University of Stuttgart
Germany

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sCO2 HeRo
The supercritical CO_2 heat removal system

Workshop "The supercritical CO2 heat removal system"

Rez, Czech Republic

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University of Stuttgart

Institute of Nuclear Technology and Energy Systems - IKE

M. Straetz, J. Starflinger

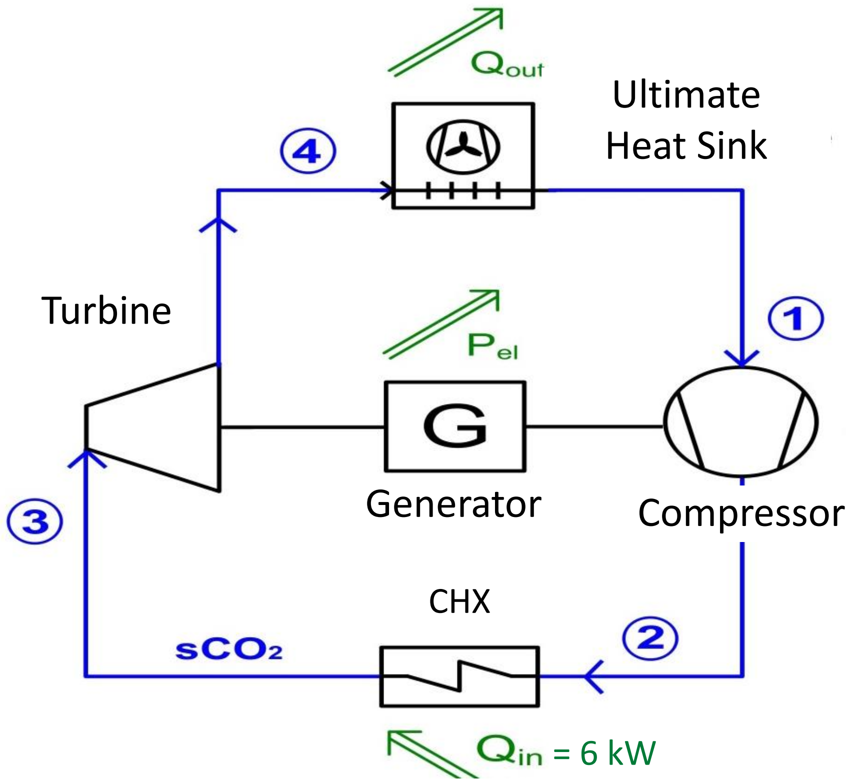
www.sCO2-HeRo.eu

Outline

- Cycle calculations
- Compact heat exchanger
- Test facilities
- Experimental investigations and results
- Manufacturing of the CHX for the glass model
- Summary

sCO_2-HeRo calculations → Glass model

- Approach: Decay heat will be used for the self sustaining of the cycle
- Objective: Maximum generator excess electricity P_{el}
- Outcome: Optimum cycle parameters (p_1, p_3, T_1, T_3 …)



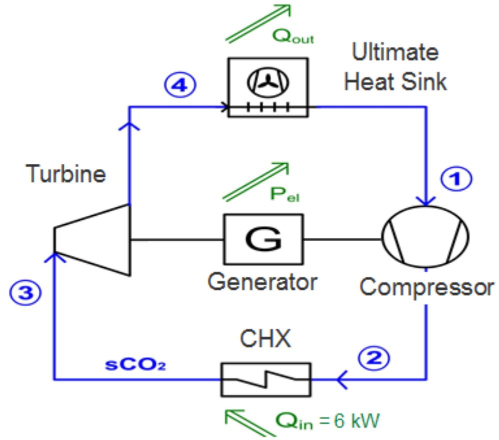
Boundary conditions:

- H_2O side:
  - Q_{in} = 6 kW
  - T_{in} = 70 °C / p_{in} = 0.3 bar
- sCO_2 side:
  - $\eta_C = 0.65$ / $\eta_T = 0.75$

