1st European Seminar on Supercritical CO_2 (sCO_2) Power Systems

Design considerations on a small scale supercritical CO_2 power system for industrial high temperature waste heat to power recovery applications

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Wien, 29/09/2016

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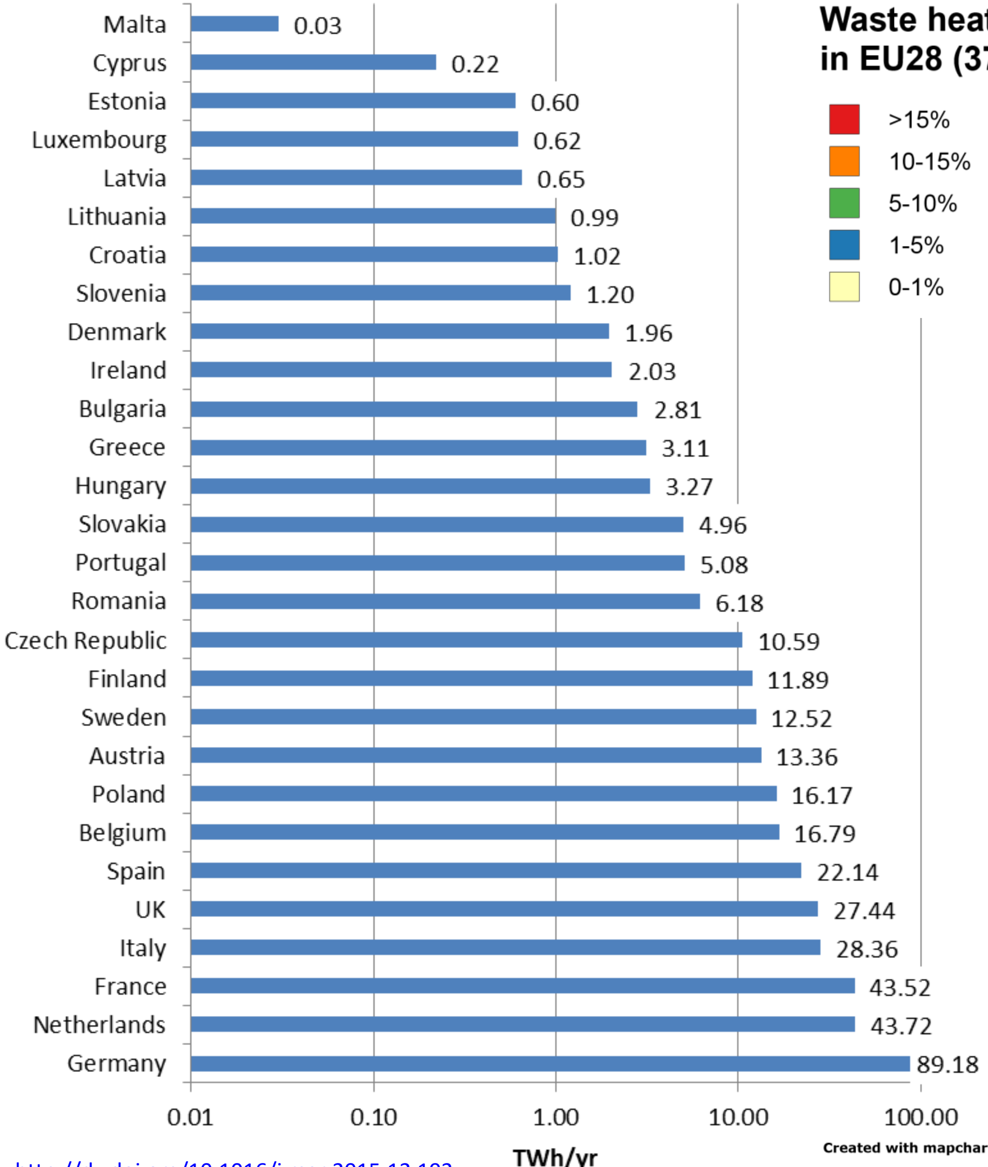
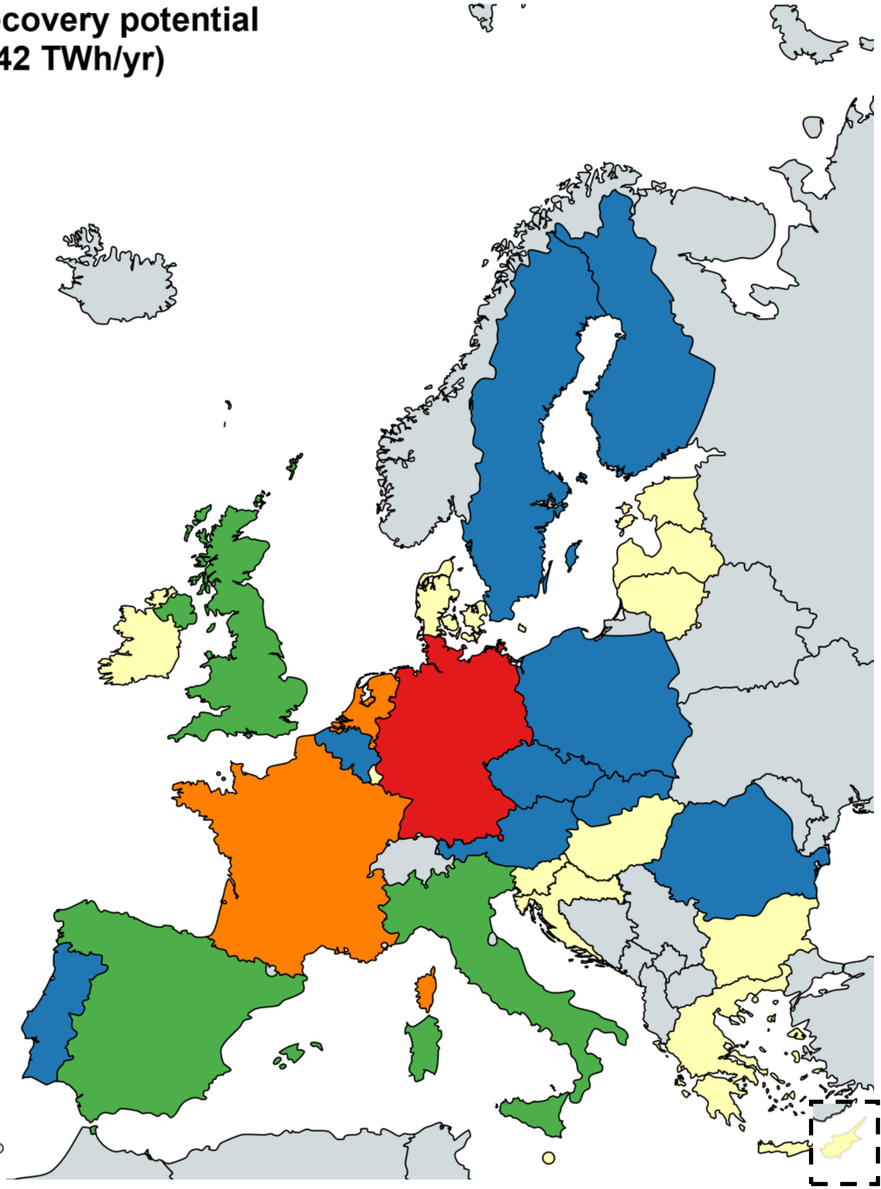
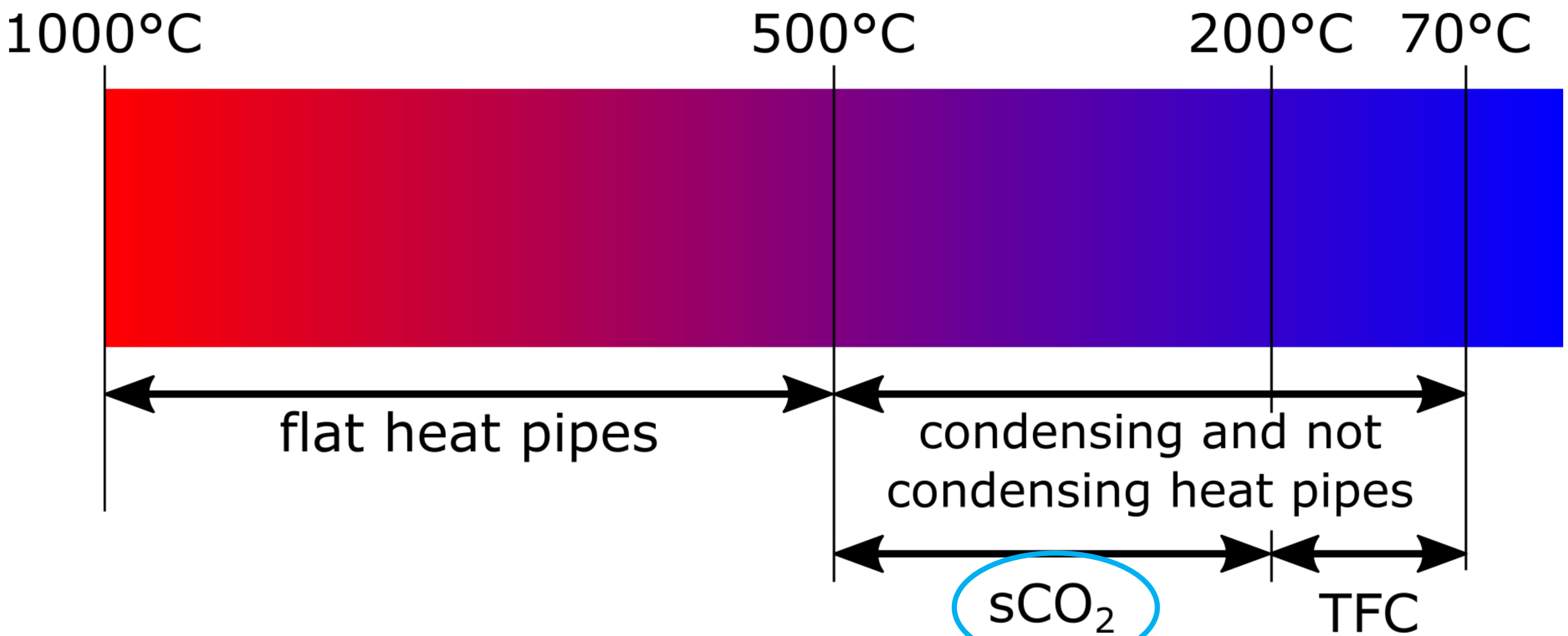




