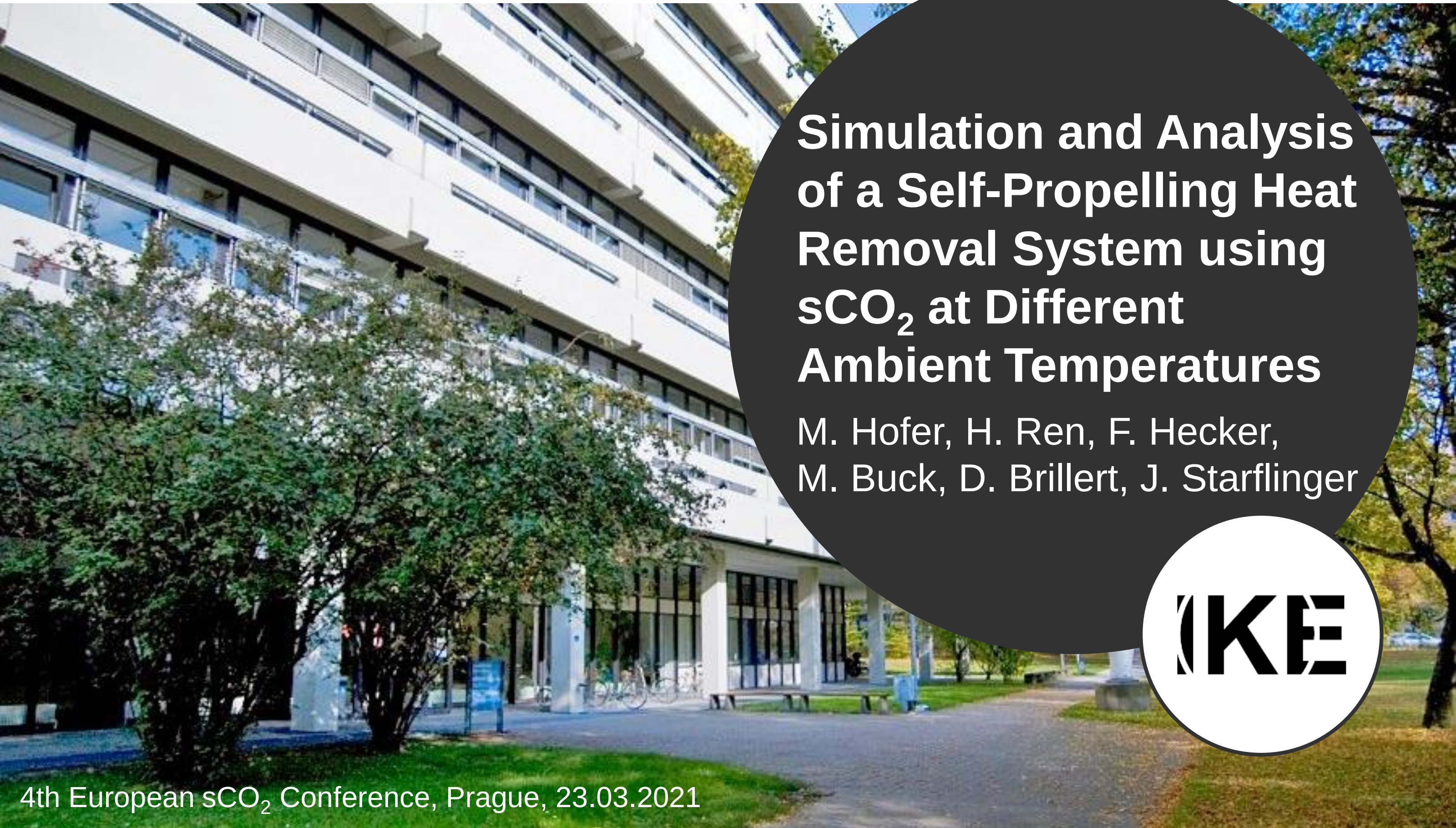
University of Stuttgart
Institute of Nuclear Technology
and Energy Systems



Simulation and Analysis of a Self-Propelling Heat Removal System using sCO_2 at Different Ambient Temperatures

M. Hofer, H. Ren, F. Hecker,
M. Buck, D. Brillert, J. Starflinger

IKE

4th European sCO_2 Conference, Prague, 23.03.2021

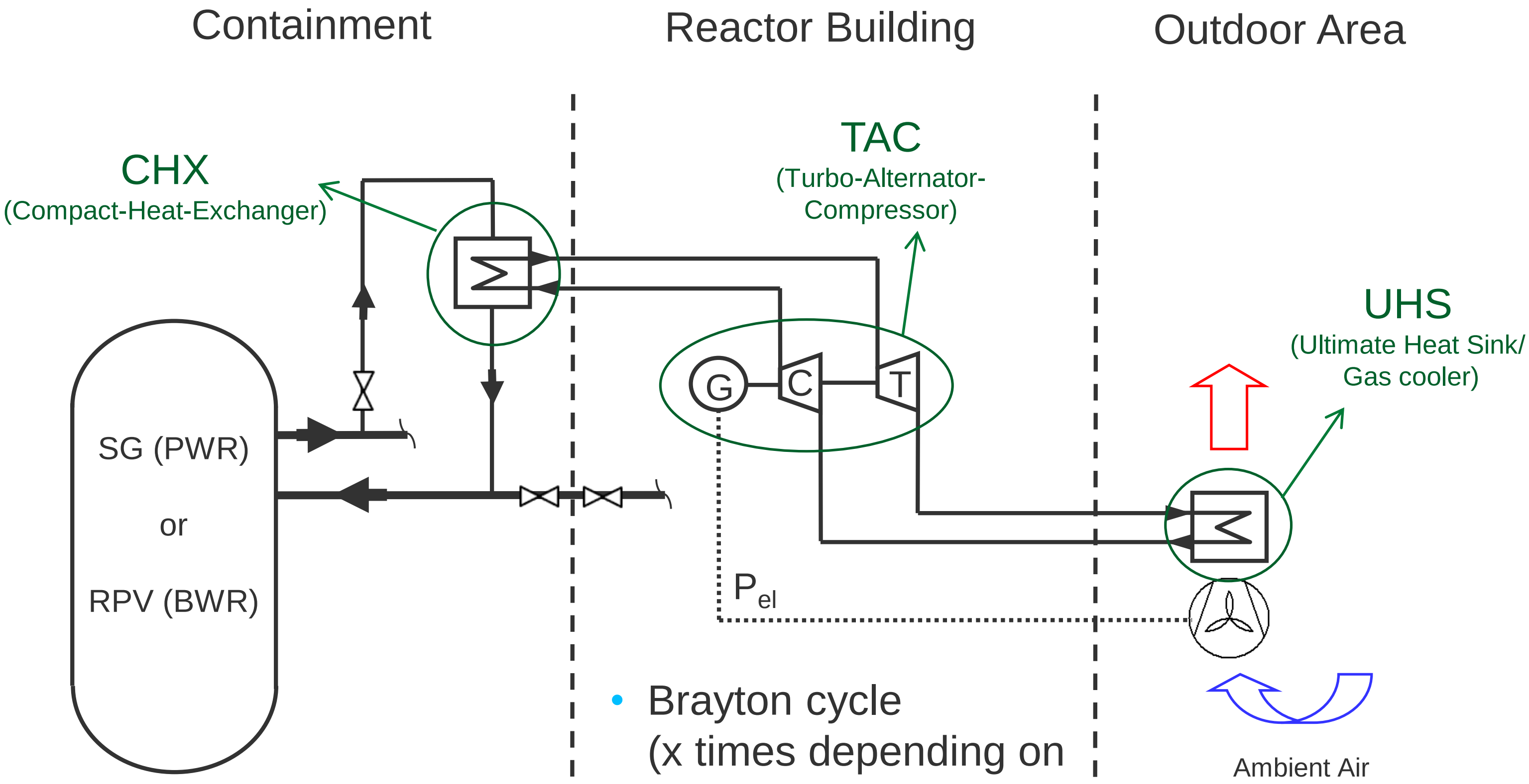
Outline

1. Introduction
2. Design, layout, control and modelling of sCO_2-cycle
3. Simulation and analysis
4. Conclusion and future work

