Research Centre Rez

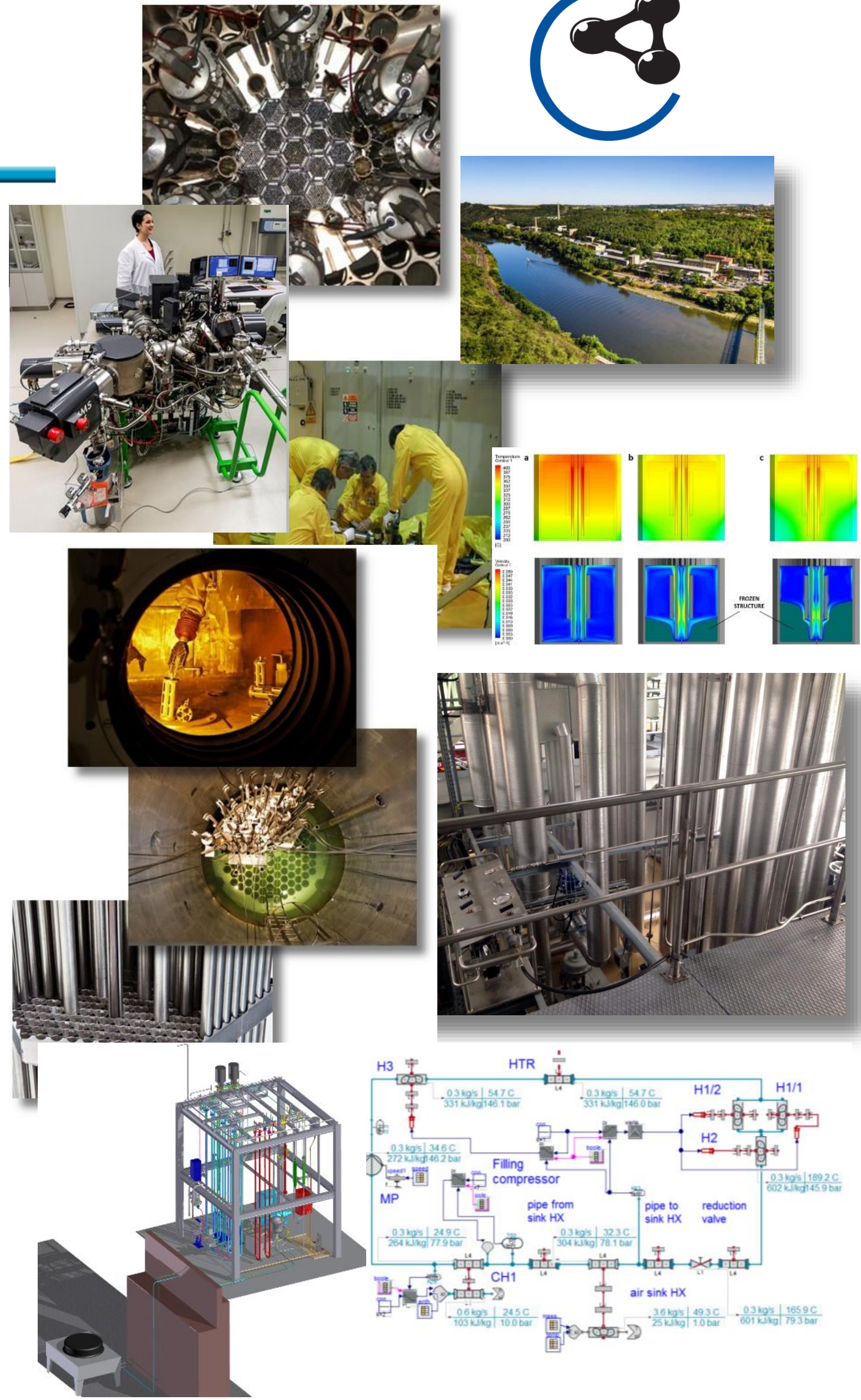
Using ClaRa for controller tuning of a sCO2 test loop