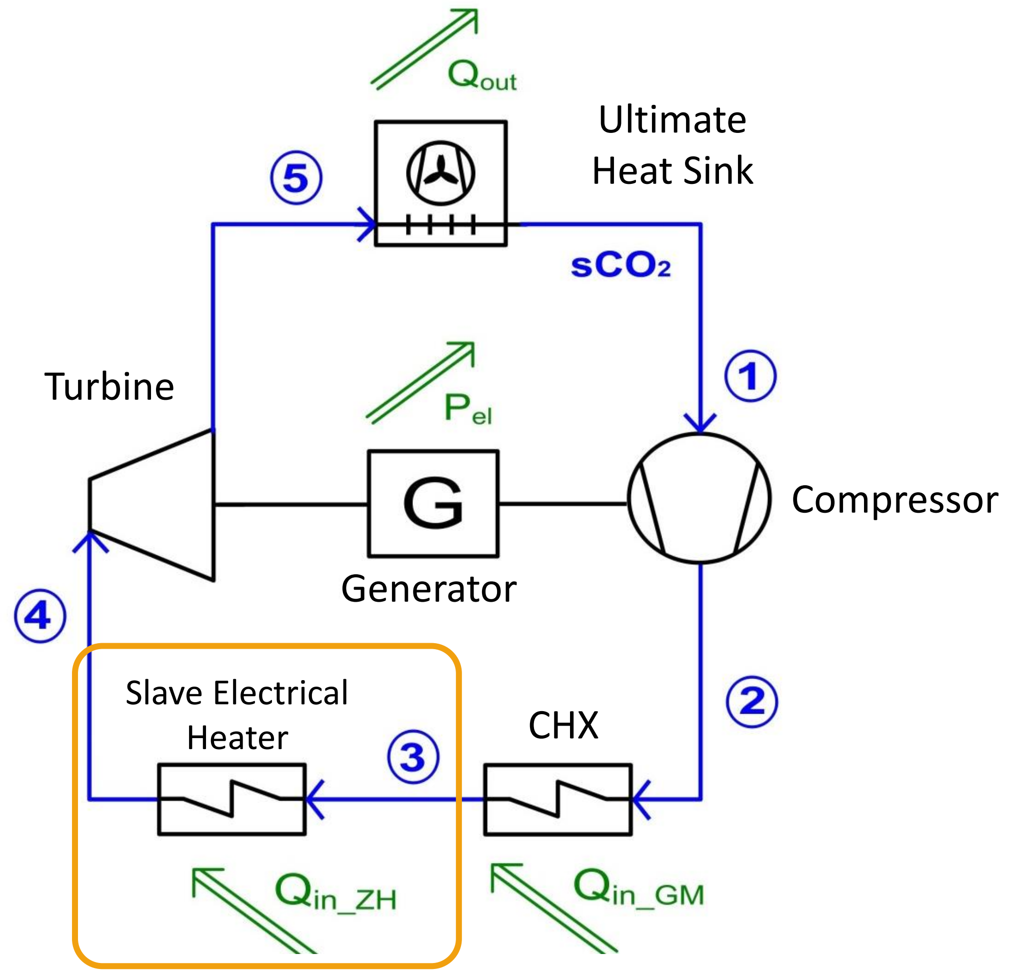
Fist calculation results:

- P_{el_max} → too low !!
  - No pressure losses considered
  - Efficiencies are not conservative
  - Achievable T_3 too low for TCS

sCO_2-HeRo calculations → Glass model (II)

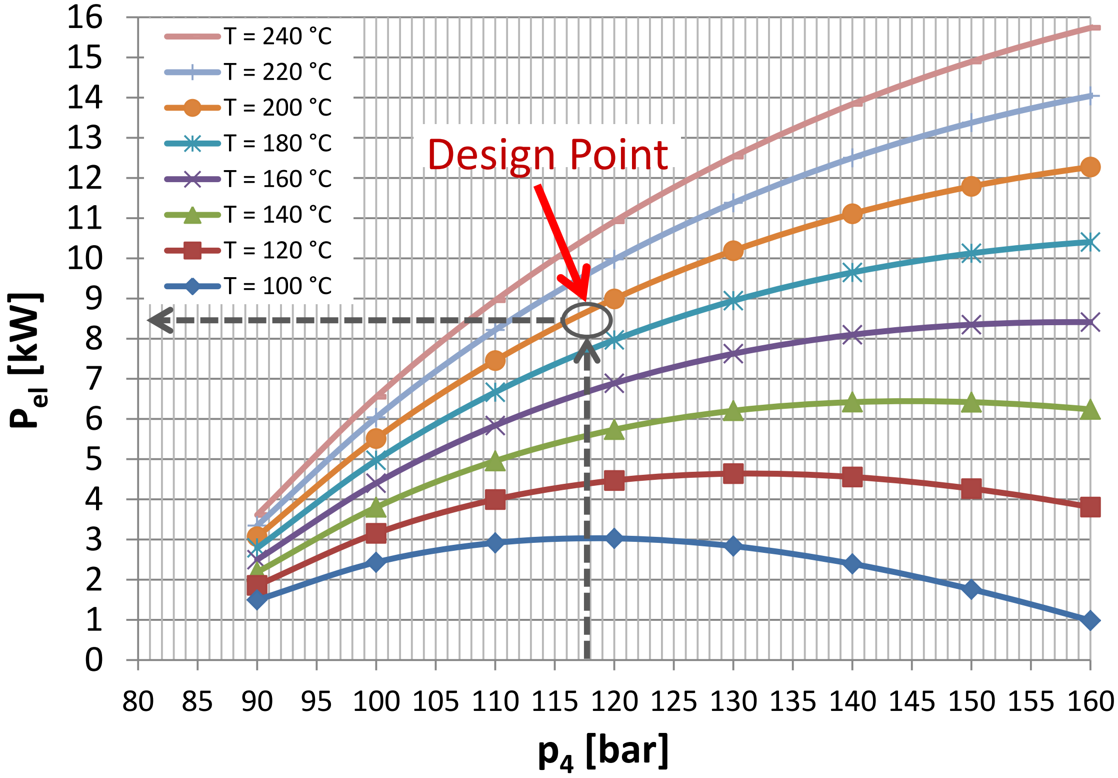


Modification



sCO_2-HeRo calculations → Glass model (III)

