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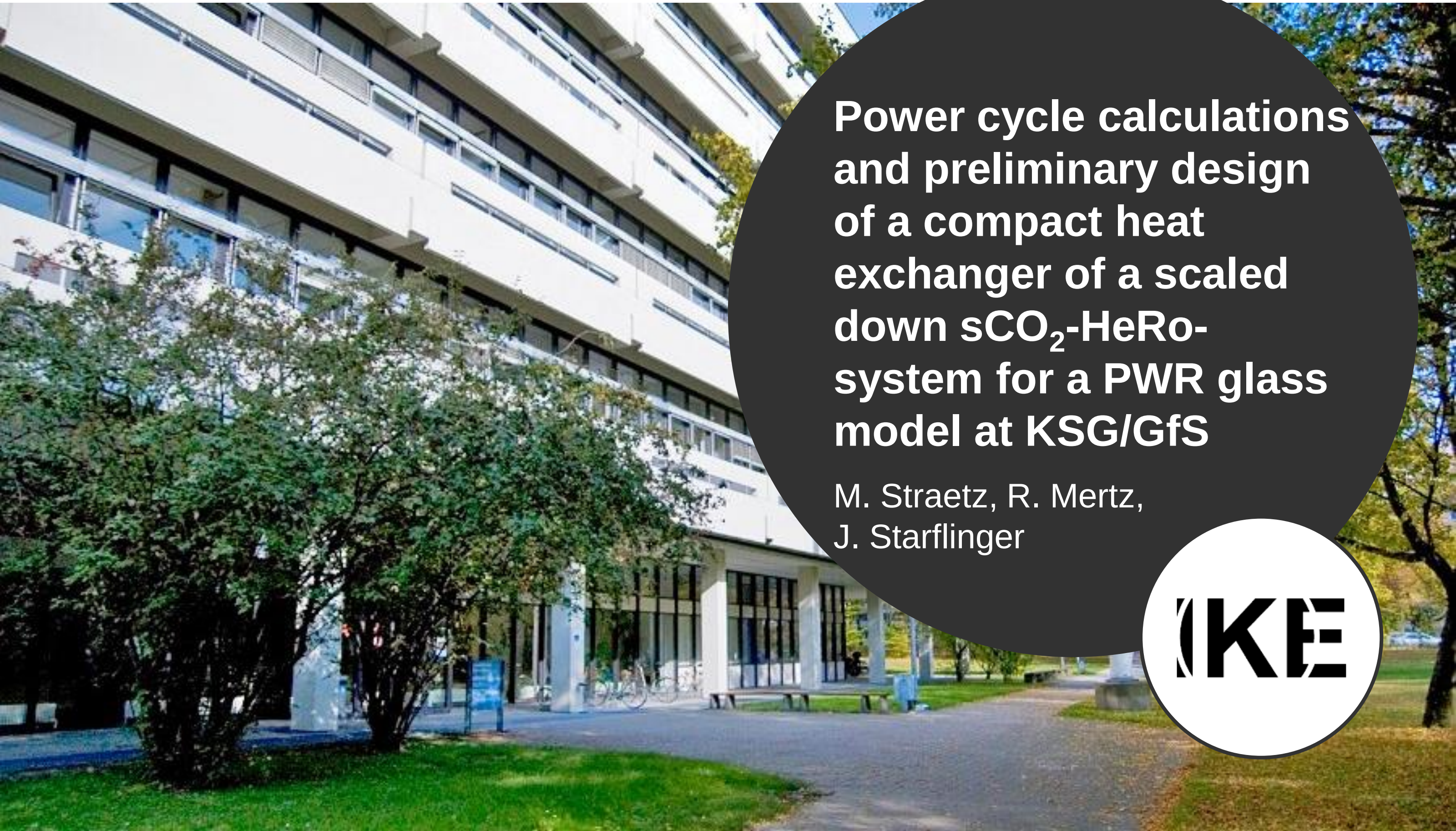

Power cycle calculations and preliminary design of a compact heat exchanger of a scaled down sCO_2-HeRo-system for a PWR glass model at KSG/GfS

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IKE

Outline

- Motivation and Aims
- sCO_2-HeRo calculations
- Compact heat exchanger
- Experimental investigation of the CHX
- Summary and Further work

Motivation

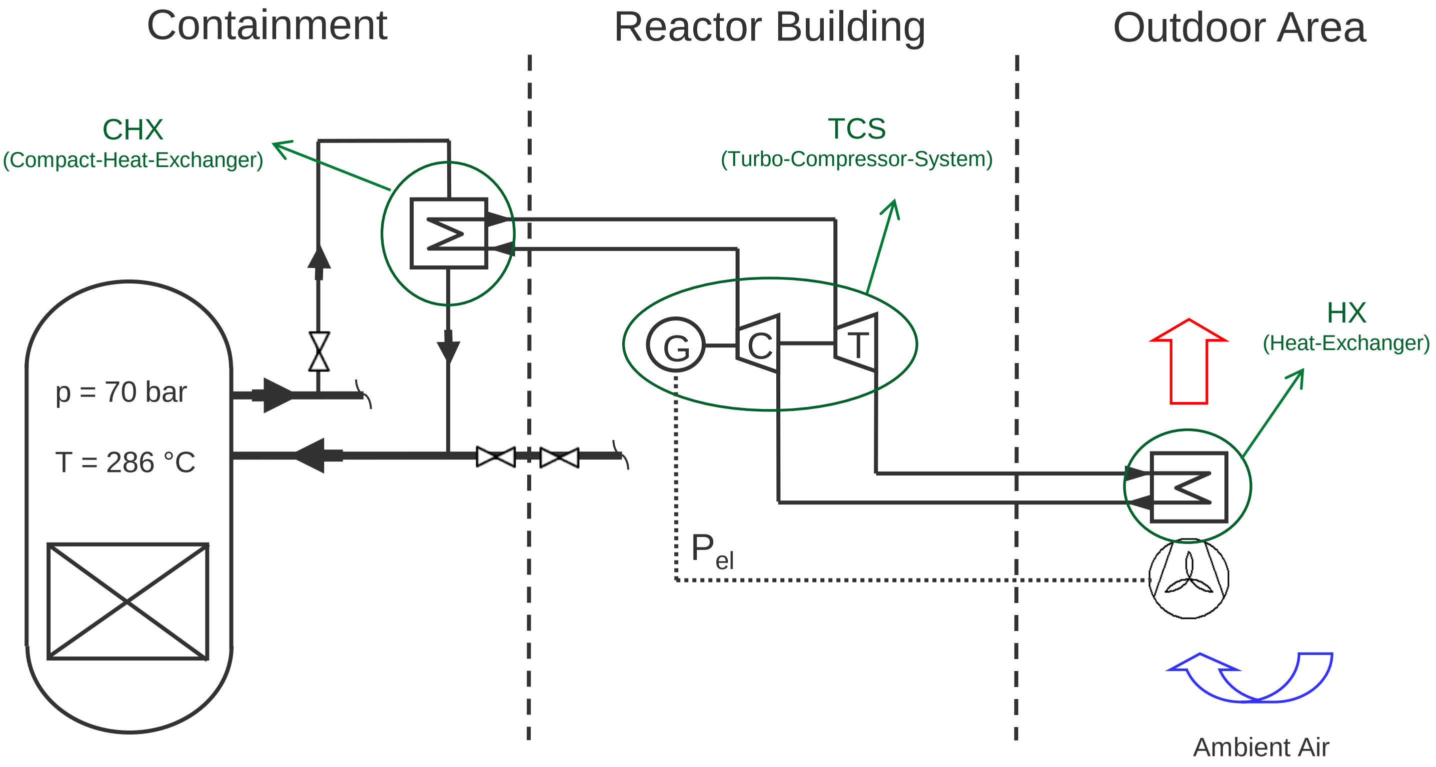
- In case of an accident in an nuclear power plant, the decay heat must be transferred reliably from the reactor core to the environment (heat sink)