A. Vojacek

2nd ClaRa User Meeting 2019
June 4, 2019, Hamburg, Germany

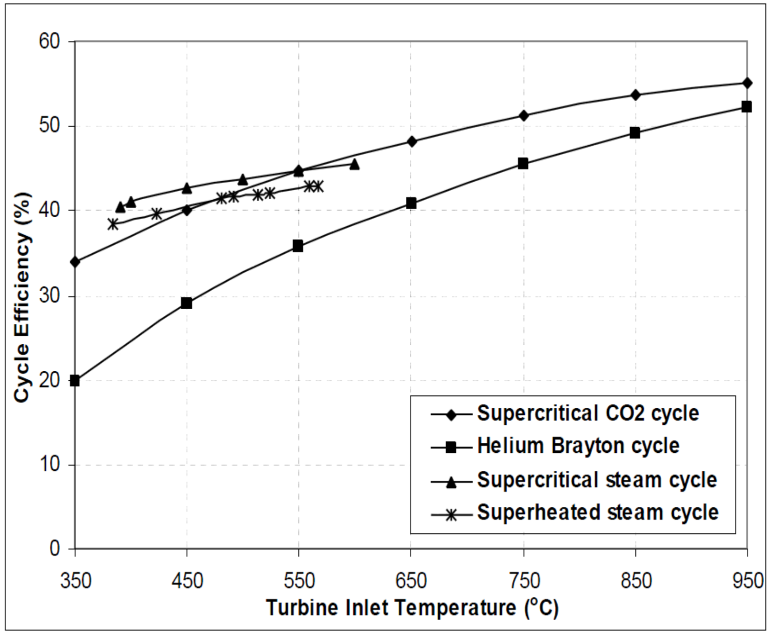
Centrum výzkumu Řež s.r.o. - CVR

- **Since 2002 (Member of the UJV Group)**
- **Research organisation concentrating on research, development and innovation in the energy sector, primarily nuclear.**
- **250 experts, engineers and technicians dedicated to new ideas and solutions**
- **Operating large research infrastructure:**
  - Water pool type reactors LVR-15 (10 MW), LR-0 (0 MW)
  - Experimental loops (sCO_2, supercritical water, helium, Pb/PbBi, FLIBE)
- **Technical calculation, Independent technical support for the nuclear regulator, Research in GEN IV technologies, Fusion, Hydrogen, Energy, storage, Fuel Inspections, Microstructural and microchemical labs, Severe accidents laboratory (LOCA), NDT and materials testing laboratories, Hot cell laboratory**

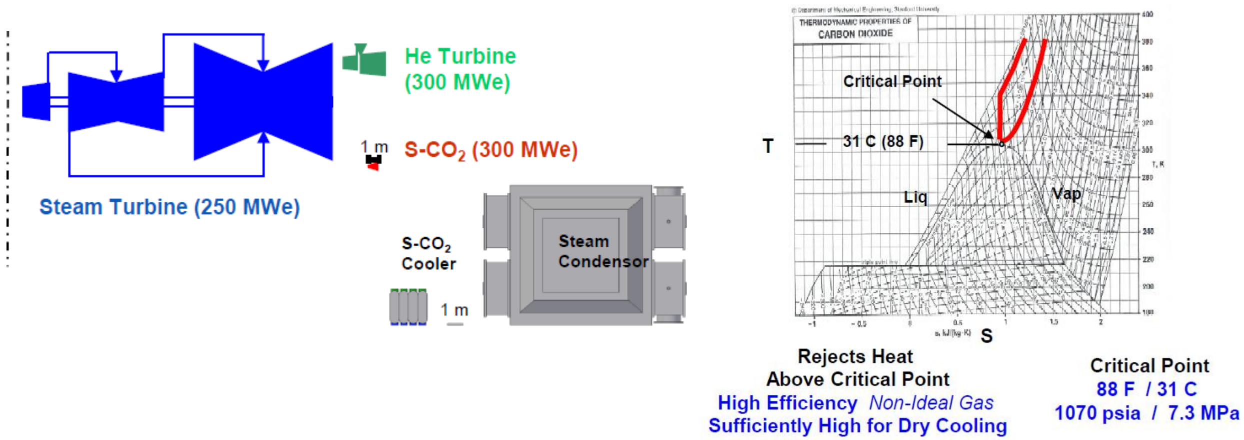


Why sCO_2 conversion cycle?

- A competitive alternative to the dominated steam Rankine cycles, gas Brayton cycles or their combination.
- sCO2 cycles combine many advantages of both the steam Rankine cycle (minimizing the power requirement for compressing the working fluid + heat rejection at low temperatures) and Brayton gas cycle (small size, modular design, fast built units, cheaper solution).



- Better flexibility of the cycle
- The whole cycle is under supercritical conditions
- – no two phase flow – no maintenance of low pressure turbine is needed due to blade damage



CVR projects

- **GoFastR (Gas cooled Fast Reactor) / FP7 / 2010-2013**
  - Partners: AMEC, Areva, KIT, Rolls-Royce, CVR …….
  - Optimisation of sCO2 cycle for GFR reactor
- **SUSEN (Sustainable Energy) / 2012 – 2017 / sCO2 loop built**
  - Design, construction, calculations, fabrication, commissioning
  - First tests finished (TG, HXs)
- **sCO2-HeRo (sCO2 Heat Removal system) / H2020 / 2015 – 2018**
  - Partners – UDE, USTUTT, GfS, TUD, CVR, UJV,
  - Goals – sCO2 safety system for present NPP, micro-scale demonstration unite
- **Internal project / 2017 – 2018 / Design of Fluoride salt cooled High temperature Reactor - potential applications for small modular reactors with sCO2 conversion cycle**
- **sCO2-Flex / H2020 / 2018 – 2020**
  - Partners – EDF, GE, FivesCryo, USTUTT, UDE, POLIMI, CVR, UJV, CSM, ZABALA
  - Goals – design of 25MWe sCO2 cycle powered by coal fired boiler
- **sCO2-4-NPP (continuation of sCO2-HeRo) / H2020 / 2019 – 2022**
  - Partners – EDF, GE, UDE, USTUTT, GfS, CVR, UJV, JSI, ARTIC
- **sCO2-EFEKT (demonstration unit of sCO2 cycle – cca. 1MWe)/ 2019-2024**
  - Partners – Doosan, Sobriety

