R&D activities on sCO_2 in Europe:
E02: Components Challenge – Compressors

5 December 2022

This webinar is in cooperation with 8 European R&D projects

COMPASsCO$_2$

SCARABEUS

CARBOSOLA

CO$_2$OLHEAT

sCO$_2$-4-NPP

sCO$_2$-Efekt

DESOLINATION

SOLAR sCO$_2$OL

Note: for more information about the above projects please refer to the proceedings from the first webinar's episode

Webinar's content & speakers

Giacomo Persico
Politecnico di Milano

Marco Ruggiero
Baker Hughes

Rasmus Rubycz
Atlas Copco

Q & A

R&D activities on sCO_2 in Europe: Components Challenge – compressors

Scientific challenges of pumps and compressors

Giacomo Persico

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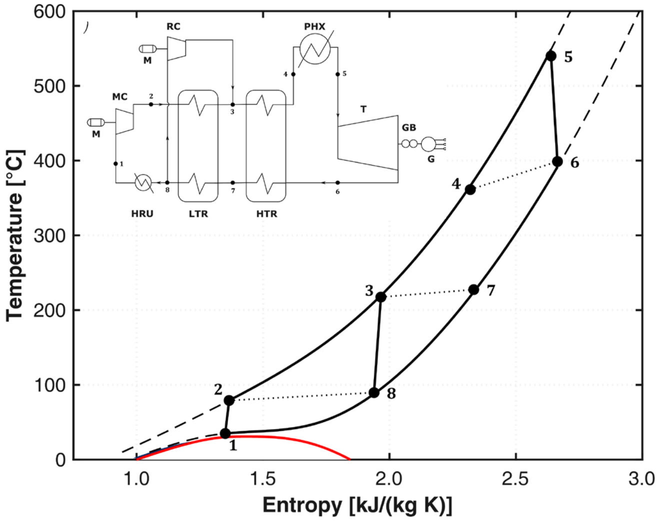
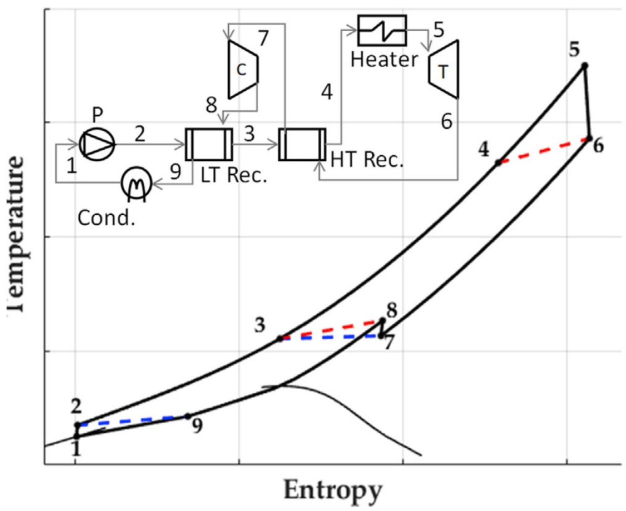
sCO2 power systems configurations

Supercritical (CO2) and trans-critical (CO2/CO2-blends)

→ near-critical compressors vs sub-critical pumps



Romei et al., Journal of Turbomachinery 2020

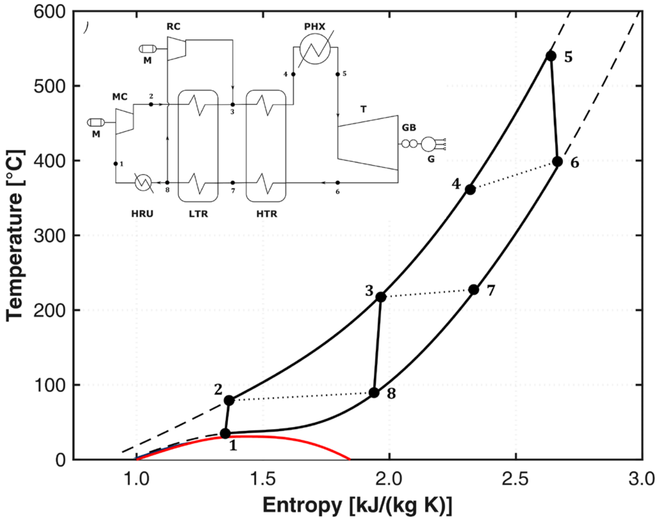


Crespi et al., Energy 2020

sCO2 power systems configurations

Supercritical (sCO2) and trans-critical (sCO2/sCO2-blends)

→ **near-critical compressors** vs sub-critical pumps



Romei et al., Journal of Turbomachinery 2020

Pros:

- ✓ Single-phase cycle
- ✓ Low compression work
- ✓ High-density → compact machines

Cons:

- ✓ Near-critical state at compressor intake

→ non-ideality, phase change (cavitation/condensation)

- ✓ Too small size for low power capacity systems

→ technology/manufacturing issues

sCO2 power systems configurations

Supercritical (sCO2) and **trans-critical** (sCO2/sCO2-blends)

→ near-critical compressors vs **sub-critical pumps**

Pros:

✓ Rankine cycle → even lower pump work

✓ Opportunity for pump standardization

✓ sCO2-blends allow changing critical state

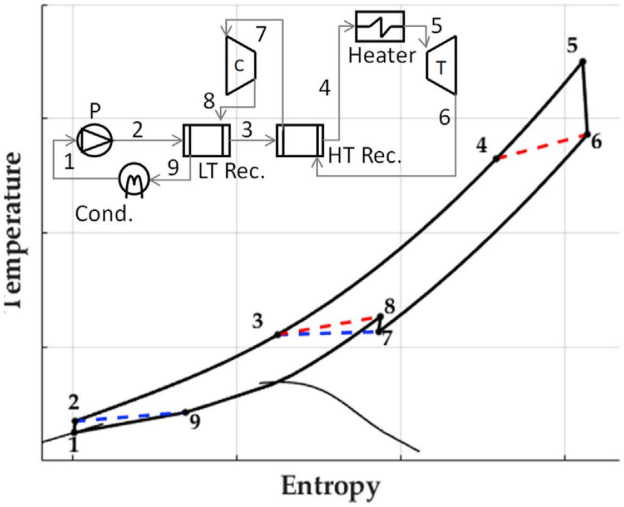
→ extend trans-critical cycle to high temperature

Cons:

✓ Severe issues of CO2 pump cavitation

✓ Compressibility effects in the CO2 pump

✓ Complex thermodynamics of sCO2-blends



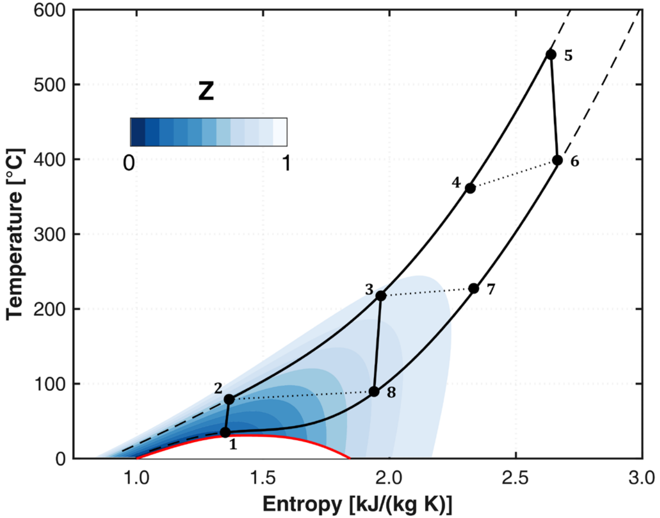
Crespi et al., Energy 2020

sCO2 compressors – fluid non ideality

For an ideal gas:

$$v_{id} = {}^{RT}/_{P} \; ;$$

$$\gamma = {}^{c_P}/_{c_v} = -\frac{v}{P}\left(\frac{\partial P}{\partial v}\right)_s = k \; .$$

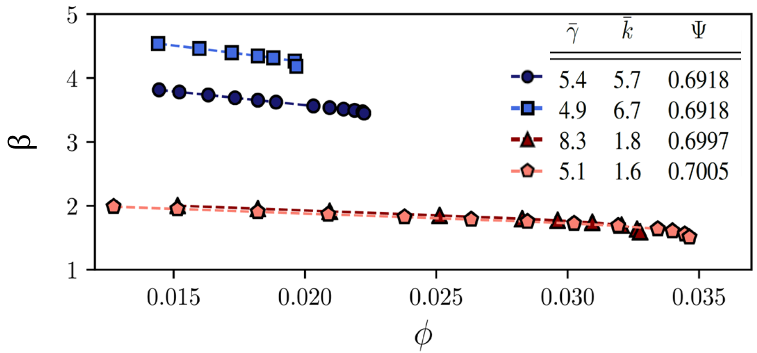


Close to the critical point:

$$v \neq v_{id} \implies Z \stackrel{\text{def}}{=} {}^{v}/_{v_{id}} \ll 1 \; ;$$

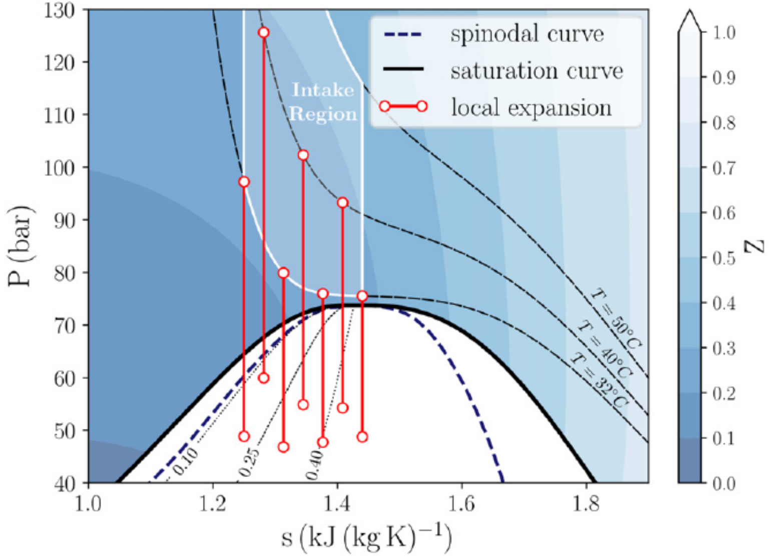
$k \neq \gamma$; $k = (T, s)$: $k \uparrow$ as entropy $\downarrow$.

$$\Psi = \frac{\Delta h_{tt,is}}{u_2^2} \approx \frac{\beta^{\frac{k-1}{k}} - 1}{M_{u2}^2 (k-1)} : k \uparrow, \beta \uparrow$$

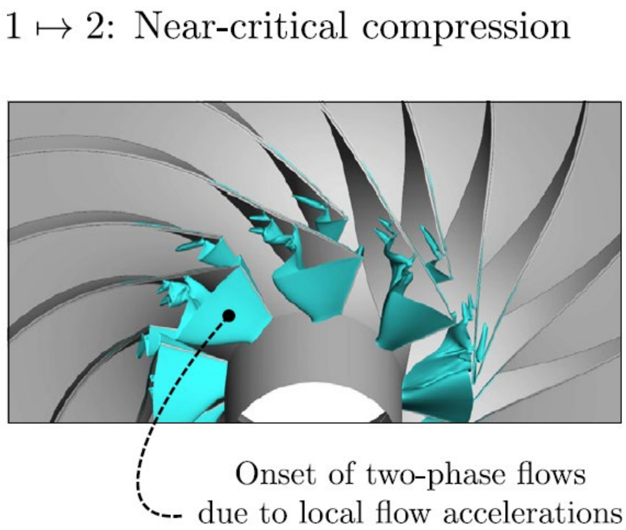


sCO2 compressors – phase change (I)

Phenomena: acceleration at intake → dive **into the dome**!



Persico et al., Journal of Engineering for gas turbines and power 2021

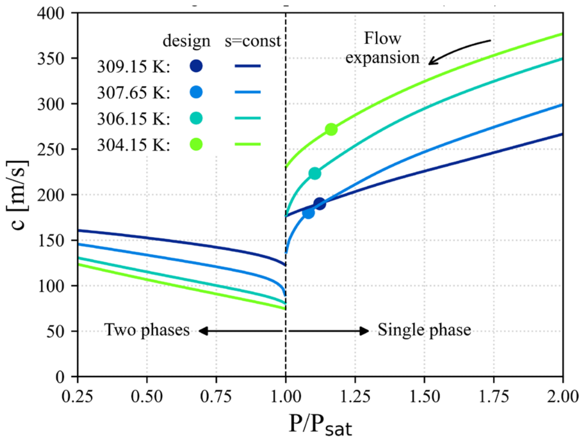


Romei and Persico, Applied Thermal Engineering 2021

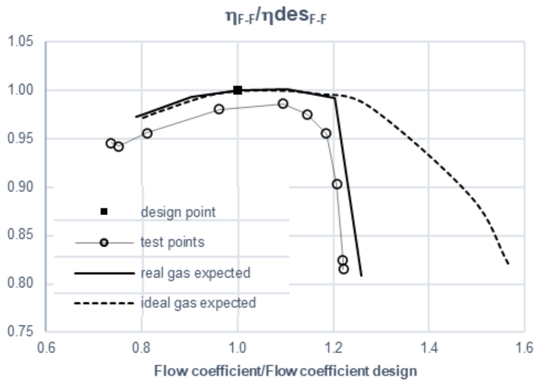
sCO2 compressors – phase change (II)