Introduction (1): Overview and motivation

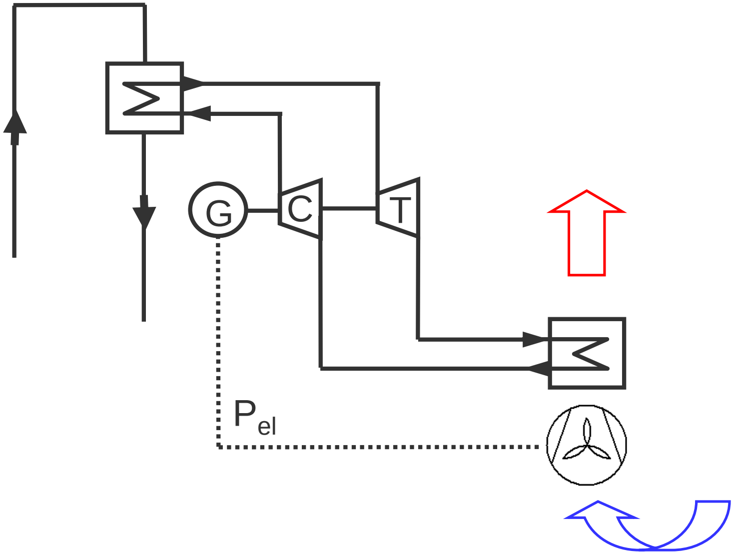
- Motivation
  - Fukushima
  - Scientific Trend: new heat removal systems
- Active Heat Removal System with Turbo-Compressor
  - sCO_2 as a working fluid
  - Air as ultimate heat sink
  - Self-propelling
  - Very compact

Introduction (2): Concept of heat removal system



- Brayton cycle (x times depending on NPP size)

Introduction (3): Objective of this presentation



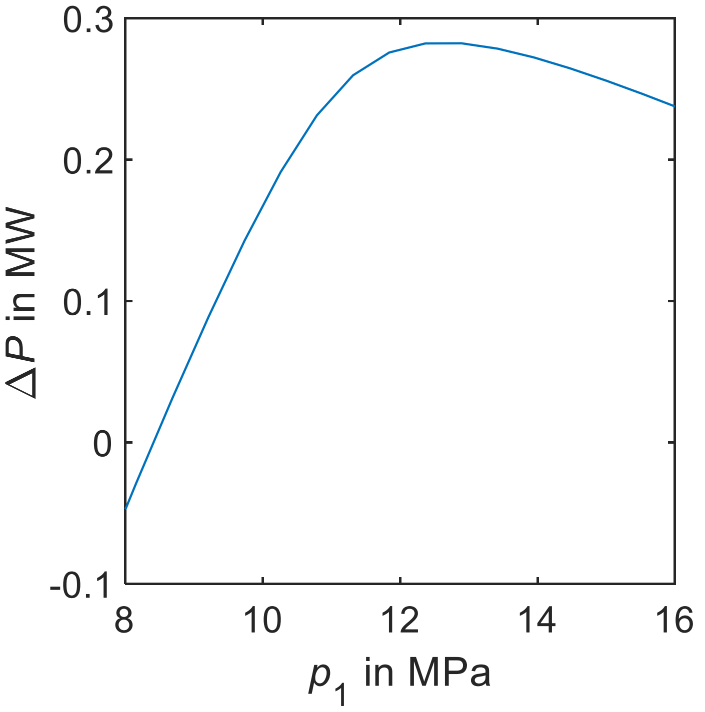
- sCO$_2$-Brayton-cycle:
  - Thermodynamic Design
  - Layout and control
  - Turbomachinery performance maps
  - Modelling and control of UHS
- Simulation
  - Start-up
  - Varying boundary conditions (especially ambient temperatures)

Modelling and simulations are performed with the thermal-hydraulic system code ATHLET (Analysis of THermal-hydraulics of LEaks and Transients)

Thermodynamic Design

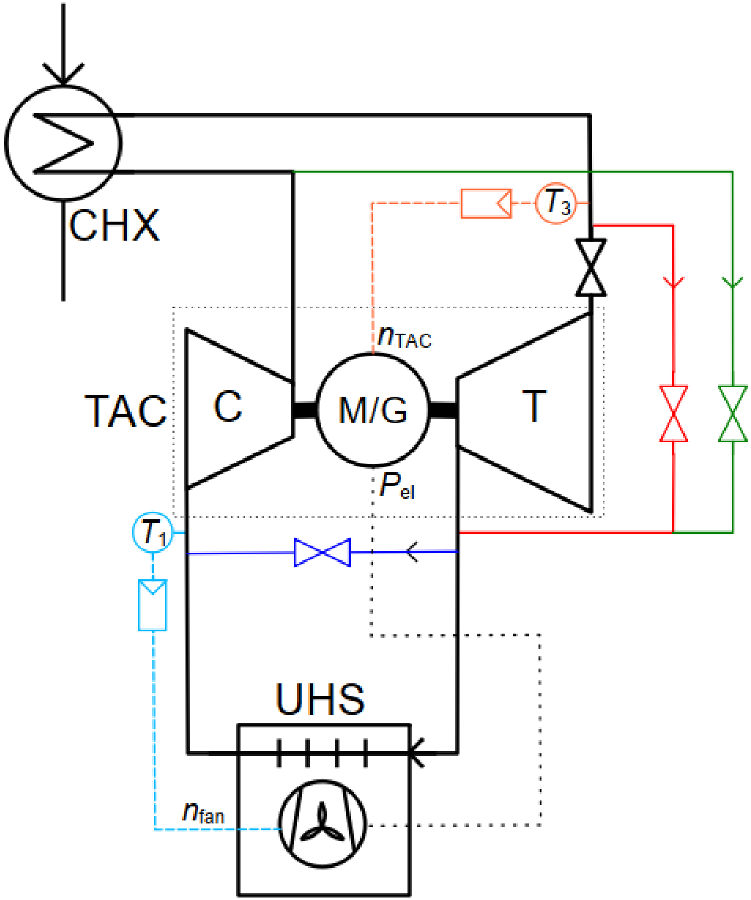
- Assumptions
  - $\dot{Q}_{CHX} = 10$ MW
  - $T_{air} = 45$ °C
  - $T_{steam,sat} = 296.5$ °C
  - $\eta_{is,c,t} = 70$ %
  - $\pi_c = 1.7$
- Optimization of compressor inlet pressure p_1 for highest excess power $\Delta P = P_t - P_c - P_{fan}$
- Result
  - $\Delta P = 283$ kW ($\eta = 2.8$ %)
  - $p_1 = 12.6$ MPa
  - Considerably above critical point of CO_2