http://dx.doi.org/10.1016/j.rser.2015.12.192

I-ThERM Project aim is to…

Investigate, design, build and demonstrate innovative plug and play waste heat recovery solutions to facilitate optimum utilisation of energy in selected applications with high replicability and energy recovery potential in the temperature range 70℃ – 1000℃



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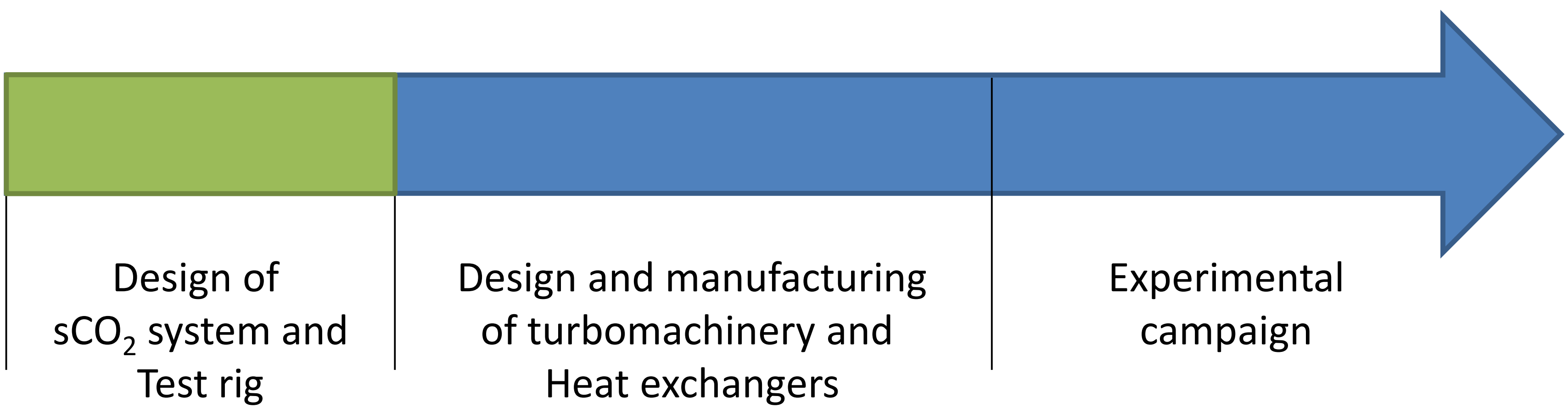
Scope of the I-ThERM's sCO_2 project

- Power output 50 ÷ 100 kWe
- 1st law efficiency ≈ 20 %
- Low CAPEX (short PBP)

