OPTIMIZED CYCLE AND TURBOMACHINERY CONFIGURATION FOR AN INTERCOOLED, RECOMPRESSED SCO2 CYCLE

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OVERVIEW

SCO2 POWER CYCLES ATTRACTIVENESS ESSENTIALLY DUE TO:

- Potential very good efficiency for a wide range of thermal sources (from biomass to CSP or nuclear)

Even the simplest cycle configurations can achieve good performances provided that the TIT temperature is high enough (650 - 700°C), without the need to approach the GTs technology state of the art

- Huge reduction in turbomachinery size and weight at same power level with respect to traditional fluid power cycles
- sCO_2 closed power loops can make carbon sequestration easier even without Allam cycle configuration

LIMITATIONS:

- Not really competitive with thermal input temperature lower than 500°C (WHR, geothermal…)
- When using combustion as thermal source because the regenerative cycle requires quite large air preheaters
- Not really competitive with water steam for F and H class GTs combined cycles

SCO2 THREADS:

Approaching critical fluid conditions to reduce compression work can result in loss of load flexibility or operational difficulties during power loop transients (even due to ambient conditions variations)

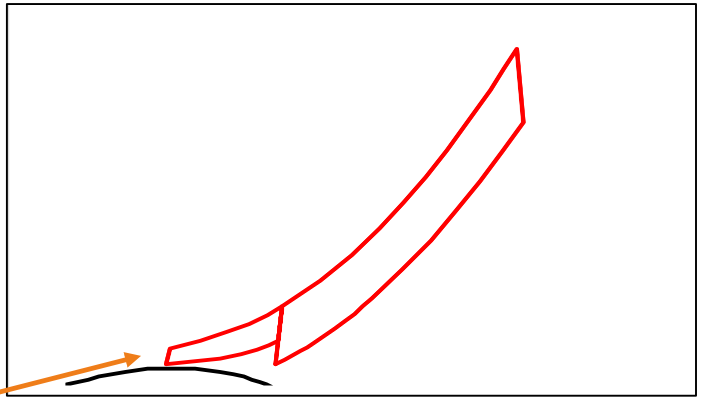
For non-condensing cycles: higher operational complexity for all gas phase closed loops with respect to condensing ones

THERMAL CYCLE AND MACHINERY HAS TO BE SEEN AS A WHOLE DURING DESIGN PROCESS TO TAKE ADVANTAGE OF SCO$_2$ FEATURES MINIMIZING RELATED DIFFICULTIES

<u>**To achieve the target of developing a sCO$_2$ cycle for short term commercial applications up to 50 MW power size:**</u>

- Avoid or reduce as much as possible the compressors inlet volumetric flow variation issue to enhance operational flexibility
- Reduce the uncertainties related to material behavior in sCO$_2$ at high temperatures
- Efficiency target for <u>non condensing</u> cycle: > 40% electrical for 20 MW thermal input power block

SELECTED CYCLE AND DESIGN FEATURES



1. Recompression
2. Minimum cycle pressure below critical
3. Reference minimum cycle temperature higher than 35°C (air cooling)
4. Intercooled compression of the main compressor flow
5. Allow the main compressor to get maximum adaptability to different operating and ambient conditions *
6. Main turbine design suitable for the entire selected range of power without major design choices changes *

FURTHERMORE, VERIFY THE POTENTIAL FOR BIGGER SIZE APPLICATIONS (100 MWE CSP AS REFERENCE APPLICATION CASE)