Cycle excess power as a function of compressor inlet pressure



Detailed Layout and Control

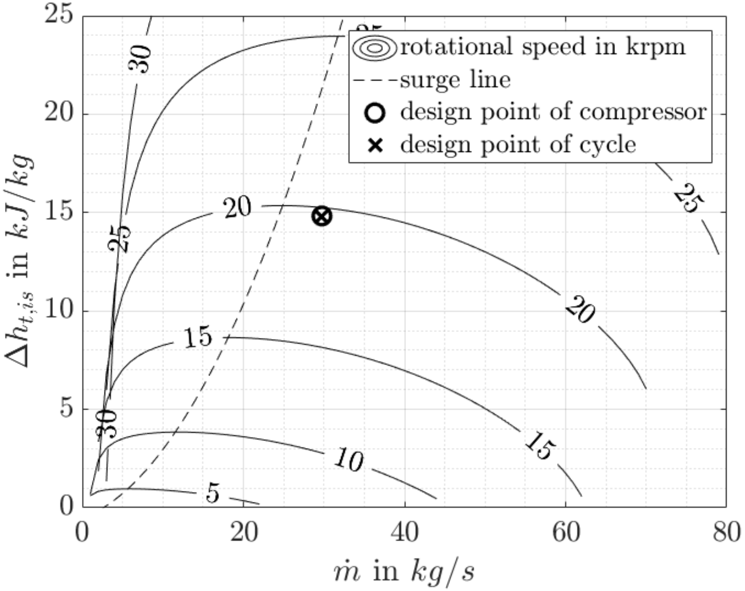
- Bypasses
  - Turbine bypass
  - Compressor recirculation
  - UHS bypass
- Control
  - Compressor inlet temperature T_1 via fan speed
  - Turbine inlet temperature T_3 via turbomachinery shaft speed



Turbomachinery Performance Maps

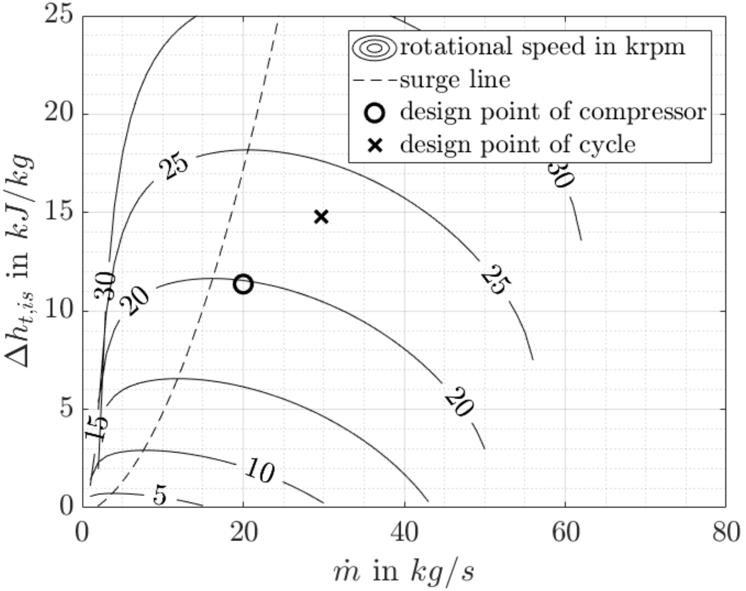
Compressor type 1:

$DP_{comp} = DP_{cycle}$



Compressor type 2:

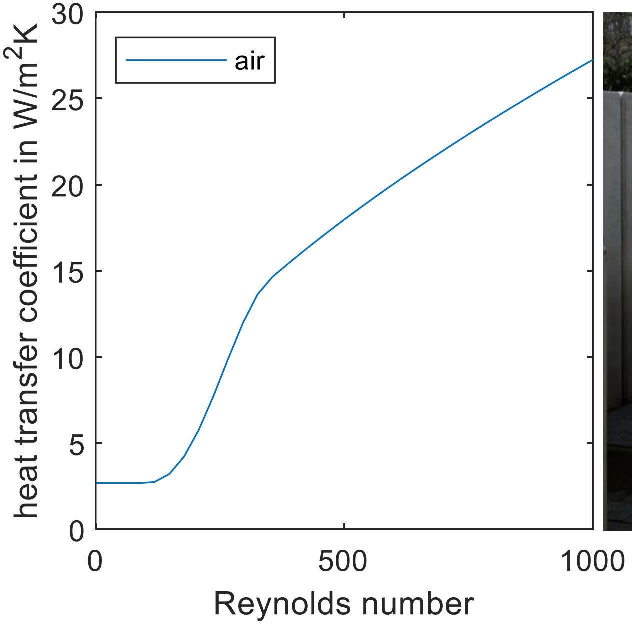
$DP_{comp} \neq DP_{cycle}$



UHS (1): Modelling

- Representative pipe with heat transfer, pressure drop via correlations
- Air side heat transfer correlation validated and extended for low Reynolds numbers with experimental data

Air-side heat transfer coeff.

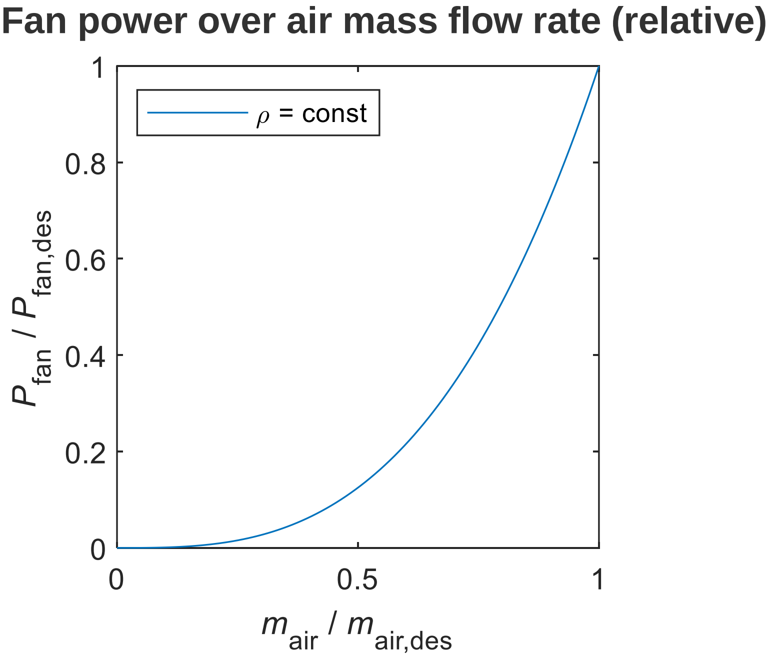


UHS at experimental test-loop (glass model)

Source: A. Hacks, UDE, Location: Essen (Germany)

UHS (2): Modelling

- Fans not modelled explicitly
- Fan power derived from proportional relationship: $P_{fan} \sim \frac{\dot{m}^3}{\tilde{\rho}^2}$