- Determination of the design point
  - Max. pressure high pressure side → compression-ratio
  - Max. temperature inlet turbine → power of slave electrical heater



Design Point:

p_1 = 78 bar

T_1 = 33 °C

p_4 = 117 bar

T_4 = 200 °C

η_C = 0.65

η_T = 0.75

$\dot{m}_{sCO2}$ = 0.65 kg/s

Q_{in_GM} = 6 kW

Q_{in_SH} = 196 kW

P_{el} = - 8.7 kW

Compact heat exchanger (CHX)

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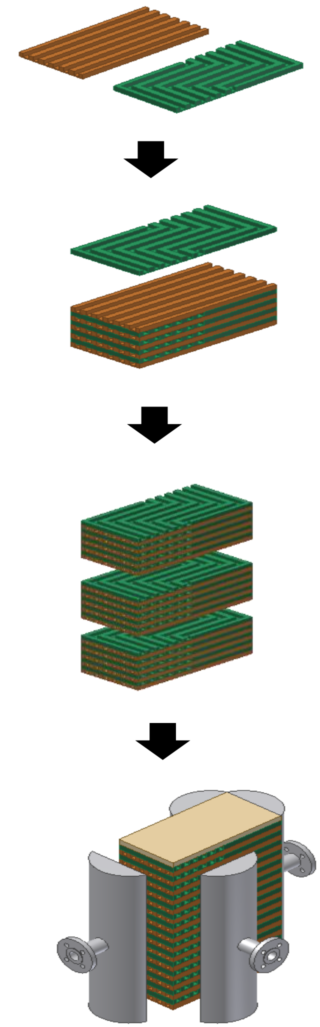
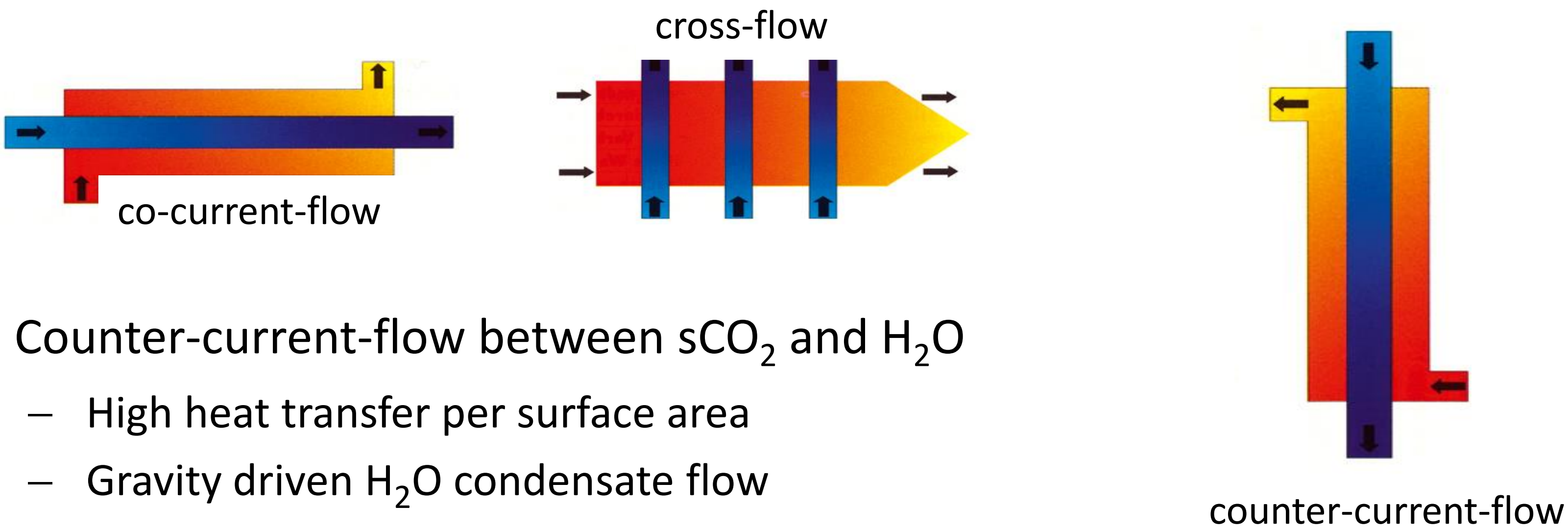
- Advantages of a compact heat exchanger (CHX)
  - High heat transfer area per volume
    → Retrofitting the CHX into existing power plants
  - CHX plates are bonded modularly by diffusion bonding
    → Homogeneous structure
  - Temperatures up to 900 °C and pressure up to 1000 bar