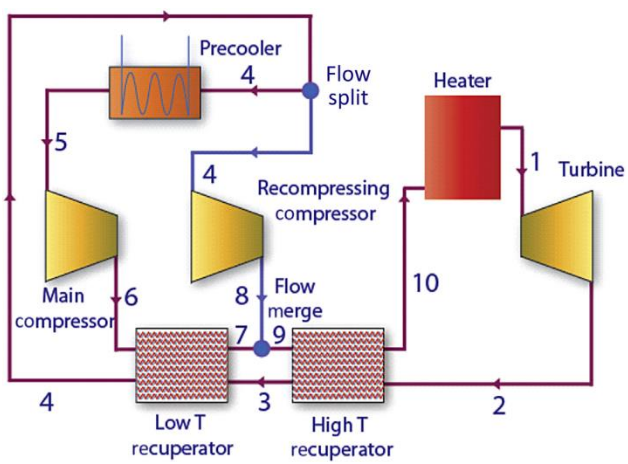


Outline

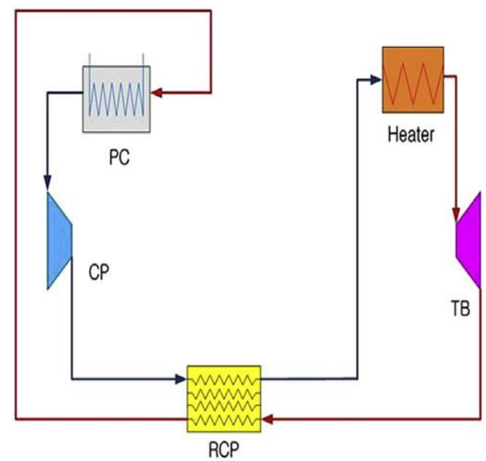
- Reference thermodynamic cycle
- Preliminary turbomachinery design
- Heat exchangers
- Simulation platform
- Results and discussion
- Future work

Thermodynamic cycle

Recompressing cycle layout is the optimal configuration for large sCO_2 installations (~MW) such as nuclear and CSP ones



2 compressors + 2 recuperators



1 compressors + 1 recuperator

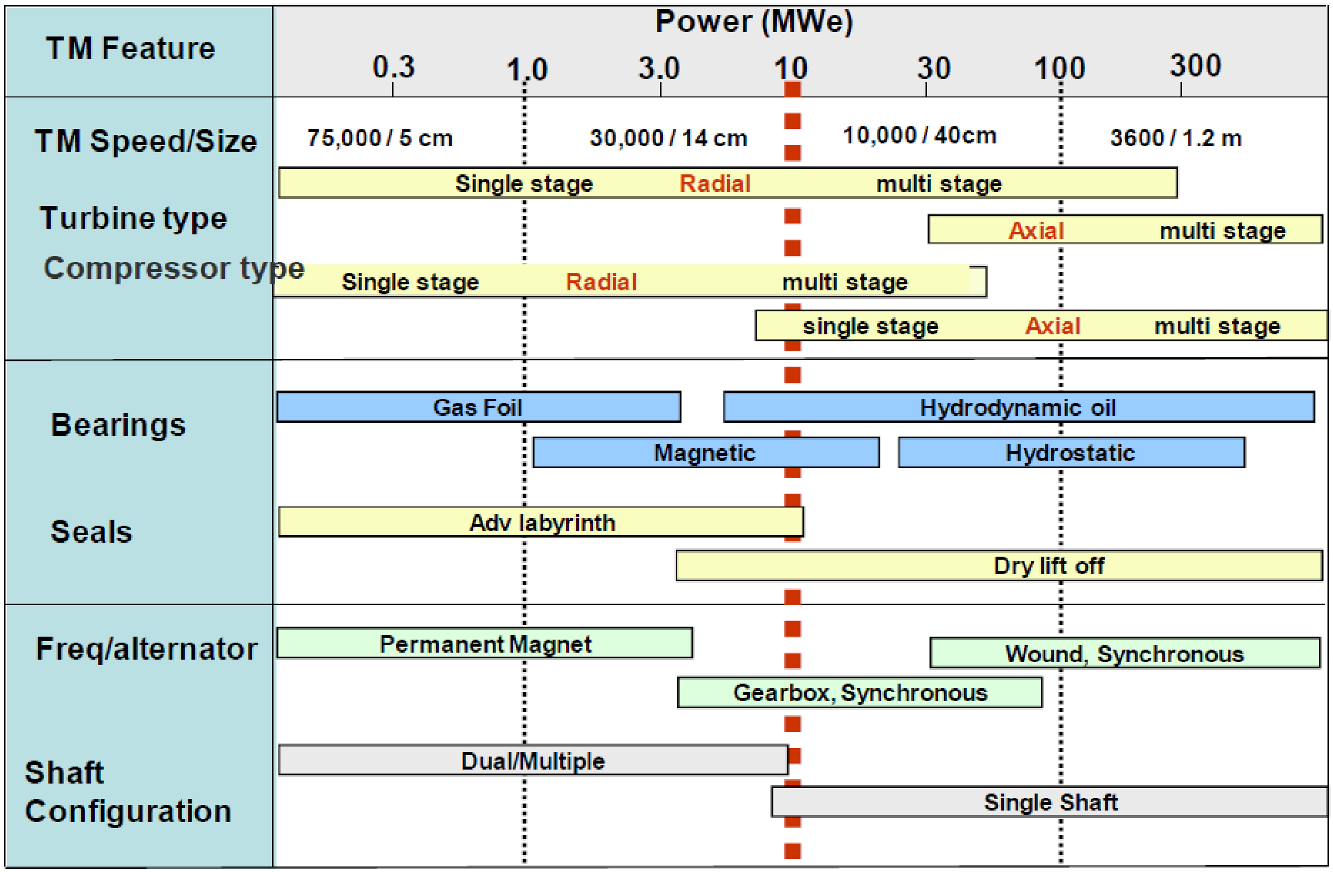
However, if target output power is smaller, **simple regenerated cycle** becomes the most suitable architecture

http://dx.doi.org/10.1016/j.energy.2015.03.066
http://dx.doi.org/10.1016/j.net.2015.06.009

The comparison of existing S–CO_2 integral test loops.