- Active safety system may possibly not work, because they require electricity for activation or during operation

- New reactor concepts are equipped with passive safety systems and redundant heat sinks, but these can not be retrofitted into existing plants

- Because of that, there was the idea of a self-launching, self-propelling and self-sustaining decay heat removal system with supercritical CO_2 as working fluid → called “sCO_2-HeRo”

sCO_2-HeRo system



1) Venker, J.: Development and Validation of Models for Simulation of Supercritical Carbon Dioxid Brayton Cycles and Application to Self-Propelling Heat Removal Systems in BWR. Dissertation, 2015

sCO_2-HeRo Project

sCO2 The supercritical CO_2 HeRo heat removal system

- Showing the feasibility of the decay heat removal system in a small-scaled demonstrator for the glass model PWR at GfS

- “Proof-of-Principle” of each component of the sCO_2-HeRo system

- 6 project partners are involved in the EU-project

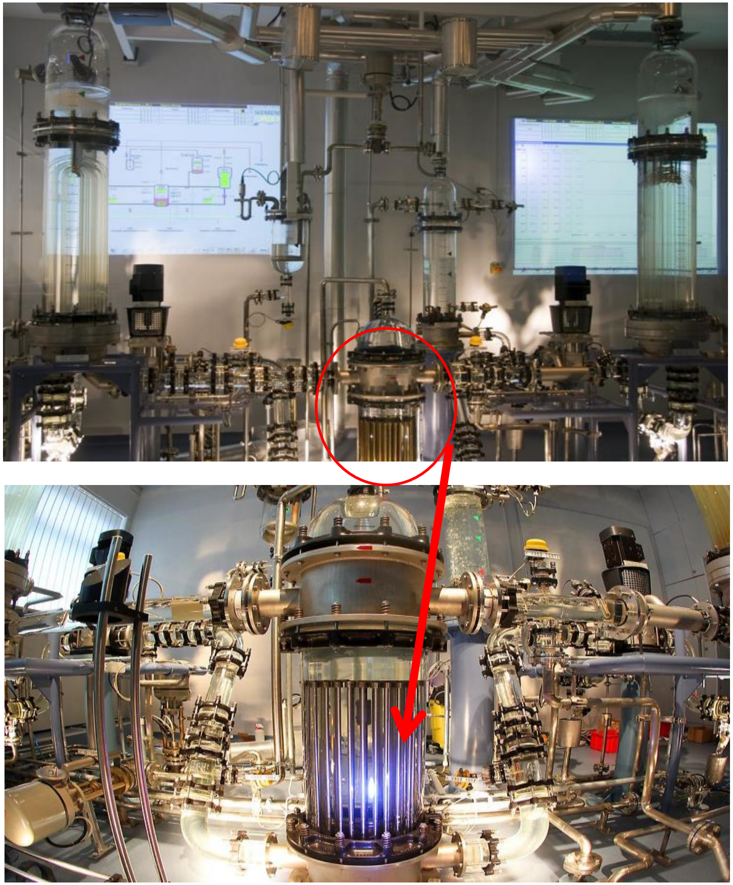
The project leading to this application has received funding from the *Euratom research and training programme 2014-2018* under grant agreement No 662116.

Objectives

- Perform thermodynamic cycle calculations for a scaled down sCO_2 heat removal system (sCO_2-HeRo) for the glass model PWR
- Determination of the optimum cycle parameters → excess electricity
- Experimental heat transfer investigations of CHX plates with sCO_2 and condensing steam in the sCO_2-test-loop and a new steam cycle
- Finally, the design and manufacturing ideas of the CHX for the glass model sCO_2 -HeRo application

Glass model at GfS

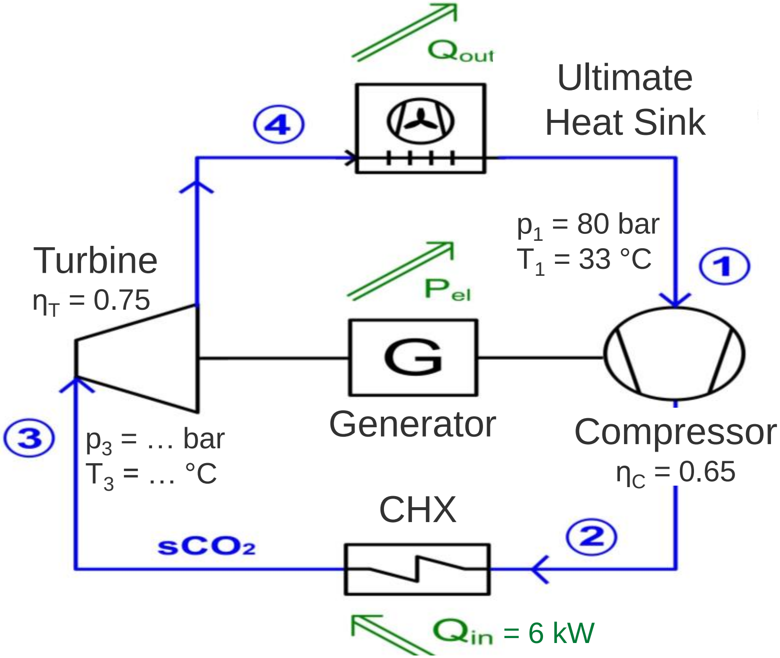
- PWR made of glass
  - Visualize the process
  - Education purpose
- Scale 1:10
- Power 60 kW_{th}
- p_{max} = 2 bar
- 2 loops with steam generators
- Simulated decay heat
  - Between 0 - 14 kW
  - Steam temperature between 60 - 90 °C → depending on the simulated decay heat power