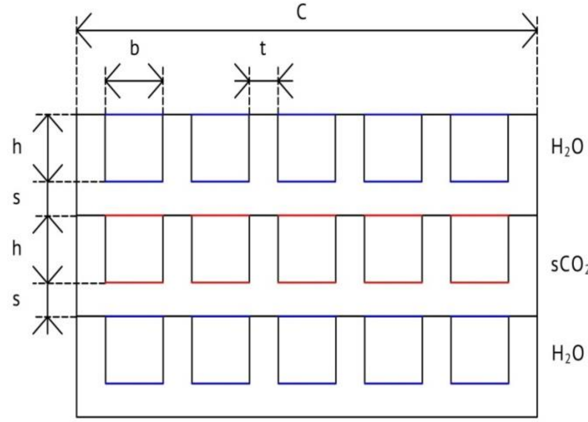
- Advantages of sCO_2 as working fluid near the critical point (T_c = 31 °C, p_c = 74 bar)
  - High specific heat capacity c_p → low mass flow rate
  - High heat-transfer coefficient α → high heat transfer
  - Low viscosity η → low pressure drop



CHX calculation → Assumptions



- Counter-current-flow between sCO_2 and H_2O
  - High heat transfer per surface area
  - Gravity driven H_2O condensate flow
- No pressure drop in the channels
- Equal amount of sCO_2 and H_2O channels
- Same channel geometry on both sides
- Heat transfer occur only at the top and bottom of the channels



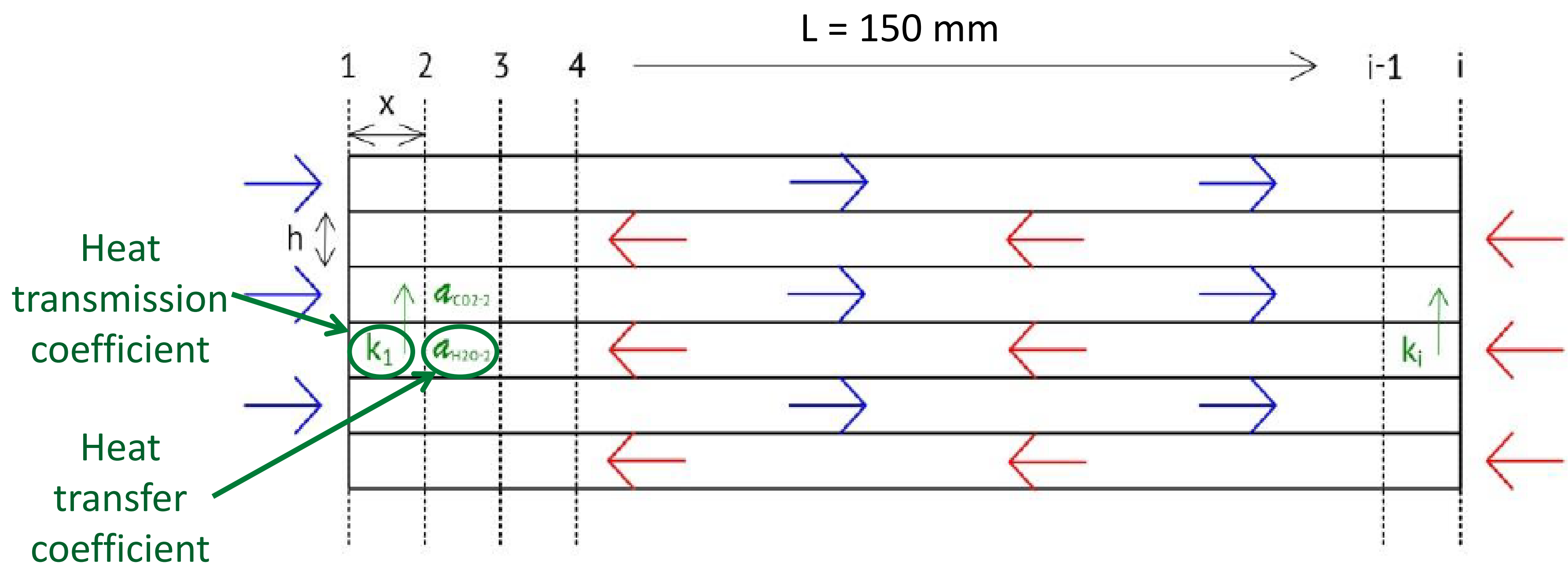
CHX calculation → Iteration scheme

sCO_2
input parameter

m_{sCO2} = f (number of channels)
T_{sCO2_in} = 47 °C
p_{sCO2_in} = 117 bar

H_2O
input parameter

m_{H2O} = f (number of channels)
T_{H20_in} = 70 °C
p_{H2O_in} = 0.3 bar
x_{H2O_in} = 100 %



CHX test plates → Manufacturing

- Steps for the experimental investigation
  1. Experimental investigation with two-plate CHX
  2. Determination of the design of the glass model CHX

- Provide drafts of the two-plate CHX
  – Maximum sCO_2 mass flow of m'_{sCO2} = 110 g/s (SCARLETT)
  – Maximum steam mass flow of m'_{H2O} = 0.69 g/s (Steam cycle)
  – Plate size at the diffusion bonding device of d = 325 mm

