Turbomachinery Challenges for sCO2 cycles

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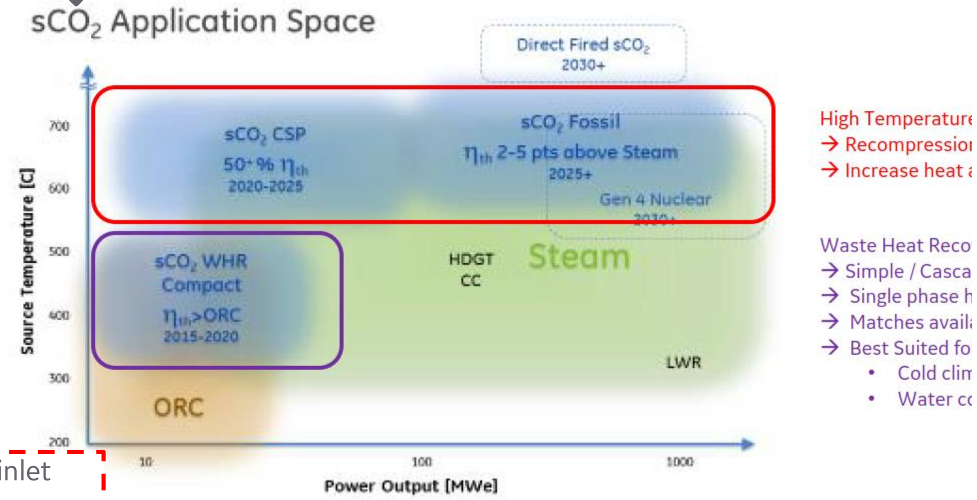
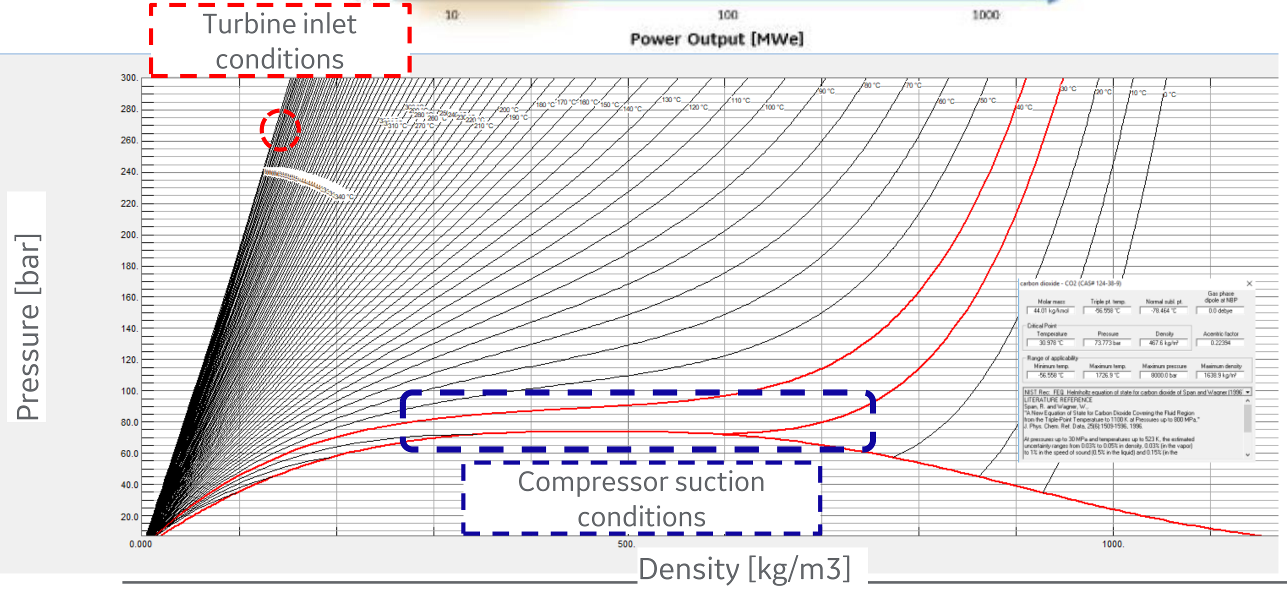
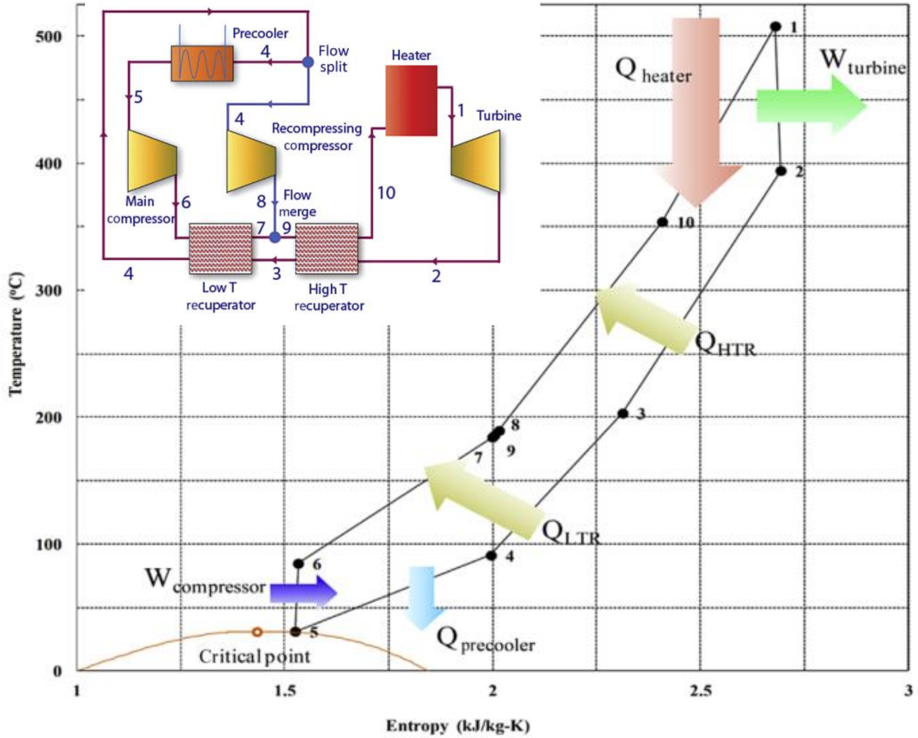
April 29, 2019