	Sandia National Lab	Knolls Atomic Power Lab & Bettis Atomic Power Lab	Institute of Applied Energy
Turbomachinery feature	2-TAC	1-TAC, 1-turbine	1-TAC (2-recuperators)
Cycle layout	Recompressing Fig. 1.	Simple recuperated Fig. 2.	Simple recuperated Fig. 3.
Heat, kW	780	834.9	160
Efficiency	31.5	14.7	7
Mass flow rate, kg/s	3.5 (target)/2.7 (achieved)	5.35 (target)/3.54 (achieved)	1.1 (achieved)
T.I.T, °C	537 (target)/342(achieved)	300 (target)	277 (achieved)
Pressure ratio	1.8 (target)/1.65 (achieved)	1.8 (target)/1.44 (achieved)	1.4 (achieved)
Rotating speed, × 1000 rpm	75 (target)/52(achieved)	75 (target)/55–60 (achieved)	69 (achieved)
Turbine efficiency, %	86 (turbine-1)/87(turbine-2)	79.8 (Power turbine)/79.7 (C-driving turbine)	65
Compressor efficiency, %	67 (MC)/70 (RC)	60.8	48

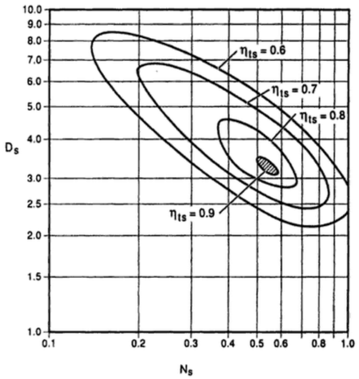
Turbomachinery for sCO_2 systems



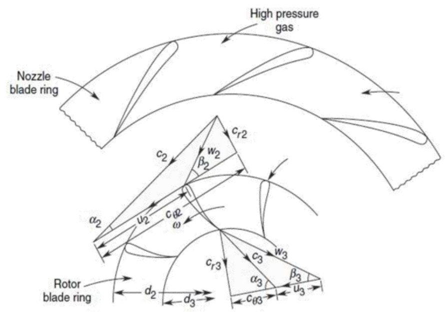
Sienicki et al. (2011)

<u>High revolution speeds + small impeller diameters</u>

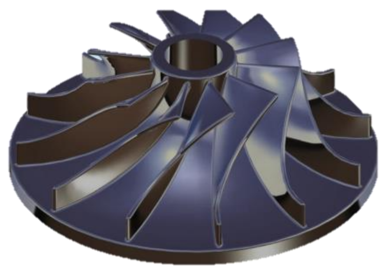
Turbomachinery Design



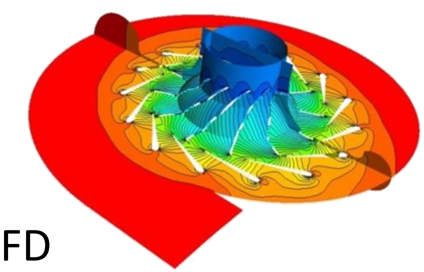
Specific speed and diameter



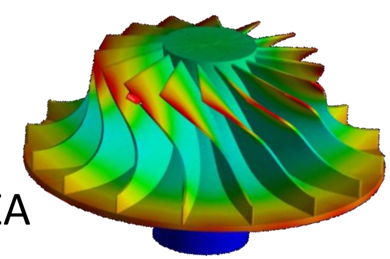
Velocity triangles



CAD



CFD

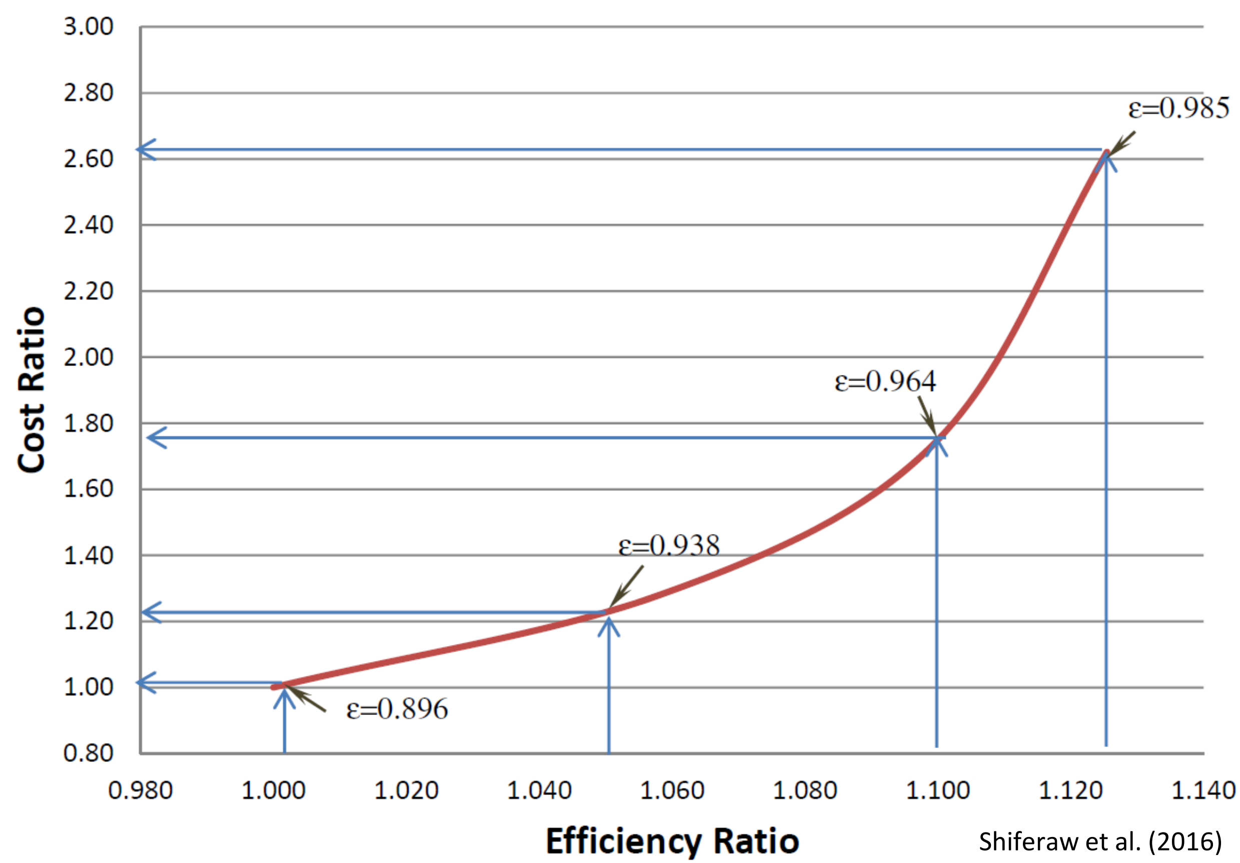


FEA

- Balje's charts available for air and water turbo machines
- Loss correlations available for air
- Need of coupling CFD tools with thermo-physical properties of CO_2 (dll libraries or look-up tables)
- Need of importing thermomechanical properties in FEA tools if custom materials are employed