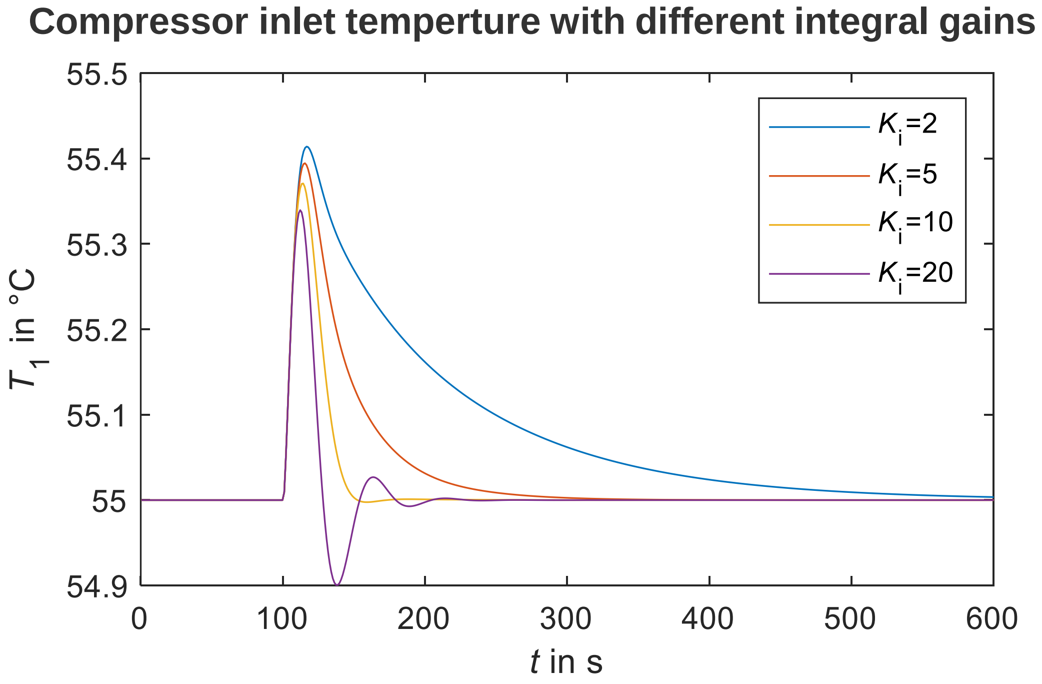


UHS (3): Control

- Motivation
  - Enable cycle operation for the whole range of ambient temperatures from –45 °C to 45 °C
  - Avoid subcritical (two-phase) conditions in the cycle
  - Avoid compressor surge
- Control of compressor inlet temperature T_1
  - PI-controller: $\dot{m}_{air}(t) = \dot{m}_{air}(t_0) + K_p^* \, \Delta T_1\,(t) + K_i^* \int_{t_0}^{t} \Delta T_1(\tau)\mathrm{d}\tau$
  - Step increase of CO_2 mass flow rate
  - First proportional gain K_p^* is determined
  - Second integral gain K_i^* is determined with selected K_p^*

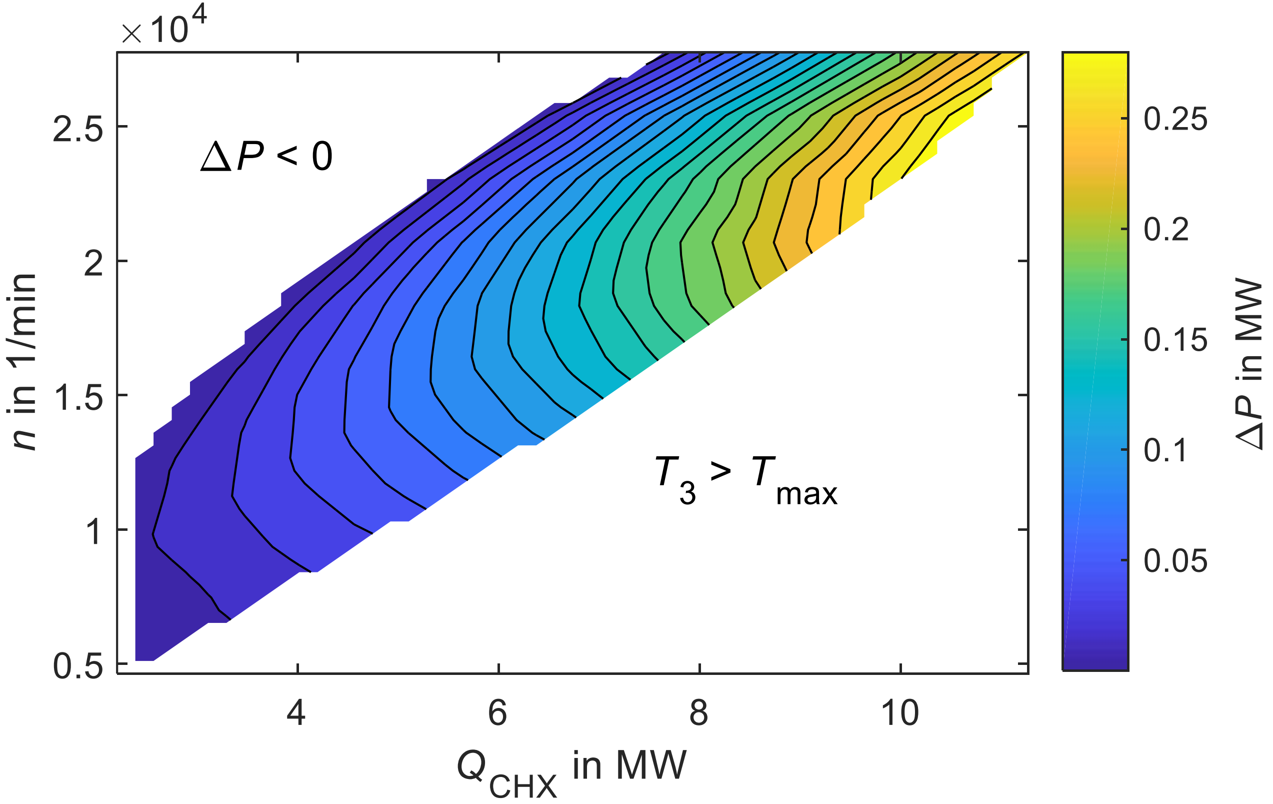
UHS (4): Control

- Tuning at design ambient temperature of 45 °C (figure)
- Tuning at –45 °C: gains should be 10 times lower