Operating conditions of compressor and turbine in sCO2 cycle



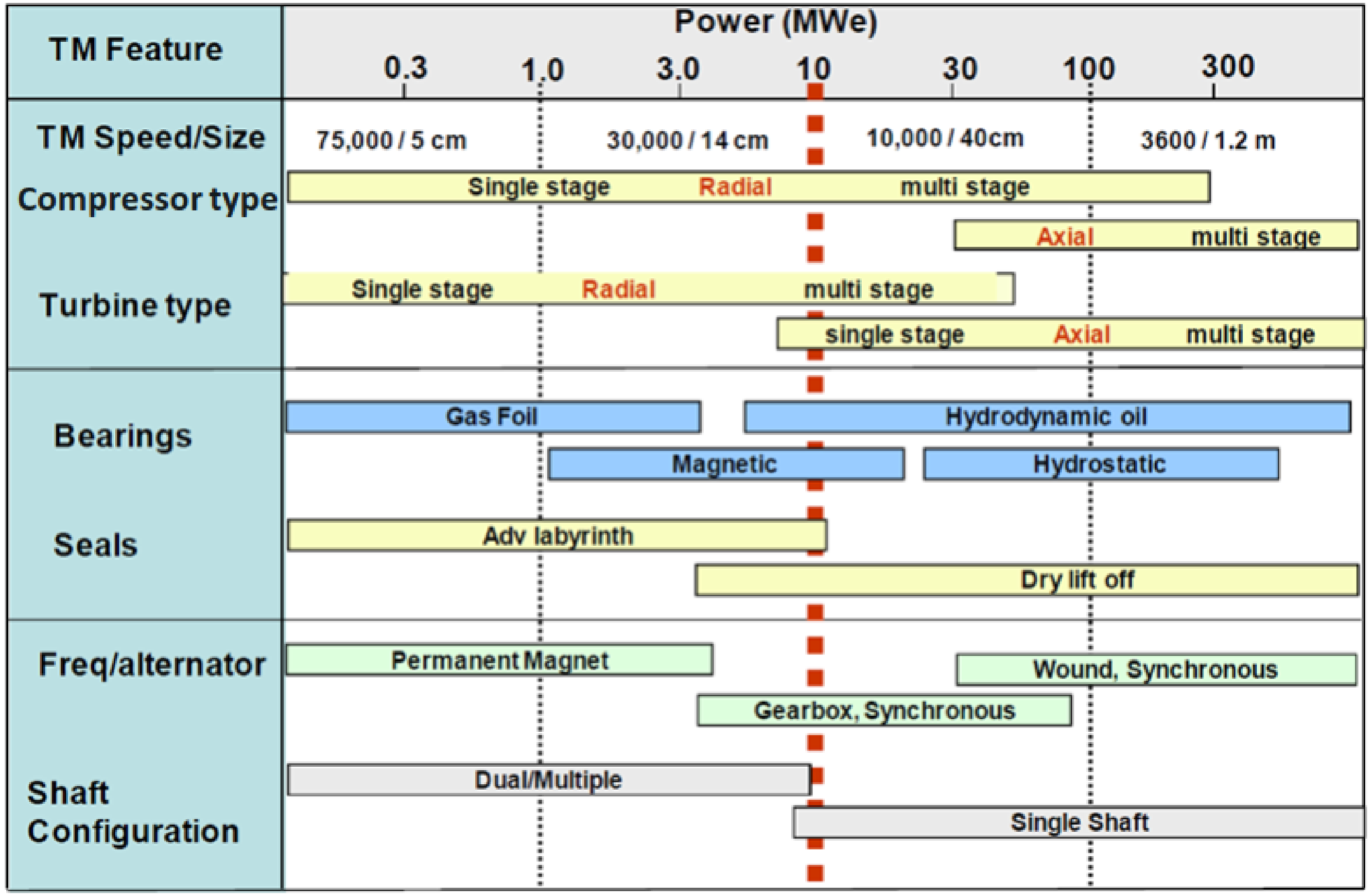




- Big changes of the compressor inlet density with small variations of pressure/temperature
- Temperature turbine inlet conditions together CO2 needs a proper material selection (>500°C) and thermal management of sealing

REVIEW OF SUPERCRITICAL CO2 POWER CYCLE TECHNOLOGY AND CURRENT STATUS OF RESEARCH AND DEVELOPMENT, AHN et alii, NuclEngTechnol 47(2015) 647-661

Technology summary for sCO2



Sienicki et al., „Scale Dependencies of Supercritical Carbon Dioxide Brayton Cycle Technologies and the Optimal Size for a Next-Step Supercritical CO2 Cycle Demonstration", SCO_2 Power Cycle Symposium, May 2011

- The high density of sCO2 allows to reduce the turbomachines footprint
- Below 10 MWe turbomachinery dimensions are very small leading to an increase of parassite losses (windage, internal leakages) with subsequent lower efficiency than larger sizes

