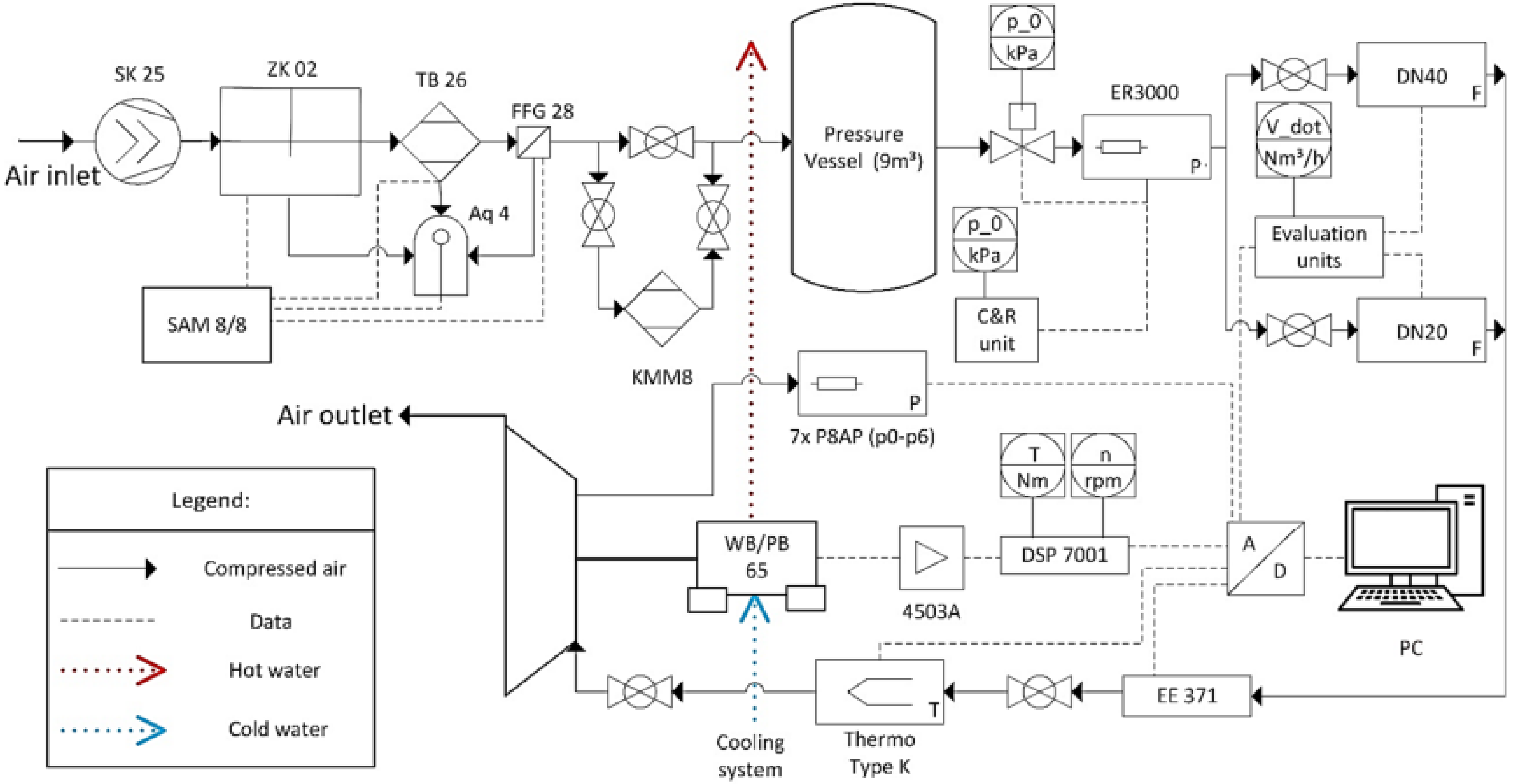
Pressurized air measurements – verification of mechanical stability and integrity throughout the operating map