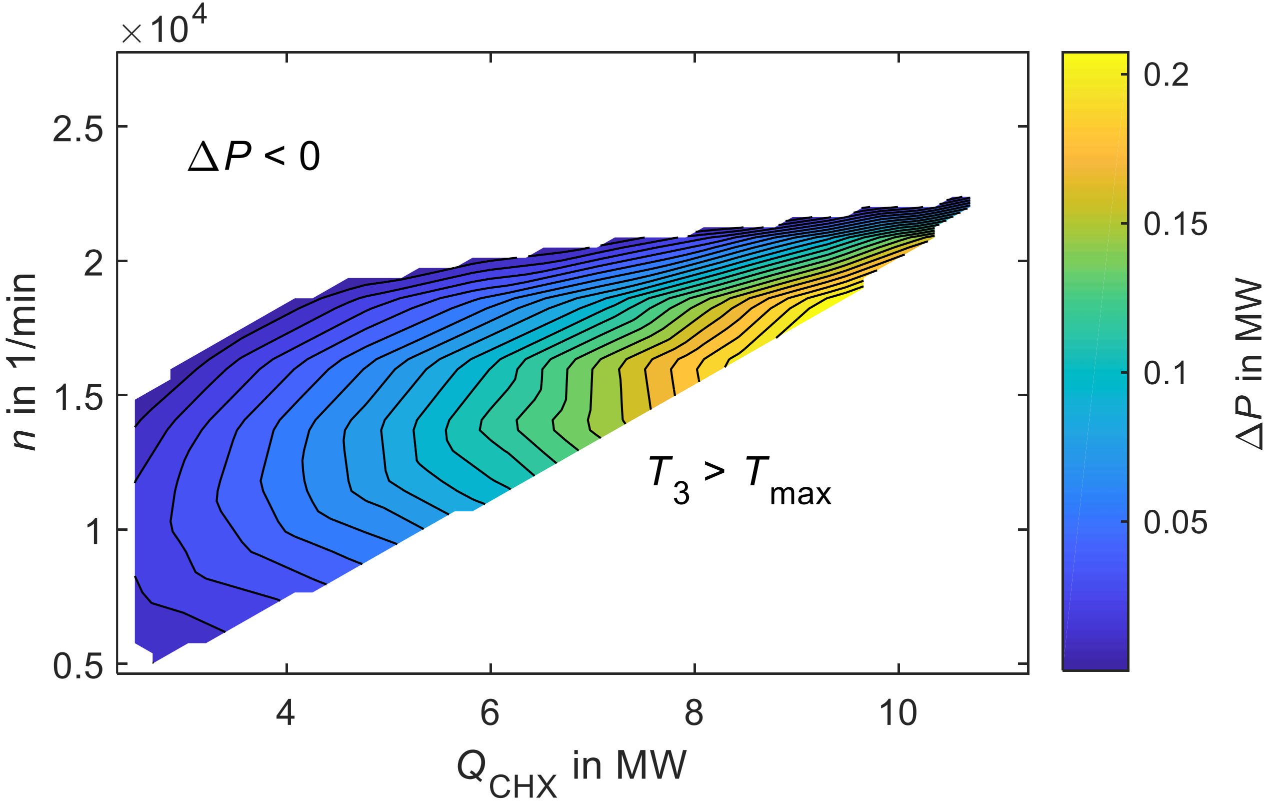
Simulation (1): Cycle performance

Excess power of cycle at $T_{comp,in} = 55$ °C and $T_{air,in} = 45$ °C



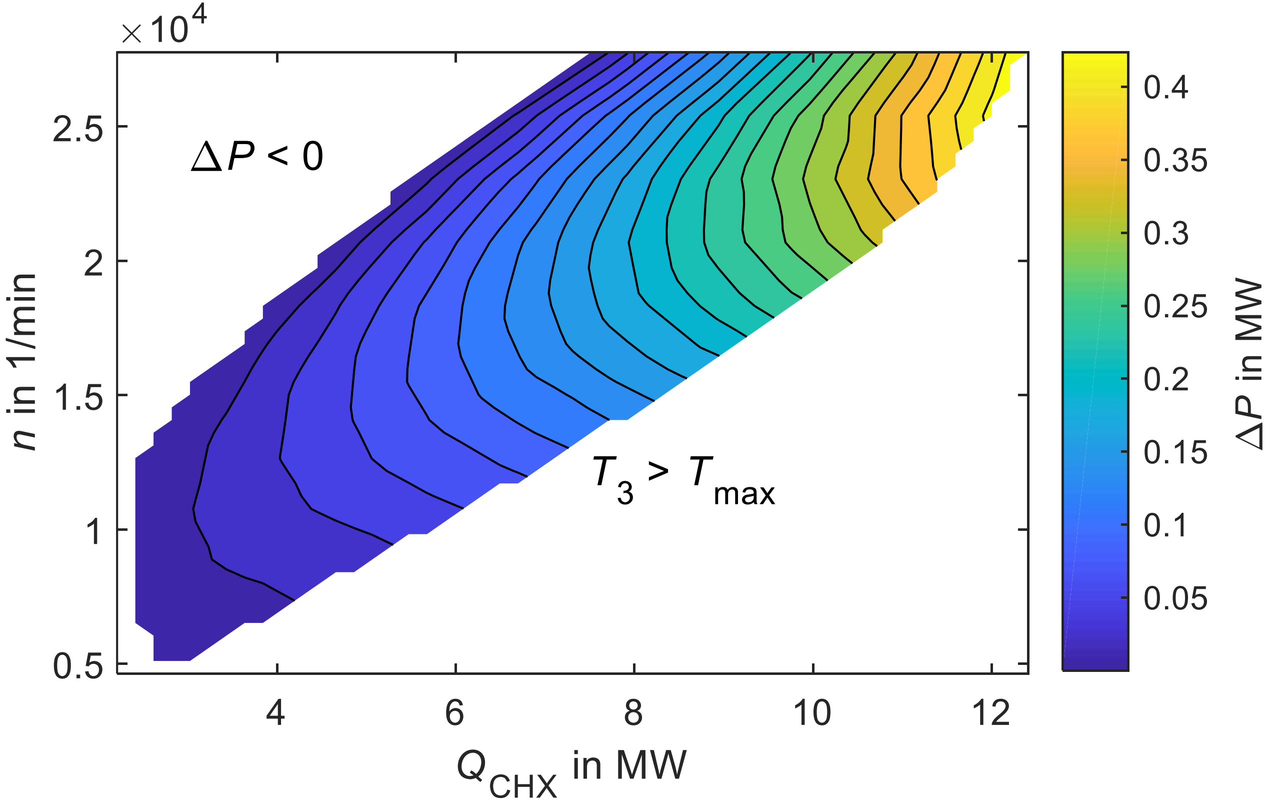
Simulation (2): Cycle performance

Excess power of cycle at $T_{comp,in} = 35$ °C and $T_{air,in} = 25$ °C



Simulation (3): Cycle performance

Excess power of cycle at $\boldsymbol{T_{comp,in} = 55}$ °C and $\boldsymbol{T_{air,in} = -45}$ °C

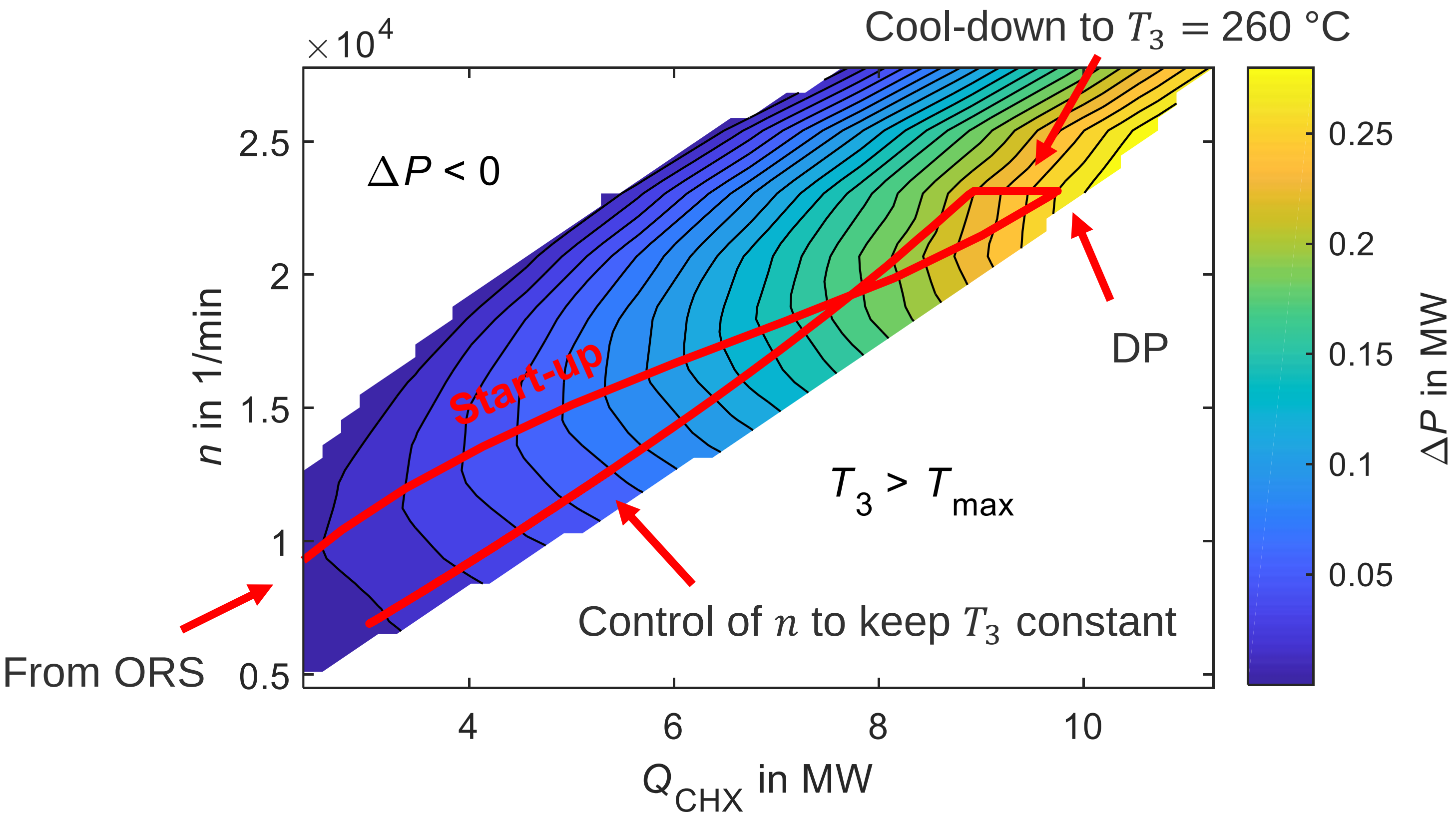


Start-up of cycle

- Cycle must be operable at any ambient temperature: –45 °C to 45 °C
- (Fast) start-up from cold shutdown conditions might not be possible
  - Material stress
  - Compressor surge
  - Fluid accumulates in UHS
- Alternative: Operational readiness state (ORS)
  - Cycle in part-load during normal operation of nuclear power plant
  - Self-propelling ORS might be possible at only 12 % of design thermal power