2) Seewald, M.: Gesellschaft für Simulatorschulung - GfS, Essen, 2016

sCO_2-HeRo calculations - Glass model

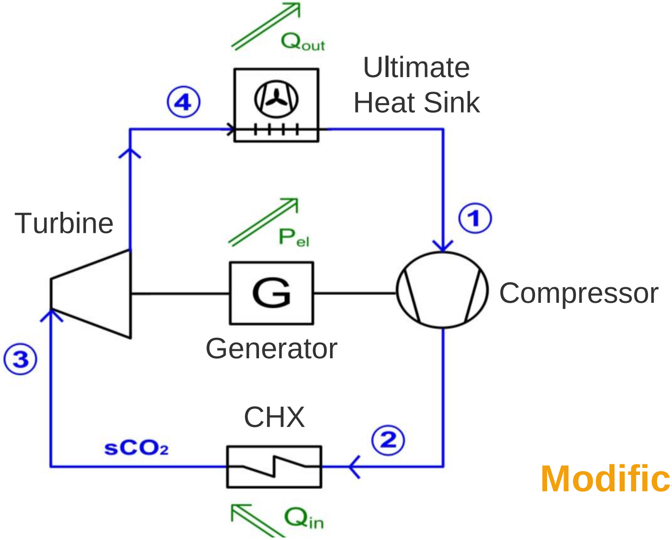
- Approach: Decay heat will be used for the self sustaining of the cycle
- Objective: Maximum generator excess electricity
- Outcome: Optimum cycle parameters (p_{high}, p_{low}, $T_{in\_Turbine}$, $T_{in\_Compressor}$ …)



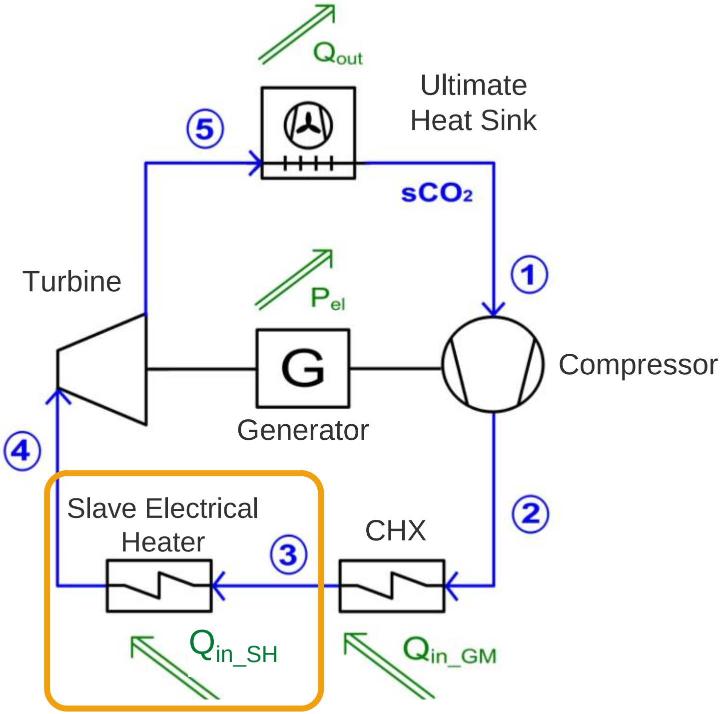
First calculations:

- $P_{el} = P_{Turbine} - P_{Compressor}$
- P_{el_max} = 0.5 kW → too low !!
  - No pressure losses considered
  - Efficiencies are not conservative
  - Achievable $T_{in\_Turbine}$ too low

sCO_2-HeRo calculations II

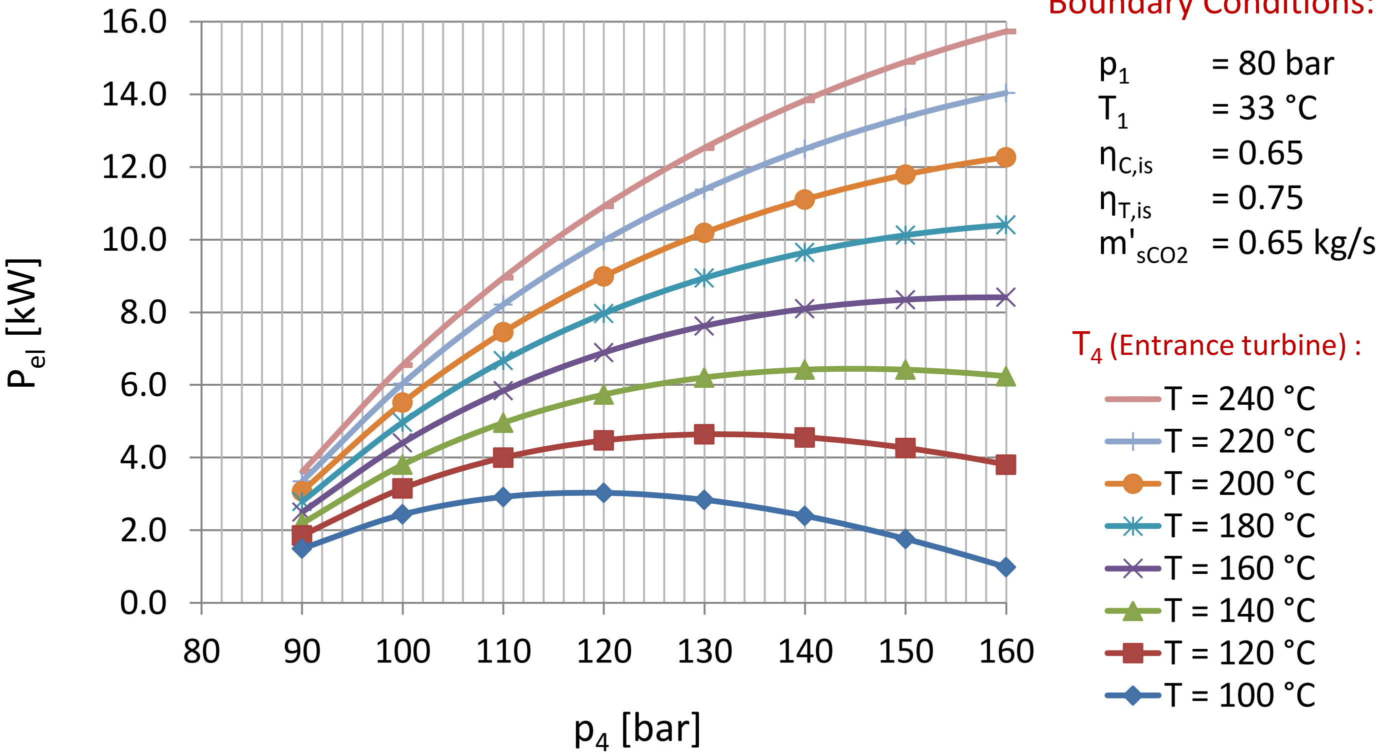


Modification



sCO_2-HeRo calculations III

- Further calculations with modified sCO_2-HeRo cycle
- Excess electricity as a function of p_4 and T_4