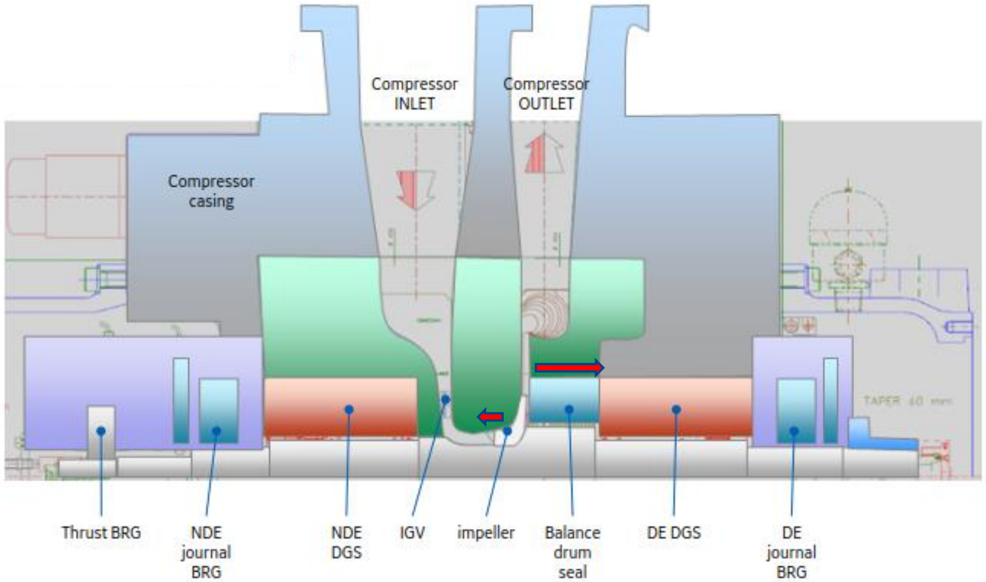
What is the «best commercial» size?

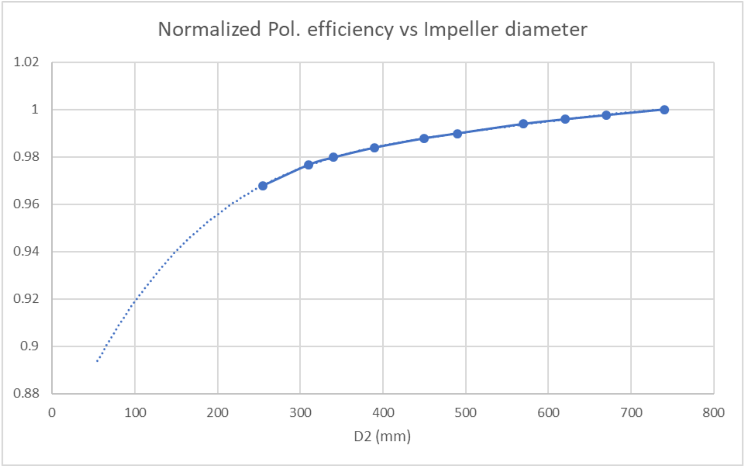
Apollo/STEP sCO2 16MW Turbine rotor
GERC Courtesy

100 MW: D = 400 mm
10 MW: D = 160 mm

$\mathbf{D_{100MW}/D_{10MW} = 2.6}$

Compressor layout for a 10MWe sCO2 cycle





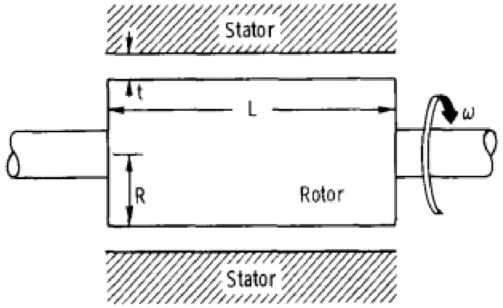
$$\begin{cases} \dot{m}_{leak} \sim seal\ gap \sim D_2 \\ \dot{m}_{main} \sim \varphi\ D_2^3 \end{cases}$$

$$\frac{\dot{m}_{leak}}{\dot{m}_{main}} \sim \frac{1}{\varphi\ D_2^2}$$

- The high density of sCO2 leads to compact machines, with small dimensions → windage and parassite losses becames important with impact on efficiency

- Moreover, the real gas effects close to the critical point jeopardize the performance predictability

- Also the thermodynamic FAT can be done only in Type I conditions. Similitude conditions are difficult to be reached (low volume ratio of Main Compressor)