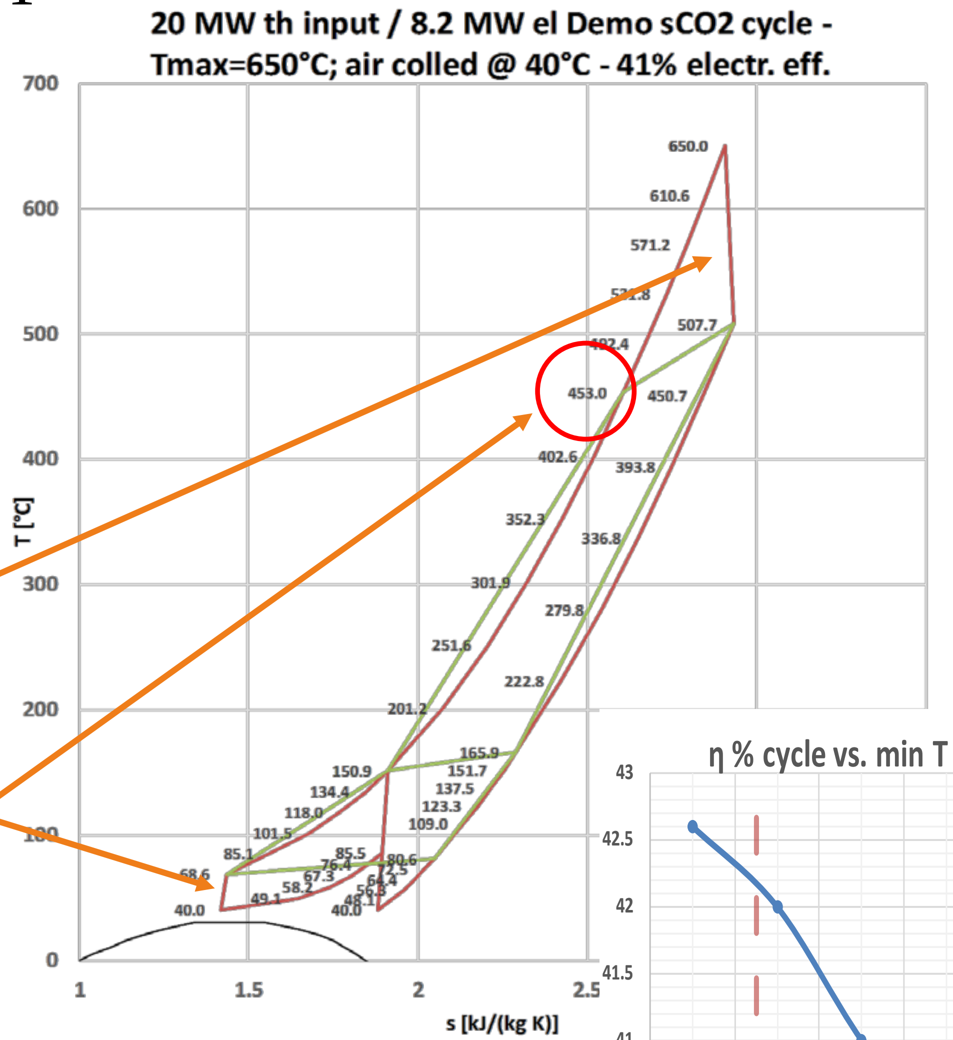
COMBUSTION DEMONSTRATOR POWER PLANT

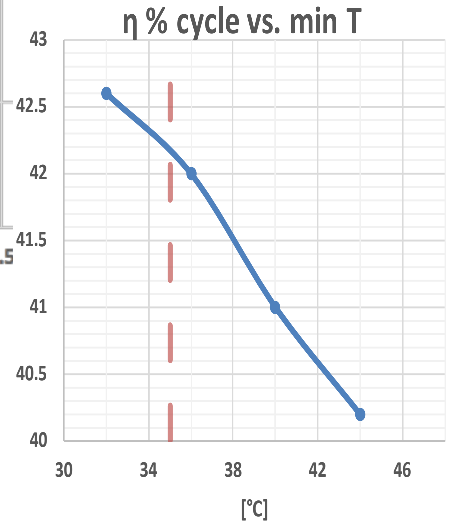
- Thermal power input: 20 MWth
- Power block electrical output: 8207 kW
- Electrical power block efficiency: 41%
- Nominal minimum CO2 temperature @MC and RC inlets: 40°C
- Max cycle temperature: 650°C
- Main Turbine inlet pressure: 180 bar
- Main Turbine exhaust pressure: 57.6 bar
- Main compressor inlet pressure: 92.8 bar
- $\sum \frac{\Delta p}{p_{max}}=0.065$

* 5. Power balanced shaft Turbocompressor

* 6. Main turbine design concepts similar to larger units

Conventional air pre-heater exch. from market





MAIN CYCLE FIGURES RESUME:

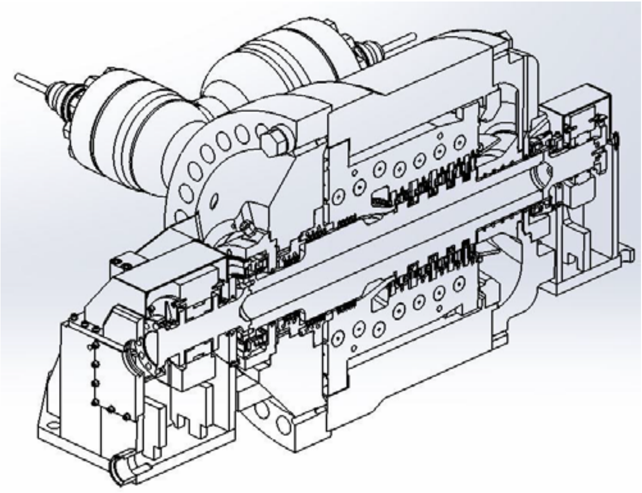
Pth in [kW]	Tmax [°C]	pmax [bar]	pmin [bar]	Tmin 1 [°C]	Tmin 2 [°C]	η MT [%]	η RC [%]	ηTC [%]	RC fr [%]	P MT [kW]	P MC [kW]	P RC [kW]	P el [kW]	η el [%]
20000	*650*	*185.5*	*55.5*	*40*	*40*	*90*	*84*	*64*	*46*	*12543*	*898*	*3980*	*8207*	*41*