Huge drop of speed of sound

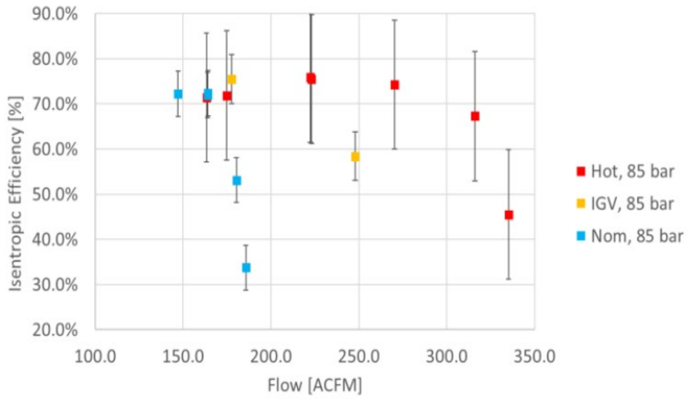
→ **anticipated choking,** impact on sCO_2 compressor rangeability!



SCO2-FLEX compressor (EU, H2020)



APOLLO compressor (US, DoE)



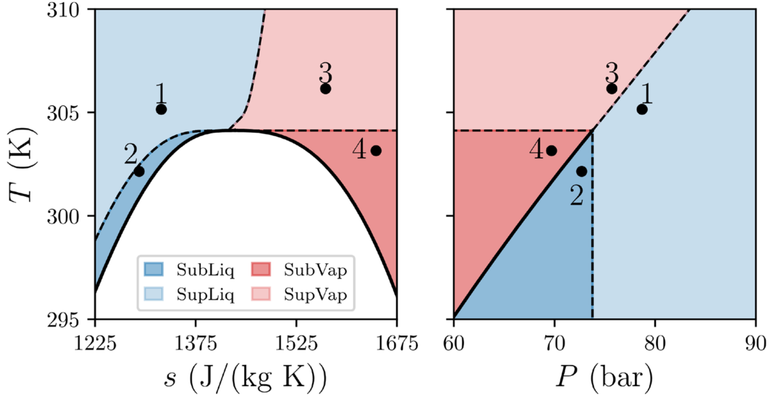
Toni et al., International sCO2 Power Cycles Symposium 2022

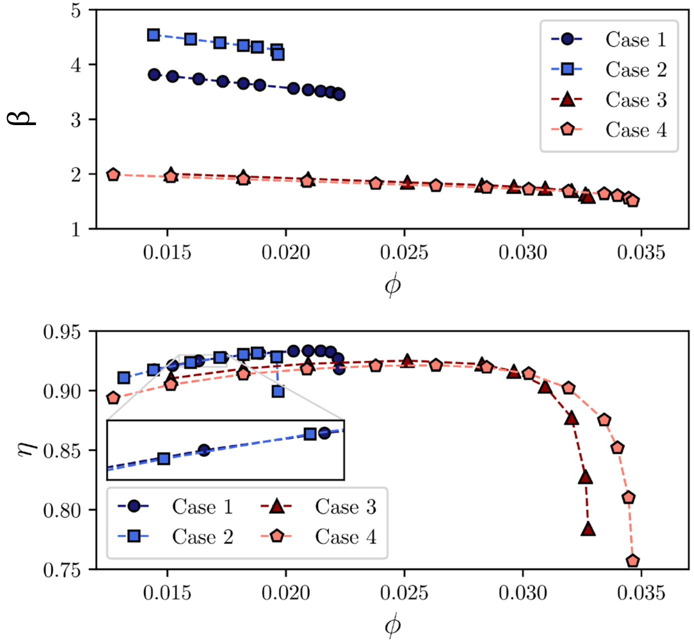
Mortzheim et al, ASME Turbo Expo 2021

sCO2 compressors – state sensitivity

Impact of intake state: pressure ratio, efficiency, rangeability

Case	P (bar)	T (K)	s/s_c	State
1	78.7	305.15	0.93	Supercritical Liquid
2	72.7	302.15	0.91	Subcritical Liquid
3	75.7	306.15	1.10	Supercritical vapor
4	69.7	303.15	1.15	Subcritical vapor



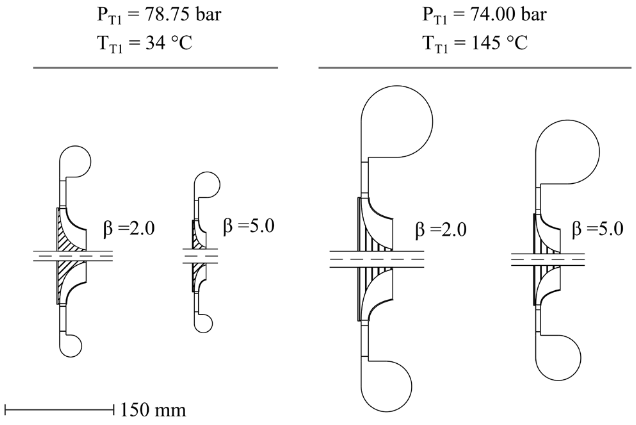


Romei et al, ASME Turbo Expo 2021

sCO2 compressors – technology

High pressure – low temperature: compact machines

✓ Low volumetric flow rate
→ radial machine for most applications
→ specific design strategies for low flow-function impellers



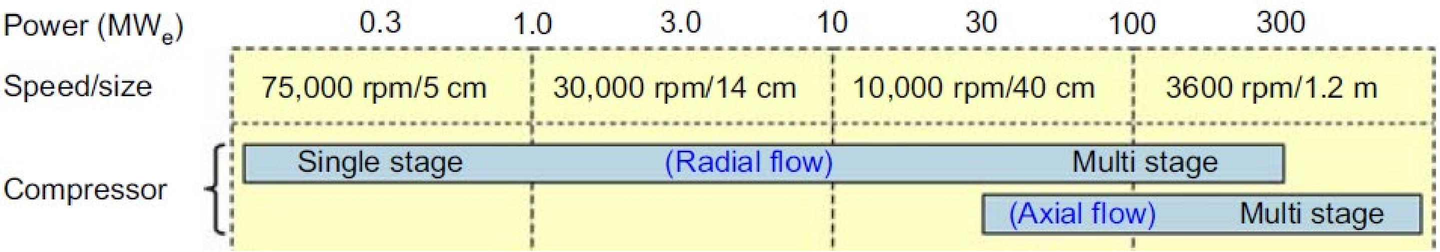
✓ Limited pressure ratio per stage (2—3)
→ relatively acceptable stresses, no creep issues
→ relatively conventional materials (supply chain issues?)