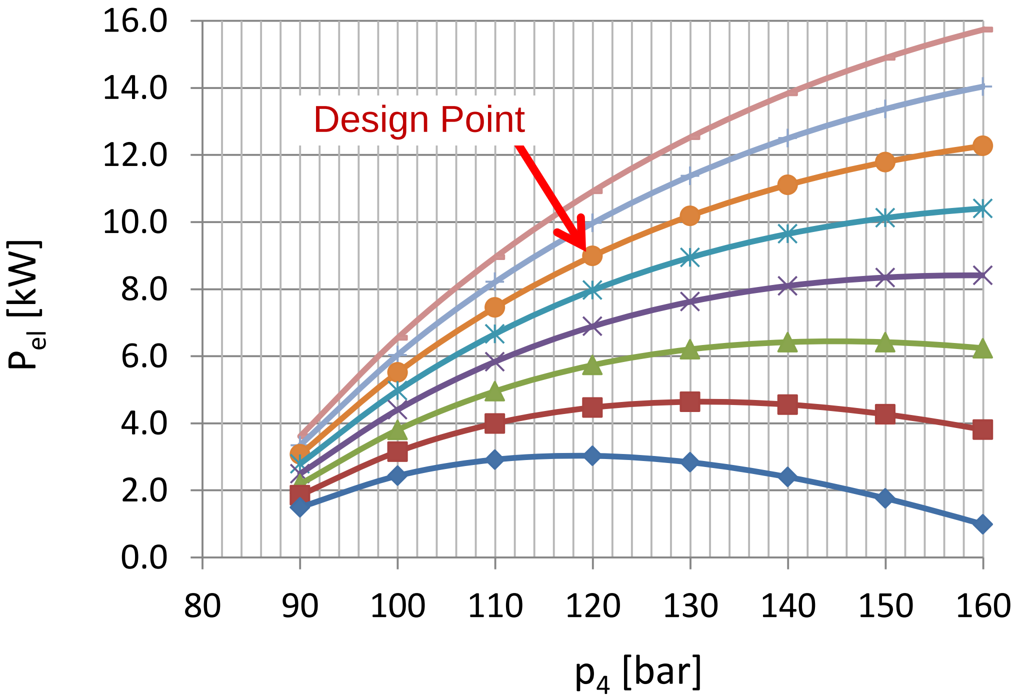


Boundary Conditions:

p_1 = 80 bar
T_1 = 33 °C
$\eta_{C,is}$ = 0.65
$\eta_{T,is}$ = 0.75
m'_{sCO2} = 0.65 kg/s

sCO_2-HeRo calculations IV

- 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

$\eta_{C,is}$ = 0.65
$\eta_{T,is}$ = 0.75

m' = 0.65 kg/s

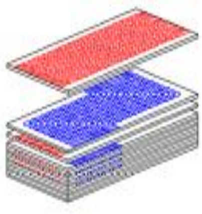
Q_{in_GM} = 6 kW
Q_{in_SH} = 196 kW

P_{el} = - 8.7 kW

Compact heat exchanger

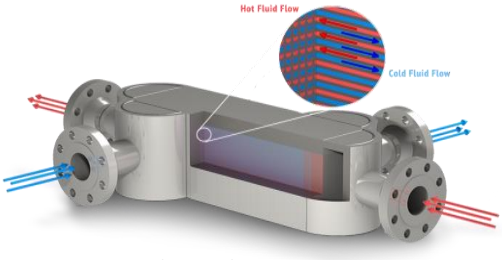
- Advantages of a compact heat exchanger (CHX)
  - High heat transfer area per volume
    → Retrofitting the CHX into existing power plants
  - CHX plates are bonded modularly by diffusion bonding
    → Homogeneous structure
  - Temperatures up to 900 °C and pressure up to 1000 bar

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



3) Heatric
http://www.heatric.com/heat_exchanger_performance.html, last used 05.2016

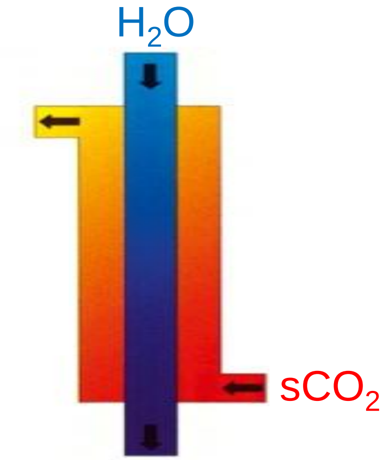
3) Nuclear Hydrogen System lab
http://cfile3.uf.tistory.com/image/1909034A5052F5B622FEC0, last used 06.2016

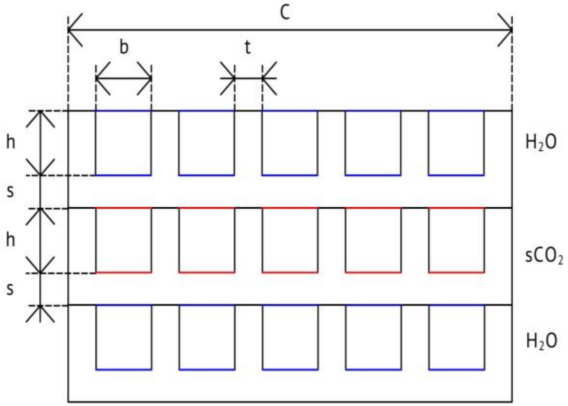


4) Heatexchanger VPE
http://heatexchanger.vpei.com/_images/product.png, last used 06.2016

Compact heat exchanger II

- Assumptions for the calculations
  - 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