Windage Power $P \sim \left(\frac{\mu}{t}\right)^{\alpha} \rho^{\beta}$

PREDICTION OF WINDAGE
POWER LOSS IN ALTERNATORS

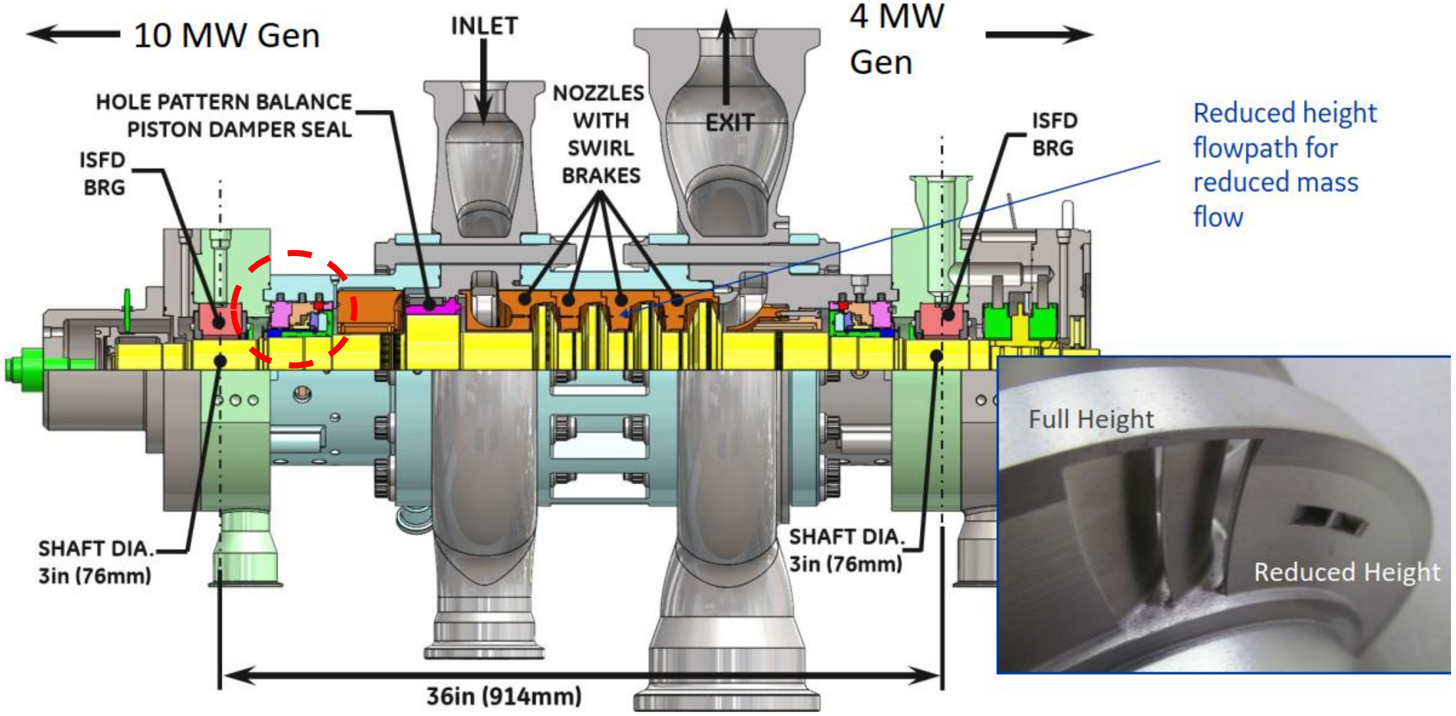
by James E. Vrancik
Lewis Research Center
Cleveland, Ohio

NASA TN D-4849

How much is important the compressor efficiency over the overall cycle efficiency?