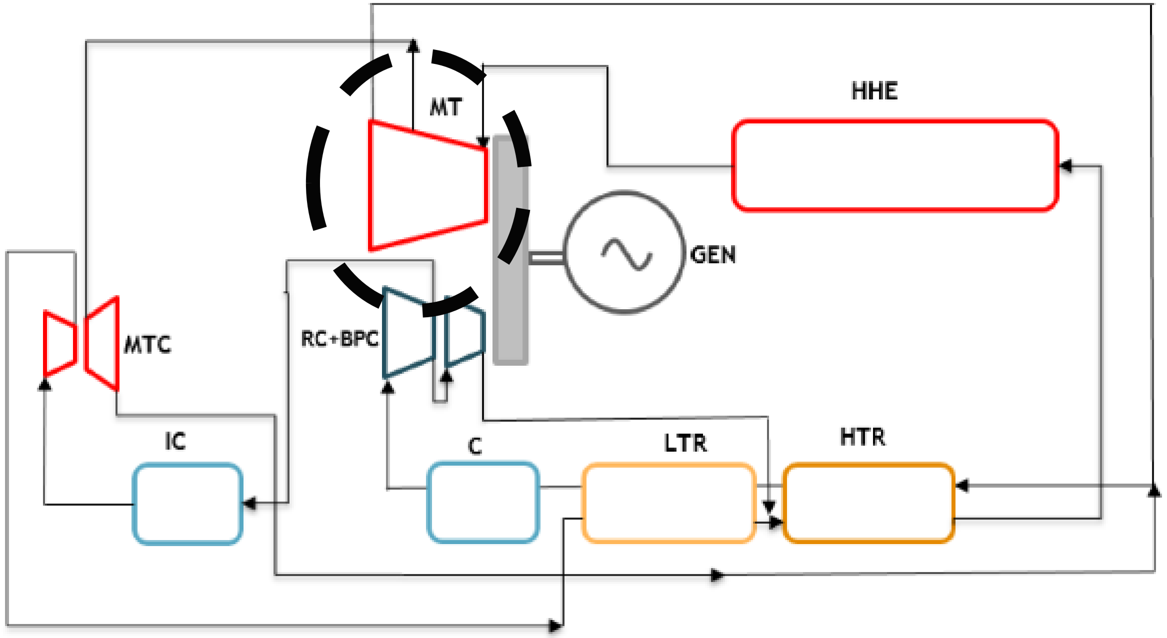
DEMONSTRATOR POWER PLANT- TURBOMACHINERY DESIGN

6. MAIN TURBINE (MT) DESIGN CONCEPTS SIMILAR TO LARGER UNITS (h/D_b WITHIN THE SAME RANGE)

50% reaction, 5 stages, 11000 rpm MT, 270 mm blades
base dimeter - $0.05 < {}^{h}/_{D_b} < 0.15$

- Barrel with inner casing, Between pedestals rotor configuration
- Tilting pads bearings
- Casings supported by pedestals with ambient between shaft ends seals and bearing casings
- Inlets equipped with one 90° stop valve plus one 90° throttling valve (plug type)
- Dry gas seals (DGS) at shaft ends
- Extensive use of internal flow path brush type seals
- Side entry roots, integral shroud, reaction advanced aerodynamic design tapered and twisted bladings