- Design of two-plate CHX test configuration
  – 1x H_2O-Plate, 1x sCO_2-Plate
  – 1x1 mm / 2x1 mm / 3x1 mm channel dimension
  – 150 mm effective channel length
  – Counter-current-flow (straight H_2O channels, Z-shape sCO_2 channels)

1

2

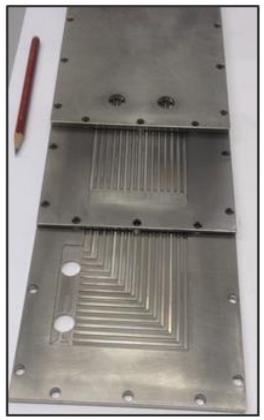
CHX test plates → Manufacturing (II)

As example: Test plates of the 2x1 mm channel dimension

→ Material: 1.4301

H_2O - Plate

sCO_2 - Plate



Stacked Plates

Test Plates

Manufacturing in the workshop:

- H_2O plate
- sCO_2 plate
- Coverplate

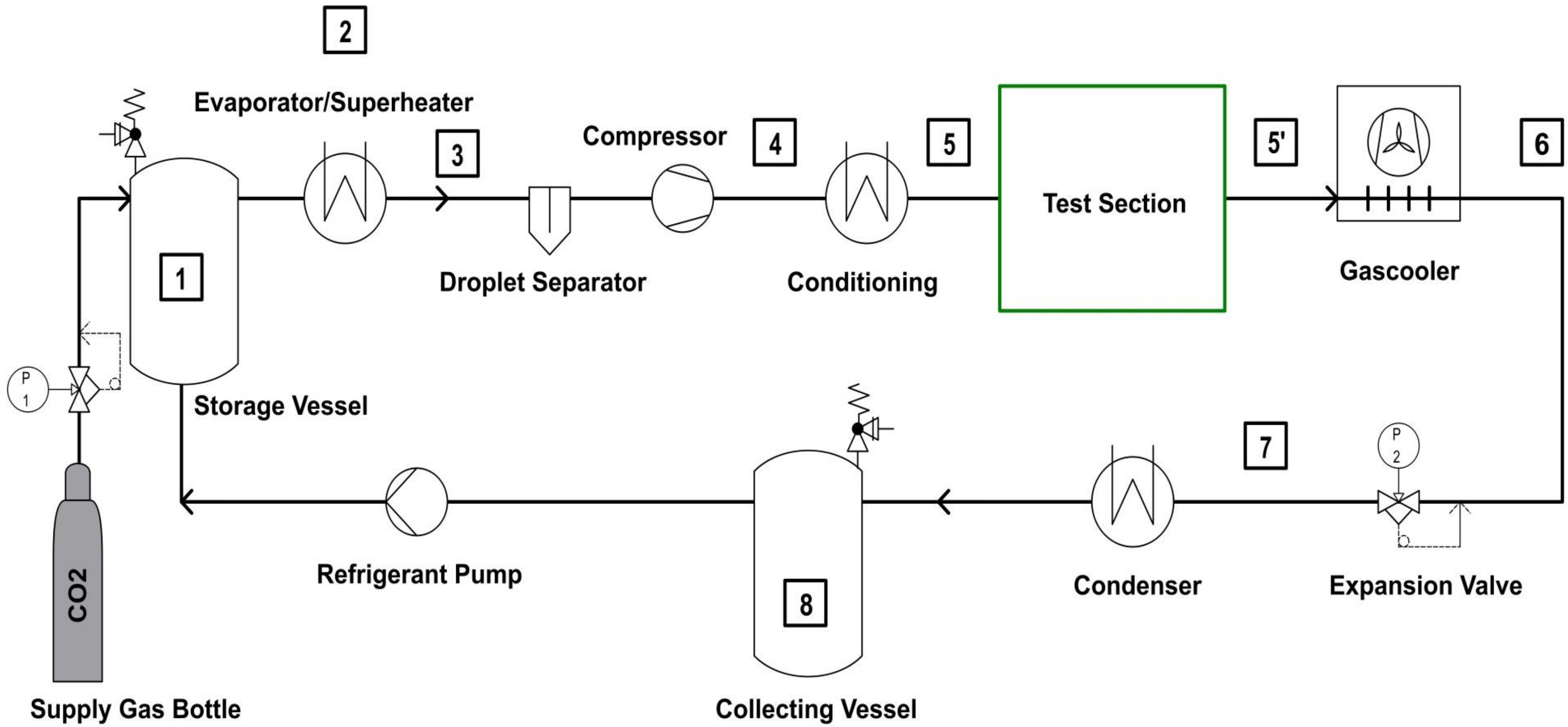
1) Diffusion bonding
2) Pipe installation
3) Welding of pipes