✓ Size:
→ manufacturing issues (DGS, surface roughness)
→ can we identify a minimum sCO2 plant capacity set by compressor manufacturing limitations?

sCO2 compressors – selection

sCO2 compressor ranges:

- ✓ Power < 1 MWe: very compact / very high-speed impellers → really feasible?
- ✓ 1 < Power < 10 MWe: compact and fast but feasible
- ✓ ~50 MWe: axial compressors become relevant
- ✓ Power > 300 MWe: only axial compressors are effective → reliable threshold?
- → can axial compressors withstand such high aerodynamic forcing → high density, thick profiles?
- → might **pump**-based trans-critical cycles be more advantageous for very high power capacity?



Musgrove and Wright, “Introduction and Background”, Fundamentals and Applications of Supercritical Carbon Dioxide (sCO2) Based Power Cycles, 2017

CO2 / CO2-blends pumps

Sub-critical fluid, liquid-like thermodynamics, small size

Compressibility effects not negligible:

→ Issues in a thermodynamic region still not consolidated (CO2-blends especially)

→ Phase changes occurs as cavitation, with $v_v \gg v_l$: bubbles not dispersed, bubble implosion might become critical

→ Phase change process in case of CO2-blends still an open issue, dedicated criteria to avoid cavitation need to be developed

Technology aspects:

→ Can we identify a minimum technology-driven size also for pumps?

→ Might the use of pumps open the way for component standardization?

→ Is there room for scalability?

R&D activities on sCO_2 in Europe: Components Challenge – compressors

Thank you!

Giacomo Persico

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R&D activities on sCO_2 in Europe: Components Challenge – compressors

Industrial experience in design and testing

Marco Ruggiero

Summary

- Baker Hughes at a glance
- sCO_2 Compressor testing experience at Baker Hughes
- Compressor challenges
- sCO_2 Pump testing experience at Baker Hughes
- Pump challenges
- Conclusions

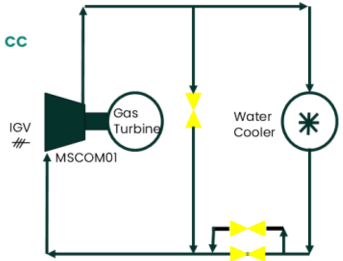
We are an **energy technology company**.

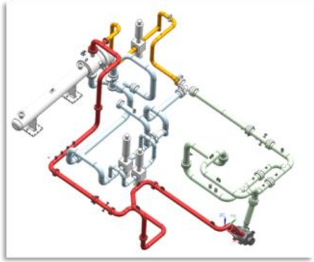
Our innovative technologies are taking **energy forward**.

sCO2 Compressor testing experience

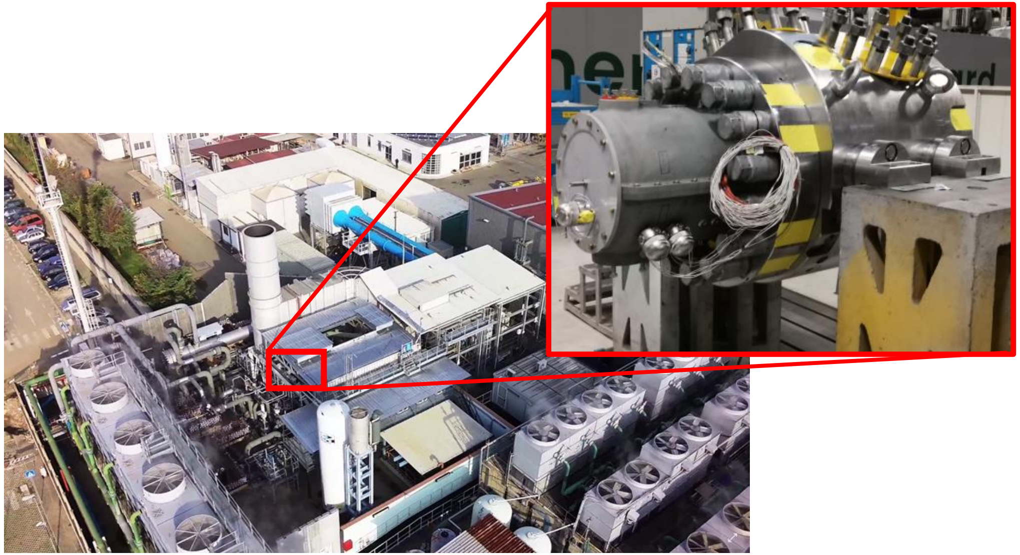
Compressor test rig @ Baker Hughes site in Florence

Main features
- 10MW driver
- Speed up to 14k rpm
- Two phase gas loop
- Designed for up to 670 bar





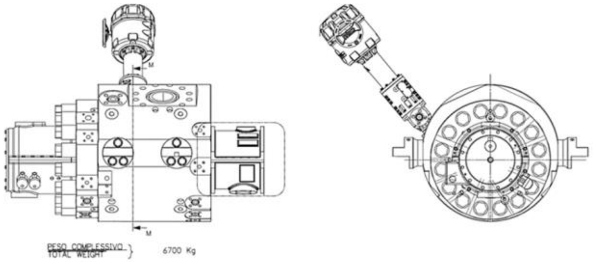
sCO2 Compressor testing experience



sCO2 compressor prototype

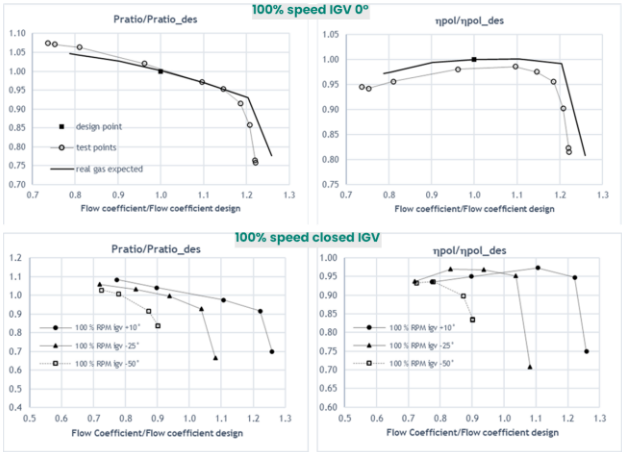
Main features

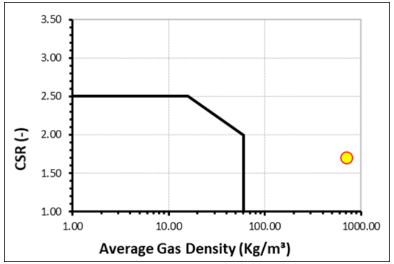
- 5MW
- Speed 11.2k rpm
- Stacked rotor
- Variable geometry IGV



sCO2 Compressor testing experience

- Suction control temperature is critical
- Results validate CFD modeling* based on barotropic relation $\rho = f(p)$
- Good rotordynamic stability even if compressor way outside the CSR and avg gas density map