MT provided with bleeding to feed MTC turbine

DEMONSTRATOR POWER PLANT- TURBOMACHINERY DESIGN

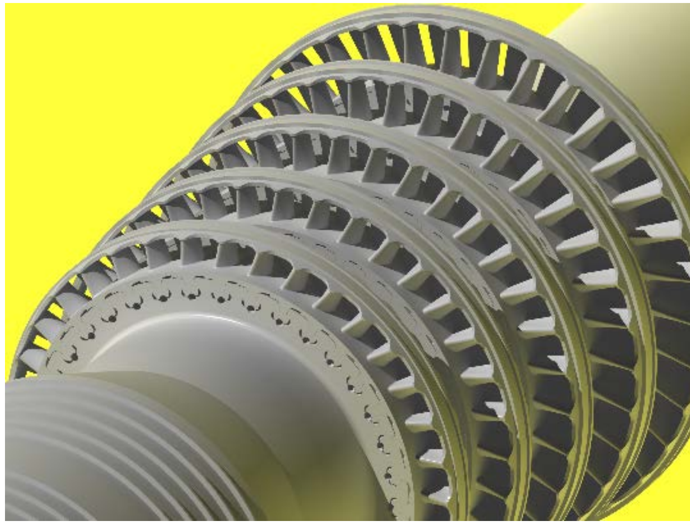
6. MAIN TURBINE (MT) DESIGN CONCEPTS

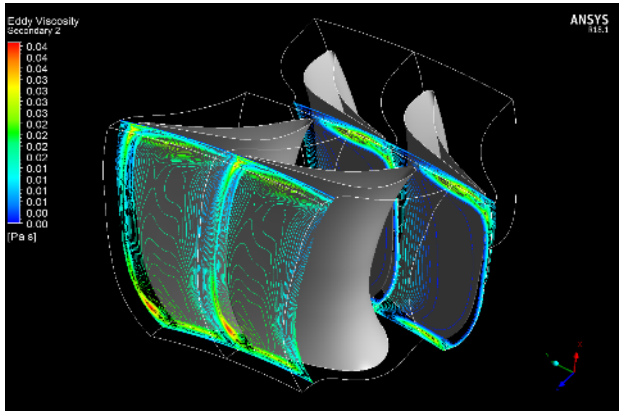
- Main turbine aerodynamic and structural design (CFD + FEM study)
- unexpected high profiles efficiencies due to Mach number range / criticality of leakage issues

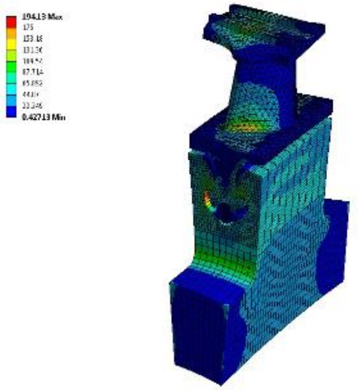
Stat.Mach	[-]	.416	.431	.442	.456	.473
Rot. Mach	[-]	.422	.434	.447	.462	.480

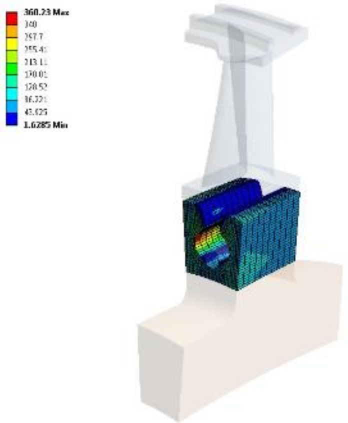
Extraction from 1D proprietary code MT flow path calc.

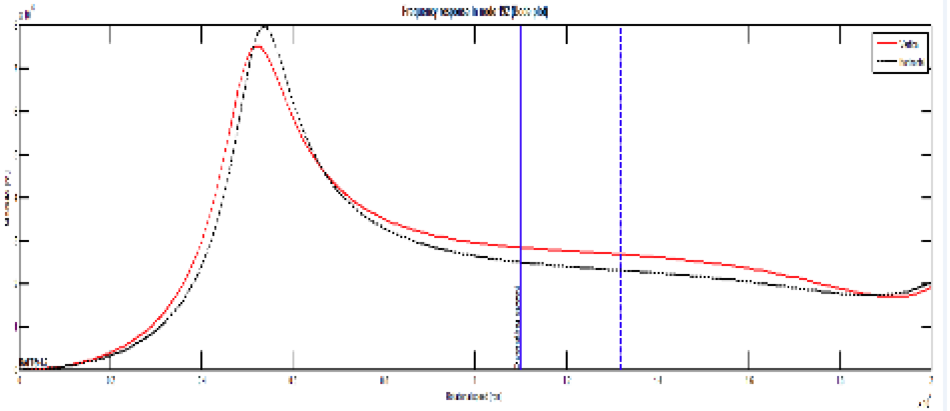
- Very high average structural loads due to high power (fluid) density with respect to steam/gas turbines