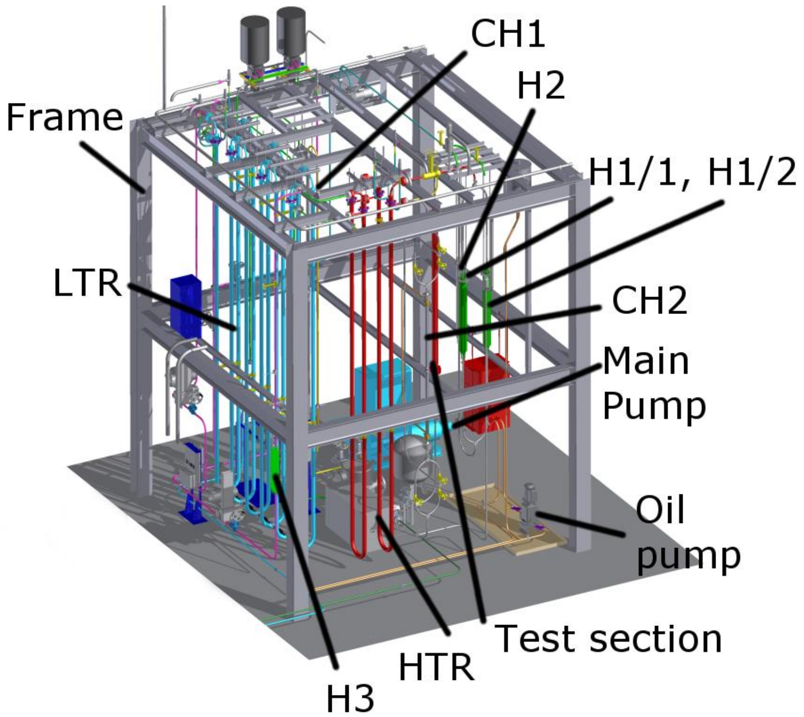
CVR sCO2 experimental loop description

- **The sCO2 experimental loop was constructed within SUSEN (Sustainable Energy) project in 2017**
- **Providing a facility to study key aspects of the sCO2 Brayton cycle (heat transfer, system dynamics, performance of compressor and turbine, corrosion, erosion etc.) with wide range of parameters: temperature up to 550°C, pressure up to 30 MPa**
- **The sCO2 loop is flexible, easy to modify and suitable for testing key components of the Brayton cycle:**
  - compressor and turbine
  - heat exchangers
  - heaters
  - Valves
- **Experimental TH data obtained from sCO2 loop is used for benchmarking, validation and further improvement of the computational codes developed.**
- **Workshops for the sCO2 community, industrial partners and students will be organized to present results and to popularize the sCO2 activities.**