* developed in collaboration with *Politecnico di Milano*

sCO2 Compressor challenges

- Maintaining compressor inlet temperature through ambient and load changes is critical for optimal efficiency
- Effects of saturation and condensation forces the development of a new aero design which includes splitter blades
- Operation of DGS to prevent leakage to ambient and solid formation in transients
- Pure radial machine only for up to 50MW; gradual migration to axial afterward (initial front stage / full axial machine). Introduction of typical axial machine challenges on front stages (flutter, 1^{st} flex mode response) in a high density environment (forcing vs damping)
- For very small machines the defining factor is the weight of leakages over main flow. Effect of non scalable geometrical features below 100mm diameter on efficiency.

CO2 Pumps testing experience

CO2 pump test rig @ Baker Hughes site in Bari

- Max flow rate 35kg/s
- Suction conditions (80-100 bar)

CO2 Pumps testing experience

Consolidated product for Enhanced Oil Recovery

Nominal speed test: 7600RPM	
Design polytropic head 3900m	
Test loop "Settle-out conditions" A (100bara, 15°C)	Test loop "Settle-out conditions" B (100bara, 40°C)
•Max deltaP delivered, ρ_{ave} = 900kg/m3 •BH model EOS accuracy of predictive model for CO_2 **liquid** pumping •DGS's flushing parameters assessment in dynamic and standstill conditions with CO_2 **liquid**.	•High compressibility, ρ_{ave} = 600kg/m3 •Max density variation through the pump. Validation of new impeller family for CO_2 application •BH model EOS accuracy of predictive model for CO_2 **supercritical** pumping. •DGS's flushing parameters assessment in dynamic and standstill conditions with CO_2 **supercritical**.

sCO2 Pump challenges

- CO_2 (and CO_2 with blends) EoS still not well characterized in liquid region
- High density variation through the pump
- Management of inlet conditions
- Upward scalability limited by volumetric flow (max about 1500 m3/h); downward scalability limited by change in pump type as below 300 NS it becomes a volumetric pump and the effect of non scalable geometrical features below 100mm diameter

Conclusions

- Consolidated experience in sCO2 pumping
- Europe first full scale sCO2 compressor tested on the critical point
- DGS leakages recompression system is our next challenge, synergistic with expander

Thank you for listening!

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Baker Hughes

R&D activities on sCO_2 in Europe: Components Challenge – Compressors

Industrial Experience sCO2 Compression

Atlas Copco Gas and Process

Rasmus Rubycz / Ulrich Schmitz - December 2022

Industrial Experience sCO_2 Compression

Atlas Copco Gas and Process

Leveraging decades of experience in CO_2 handling for the next phase of sCO_2 turbomachinery evolution

This is the Atlas Copco Group

- Customers in more than **180** countries
- **43 000** employees in **70** countries
- Established in **1873** Stockholm, Sweden
- Turnover of **111** BSEK/ **11** BEUR
- Operating margin of **21.2%**

Atlas Copco Gas and Process

ETN Global

BOARD OF DIRECTORS

PRESIDENT AND CEO

GROUP MANAGEMENT

COMPRESSOR TECHNIQUE

- Compressor Technique Service
- Industrial Air
- Oil-free Air
- Professional Air
- Gas and Process
- Medical Gas Solutions
- Airtec

VACUUM TECHNIQUE

- Vacuum Technique Service
- Semiconductor Service
- Semiconductor
- Semiconductor Chamber Solutions
- Scientific Vacuum
- Industrial Vacuum

INDUSTRIAL TECHNIQUE

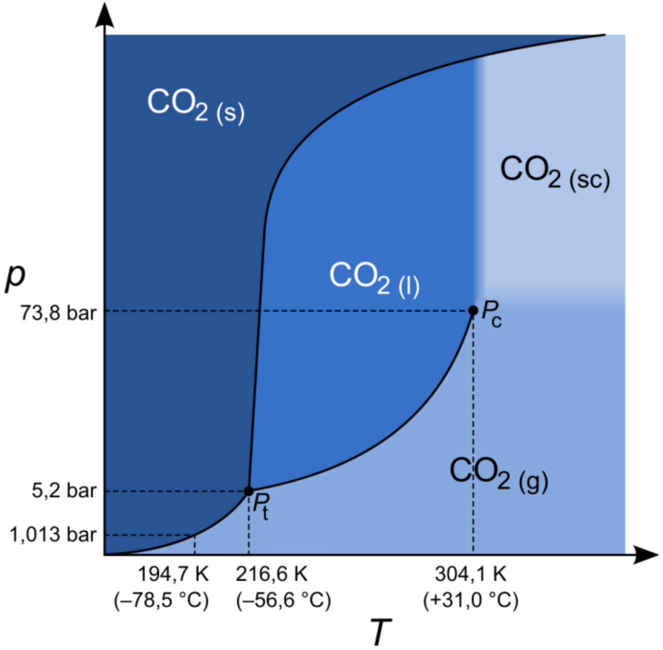
- Industrial Technique Service
- MVI Tools and Assembly Systems
- General Industry Tools and Assembly Systems
- Chicago Pneumatic Tools
- Industrial Assembly Solutions
- Machine Vision Solutions