Heat exchangers

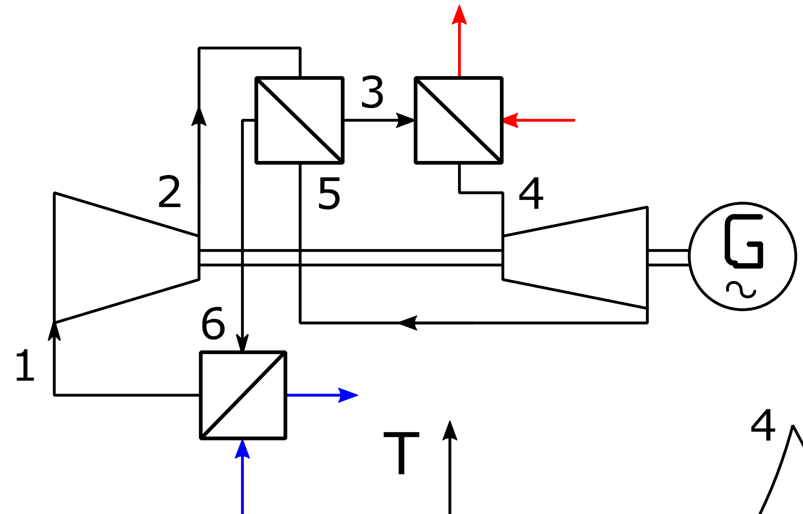
- Multiple technologies currently available
- Corrosion issues to be considered
- High thermal stresses
- HXs account for up to 90% of the overall CAPEX
- Aggressive designs might spoil the overall economic feasibility of system

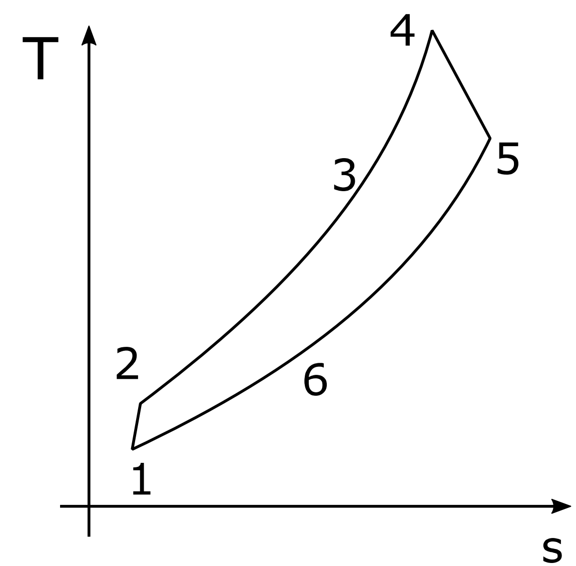


Shiferaw et al. (2016)

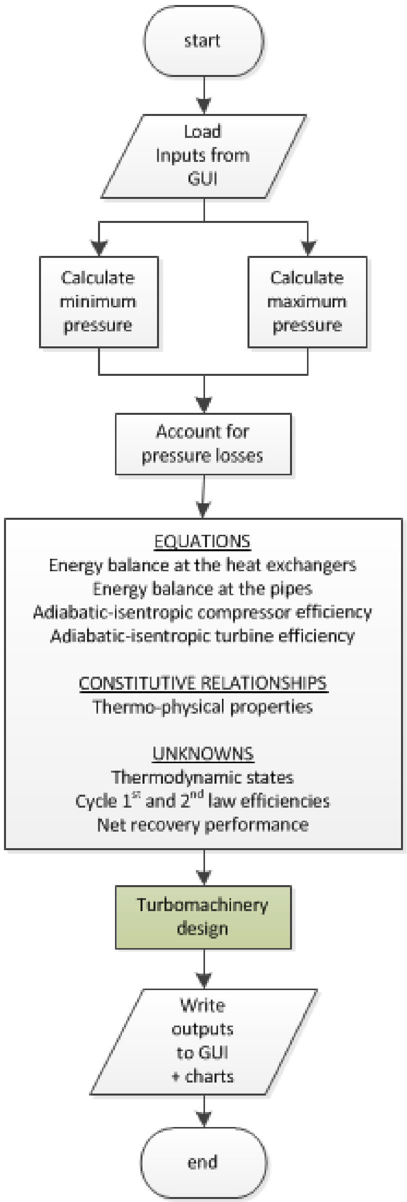
sCO_2 Modelling approach

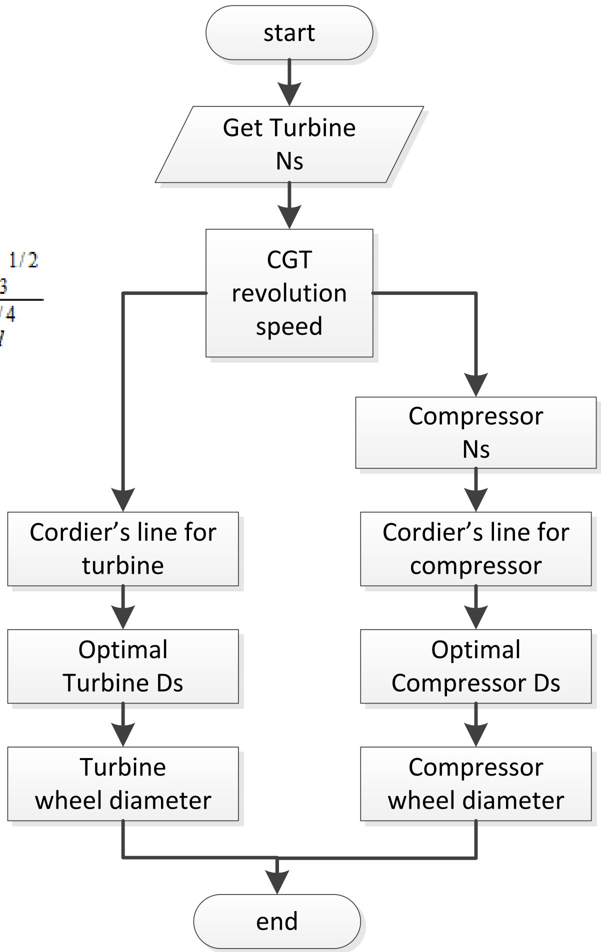
- Simple regenerated cycle
- Real gas properties
- 1st and 2nd law analyses
- Detailed loss breakdown
- Steady state approach
- Implemented in EES





- Input data:
  - Inlet conditions of hot heat source (exhaust gas)
  - Inlet conditions of cold heat source (water)
  - HXs and machines efficiencies
  - Pipes pressure and heat losses
- Parameters:
  - Min and max temperature
  - Min and max pressure
  - Recuperation ratio (R)
- Output data:
  - Electrical power recovered
  - Cycle efficiencies (1st,2nd law)
  - Loss breakdown
  - Turbomachinery design