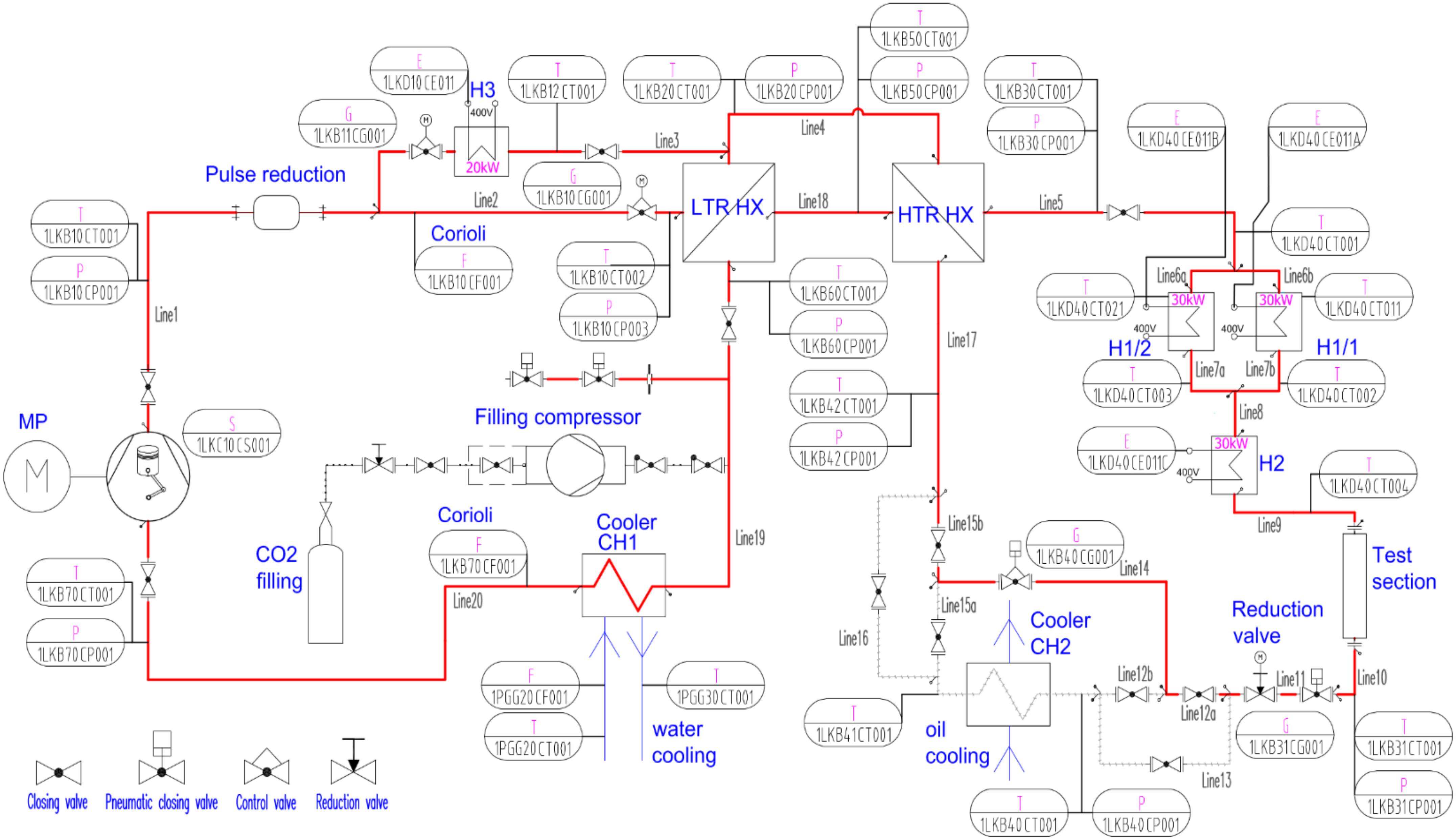
CVR sCO2 experimental loop description

- **The main operating parameters of the sCO2 primary loop**

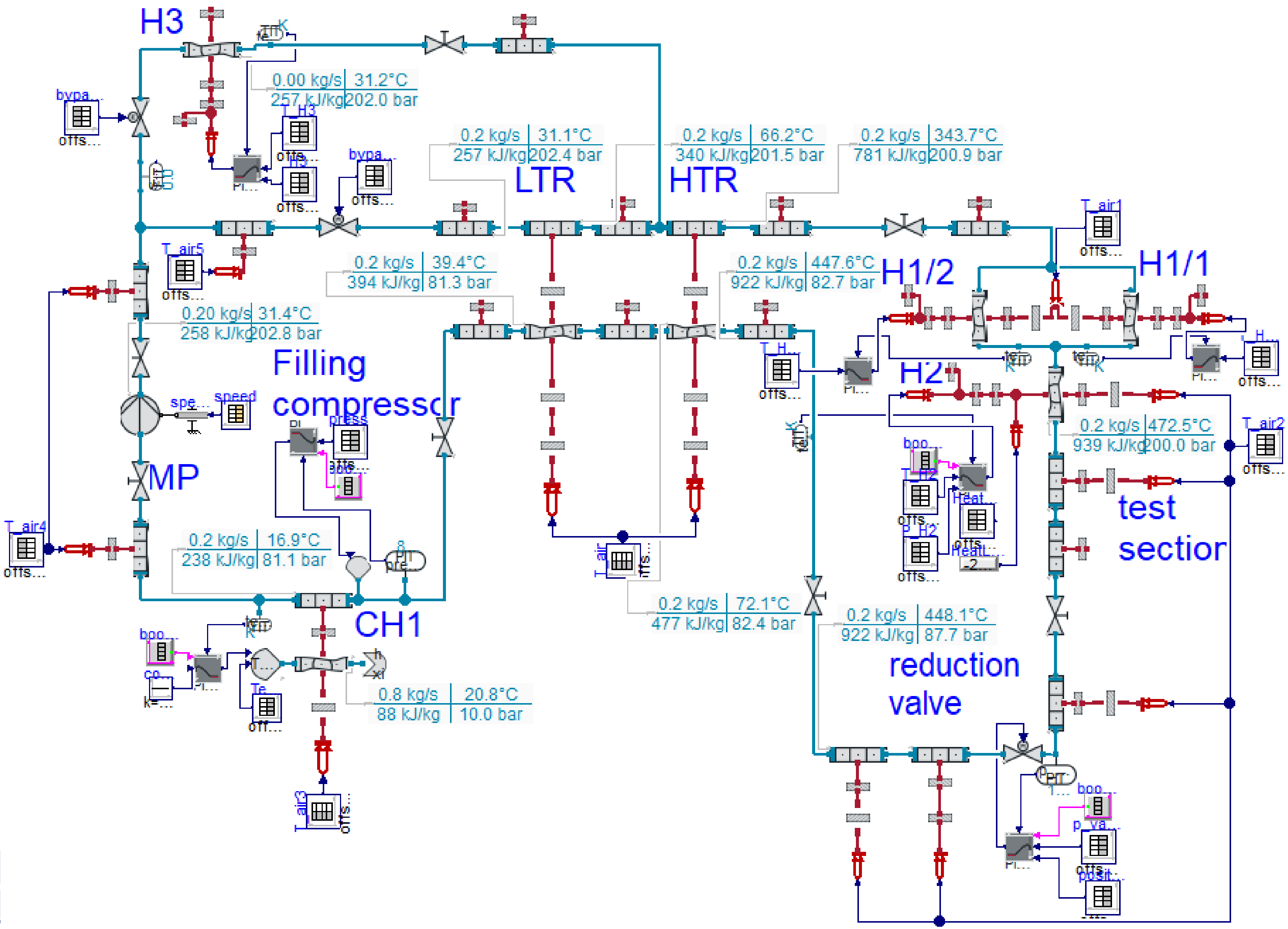
Parameter	Value
Maximum operation pressure	25 MPa
Maximum pressure	30 MPa
Maximum operation temperature	550°C
Maximum temperature in HTR	450°C
Maximum temperature in LTR	300°C
Nominal mass flow	0.35 kg/s
Total heating power	110 KW