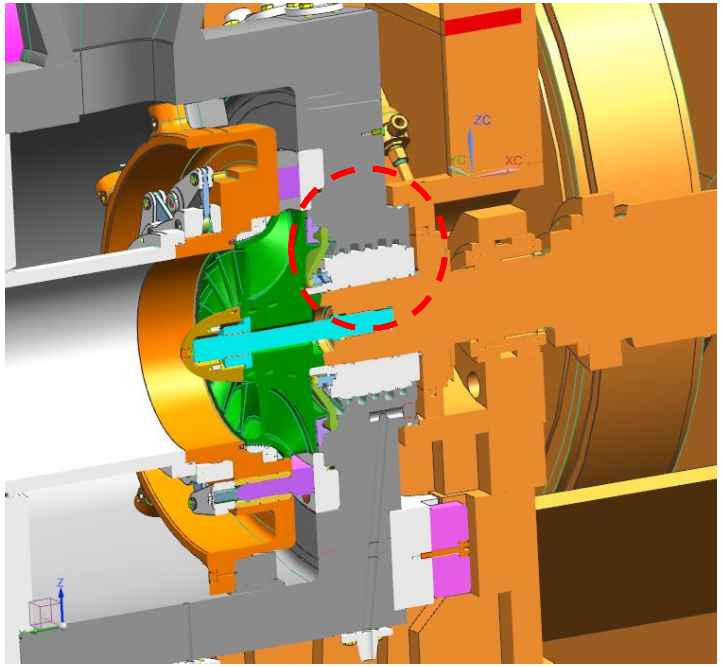
Turbine

Sunshot Turbine Design



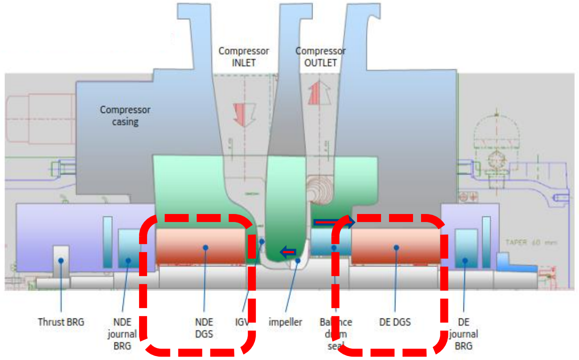
Supercritical CO2 Power Cycles, AIAA SciTech, Jan 2019, Douglas Hofer, GE Research

Radial centripetal turbine (Oregen)



- For small power, radial and axial turbines have comparable efficiencies
- Predictability of performances is better than compressor (gas is more «ideal»)
- High temperature and heat management at end seal location ⚠