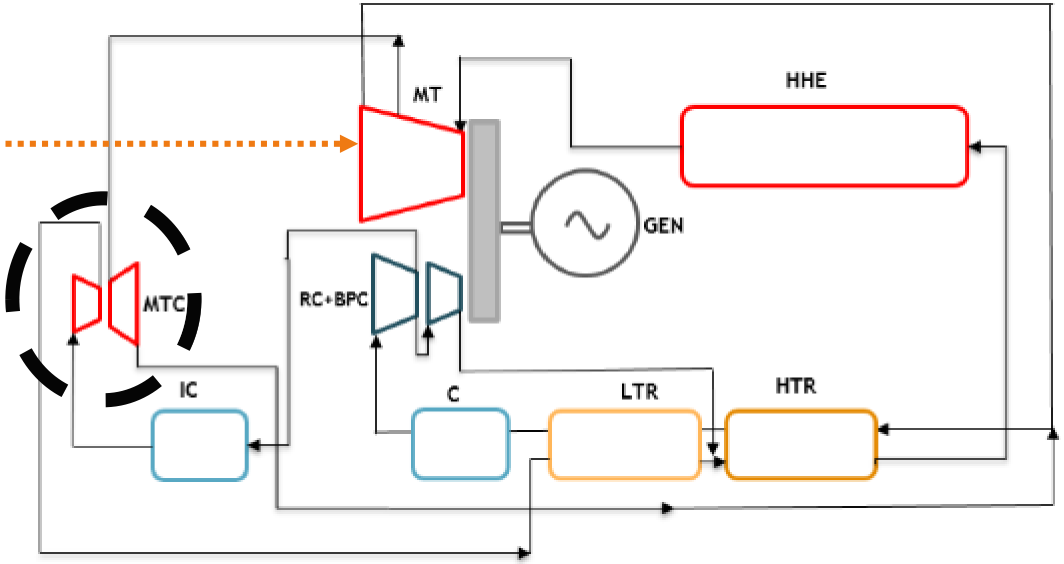
ROTORDYNAMIC VERIFICATION WITH SPECIAL ATTENTION TO STABILITY ISSUES

ROTOR (SHAFT + BLADES) SELECTED MATERIAL UP TO 650°C: FE-NI ALLOY 1.4980 (A 286) – [CURRENTLY UNDER TESTING]

DEMONSTRATOR POWER PLANT- TURBOMACHINERY DESIGN

5. POWER BALANCED SHAFT TURBOCOMPRESSOR MTC)

35000 rpm @nominal condition, variable speed power balanced shaft (MAGNETIC BEARINGS)



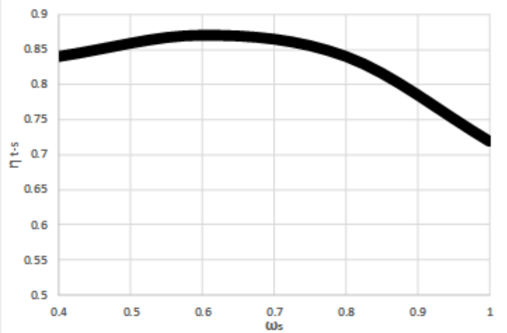
<u>To achieve proper design @same compressor speed, the driving turbine is fed by a bleeding from the MT (exhaust of 3^{rd} stage)</u> **<u>so that MTC turbine specific speed falls within good practice range</u>**

$$\omega_s = \omega \frac{\sqrt{\dot{Q}_{in}}}{\Delta h_{is}^{0.75}} \qquad D_s = D \frac{\Delta h_{is}^{0.25}}{\sqrt{\dot{Q}_{in}}}$$