SUSEN sCO2 loop



sCO2 SUSEN loop in ClaRa – steady state

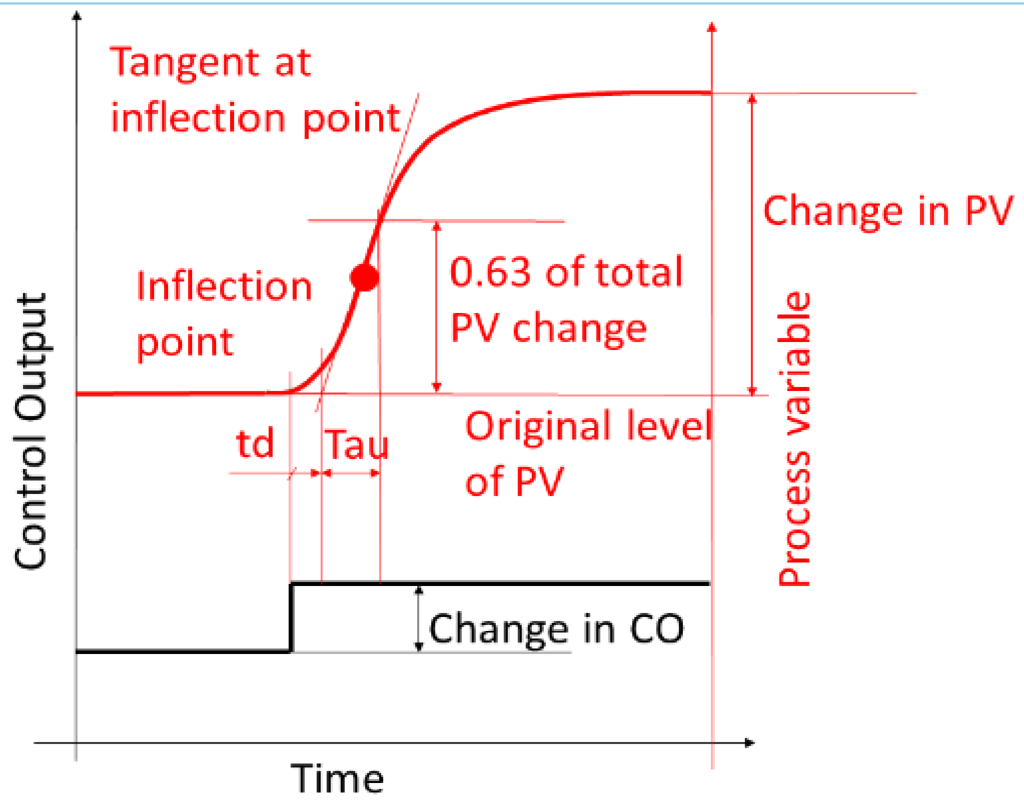


Tuning of PID controllers

- Currently the PID algorithm is the most popular feedback controller used in industry.
- Many tuning techniques have been developed over the past several decades.
- Cohen-Coon tuning rules is one of the most used technique in industry since it is suited to a wider variety of processes.
- Important: Knowing the form of the algorithm used for the PID controller tuning (The main PID structures (Interactive, Non-interactive and parallel).

$$CO = K_c \cdot \left(e(t) + \frac{1}{T_i} \int e(t)\, dt + T_d \frac{de(t)}{dt} \right)$$