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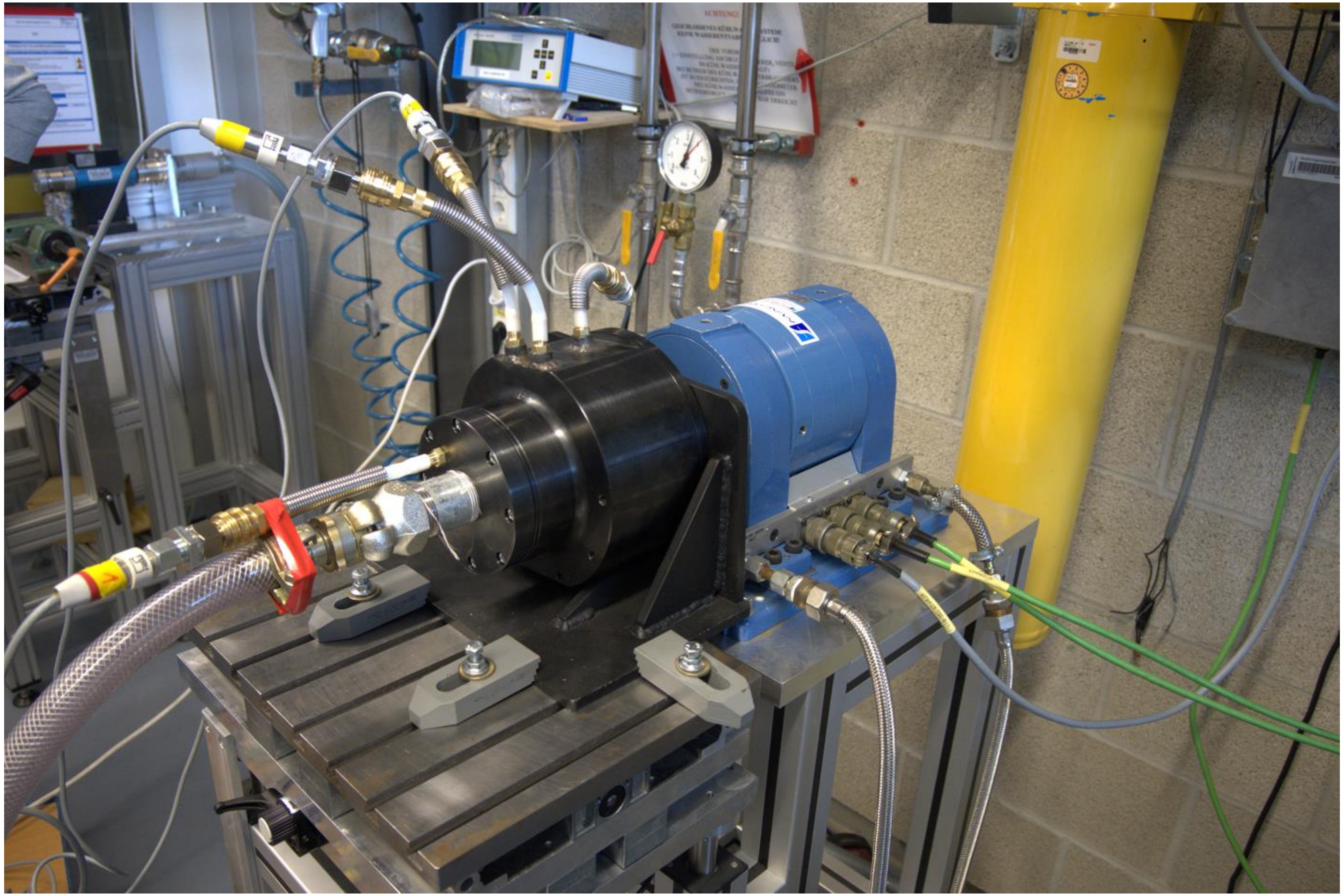
Pressurized air measurements – verification of mechanical stability and integrity throughout the operating map