$\dot{Q}_{out}$ for turbines

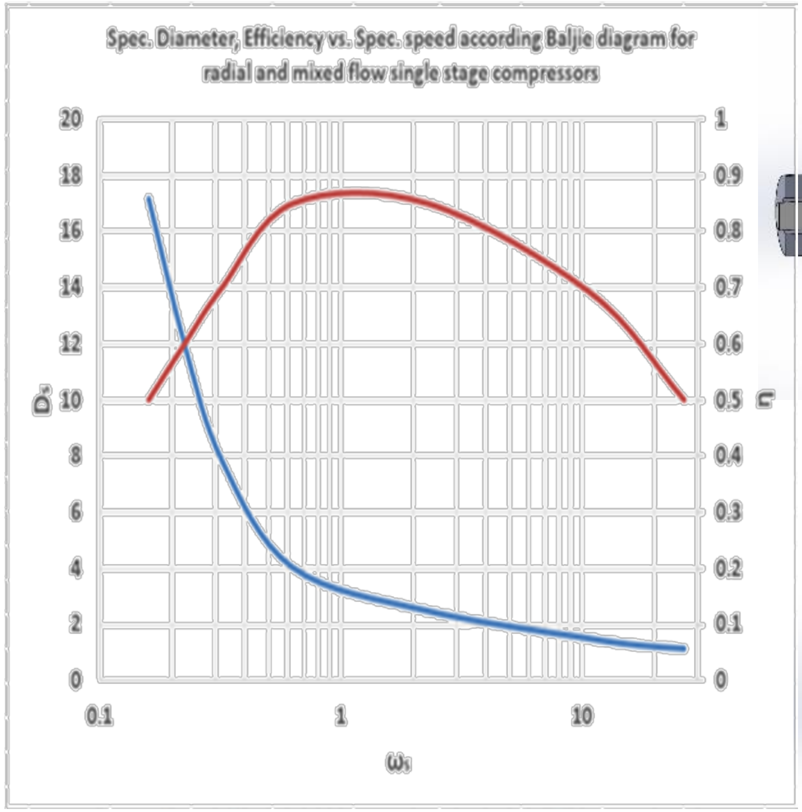
FOR RADIAL/MIXED FLOW COMPRESSORS
$0.2 < \omega_s < 2$ $selection\ for\ MTC \omega_s = 0.76$ @ 35000 rpm Compressor impeller diameter $\cong 100\ mm$

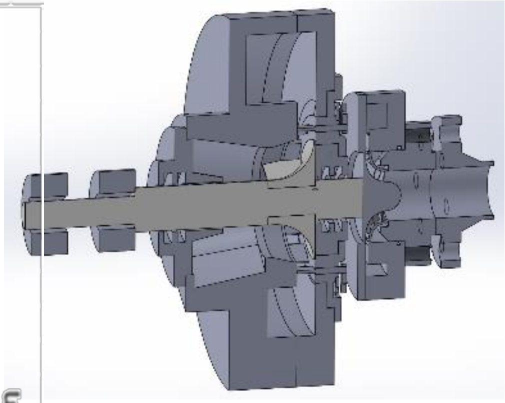
FOR RADIAL TURBINES
$0.4 < \omega_s < 1.2$ for radial turbines; through bleeding from turbine $\omega_s = 0.55$ instead of $\omega_s = 0.161$ *can be achieved thanks to the reduced enthalpy drop* @ same spped of the compressor

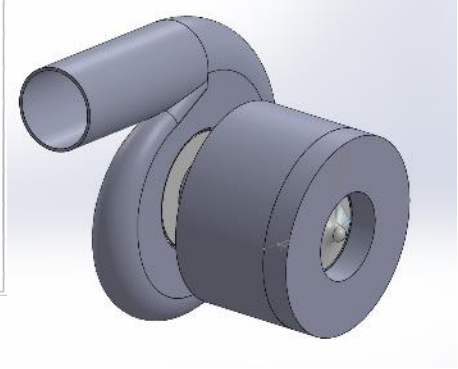


$$\& \quad \dot{m}_{MTCt} = \frac{\dot{m}_{Mc} \Delta h_{is\ Mc}}{\eta_t\, \eta_c \eta_{m\ MTC} \Delta h_{is\ MTCt}}$$

MTC BASIC ENGINEERING (IN PROGRESS)