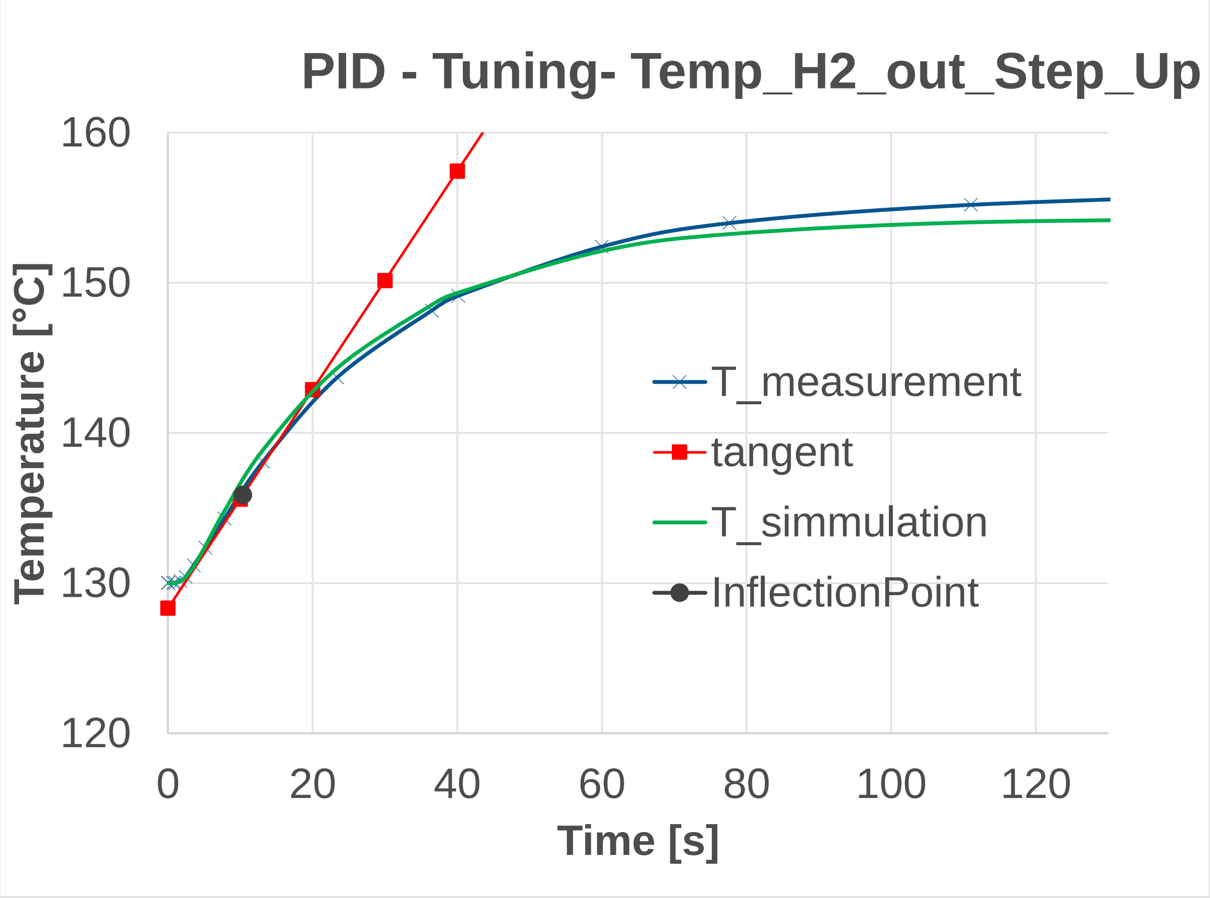
Tuning of PID controllers



	K_c	T_i	T_d
P controller	$\frac{1.03}{GP}\left(\frac{Tau}{td}+0.34\right)$		
PI controller	$\frac{0.9}{GP}\left(\frac{Tau}{td}+0.092\right)$	$3.33td\left(\frac{Tau+0.092td}{Tau+2.22td}\right)$	
PD controller	$\frac{1.24}{GP}\left(\frac{Tau}{td}+0.129\right)$		$0.27td\left(\frac{Tau-0.324td}{Tau+0.129td}\right)$
PID controller	$\frac{1.35}{GP}\left(\frac{Tau}{td}+0.185\right)$	$2.5td\left(\frac{Tau+0.185td}{Tau+0.611td}\right)$	$0.37td\left(\frac{Tau}{Tau+0.185td}\right)$

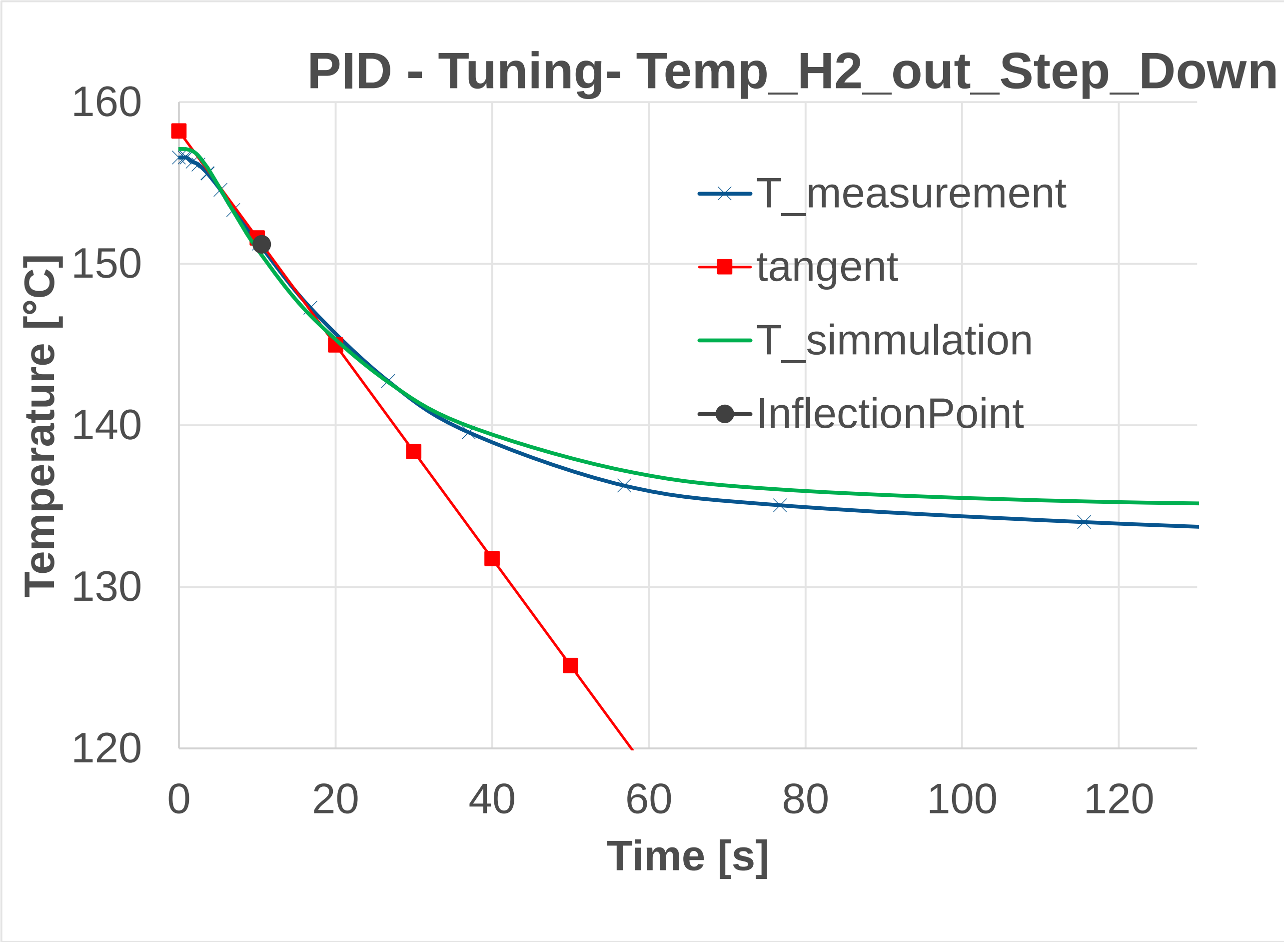
Tuning of PID controllers and comparison with measured data