Pressure test - 180 bar

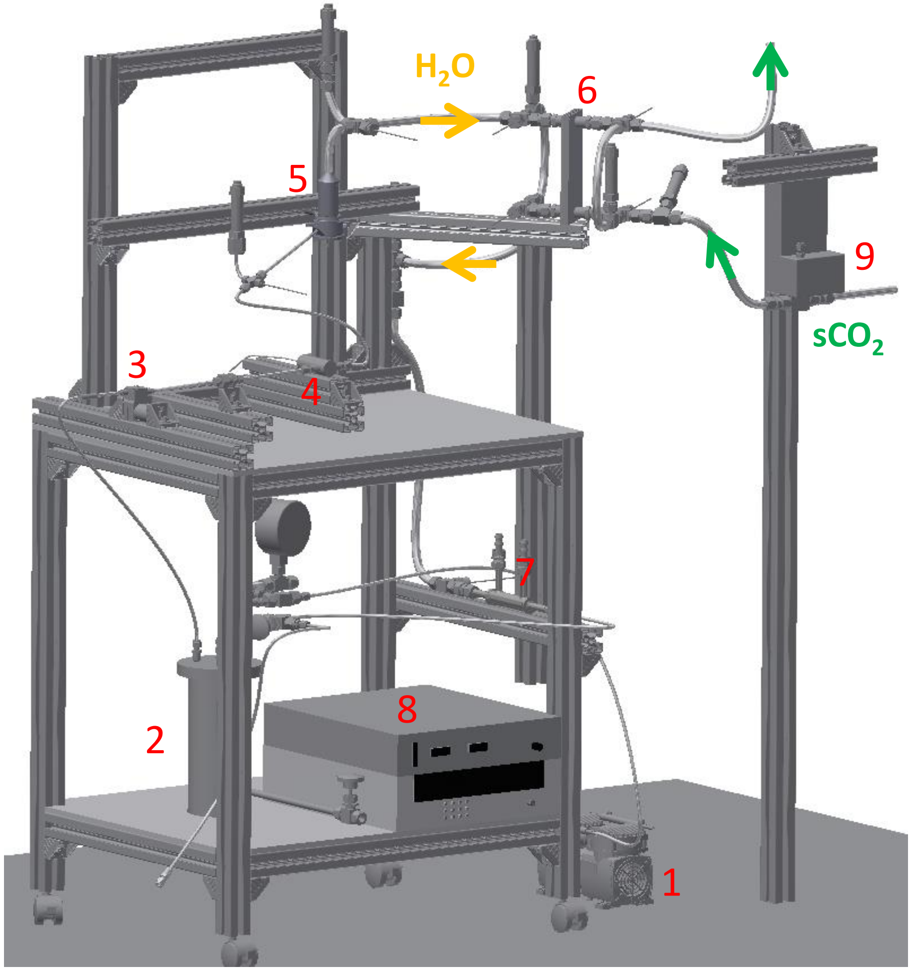
→ ready for installation into test section !