NPP simulation: First results

Excess power of cycle at $\boldsymbol{T_{comp,in} = 55}$ °C and $\boldsymbol{T_{air,in} = 45}$ °C



Cool-down to $T_3 = 260$ °C

DP

Control of n to keep T_3 constant

From ORS

Conclusion

- Design, layout, control and modelling of sCO_2 heat removal system
- Start-up from operational readiness state
- Type 2 turbomachinery preferred due to higher surge margin
- Compressor inlet temperature should always be kept constant at 55 °C

- Future Work
  - Further improvement of component models
  - Simulation of the sCO_2-HeRo-System attached to the NPP (in progress)

The presented work is funded by the **German Ministry for Economic Affairs and Energy** (**BMWi**. Project no. 1501557) on basis of a decision by the German Bundestag.

Federal Ministry
for Economic Affairs
and Energy

sCO2 4 NPP

THANK YOU

eDF

CVŘ | Research Centre Řež

ÚJV | NUCLEAR RESEARCH INSTITUTE

Das Simulatorzentrum
KSG | GfS

"Jožef Stefan" Institute Ljubljana, Slovenia

fives

UNIVERSITÄT DUISBURG ESSEN
Open-Minded

ARTTIC
a PNO international management services company

University of Stuttgart
Germany

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847606. This text reflects only the author's views and the Commission is not liable for any use that may be made of the information contained therein.

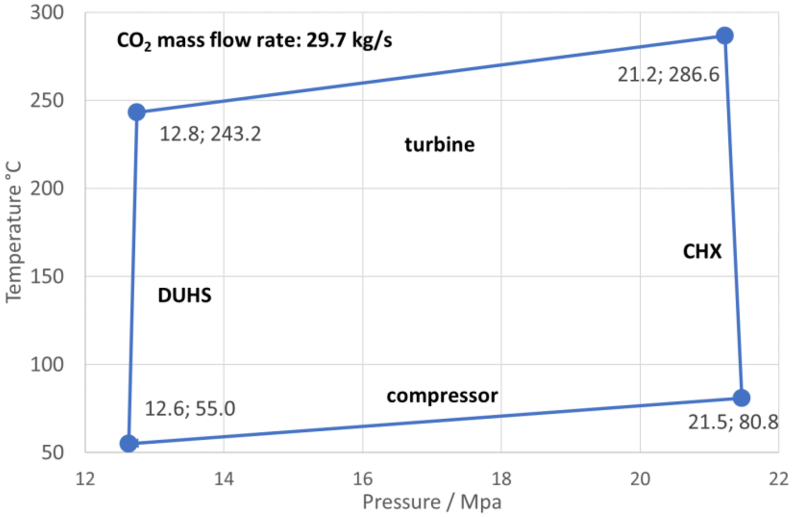
Thank you!

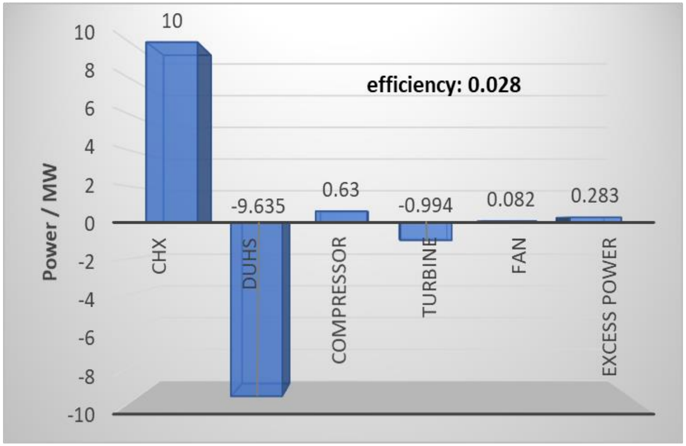
Markus Hofer

e-mail markus.hofer@ike.uni-stuttgart.de
phone +49 (0) 711 685-60855
fax +49 (0) 711 685-62010

University of Stuttgart
Institut für Kernenergetik und Energiesysteme
Pfaffenwaldring 31 • 70569 Stuttgart

Thermodynamic Design

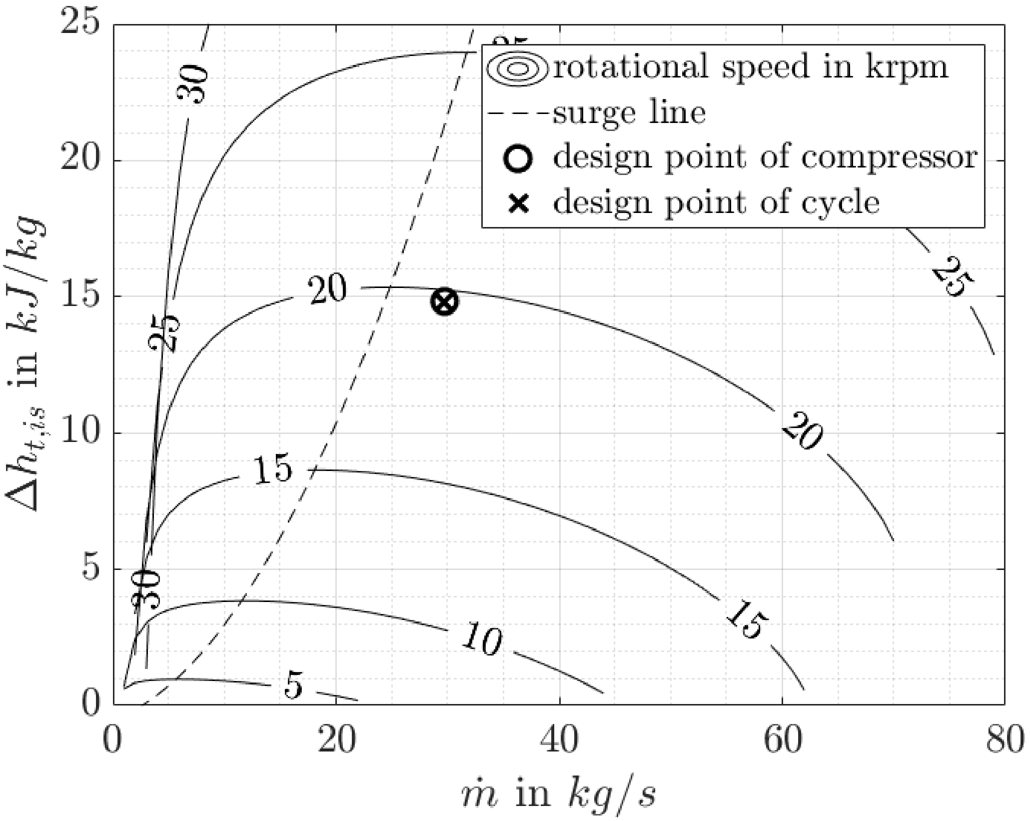




- Design parameters chosen to guarantee nominal heat removal (10 MWth) at conservatively high ambient temperature (45°C)
- Major criterion: heat removal; efficiency of minor importance
- Takes into account technical design constraints identified in cooperation with WP4 (e.g. maximum temperature difference in HXs)