Compact heat exchanger III – Iteration scheme

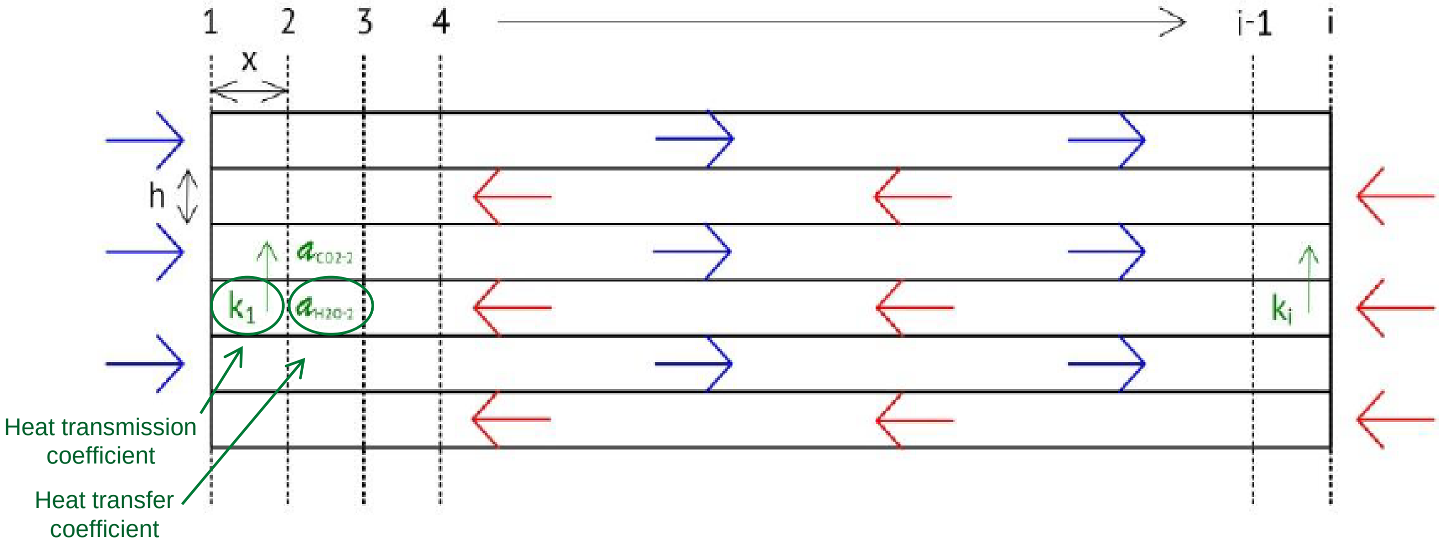
sCO_2
input parameter

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 %

L = 150 mm

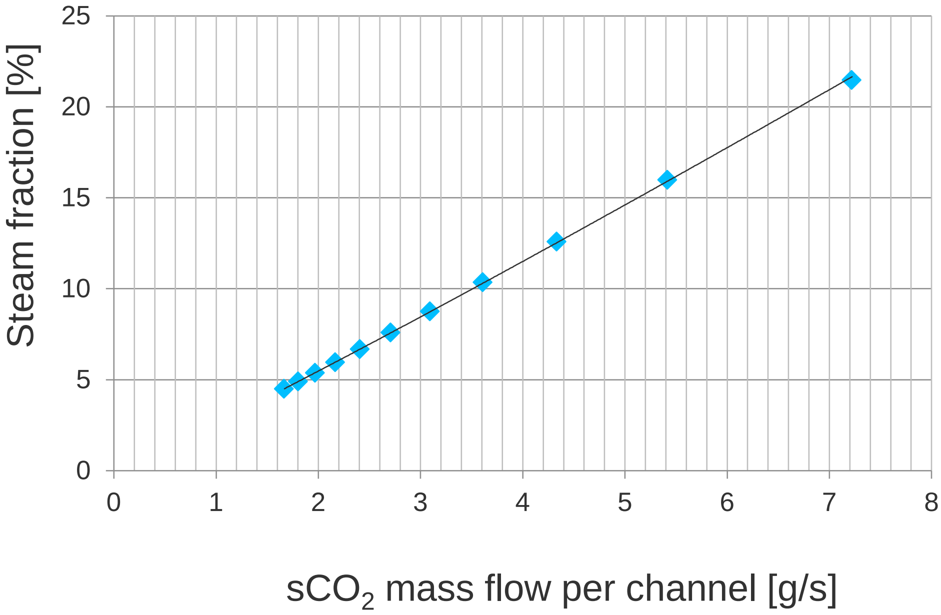


Heat transmission coefficient

Heat transfer coefficient

Compact heat exchanger VI

- Example of calculation results for 3x1 mm channel geometry



→ m_{sCO2} = 650 g/s

→ $n_{Channel}$ = 90 - 390

→ $m_{sCO2\_p.c.}$ = 7.2 -1.7 g/s

→ Re_{sCO2} = 77 000 - 17 700

→ Results must be validated in laboratory scaled experiments at USTUTT

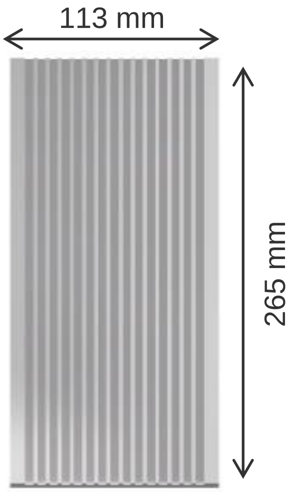
Manufacturing of the CHX plates

- Steps for experimental investigation

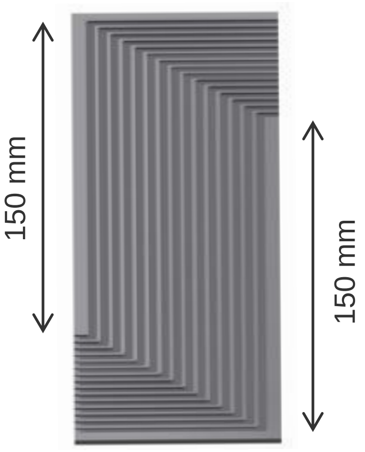
  1. Two-plate CHX test
  2. Determine the glass model CHX

- Provide drafts of the two-plate CHX
  - maximum sCO_2 mass flow of $m'_{sCO2} = 110$ g/s
  - maximum steam mass flow of $m'_{H2O} = 0.69$ g/s
  - plate size at the diffusion bonding device

- As example the plate design for experimental investigation of the 3x1 mm channel geometry
  - Effective channel length: 150 mm
  - Number of channels: 15