- ***Step-up***
- **Firstly, a sudden step-up increase in H2 power output (from initial 6.2 kW to final 10.9 kW) was initiated at stable system. The response curve of the process variable (temperature)**



Tuning of PID controllers and comparison with measured data

- ***Step-down***
- **In order to verify the first test, second step test was conducted after the stabilization of parameters in the system. A sudden step-down decrease in H2 power output (from initial 10.9 kW to final 6.6 kW) was initiated at stable system. The response curve of the process variable (temperature)**



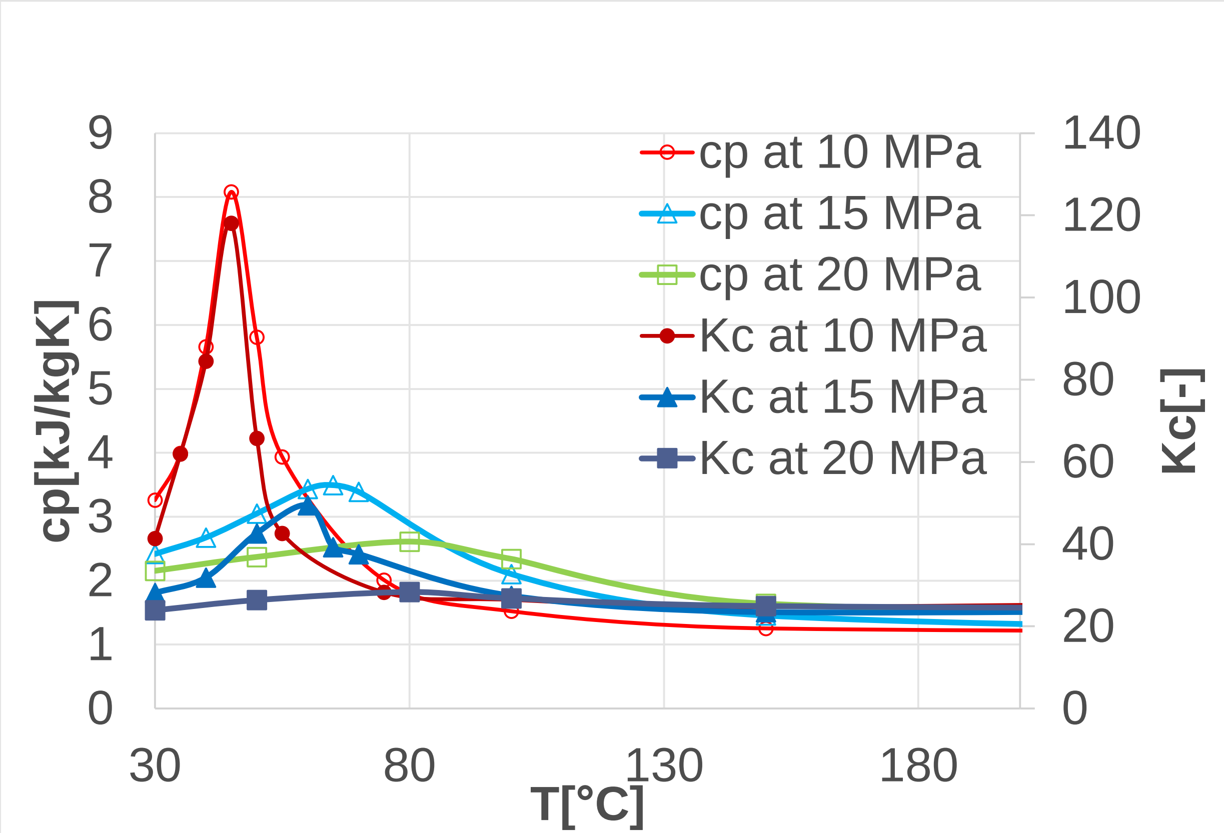
Tuning of PID controllers and comparison with measured data

- PID tuning settings for measured and simulated data

	Kc	Ti	Td
Step-up test – measured	29.14	5.60	0.85
Step-down test - measured	26.79	5.97	0.90
Average - measured	27.96	5.79	0.88
Step-up test – simulated	26.79	5.35	0.81
Step-down test - simulated	26.33	5.24	0.79
Average - simulated	26.56	5.30	0.80