Dry Gas Seal technology



Recovering system

CO2+AIR

CO2

CO2+AIR

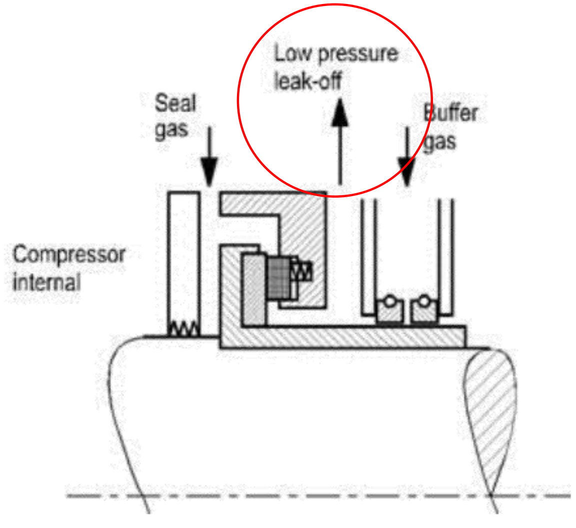


Figure 15 – SINGLE SEAL TYPE

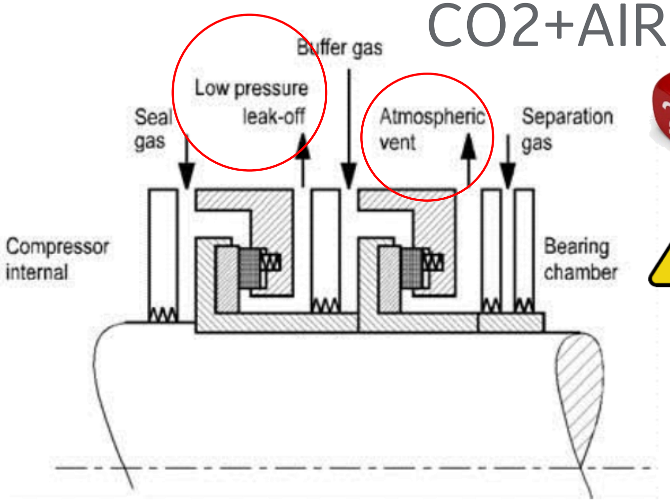


Figure 17 – Tandem seal with intermediate labyrinth seal

<u>Current DGS technology</u>.

Example on a 80bar CO2 sealing

- Expected leakage/seal: 0.0006 kg/s
- Total CO2 leakage from turbomachines:

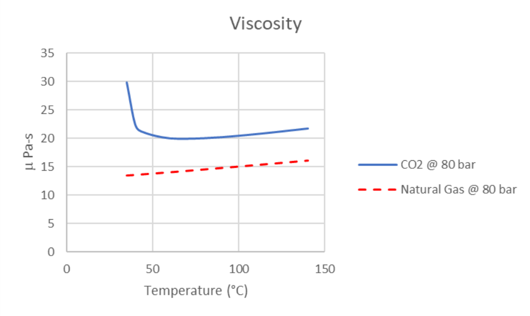
0.0006 x 2 (DGS) x 3 (2 CC + 1 TUR) = 0.04 kg/s

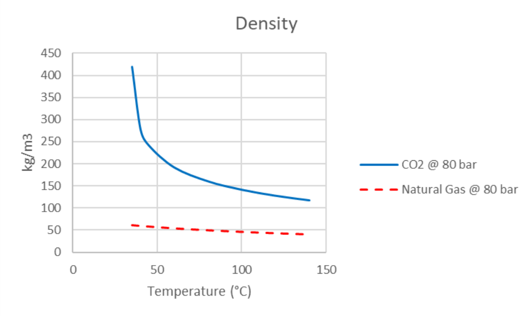
Single DGS arrangement offers a shorter machine (good for rotordynamics) but leakage cannot be recovered