Test facility → SCARLETT

- P&I diagram of the sCO_2 SCARLETT test facility

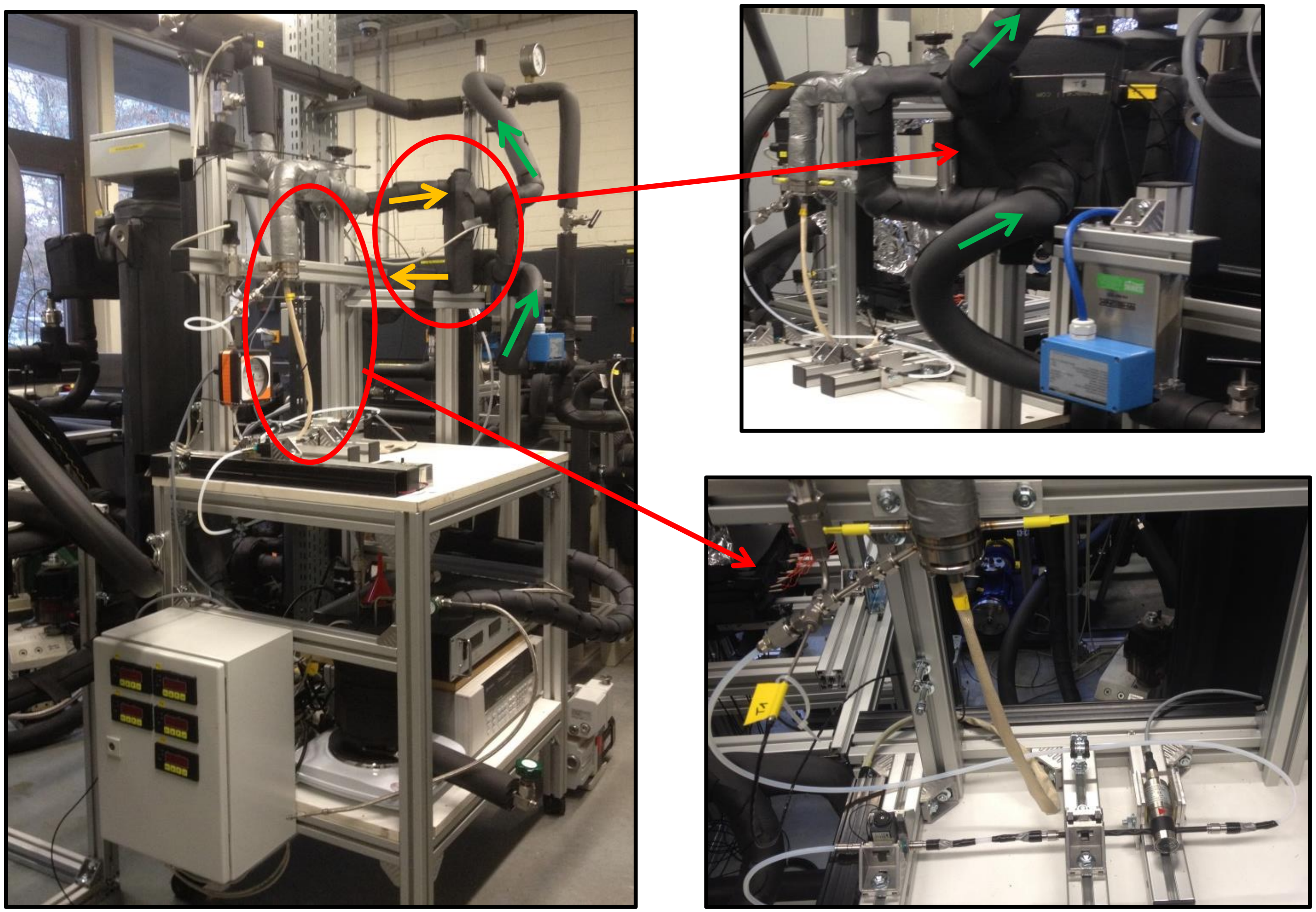


Test facility → Steam cycle



1. Vacuum pump
2. Water storage vessel
3. Membrane pump
4. Measurement devices
5. Evaporator
6. 2-plate CHX
7. Condenser
8. Measurement data acquisition
9. Coriolis mass flow meter

SCARLETT laboratory



Measurement points

- 3 x “Design point” measurement camp.

→ $$\frac{\mathrm{m}_{water}}{m_{water\_GM}} = \frac{m_{sCO2}}{m_{sCO2\_HeRo}}$$

→ 3 x sCO_2 inlet pressures and corresponding inlet temperatures

→ 4 x sCO_2 mass flow rates and corresponding H_2O volume flows

- 3 x “Out of design point” campaigns

→ $$\cancel{\frac{\mathrm{m}_{water}}{m_{water\_GM}} = \frac{m_{sCO2}}{m_{sCO2\_HeRo}}}$$

→ 3 x sCO_2 inlet pressures and corresponding inlet temperatures

→ 1 x sCO_2 mass flow rate and 7 x H_2O volume flow rates

Experimental results

- Pressure drop P05 as a function of the sCO_2 mass flow rate $\dot{m}_{sCO2}$
  - → Available sCO_2 mass flow rate $\dot{m}_{sCO2}$ = 68 g/s is limited by the SCARLETT loop
  - → Non-linear tendency according to Eq. $P05 = \xi \cdot \frac{\rho}{2} v^2 = \frac{\xi}{2\rho}\left(\frac{\dot{m}}{A}\right)^2 \rightarrow \Delta p \sim \dot{m}^2 \rightarrow \Delta p \sim \left.\frac{1}{\rho}\right|_{\dot{m}=constant}$ can be shown in the experimental results

- sCO_2 heat input Q_{sCO2} as a function of the steam condensing power Q_{H2O}
  - → Q_{H2O} is limited by the electrical heating power of the evaporator (P_{el} = 1500 W)
  - → Linear tendency of the steam condensing power Q_{H2O} compared to the sCO_2 heat input Q_{sCO2} (heat transfer in the CHX) with a discrepancy of less than 10 % was carried out

- sCO_2 temperature increase T08-T07 as a function of heat input Q_{sCO2}
  - → Q_{H2O} and therefore Q_{sCO2} is limited by the heating power of the evaporator (P_{el} = 1500 W)
  - → Linear tendency according to Eq. $Q = \dot{m} * c_p * \triangle T = \dot{m} * c_p * (T08 - T07) \rightarrow$

    $T08 - T07 = \frac{Q}{\dot{m} * c_p} \rightarrow T08\text{-}T07 \sim Q$ can be shown in the experimental results

Manufacturing of glass model compact HX

Taken into account the carried out experimental results and the existing boundary conditions (H_2O and sCO_2 side):

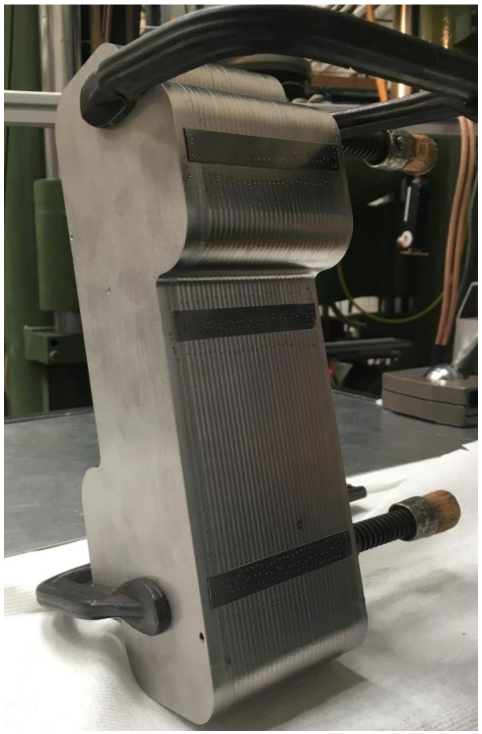
- Pressure drop P05 is the most important parameter → less net power of TCS, if too high
- Heat transfer capacity is conservative for the CHX → “Out of design point” investigations