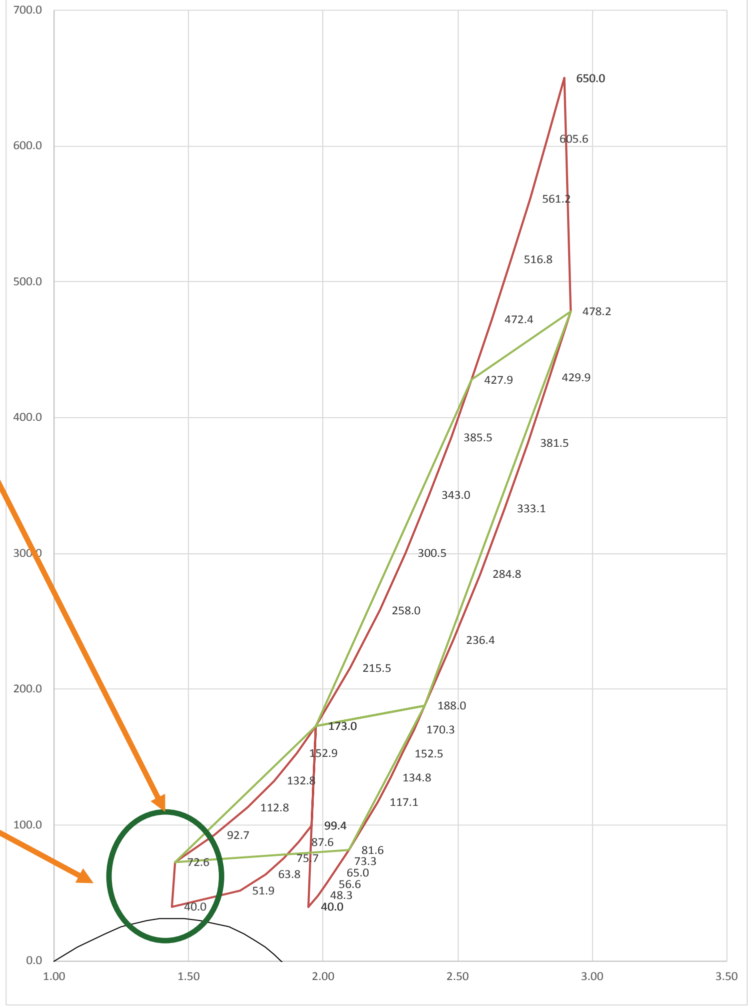






Overhung compressor side

Overhung turbine and compressor



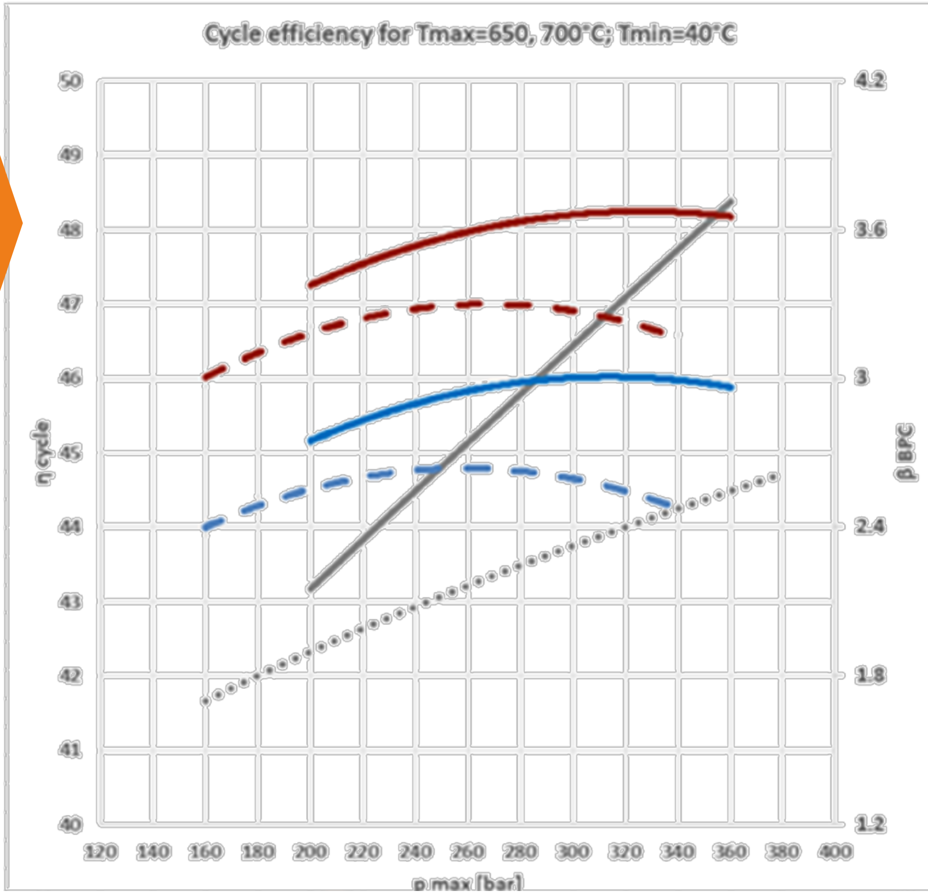
SCALING UP TO CSP 100 MWEL SIZE POWER BLOCK

- 650 & 700 °C simulation
- MT performance s from its estimated operating curves trough 1D code (and compressors from typical ones)

The dashed curves are referred to calculation keeping equally fractioned the total pressure ratio on the RC and on the BPC, while the continuous curves are referred to optimum fractioning of the pressure ratio on the two compressors. Grey lines give the pressure ratio for the BPC. The continuous line is referred to optimum fractioning, while the dashed one gives the pressure ratio when equally fractioned on the two compressors.