POWER TECHNIQUE

- Power Technique Service
- Specialty Rental
- Portable Air
- Power and Flow

sCO2 properties are challenging

Comparing Air with sCO2

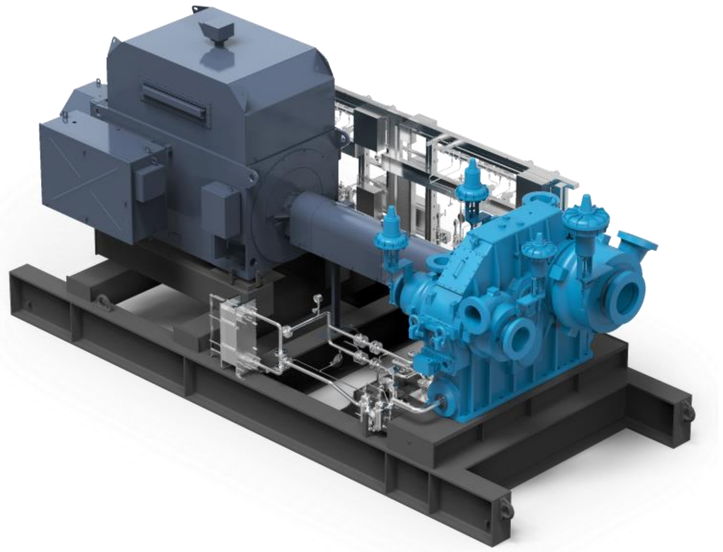


Source: https://de.wikipedia.org/wiki/Kritischer_Punkt_%28Thermodynamik%29

	Air	sCO2
Pressure	74bar	74bar
Temperature	31°C	31°C
Density	85 kg/m³	486 kg/m³
Diffusion in Elastomers	Low	High

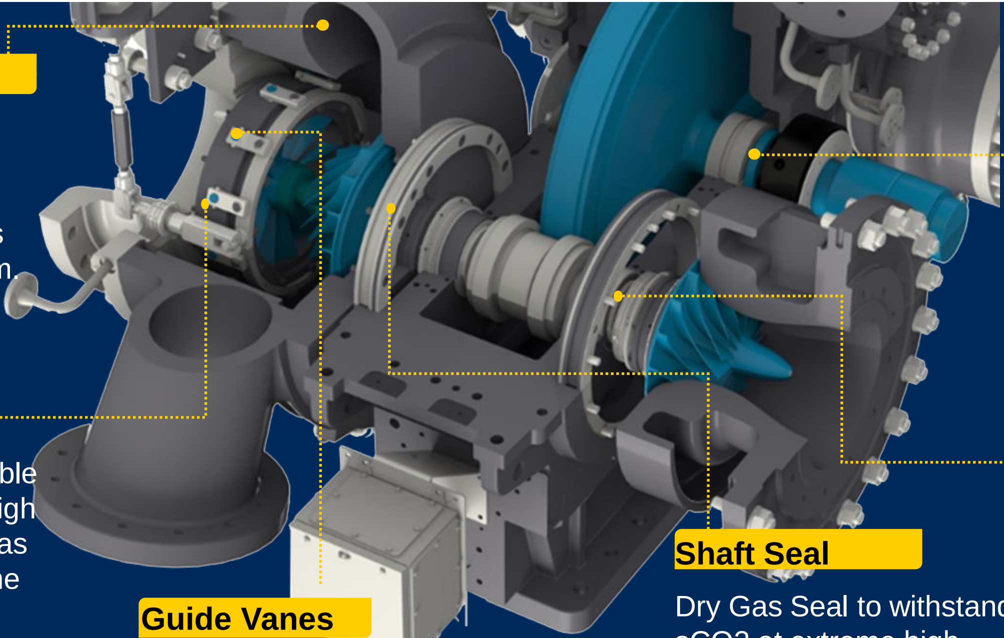
sCO2 Component Challenge – General

sCO2 is not just another gas



	Typical Turbocompressor or -expander	Supercritical CO2 Turbocompressor or -expander
Pressure	0 to 50 bara	30 to 300 bara
Temperature	-196 to 250°C	0 to 500°C
Power	200 to 25 000 kW	200 to 25 000 kW
Impeller Diameter	150 to 1530 mm	150 to 500 mm
Impeller power density (kW/cm²)	0,1 to 0,8	3 to 20

sCO2 Component Challenge – in Detail



Volute

Static parts to withstand high pressure, temp. and cyclic loads under sCO2 atm.

Impeller

Needs to be able to withstand high temperatures as well as extreme power density

Guide Vanes

High mechanical load due to high density and temperature

Shaft Seal

Dry Gas Seal to withstand sCO2 at extreme high pressures and high temperatures

Bearing

High load due to high power density

Pinion

High-speed with high torque due to high density sCO2

Innovation in CO_2 compression

Major Milestones

1869
First definition of the critical point of fluids

1922
Bosch-Meiser Urea synthesis utilizes as first industrial process sCO_2 in large scale

1950s
First use of integrally geared (IG) air compressors in industry

1975
First use of Dry Gas Seal (DGS) by Turbonetics Ind. (now Atlas Copco)

1980s
Atlas Copco IG compressors with intercooling allow efficient, large scale CO_2 compression

2008
6-Stage sCO_2 compressor with intercooling in industrial plant (83bar, 120°C)

2015
AC and seal OEM test high speed DGS under severe sCO_2 conditions (200bar, 140°C) to allow higher pressures and temperatures

2016
AC delivers two 8-Stage sCO_2 compressors with DGS and intercooling to Urea plant (200bar, 120°C)

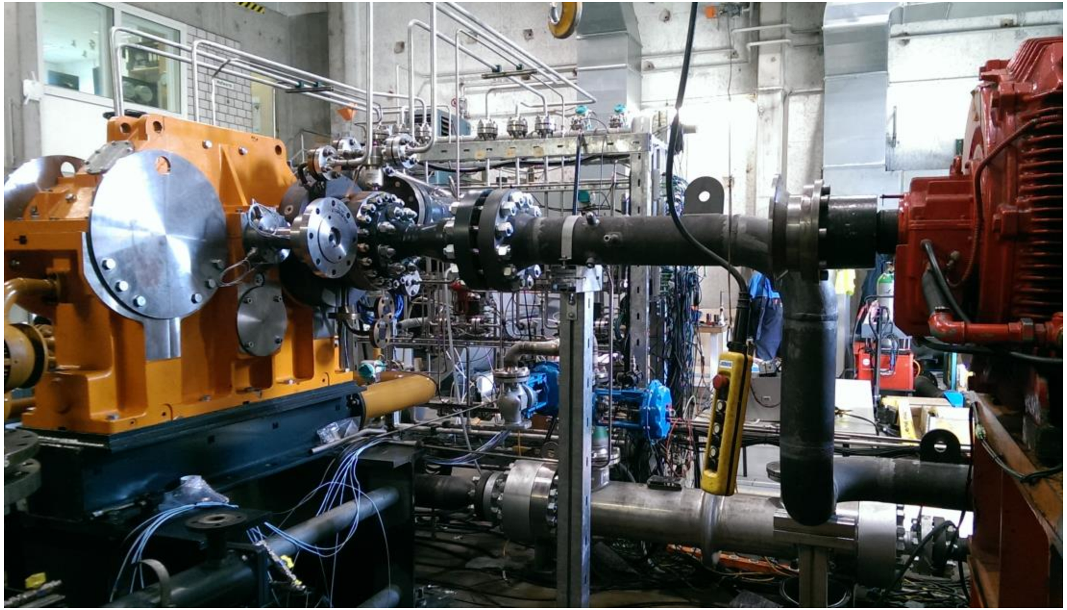
2016
AC delivers compressors for NetPower sCO_2 OxyFuel powerplant