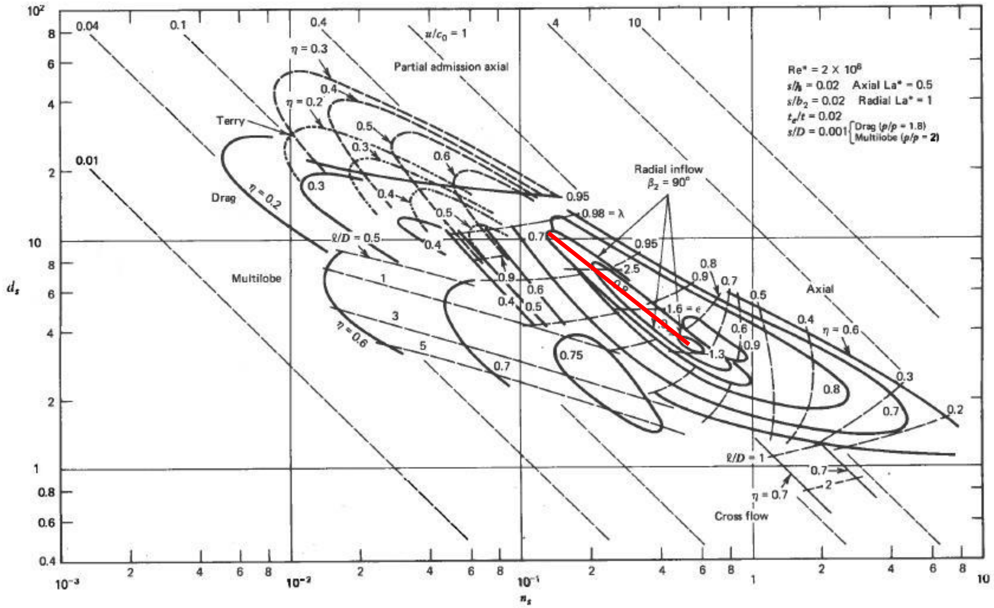
$$N_s = \frac{N \cdot Q_3^{1/2}}{H_{ad}^{3/4}}$$

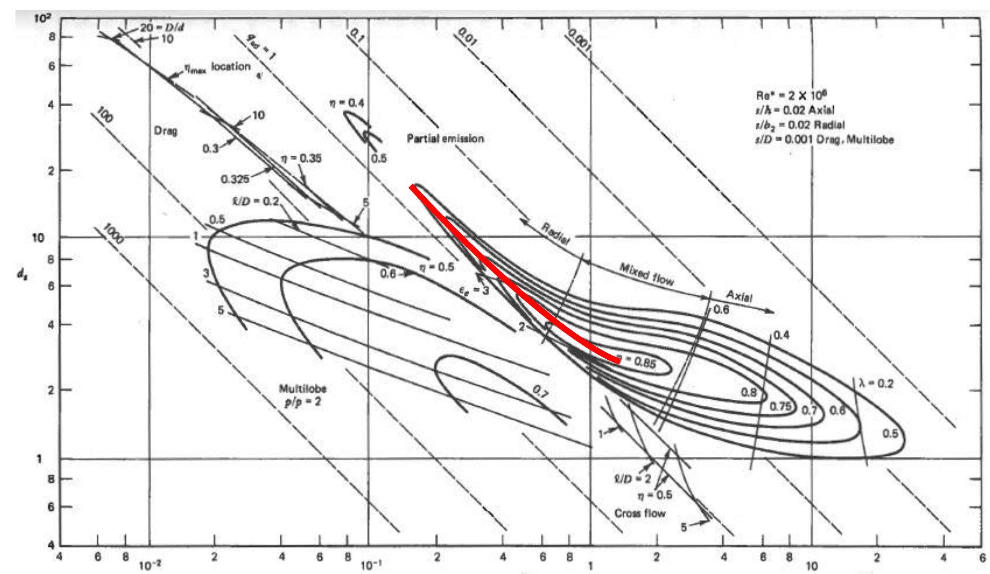
$$D_s = \frac{D \cdot H_{ad}^{1/4}}{Q_3^{1/2}}$$

$$D_{s,c} = 2.719\, N_{s,c}^{\,-1.092}$$

$$D_{s,t} = 2.056\, N_{s,t}^{\,-0.812}$$

only for radial machines





Design choices

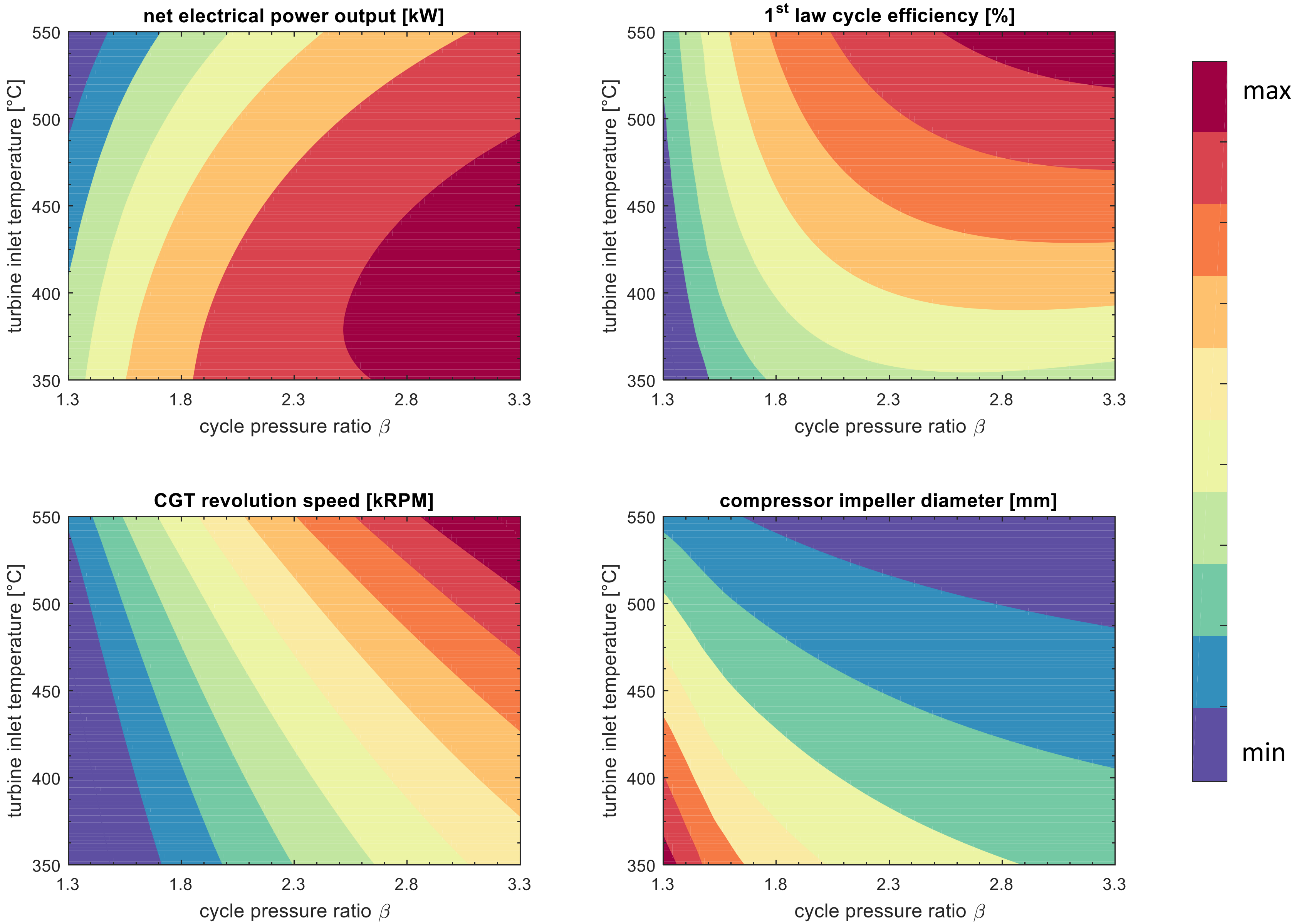
- Turbomachinery
  – Revolution speed <100 kRPM
  – Wheel diameters >40 mm
  – Subsonic flows
- Heat exchangers
  – Adequate pinch point ΔT
  – Moderate temperature levels