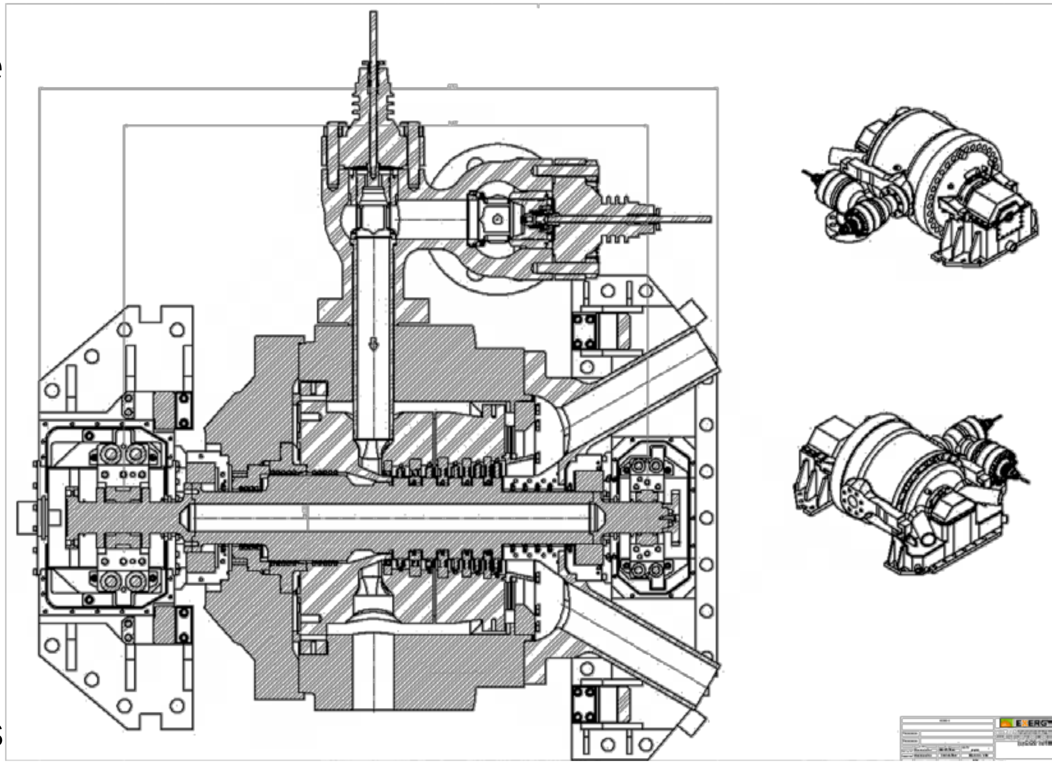
Th Pwr fract [%]	El Pwr [kW]	MT flow [kg/s]	p min [bar]	T in RC [°C]	RC pout [bar]	Tin MC [°C]	MT p in [bar]	MT T in [°C]	HT Rec out T [°C]	HT Rec eff. [%]	LT Rec eff. [%]
100%	109535	837.8	55.5	40	94	40	224	649.9	420.6	95.1%	91.8%
90%	97681	784.3	55.5	40	93.6	40	210.1	649.9	428.8	95.3%	91.5%
80%	85397	735.5	55.5	40	93.1	40	195.4	639.9	429.7	95.4%	91.1%
70%	72466	687.7	55.5	40	92.6	40	182.3	629.9	432.2	95.5%	90.7%

			Comp.s power			Vol. flow fract.					
Th Pwr fract [%]	Th. Cycle eff [%]	BP fract [%]	RC+BPC [kW]	MC [kW]	MT eff. [%]	MC [%]	RC [%]	BPC [%]	RC eff. [%]	BPC eff. [%]	MC eff. [%]
100%	45.6%	41%	42042	13104	92.1%	100%	100%	100%	88.0%	88.0%	84.0%
90%	45.2%	42%	40603	11153	92.1%	93%	94%	96%	87.3%	86.4%	83.0%
80%	44.5%	43%	35078	9234	92.1%	87%	88%	94%	87.9%	86.3%	83.0%
70%	43.1%	44%	31182	7605	90.5%	81%	82%	90%	87.8%	85.9%	83.0%



CONCLUSIONS

- Among the wide range of possible applications of sCO2 cycles, an estimate of the most promising ones have been made to give the base of a power loop type design
- A recompressed, intercooled cycle configuration, achieving good cycle performances on a wide range of possible applications, has been selected
- Specific cycle and turbomachinery solutions in order to reduce or avoid operational flexibility detriment due to compressors inlet volumetric flow variations have been studied
- Detailed main turbine design of a 20 MWth input cycle has been carried out, with the aim to reduce as much as possible the deviations from future industrial most common applications similarity
- A transposition to CSP 100 MWel power block has been considered



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