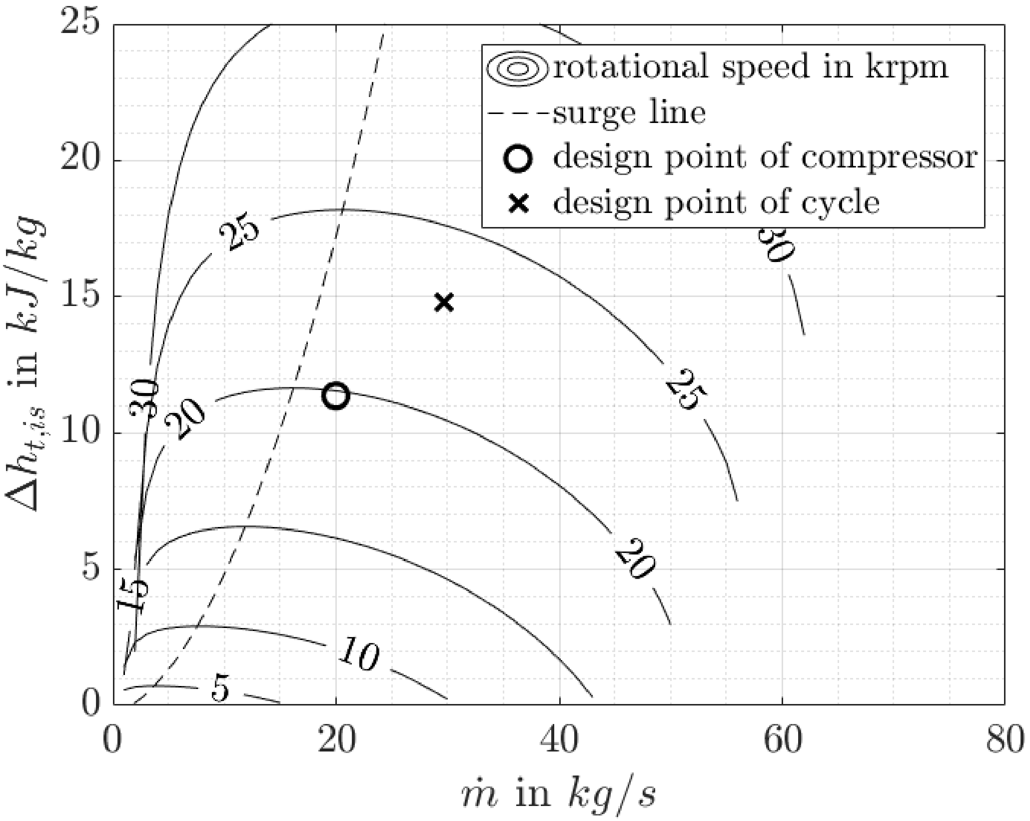
Turbomachinery Performance Maps

Compressor type 1: $DP_{comp} = DP_{cycle}$



Turbomachinery Performance Maps

Compressor type 2: $DP_{comp} \neq DP_{cycle}$



UHS (1): Modelling

- Representative pipe with heat transfer, pressure drop via correlations
- Experimental data was used to fit air side heat transfer for low Reynolds numbers
- Fans not modelled explicitly
- Fan power derived from proportional relationship: $P_{fan} \sim \frac{\dot{m}^3}{\tilde{\rho}^2}$
- Fans for NPP-UHS are located at the bottom: $\dot{V} = \frac{\dot{m}}{\rho_{in}}$
- More detailed: $P_{fan} \sim \Delta p \dot{V} \sim \frac{\dot{m}^2}{0.5(\rho_{in}+\rho_{out})} \frac{\dot{m}}{\rho_{in}}$
- Design point power is calculated assuming a specific power consumption

$$\Delta P_{fan,des} = \dot{Q}_{UHS} * 8.5\ \mathrm{kW_{el}/MW_{th}}$$

UHS (2): Control

Compressor inlet temperature vs. density control

- Operation points considerably above critical point → gradients in thermodynamic properties are lower

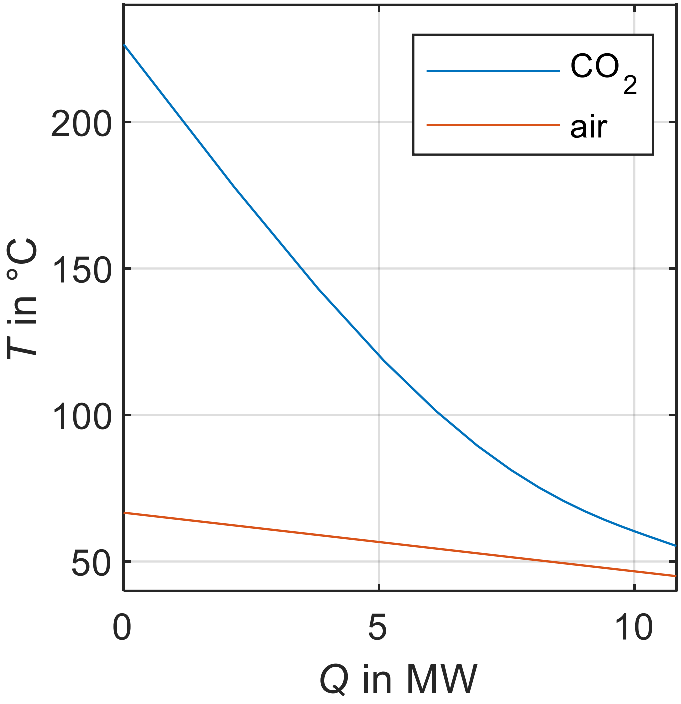
- No inventory control
  - Pressures and temperatures are linked
  - E.g. when air flow rate is increased, compressor inlet temperature and pressure will decrease
  - Resulting in almost constant compressor inlet density
  - Difficult to use density as a control parameter

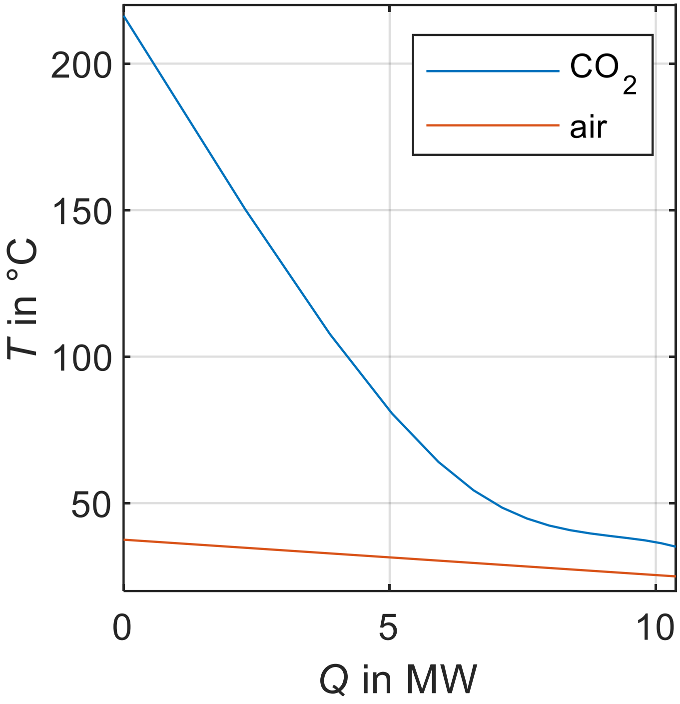
Start-up of cycle

	Unit	ORS1	ORS2	ORS3
Turbomachinery speed relative to the cycle design point	%	20	20	20
Turbine bypass valve	%	58	24	0
Turbine valves	%	0	0	100
Compressor inlet p	bar	117.3	122.1	122.6
Compressor outlet p	bar	119.4	125.2	125.7
CHX outlet T	°C	111	150	155
CHX thermal power	MW	1.2	1.2	1.2
Mass flow rate (CO_2)	kg/s	8.5	5.9	5.7
Compressor efficiency	%	50.7	68.2	68.9
Turbine efficiency	%	0	0	71.4
Compressor power	kW	7.1	5.0	4.9
Turbine power	kW	0	0	6.5
Fan power	kW	0.6	0.4	0.4
Total power	kW	-7.7	-5.4	1.2