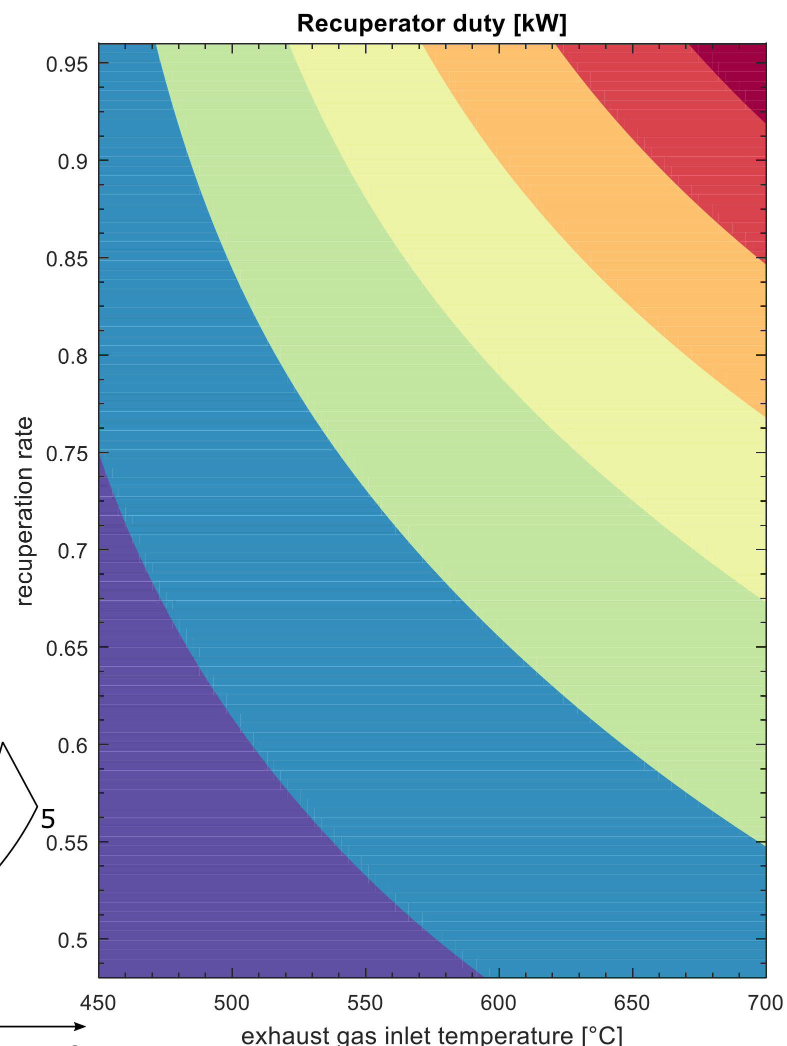
Assumptions

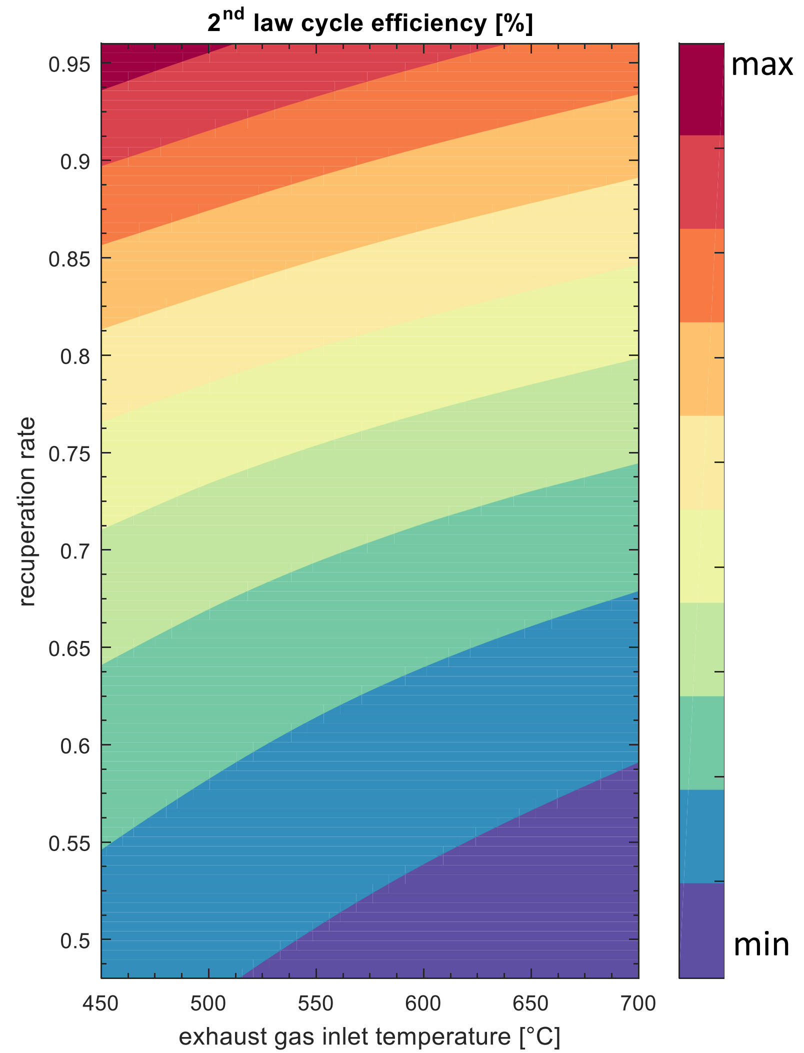
- Constant compressor and turbine isentropic efficiencies
- Constant HXs effectiveness
- Gaseous fluid at compressor inlet
- No pipe pressure drops or thermal losses