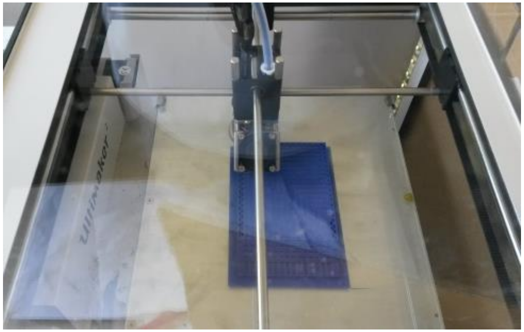
H_2O - plate

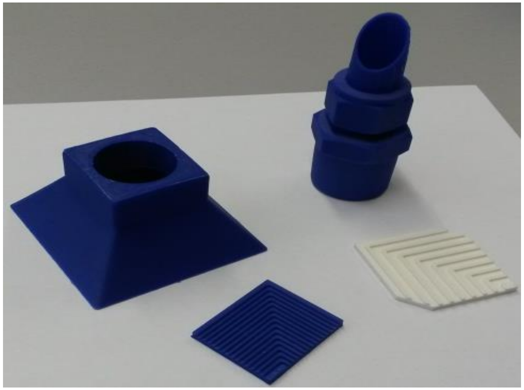


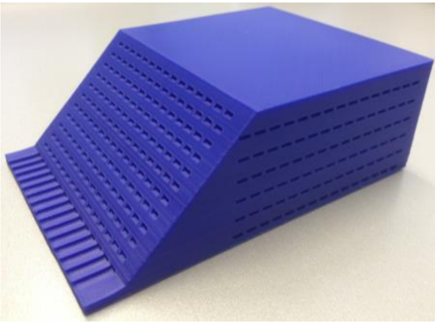
sCO_2 - plate

Manufacturing of the CHX plates II

- 3-D print for visualization







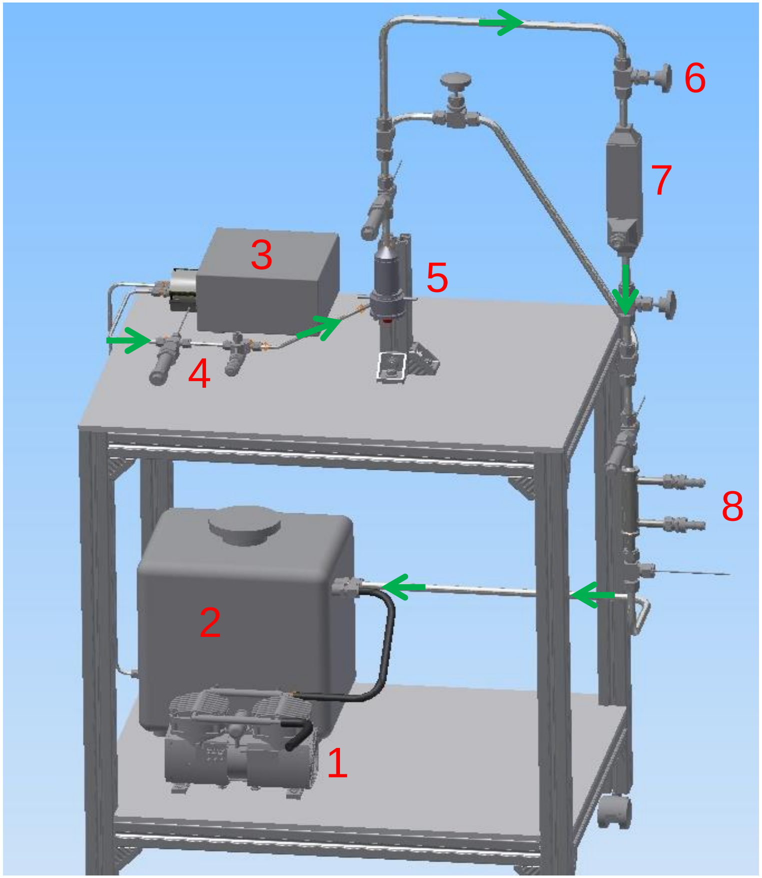
3-D print of stacked plates
3x1 mm channel geometry

Detail of the CO_2-test plate
1x1 mm channel geometry

Experimental investigation of the CHX

- Experimental investigation of the CHX plates take place at the SCARLETT test loop and the new build up steam cycle

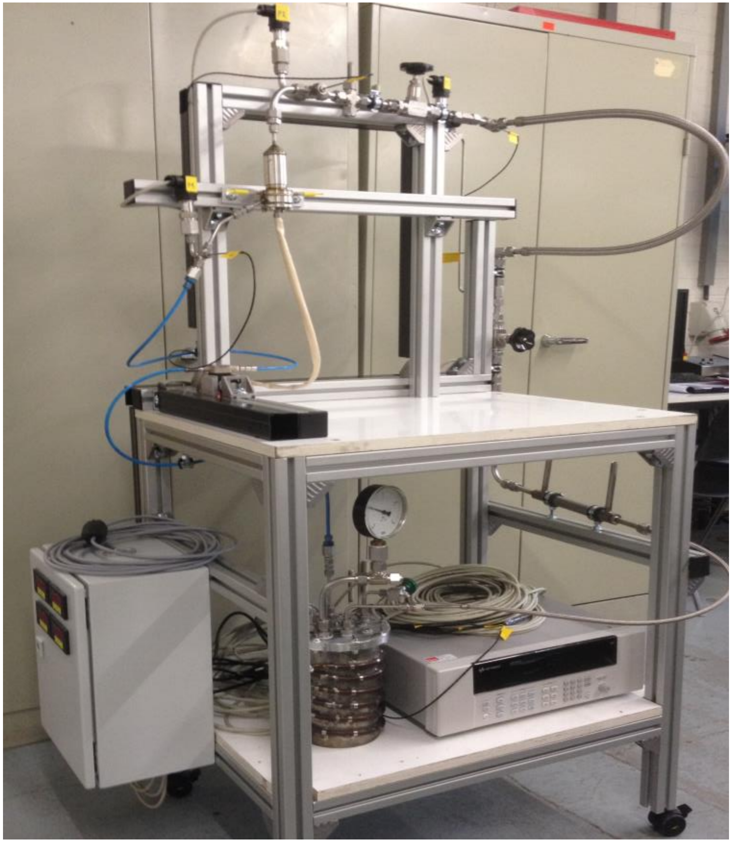
1. Vacuum-Pump
2. Storage Vessel
3. Membrane-Pump
4. Measurement Devices
5. Evaporator
6. Valves
7. CHX Plates
8. Condenser & Kryostat



Experimental investigation of the CHX II

- Build-up status:
  - Mechanical work → finished
  - Electrical work → in progress
  - Data acquisition → in progress
  - CHX plates → in progress

* Start of operation: End of 2016 *



Summary

- Thermodynamic sCO_2 cycle calculations were carried out and cycle parameters were determined with respect to the maximum generator excess electricity
- Design of the first CHX-test-plates for the experimental investigations in the steam cycle are completed
- Steam cycle was designed, drafts were provided, components bought and the test loop is under construction

Further work

- Finalize build-up of the steam cycle and data acquisition
- Experimental investigation of the heat transfer in the two-plate CHX
- Manufacturing and testing of the CHX for the glass model in 2017

Thank you!