Tandem DGS arrangment offers a better recovery of leakage, but higher cost, longer rotor, lower reliability

How much important is this leakage respect to other leaking parts (e.g. Flanges, valves, etc. etc.) ?

DGS operating with high viscosity, high density gas. Heat management of seals.





Integrated solutions

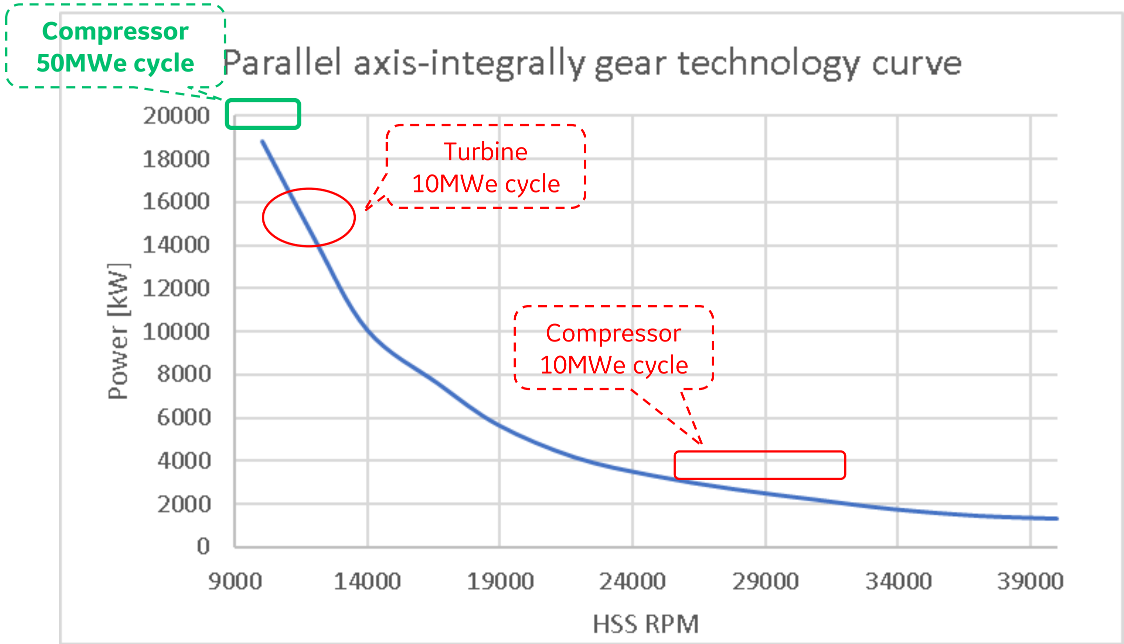
- Turbine and compressor in the same casing
  - Pro’s: minimization of the number of DGS, compact solution
  - Con’s: rotordynamics, plant start-up, thermal management, complex solution