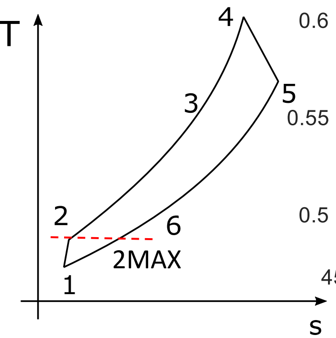
Simulation parameters

- Turbine inlet temperature and pressure (i.e. cycle pressure ratio)
- Inlet conditions of exhaust gases (flow rate and temperature)
- Influence of recuperation
- Turbine specific speed


net electrical power output [kW]
1st law cycle efficiency [%]
CGT revolution speed [kRPM]
compressor impeller diameter [mm]
turbine inlet temperature [°C]
cycle pressure ratio β
550
500
450
400
350
1.3
1.8
2.3
2.8
3.3
max
min

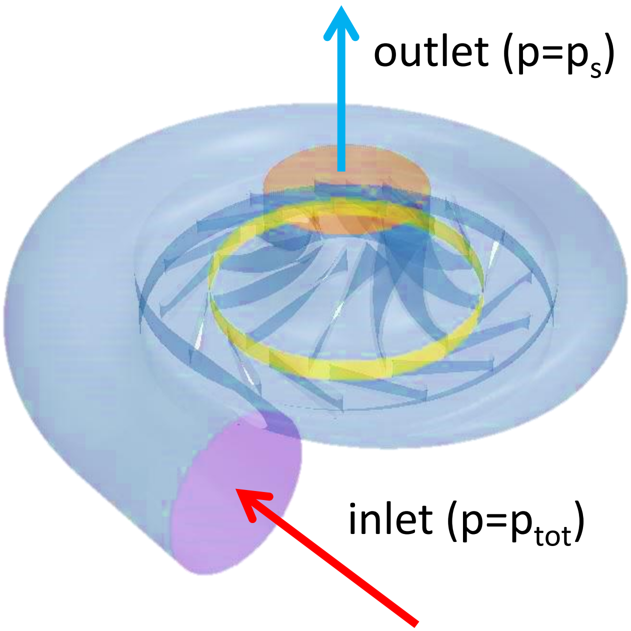


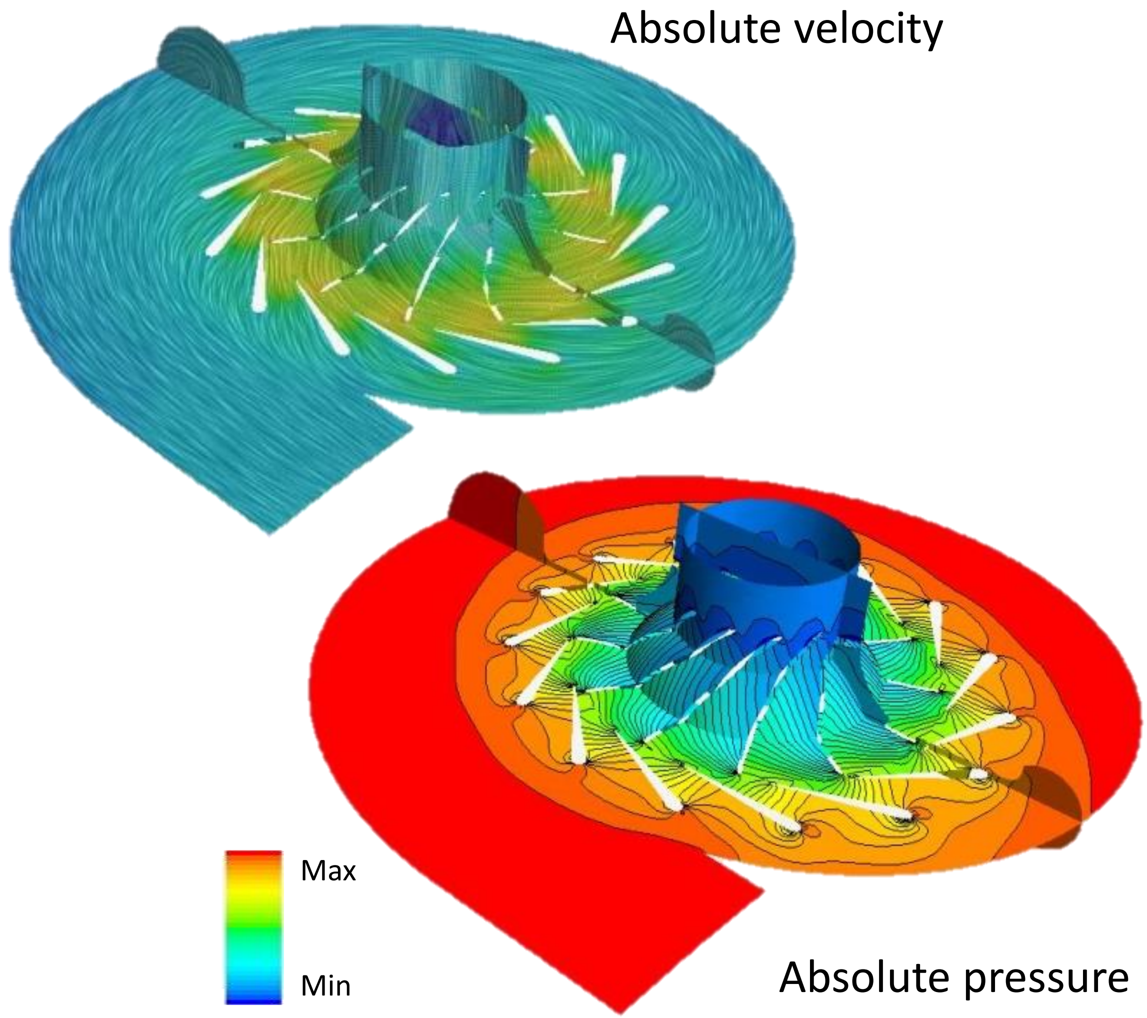




$$R = \frac{h_5 - h_6}{h_5 - h_{2MAX}}$$

Turbine design





- Mixing plane approach
- RANS equations
- Steady state simulations
- Peng-Robinson EOS
- Star-CCM+ software

Conclusions

- sCO_2 systems could be successfully applied on industrial waste heat to power generation applications
- The most limiting device in small-scale sCO_2 units (50-100 kWe) is the compressor
- Theoretical performance of the I-ThERM's demonstration unit exceed 21% global cycle efficiency

Future work

- Design and manufacturing of the compressor-turbine-generator (CGT) unit and its controls
- HXs selection and design
- Transient modelling of the sCO_2 system
- Experimental campaign

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