Simulation (4): UHS-QT-diagram

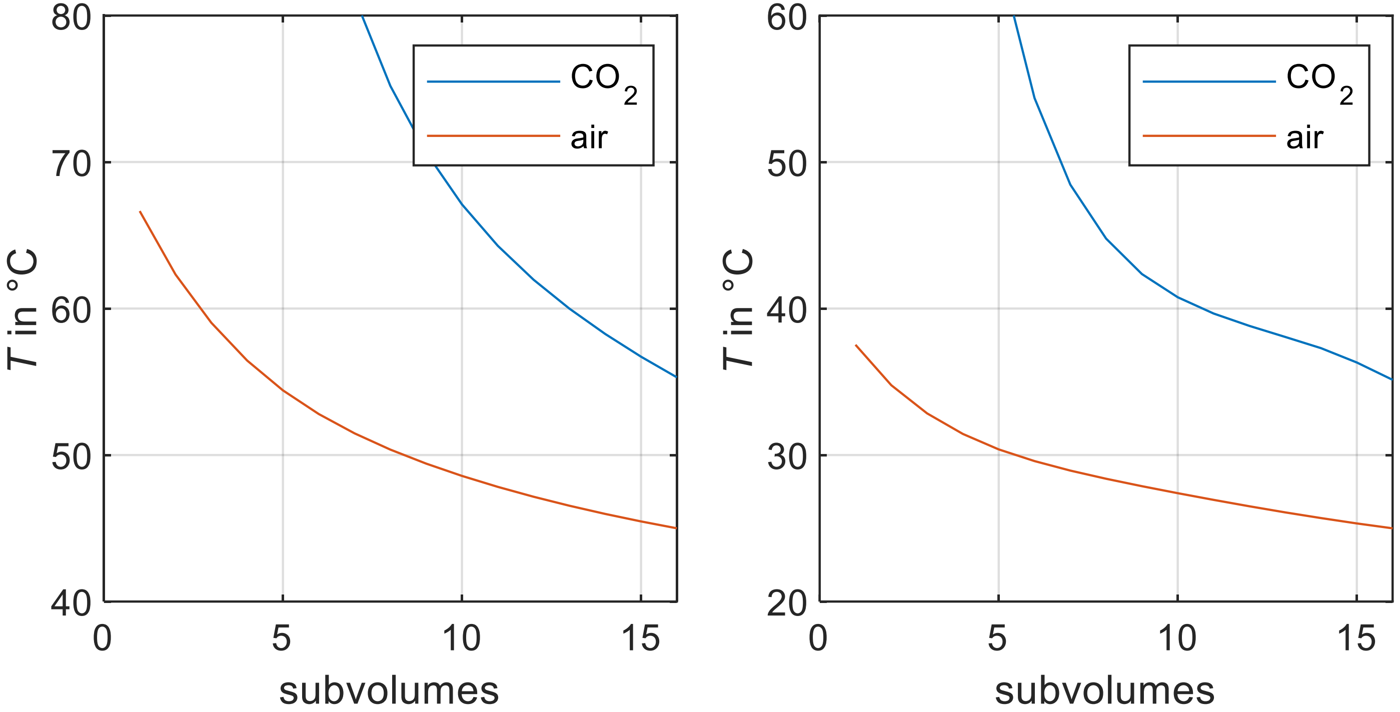
- $\boldsymbol{T_{comp,in}} = \mathbf{55}$ °C, $\boldsymbol{T_{air,in}} = \mathbf{45}$ °C vs. $\boldsymbol{T_{comp,in}} = \mathbf{35}$ °C, $\boldsymbol{T_{air,in}} = \mathbf{25}$ °C





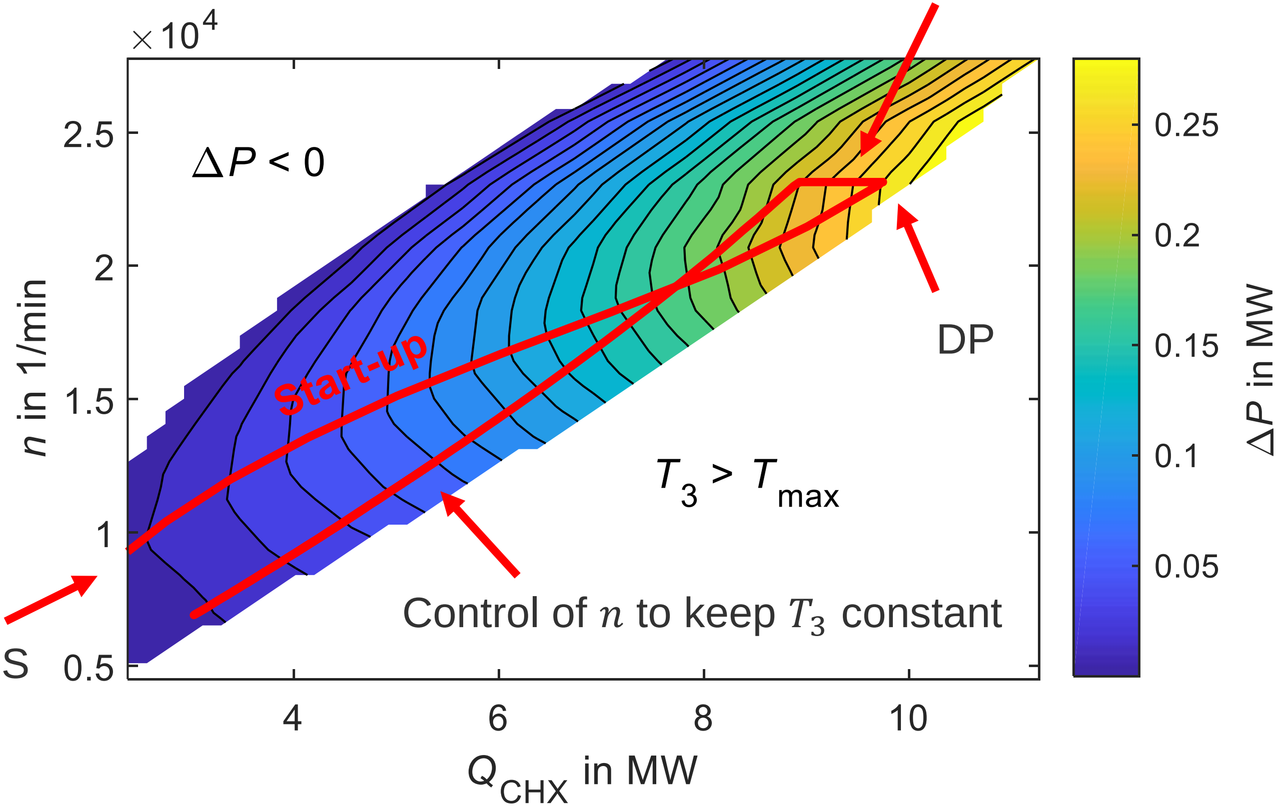
Simulation (5): UHS-subvolumes-T-diagram

- $T_{comp,in} = 55$ °C, $T_{air,in} = 45$ °C vs. $T_{comp,in} = 35$ °C, $T_{air,in} = 25$ °C



NPP simulation: First results

- $\boldsymbol{T_{comp,in}} = \mathbf{55}$ °C and $\boldsymbol{T_{air,in}} = \mathbf{45}$ °C



Cool-down to $T_3 = 260$ °C

DP

Control of n to keep T_3 constant

From ORS

NPP simulation: First results

4 systems (with adaption to decay heat curve)

- Control of turbomachinery speed and subsequent shutdown
- Systems can run for more than 72 h
- Excess power always higher than zero