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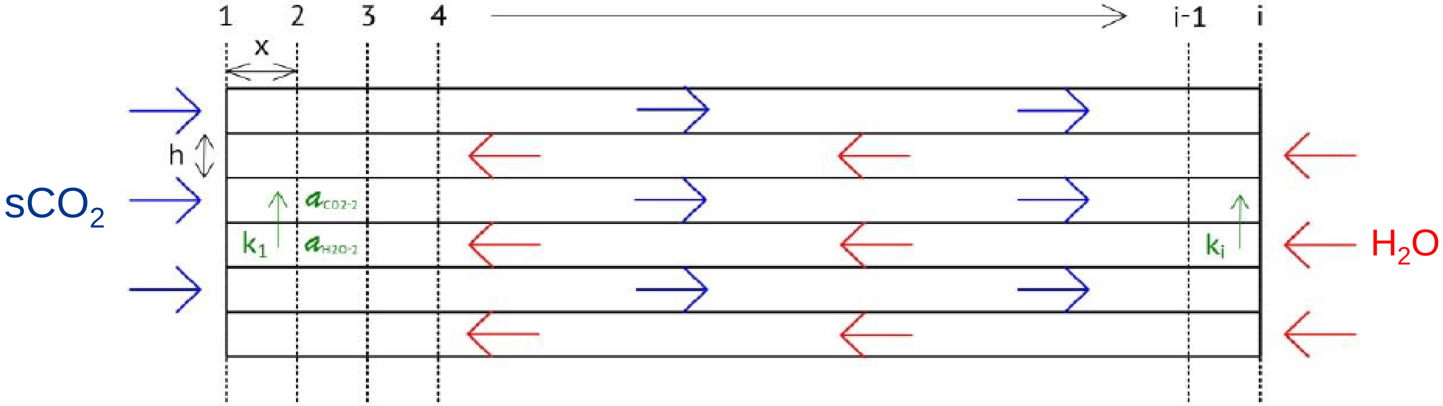
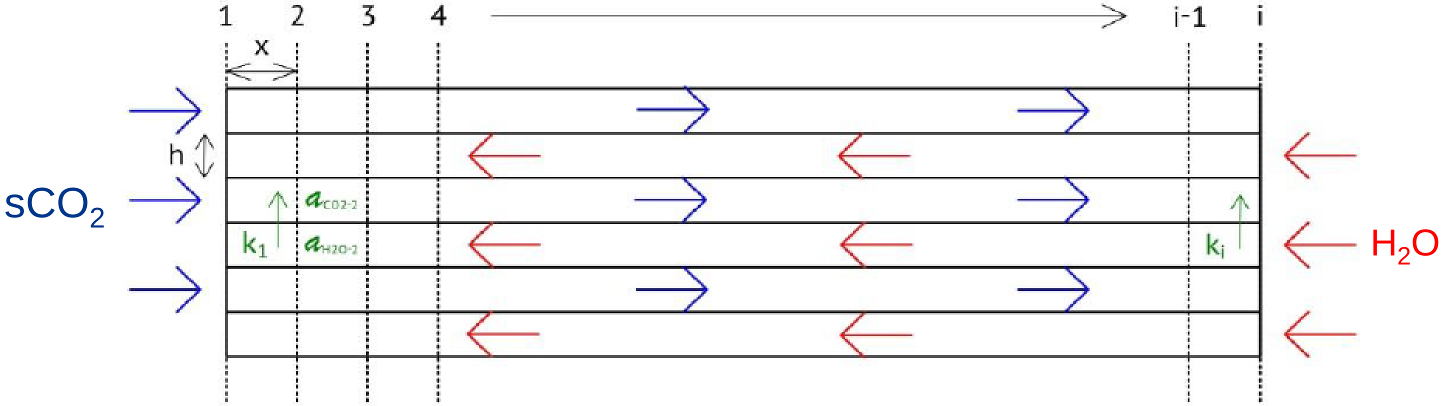
Compact heat exchanger IV

1. Educated guess of m_{H2O_1-i} in each section i (x = 0.5 mm), to calculate the heat transfer coefficients α_{H2O_1-I} by Carpenter&Colburn correlation
2. Calculation of the heat transfer coefficient α_{CO2_1} by Gnielinski and the Nu-number
3. Consider the plate thickness s between H_2O and sCO_2 channel and the heat conductivity ƛ of stainless steel
4. Calculation of the heat transmission coefficient k_1 by equation $\frac{1}{k_1} = \frac{1}{\alpha_{H2O-1}} + \frac{s}{\lambda} + \frac{1}{\alpha_{CO2-1}}$
5. Calculation of the transferred heat Q_1 in discretisation section 1-2 with $Q_1 = k_1 * A_1 * \Delta T$