Tuning of PID controllers for multiple Process conditions

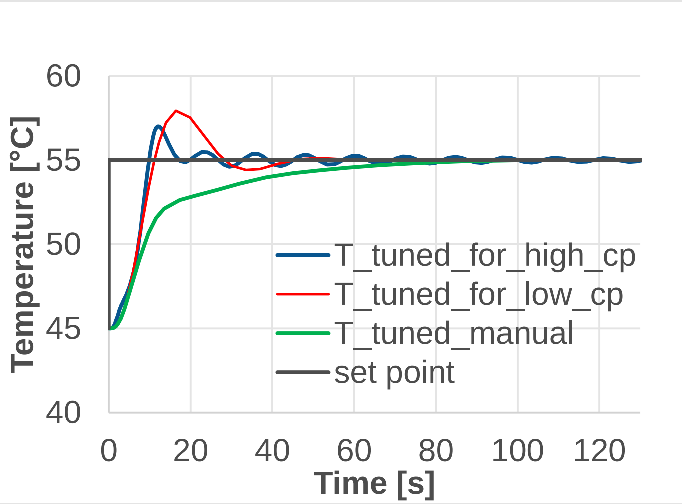
- **Fluid properties of the sCO2 near the critical point experiences highly non-linear variations.**
- **To demonstrate that series of response curves with different conditions (pressure 10 MPa ÷ 20 MPa, temperature 30 °C ÷ 400 °C) were simulated and tuning constants of the PID controller were derived using Cohen-Coon method for each case.**

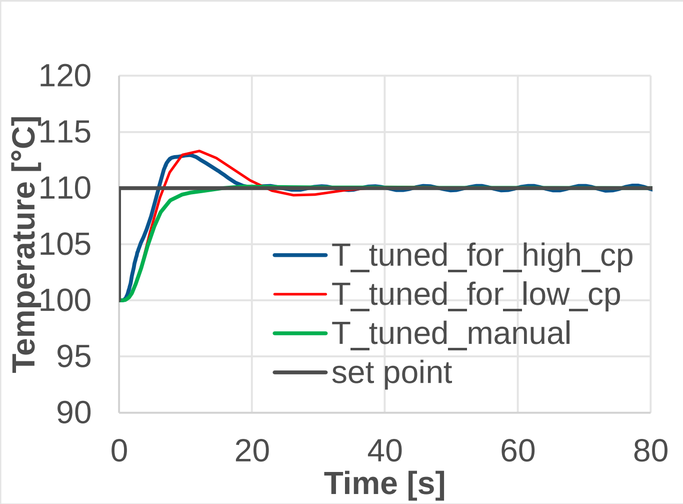


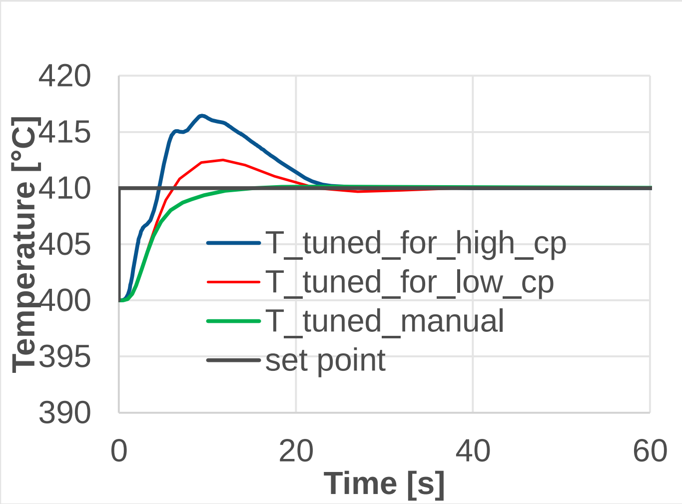
- **The specific heat capacity (cp) is peaking at so called pseudo-critical temperatures and similarly the controller gains.**

Testing of settings

- **Testing of behavior of PID controller of the temperature outlet from H2 during the step change of set point. For demonstration, two extreme PID sets were chosen together with manually tuned constants.**
  - parameters tuned for the highest cp approx. 8 $kJ \cdot kg^{-1} \cdot K^{-1}$ (Kc=118, Ti=3.7 s, Td=0.6
  - lowest cp approx. 1 $kJ \cdot kg^{-1} \cdot K^{-1}$ (Kc=25, Ti=5 s, Td=1 s)
  - manually tuned PID following constants (Kc=25, Ti=20 s, Td=1 s)







- **process variable, controlled by PID with settings tuned for high cp, exhibits comparatively high overshoots and instabilities, especially for the higher temperatures test cases (above 100°C). Improvement can be seen for the low cp tuning. It still exhibits quite high overshoots, however the oscillations were significantly reduced. The manually tuned controller behaves well for all 3 tested temperatures.**

Conclusion

- Dynamic model of sCO_2 was created using ClaRa
- Firstly, numerical model was checked with experimental data on steady/transients states
- Secondly, transient tests covering the tuning procedure of the PID controllers were performed. The scope of the study is to give a first approximation of tuning parameters of such a system. For this purpose, one of the most utilized tuning technique, the Cohen-Coon (C-C) method, was deployed.
- The discrepancy of the PID sets derived from simulations and experiment is within 10%.
- Different settings of PID controller were tested on several examples. It has been found that the tuned PID constants according to C-C method exhibits relatively high overshoots. It is due to the fact that different tuning techniques gives preferences to fast response prior to stable behavior. The results from the study indicates that C-C method prefers fast response.