- Sealed solution (integrated machine):
  - Pro’s: no leakages, oil free
  - Con’s: motor and compressor shall have the same speed … Limits on max power/speed, magnetic bearings working with high density fluid

- Advanced technology
  - Plasma seals (max pressure?)
  - Magnetic couplings (max torque?)
  - Magnetic gear (max torque / speed ratio?)

Example of integrated machine
BHGE - Integrated Centrifugal Compressor (ICL)

Gearbox



Parallel Axis:
Gear Ratio ≤ 6
Max Power: 45 MW

Power distribution
Gear Ratio > 6
Max Power: 45 MW

Parallel axis gearboxes can be used only for compressors in a hypotetical 50MWe cycle

Epicyclical gears are good for high gear ratios and they are applicable on the turbine up to 30MWe power cycle

For a 50MWe cycle the constraints on gearbox could force the compressor selection to a not optimal choice.

Gearbox cannot be used in cycles with Power cycle >100MWe, efficiency gain but forced to run at electric machine speeds

How important is the efficiency of turbomachinery in the overall cycle economy?

Materials

- CO_2 at temperatures up to 350 °C and pressure higher than 15 bar oxidites metals. The corrosion rate is usually mderate to allow the use of mild steels.
- **Material selection for compressors can be standard as per manufacturer experience. Stainless steel or coatings are however reccomended to protect from general corrosion (humidity)**
- Above 350°C the metal carburization occurs, only few experimental data at long exposure time are available in CO_2 in thse conditions
- Up to 500°C, >18%Cr stainless steels seem to give small corrosion rates. Good compromise between durability and cost
- For T>500°C Ni-based alloys shall be used. High cost.
- **Material selection for turbine shall include Ni-alloys. Coatings are desiderable to reduce cost and to allow raw material availability**

Operability

- The high density variations close to the critical point leads to a proper control of MAIN compressor in order to make it working in optimal conditions
- Main Compressor control strategies shall include speed variation and Movable Inlet Guide Vanes (MIGV). The use of both could give good combination in the flow-head diagram with proper efficiency
- The turbine could be controlled with valve (to be checked the leakages). Mechanical design of movable nozzles are challenging because of the high temperature
- Understanding operability in transient conditions is very important to chech the machine controllability
- The partial load management is also important. High operative envelope leads to lower efficiencies
- **The final application of the plant could have an impact on the turbomachinery selection and performances**

Conclusions and discussion points

Conclusions and further development

- Turbomachines are more challenging when dealing with small cycle power (small dimensions). Standardization of components will be beneficial. **Proper commercial scale still to be defined.**
- Turbomachine efficiencies increase with dimensions
- Thermal management of the turbine needs additional insights
- Operability of the compressor close to the critical point needs additional insights (tests)
- A >150 MWe cycle could use turbomachines with «normal» size
- Sensitivity of the cycle efficiency with the turbomachinery efficiencies: is maximizing the turbomachine's efficiency the best optimization objective function?
- How can the market be segmented in order to have the best options (e.g. Efficiency vs flexibility)?

BAKER HUGHES
a GE company