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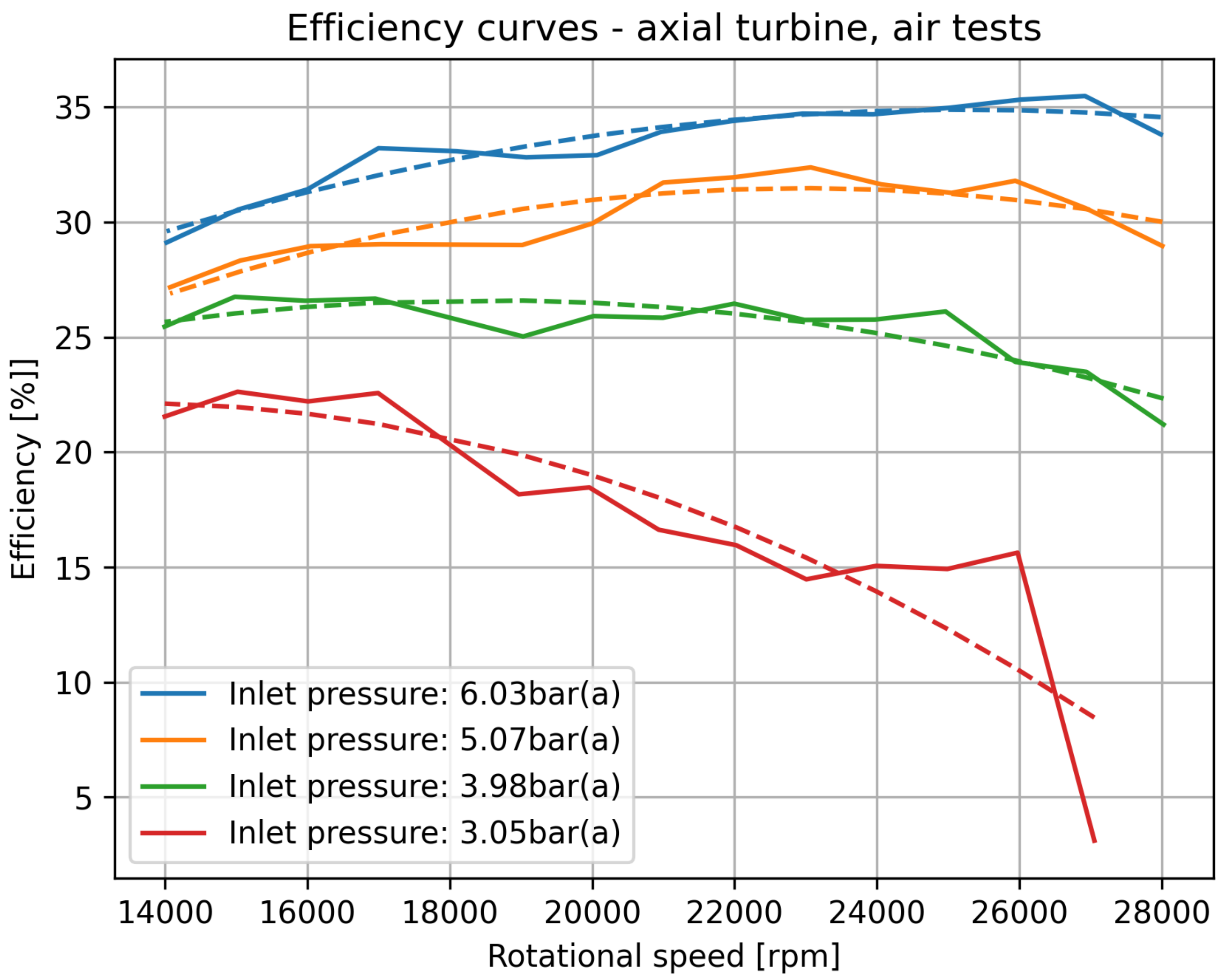
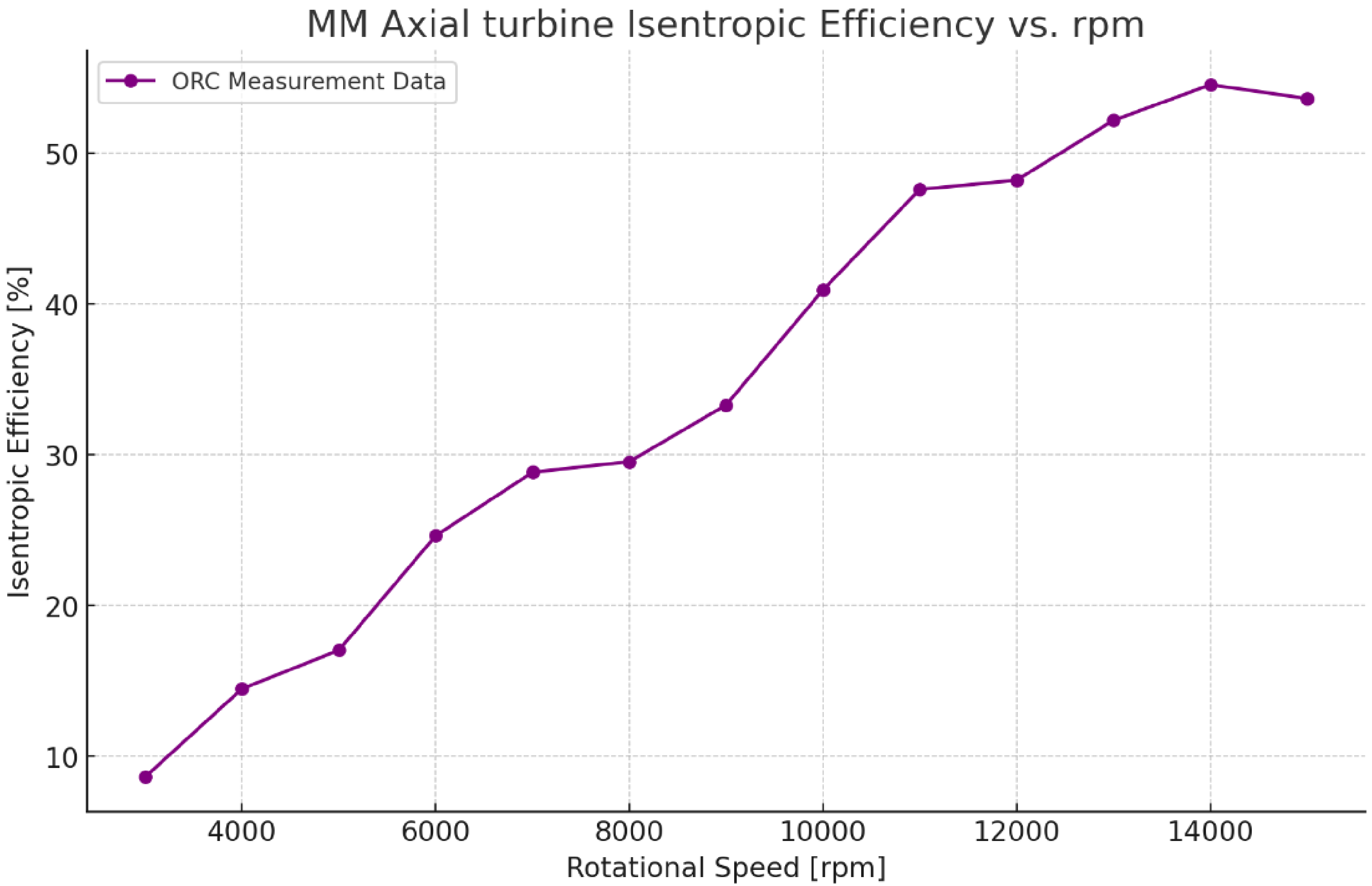
Pressurized air measurements – verification of mechanical stability and integrity throughout the operating map



5. EXPERIMENTAL RESULTS

- Turbine mounted into the ORC rig
- updated electrical power output switchboard
- Low-speed off-pressure ratio performance exceeds expectation
- vibration issues at higher rotational speeds
- for safety reasons, max speed cap at 15 000 rpm
- will be updated with a new assembly – more stable mode of operation, avoiding critical speeds
- a lot of experimental data collected and shared open-source (GitHub repository)

5. EXPERIMENTAL RESULTS



6. FUTURE WORK

6. FUTURE WORK

- Collecting even more (especially high speed, higher pressure ratio) data with the v2 Axial MM turbine
- Reducing manufacturing costs – casting the casing instead of milling (molds)
- Comparing the effect of „simple“ to „MoC“ supersonic nozzles
- Optimization of the diffuser section of the turbine
- Reduction of the boundary layer separation in the rotor buckets suction side outlet
- Longevity and accelarated life testing of the turbine (bearings, generator unit)
- A publication comparing three types of expansion devices for the same unit and boundary conditions (RVE, Elektra, Axial) + sharing the raw experimental data open source (Mendeley Data, referenced in the publication)

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