2019
AC develops sCO_2 Waste Heat Recovery “Compander” for >200bar and >200°C

2021
Concepts for sCO_2 use in large heat pumps

R&D Activities at Atlas Copco GAP

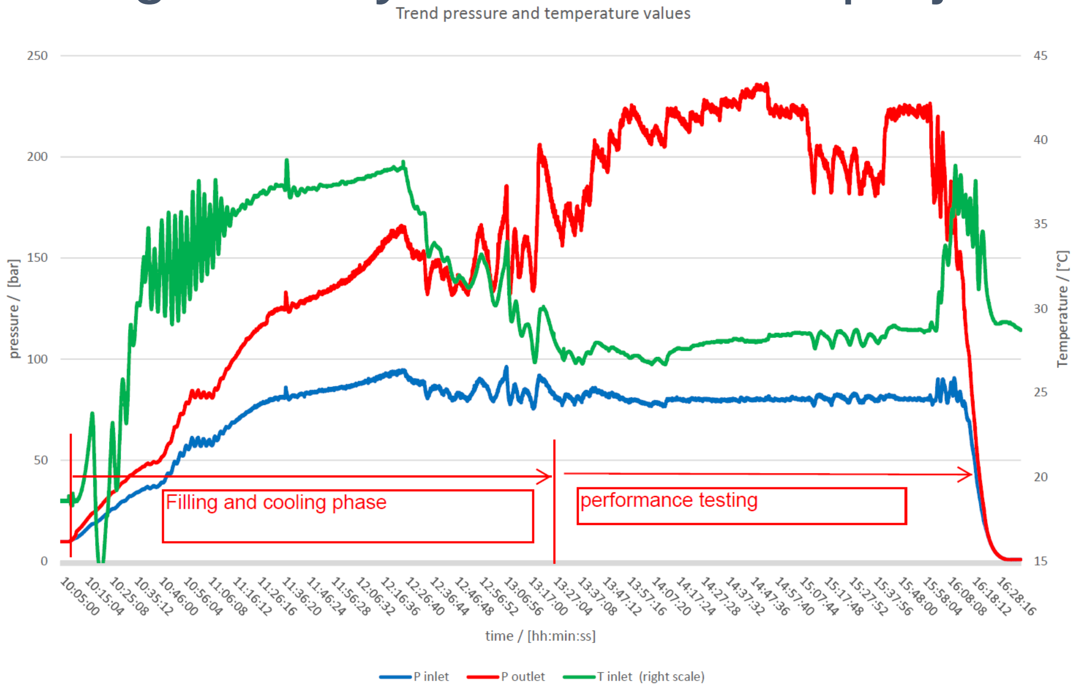
Paving the way to commercial projects



- In-House testing of Dry Gas Seal (DGS) in collaboration with Seal OEM
- Special compressor stage mock-up for testing
- Target: Qualification of DGS for severe sCO_2 operation conditions >200bar & >200°C
- Successful implementation of results in commecial project

R&D Activities at Atlas Copco GAP

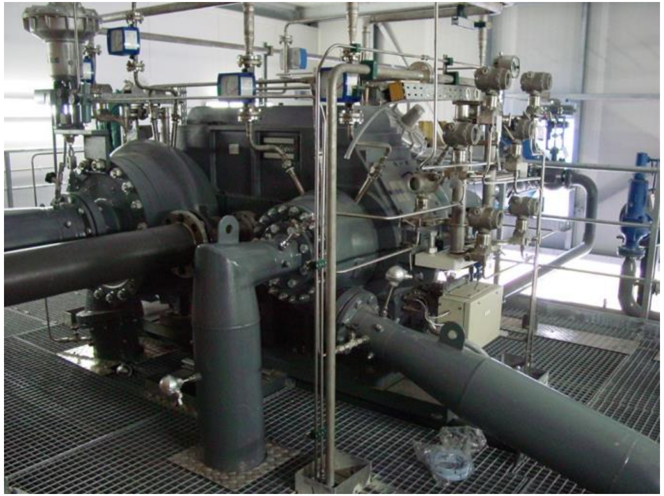
Paving the way to commercial projects



- Verification of database values on sCO2 fluid properties
- Calibration of CFD calculation models by real teststand data
- Iterative correction of mathematical models lead to high precision in machine design

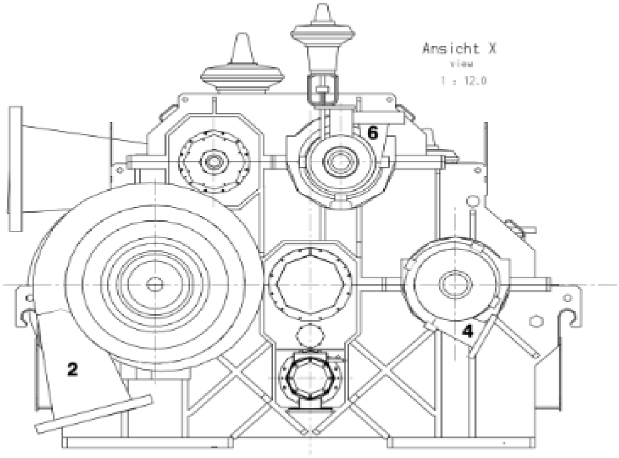
Industrial Experience – Greenhouse NL

Year Ordered	Code Word	Name of Buyer	Compressor Type	Q'ty	Gas Handled	Volume m³/h	t1 °C	P1 bar(a)	P2 bar(a)	Speed Rotors rpm	Driver Power kW	Driver Speed rpm	Name of End User	In Country
2005	Greenhouse	Hoek Loos (Linde)	GT050T4K1	3	CO_2	18 544	25	1,06	22	13 658 26 558	2 650	2 960	Hoek Loos (Linde)	The Netherlands