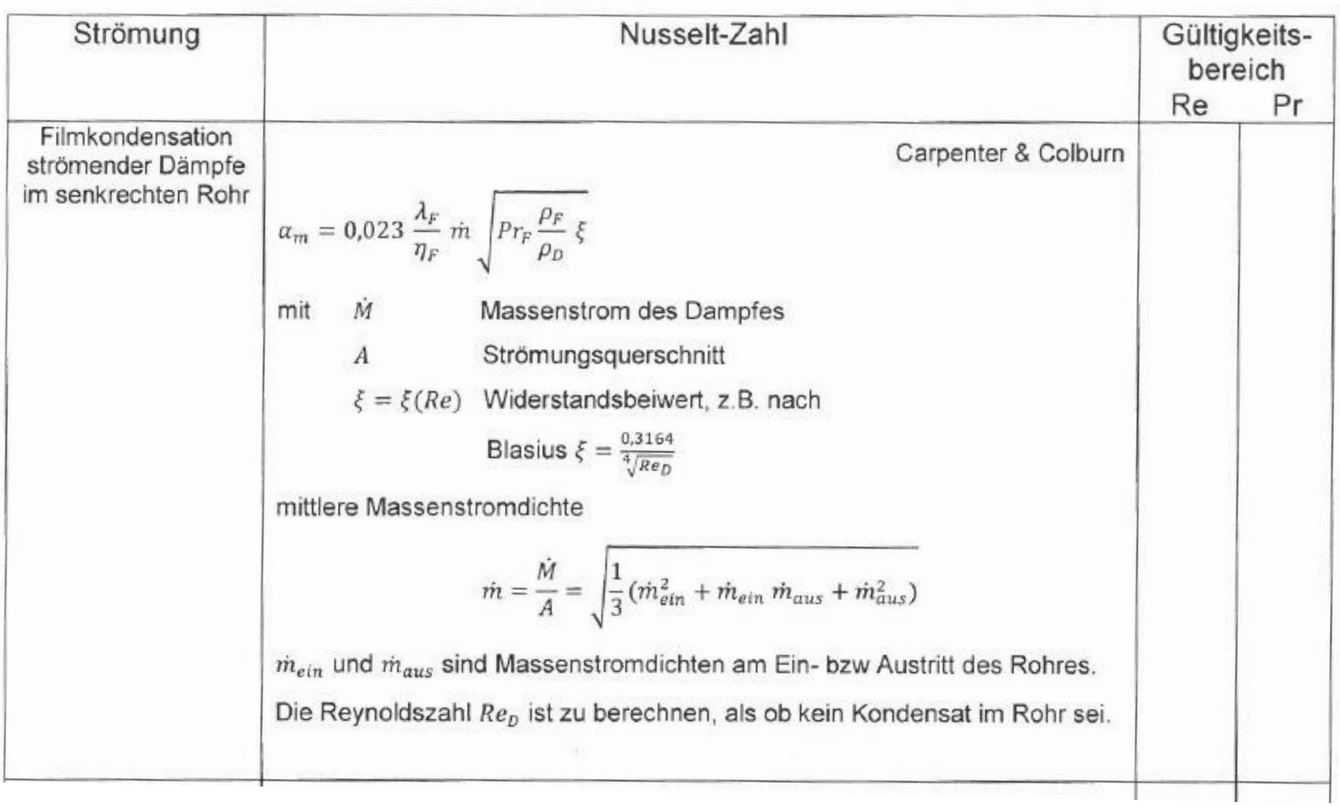
Compact heat exchanger V

6. Calculation of sCO_2 temperature T_{2_sCO2} at point 2 with Q_1 and m'_{sCO2}
7. Calculation of H_2O condensate from 1 → 2 with Q_1 and the enthalpy of condensation
8. Calculation of steam “new” mass flow m_{H2O_2} at point 2 with calculated amount of condensate from 1 → 2
9. Calculation done for the entire length of the CHX, followed by an iteration process



Back-up

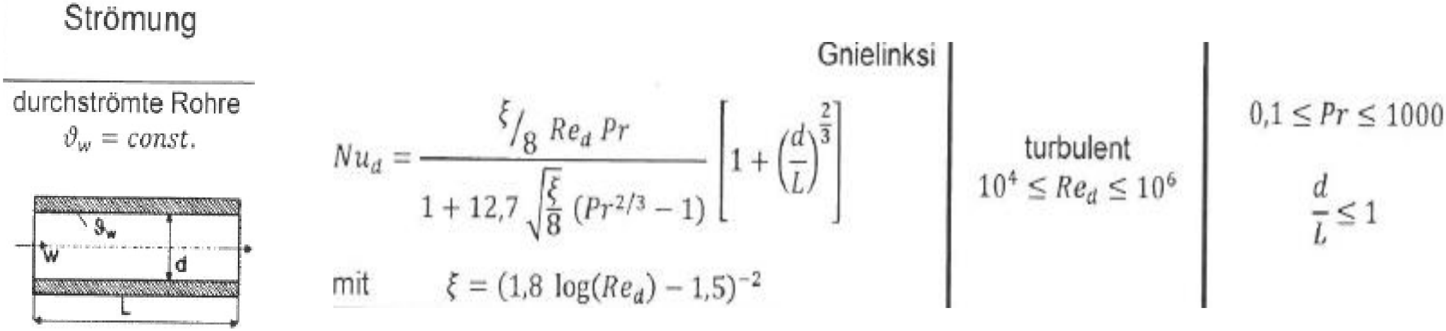
(1) Carpenter & Colburn correlation



Strömung	Nusselt-Zahl	Gültigkeits-bereich	
		Re	Pr
Filmkondensation strömender Dämpfe im senkrechten Rohr	Carpenter & Colburn $\alpha_m = 0{,}023 \frac{\lambda_F}{\eta_F} \dot{m} \sqrt{Pr_F \frac{\rho_F}{\rho_D} \xi}$ mit $\dot{M}$ Massenstrom des Dampfes A Strömungsquerschnitt $\xi = \xi(Re)$ Widerstandsbeiwert, z.B. nach Blasius $\xi = \frac{0{,}3164}{\sqrt[4]{Re_D}}$ mittlere Massenstromdichte $\dot{m} = \frac{\dot{M}}{A} = \sqrt{\frac{1}{3}(\dot{m}_{ein}^2 + \dot{m}_{ein}\,\dot{m}_{aus} + \dot{m}_{aus}^2)}$ $\dot{m}_{ein}$ und $\dot{m}_{aus}$ sind Massenstromdichten am Ein- bzw Austritt des Rohres. Die Reynoldszahl Re_D ist zu berechnen, als ob kein Kondensat im Rohr sei.		

Back-up

(1) Gnielinski correlation



Strömung	Gnielinksi		
durchströmte Rohre $\vartheta_w = const.$ 	$Nu_d = \frac{\xi/8 \; Re_d \, Pr}{1 + 12{,}7 \sqrt{\frac{\xi}{8}} \left(Pr^{2/3} - 1\right)} \left[1 + \left(\frac{d}{L}\right)^{\frac{2}{3}}\right]$ mit $\xi = (1{,}8 \, \log(Re_d) - 1{,}5)^{-2}$	turbulent $10^4 \leq Re_d \leq 10^6$	$0{,}1 \leq Pr \leq 1000$ $\frac{d}{L} \leq 1$

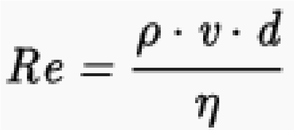
(2) Nußeltzahl

Definition	$Nu = \frac{\alpha \cdot L}{\lambda_l}$

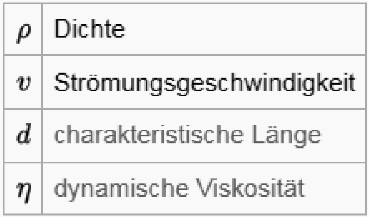
α	Wärmeübergangskoeffizient
L	charakteristische Länge
λ_l	Wärmeleitfähigkeit des Fluids

Back-up

(1) Reynoldszahl



$$Re = \frac{\rho \cdot v \cdot d}{\eta}$$



ρ	Dichte
v	Strömungsgeschwindigkeit
d	charakteristische Länge
η	dynamische Viskosität