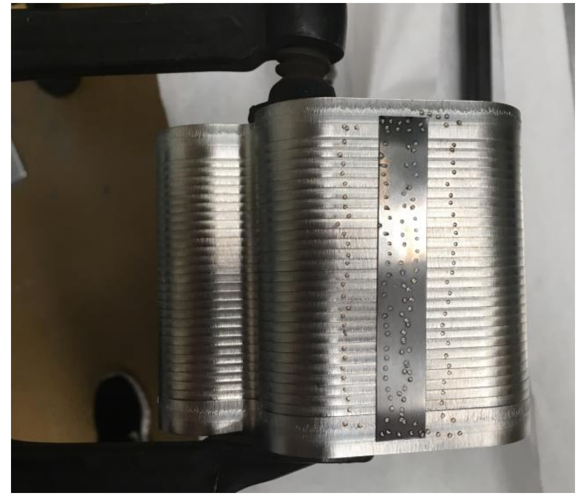
CHX design for the glass model

- 14 pair of plates on the H_2O and sCO_2 side
- $Q_{possible} > 3x\ Q_{necessary}$ → “Out of design point” experiments
- FEM simulations with COMSOL and calculations with the “Kesselformel” were carried out for the determination of the plate and wall thicknesses

Manufacturing of glass model compact HX (II)

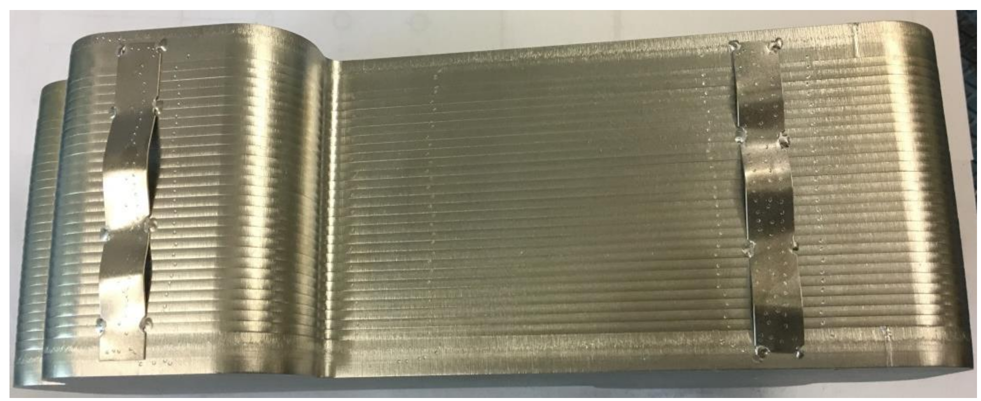
Preparation for diffusion bonding





Installation of additional metal straps

After diffusion bonding



Manufacturing of glass model compact HX (III)

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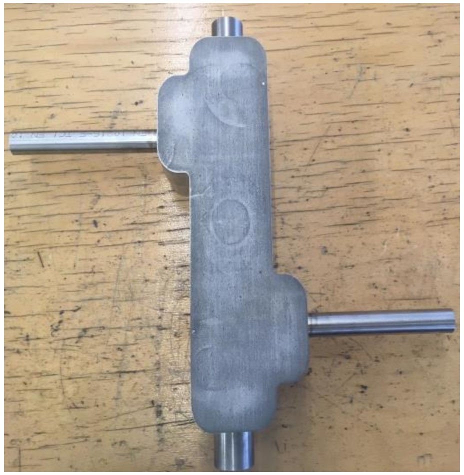
Leakage test with helium

Pressure test in the laboratory - 180 bar

Manufacturing of glass model compact HX (IV)

Milling of the flange and pipe connections

Electronical beam welding of sCO_2 pipes



Welding of H_2O flanges

After each welding step: Leakage test!

Finally: Pressure test at MPA with certificate

Manufacturing of glass model compact HX (V)

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Ready for installation into the PWR glass model in Essen !

Summary

- Thermodynamic cycle calculations were carried out and cycle parameters were determined with respect to maximum generator excess electricity
- The heat transfer capability in the CHX was calculated by correlations of Gnielinski and Carpenter&Colburn
- Two-plate CHX test configurations with different channel dimensions were design, manufactured and installed into the SCARLETT test facility
- Performance tests of the two-plate CHX's were carried out in the laboratory with "Design point" and "Out of design point" measurement campaigns
- Under consideration of the carried out experimental results, the design of the glass model CHX was determined and manufactured

Thanks for attention !

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