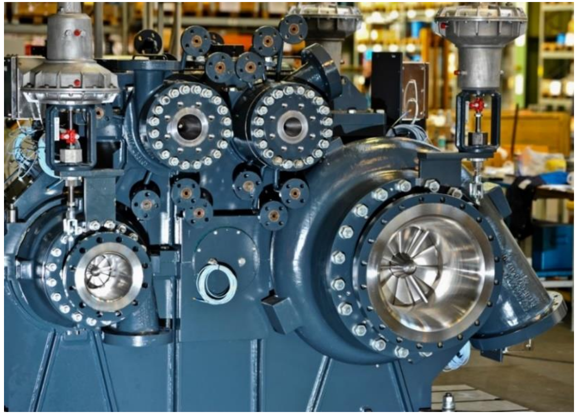
Industrial Experience – Datang China

Year Ordered	Code Word	Name of Buyer	Compressor Type	Q'ty	Gas Handled	Volume m^3/h	t1 °C	P1 bar(a)	P2 bar(a)	Speed Rotors rpm	Driver Power kW	Driver Speed rpm	Name of End User	In Country
2008	Datang CO_2	CNWR & EPM&E	GT070T5K1/ 021T1K1	3	CO_2	43 410 46 548	12 87	1,09 55,43	55,47 82,37	10 364 32 465 28 500	9 300	6 000	Datang International Power	China



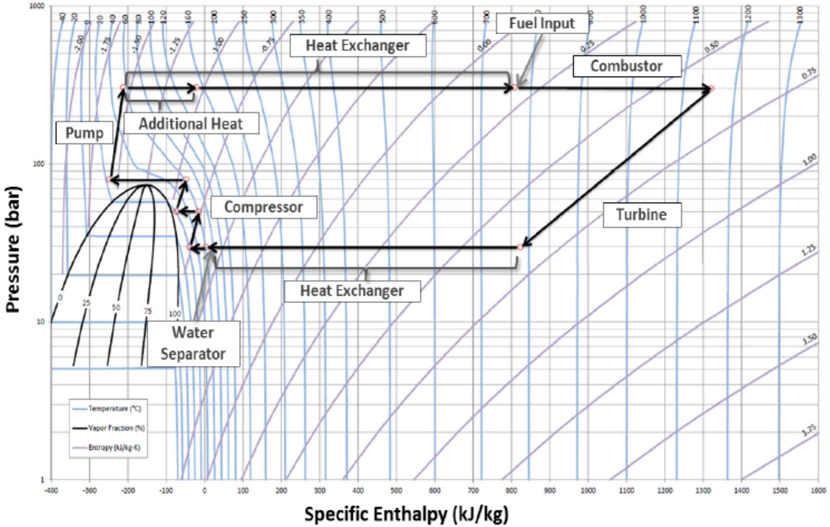
Industrial Experience – Acron Russia

Year Ordered	Code Word	Name of Buyer	Compressor Type	Q'ty	Gas Handled	Volume m³/h	t1 °C	P1 bar(a)	P2 bar(a)	Speed Rotors rpm	Driver Power kW	Driver Speed rpm	Name of End User	In Country
2013	Veliky Novgorod	Acron	GT040T8S1	2	CO_2	21 999	45	1,06	202	18 034 32 461 36 068 37 455	5 150	2 960	Acron	Russia

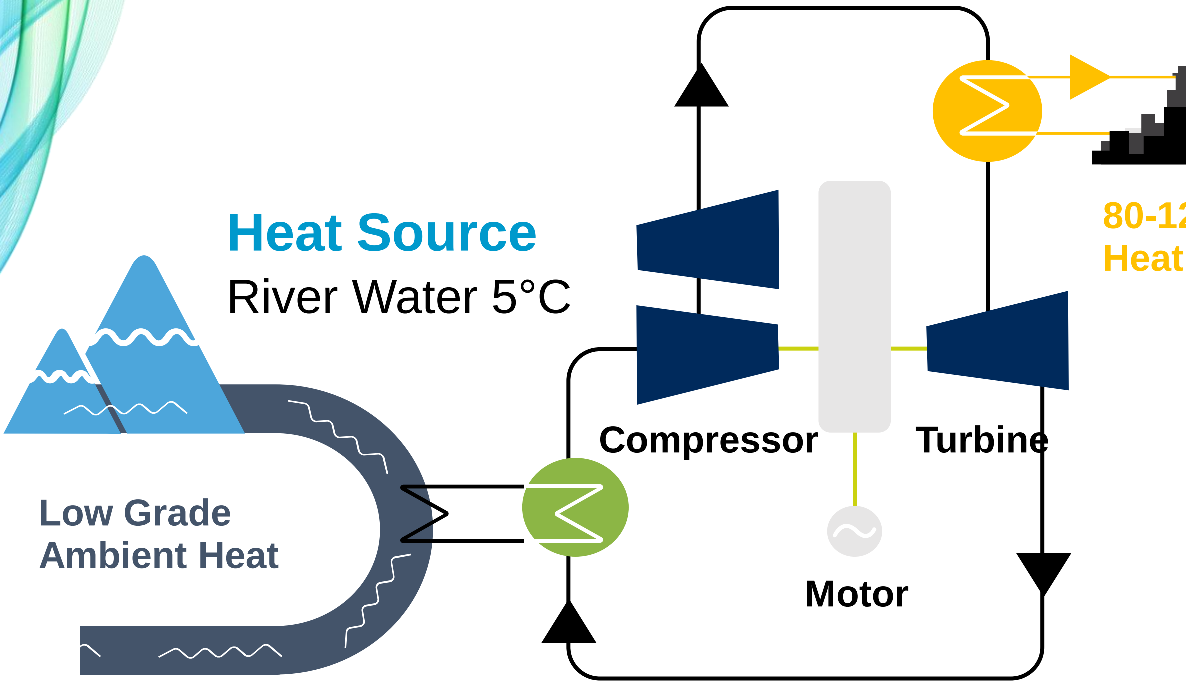




Industrial Experience – NetPower USA

Year Ordered	Code Word	Name of Buyer	Compressor Type	Q'ty	Gas Handled	Volume m³/h	t1 °C	P1 bar(a)	P2 bar(a)	Speed Rotors rpm	Driver Power kW	Driver Speed rpm	Name of End User	In Country
2016	NetPower CO2	CB&I	TP14T22D1	1	CO_2	6 880	34	27	91,7	-	9 650	2 960	NetPower	USA



Upcoming Market – Large Heat Pumps



80-120°C High Grade Heat for District Heating

- sCO2 Heat Pump has high power density
- Power rating up to 50MW thermal per unit
- sCO2 is a natural refrigerant with ODP=0 and GWP=1

Leveraging the experience of decades

Summary – top priorities for further design Evolution

- Thermodynamic and fluid property challenge – Compare theoretical predictions with field experience of compressor operation near the critical point
- Material Challenge – refine current material selections to push the limits even further in the supercritical region
- Improve performance of sealing systems (lower leakage, higher pressure and temperature) in collaboration with sealing OEMs
- Apply technology advances to other areas than power generation, such as industrial heat pump systems and mobile waste-to-power recovery systems

Thank you!